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Haptic Feedback for Flight Envelope Protection

Dirk Van Baelen

Haptic Feedback
for
Flight Envelope Protection

HAPTIC FEEDBACK FOR FLIGHT ENVELOPE PROTECTION

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. dr. ir. T.H.J.J. van der Hagen,
voorzitter van het College voor Promoties,
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door

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Propositions

accompanying the dissertation

HAPTIC FEEDBACK FOR FLIGHT ENVELOPE PROTECTION

by

Dirk VAN BAELEN

1. Aircraft manufacturers should implement task-related haptic feedback on the flight deck. (this thesis)
2. Asymmetric vibrations can not only be used to alert pilots when unsafe aircraft states are imminent, but also to provide them with directional cues for control inputs towards safer states. (this thesis)
3. Asymmetric vibrations improve pilot learning rate to stay within flight envelope limits and - combined with their relatively low-cost implementation - should be used in flight training simulators. (this thesis)
4. Haptic guidance cues immediately increase a pilot's capability to stay within flight envelope limits, and should therefore be used in real flight, despite being more intrusive. (this thesis)
5. When applying Billings' design principles to haptic feedback, it follows that pilots should always be able to overrule any haptic feedback provided.
6. There is an inherent ambivalence in investigating pilot behaviour at the edges of the flight envelope: you want the pilot to approach the limit to see how (s)he behaves, and you want the pilot to stay away to prove the validity of your design.
7. Experiments with humans inherently have at least two confounding factors:
the participant and the experimenter.
8. Time spent on activities not related to the doctoral study is a good indicator of progress in the doctoral study.
9. Trying to think of a proposition which proves the uselessness of propositions, actually proves the usefulness of propositions.
10. A nice cycling ride in Belgium gets you the fastest on top of the highest ~~mountain~~ hill; a nice ride in the Netherlands is neither the highest, nor fastest, it is one that does not end in a ditch ("gracht"). (home-work travel)

These propositions are regarded as opposable and defendable, and have been approved as such by the promotors dr. ir. M. M. van Paassen and prof. dr. ir. D. A. Abbink.


LET ISABELLE GUIDE YOU
THROUGH MY THESIS
LIKE SHE DID FOR ME

SUMMARY

Improving the safety level of aviation is vital to prevent serious accidents. One key area where improvements can be made is the prevention of loss of control occurrences, by preventing the aircraft state to pass beyond the limits from which no recovery is possible. Such improvements can focus on improved monitoring of the main flight parameters and active automation modes.

The limits of an aircraft are typically expressed in terms of a flight envelope which represents the allowable region of load factor versus velocity. Modern day aircraft can support pilots in monitoring the main flight parameters by employing a flight envelope protection system: the inputs of the pilots are routed to the flight control computers which can impose limits on those inputs. In doing so, the computers are protecting the aircraft state from leaving the flight envelope.

When the control device is linked to the control surfaces, for example using cables and pulleys, any limit imposed by the flight control computer can be felt by the pilot. With the advent of fly-by-wire control devices, the mechanical link is replaced by an electrical connection, resulting in the loss of this information using the sense of touch. This haptic information was initially not included as it requires active control devices which had issues regarding the size, power and stability requirements. The lack of such haptic information on the flight envelope protection system might have been a contributing factor in some accidents.

Nowadays active control devices do meet the requirements in terms of size, power and stability, and offer the possibility to re-introduce haptic feedback in fly-by-wire control systems. Therefore, this thesis looked at adding haptic feedback to the control device of a modern aircraft to increase pilot awareness of the flight envelope protection system.

First design iteration Based on literature, two main groups of haptic feedback were identified: vibro-tactile cues, for example vibrations on the side stick, and force feedback, such as changing stiffness for certain deflections. A first iteration, based on previous exploratory research, included both vibro-tactile cues and force feedback.

The design provided the pilots with a total of five cues: it (i) informs the pilot about an approaching limit using a single force pulse, called a 'tick-on-the-stick', (ii) indicates a non-desired control direction using the spring coefficient, (iii) warns the pilot of a dangerously low velocity using a stick shaker, (iv) shows a desired control input during an over-speed event by moving the control device, and (v) indicates the required control input at low velocities when a stick neutral position is not sufficient by moving the control device.

An evaluation using eleven professional Airbus pilots who flew a windshear and an icing scenario showed no significant changes in performance and safety margins for any of the conditions. It did show that the haptic feedback is not hindering pilots in performing their tasks and in the debriefing pilots indicated that they had an increased

situation awareness. The pilots expressed a clear potential benefit of implementing the haptic feedback system on a fly-by-wire flight deck.

This first experiment did show two possible points of improvement: the reason for the haptic feedback cues was not always clear, and the direction included in the tick-on-the-stick was ambiguous. To further investigate these challenges, they are isolated and analysed in smaller experiments.

Complementing visuals To make the triggering of the haptic feedback more transparent, a visual display was designed to supplement the haptic feedback. This new visual display, based on the existing primary flight display, showed all relevant variables for the haptic feedback. Using uniform colours, the triggering points were indicated, together with line thicknesses indicating the strength and direction of the haptic feedback.

The visual display was evaluated using sixteen professional Airbus pilots who flew a windshear, sidestep and go-around scenario. Results did not show significant differences in performance or safety margins when enabling or disabling the new display. The debriefing did show that pilot appreciation of the haptic feedback marginally increased and that they better understood the haptic feedback. Hence, we recommend to supplement haptic feedback on a flight deck with a visual support.

Vibrations design A haptic feedback system which involves only one group of haptic feedback, i.e., either vibro-tactile or force feedback, might be simpler to design and certify. Since the initial tick-on-the-stick was particularly well received by the pilots, a design with only vibro-tactile cues was considered next. Pilots did indicate that the direction of the cue was not clear, which required an investigation in a more effective vibration.

Using a just-noticeable-difference experiment, where the lowest perceivable threshold is determined, a sawtooth-shaped vibration was found to have best properties. Participants were able to indicate that a cue was provided and which direction it indicated. This type of vibration was therefore used in a next haptic feedback system to provide the pilot with a cue on the onset of the flight envelope protection, and an intermittent vibration for the duration of the protection activation.

This design was evaluated using 24 PPL/LAPL pilots who flew a challenging profile and encountered a windshear. Results showed again that the metrics did not change significantly. The results did show that the group of twelve participants who started with haptic feedback had a higher learning rate, compared to the other group of twelve participants who started without haptic feedback, and the former group did not have a change in metrics when the feedback was removed. This indicates a training benefit of the haptic feedback design using vibrations.

Guidance design Next, a haptic feedback system using the other group of feedback, force feedback, was designed. Literature showed that this system should be able to support the pilot from the first use, which was not the case for the vibration design. The force feedback design is actively moving the side stick to indicate the required input by the flight envelope protection system, and is increasing the stiffness for deflection which bring the aircraft state closer to the limits.

It was evaluated using another 24 PPL/LAPL pilots who flew the same scenarios as for the vibrations design: a challenging profile with a windshear encounter. Results showed that the twelve participants who were provided with the guidance design achieved improved safety margins from the first use, yet a deterioration was present when the feedback was no longer present. Participants who received no haptic feedback at all, confirmed the improved learning rate of the vibrations design, and the improved metrics at first use of the guidance design.

Conclusion Although the first design iteration had no conclusive results, the last two experiments showed that haptic feedback can be a useful addition to the flight deck. A vibration-based design can improve learning rate, which shows that pilots become more aware of the flight envelope, and is therefore recommended for use in training simulators. A guidance design can support pilots from the first use, again showing that pilot are more aware of the flight envelope, yet thie support has to be always provided. In conclusion, haptic feedback can be used to improve pilot situation awareness of the flight envelope protection system.

CONTENTS

Nomenclature

ADIRU	Air Data and Inertial Reference Unit
ATC	Air Traffic Control
ELAC	Elevator & Aileron Computer
FAC	Flight Augmentation Computer
FBW	Fly-By-Wire
FCC	Flight Control Computer
FCOM	Flight Crew Operation Manual
FCU	Flight Control Unit
FD	Flight Director
FEP	Flight Envelope Protection
FMGC	Flight Management Guidance Computer
HFL	Haptic Feedback Law
HMI	Human Machine Interaction
ILS	Instrument Landing System
LAPL	Light Aircraft Pilot License
LGCIU	Landing Gear Control Interface Unit
ND	Navigation Display
PFD	Primary Flight Display
PPL	Private Pilot License
RA	Radio Altimeter
RSME	Rating Scale Mental Effort
SEC	Spoilers & Elevator Computer
SFCC	Slat Flap Control Computer
SIMONA	Research Facility for SImulation, MOtion and NAvigation
THS	Trimmable Horizontal Stabilizer
TOGA	Take Off/Go Around

Greek Symbols

α	Angle of attack, rad
β	Side slip angle, rad
γ	Flight path angle, rad
δ	Control device deflection, rad
θ	Pitch angle, rad
ρ	Density, kg/ m^3
ϕ	Roll angle, rad

Roman Symbols

a	Acceleration, m/ s^2
b	Damping, Nm s/rad
C_L	Lift coefficient, -
D	Drag, N
F	Force, N
g	Gravitational acceleration, m/ s^2
I	Amplitude of the discrete tick, Nm
K	Gain, -
k	Spring, N/ rad
L	Lift, N
M	Mach, velocity relative to the speed of sound, -
m	Mass, kg
n	Load factor, g
q	Pitch rate, rad/ s
S	Surface, m^2
T	Thrust, N
t	Time, s
V	Velocity, m/ s
W	Weight, N
x	Distance from starting position, m

Subscripts

a	Aerodynamic reference frame
b	Body reference frame
br	Breakout
E	Vehicle-carried normal Earth reference frame
$haptic$	Contribution of the haptic feedback system
$human$	Human/pilot contribution
lat	Lateral value
lon	Longitudinal value
max	Maximum value
MO	Maximum operational value
min	Minimum value
nom	Nominal value
np	Neutral point
$prot$	Protected region value

1

Introduction

TRANSPORTATION safety is important for public trust and maintaining or increasing the safety level is essential, particularly in aviation where accidents are highly visible. [1] In order to make sure that the number of accidents does not grow, and even decreases, the current aviation safety level should be maintained and preferably improved. When looking where this improvement can be made, aviation safety boards, such as the European Union Aviation Safety Agency EASA, and airline associations, for example the International Air Transport Association IATA, indicate that one key area to improve is the number of occurrences of loss of control in flight. [2, 3] A loss of control event occurs when the aircraft reaches an unintended state, beyond intended operating limits, from which recovery to a state back into desired operating limits may be difficult or impossible before collision or disintegration. Looking into the details of the annual safety reports of the respective boards, aircraft limit excursions due to weather phenomena, and inadequate monitoring of main flight parameters or autopilot modes, are identified as some of the main contributors to loss of control. As such, improving the monitoring of main flight parameters and automation modes is a key step in ensuring future safe aviation.

Steps have been made in the past to ensure that pilots are informed about the limits, and even to prevent them to exceed the limits of the airplane. These allowable aircraft limits can be described in multiple ways, of which the most important for the current thesis is the flight envelope, which describes an allowable region of velocity and load factor combinations. In current day aircraft, these limits can be guarded by a Flight Envelope Protection (FEP) mechanism: the inputs from pilots are routed to the flight control computers which can act on approaching limits. One possibility is to impose hard limits on those input and, in doing so, the computers are effectively making sure that an input does not result in an aircraft state outside the allowable region, hence keeping the aircraft within an acceptable flight envelope.

When such a system is implemented on a set of reversible flight controls, i.e., there is a hard link from the control surfaces to the control device by for example a combination of cables and pulleys, any limit imposed by the FEP can be observed by the pilot by *feeling* what the controls are doing, i.e., by the haptic feedback present in the control device. A typical example with extreme effect: a stick-pusher as present in some high-tail configuration aircraft such as the Lockheed F-104 Starfighter, which provides a strong stick-forward force for high pitch rates and angles of attack, resulting in a nose-down input and protecting the aircraft from stalling. [4]

With the advent of fly-by-wire control devices, the mechanical link between the control device and control surfaces is lost, however, and sensors register the control device properties and use electrical wires to communicate pilot intent to the computer. The information of the FEP is therefore not observable anymore by the pilot using the sense of touch. Losing the direct mechanical connection from the pilot to the protection system might give rise to miscommunication between the pilot and the automation. [5, 6]

Air France 447 was an Airbus A330, a fly-by-wire aircraft with a passive control device, flying from Rio de Janeiro to Paris. Two hours in flight, the aircraft reverted to a less stringent FEP system due to a sensor failure. Surprised by the high altitude dynamics of the Airbus A330 aircraft and confused about the active FEP modes, the pilots stalled the aircraft, resulting in a fatal crash. The approaching stall would have been seen on the display in front of the pilots in a normal situation. Unfortunately, due to the sensor failure, this visual information was not present. The stall was only communicated to the pilots with an aural warning, initially masked by a master caution warning. A buffet could occur, yet no clear mentioning of the buffet phenomenon is made in pilot training. The accident report indicates that “The addition of a visual signal to supplement the audible signal (warning) and the proprioceptive signal (the buffet), would provide the crew with additional information to enable them to escape from an erroneous understanding of the situation.”. [7] Although not discussed in the accident report, this additional signal on the stall does not necessarily need to be a visual signal. Such a signal could be provided to the pilot using the sense of touch, which requires an active control device.

In another case, Air Asia 8501, an Airbus A320 rudder limiter malfunction, resulted in a degraded FEP mode which disengaged the autopilot. It took the pilots nine seconds before a correcting action was inputted, in which time the aircraft had reached a bank of 54°. The delayed response of the pilot was likely due to his attention not being on the primary display. Their subsequent actions resulted in extreme bank angles and a prolonged stall. This flight also crashed, resulting in loss of life for all crew and passengers. [8] In order to prevent similar accidents from re-occurring, the author feels that the pilot should be supported with information on the crucial states, especially during the initial bank where the attention of the pilot was distracted from the displays. One possibility to support the pilot during such a situation could be to use human sense other than the visual: an aural warning, or, again, a signal using the sense of touch.

In both cases, the aircraft, an A330 and A320, have a computerized system providing FEP, and a passive control device, providing pilots with no direct haptic feedback on that system. These examples indicate that not having this direct means of feedback might contribute to reduced pilot awareness on the aircraft state, which poses dangers especially when sensor failures occur and the FEP system reverts to less protected regimes.

A reason that this haptic information was not fully integrated after the introduction of fly-by-wire systems, is the device itself required to implement the forces. This used to be an issue because of the size, power and stability requirements resulting in certification problems. However, nowadays low-weight reliable force feedback for control devices offer the possibility to re-introduce haptic feedback in the fly-by-wire control systems. [9]

Connecting the pieces of the puzzle presented above, increased automation on the protection of the aircraft limits, and the loss of haptic information to the pilot, gives us a straight-forward possibility: use the haptic feedback to present pilots with information on the FEP. This could be done by replicating the force felt on the control device in the ‘old’ system. Nevertheless, since the fly-by-wire setup is present, the feedback is not limited to these options. Using the information of the latest FEP systems and their parameters, much more advanced and/or innovative designs are possible. This is the main topic of this thesis: how to supply the pilot with haptic feedback on the FEP.

First, the information which is being provided to the pilot is explained in Section 1.1. To explore the possibilities of using the sense of touch as feedback to the pilot, Section 1.2 discusses existing solutions, in which haptic feedback is provided to a human operator, followed by the haptic feedback design options considered in this thesis in Section 1.3. Finally, the scope for the current research and the outline of the thesis are shown in respectively Sections 1.4 and 1.5.

1

1.1. Flight Envelope Protection

Although the haptic feedback concepts developed in this thesis are applicable to multiple environments, this thesis will use a setup similar to an Airbus A320. While the current A320 aircraft flight deck comprises a side stick, rudder pedals, and passive throttle levers, this thesis will focus solely on the side stick. As mentioned before, this is a fly-by-wire system, an (electrical) signal is sent from the side stick to the computers, no mechanical connection exists between the control surfaces and the side stick. During flight, the side stick is used to provide pitch attitude change commands to the flight control computers using a control law called C^*, which is further elaborated in Chapter 2. [10–13]

The flight envelope represents the allowable operating space of an aircraft, typically expressed in terms of limits on variables or combinations of variables. Different combinations of variables are used, for example the allowable angle of attack versus side slip angle, or roll rate versus velocity. When the aircraft is maneuvered to a state close to the edges of the nominal flight envelope, the computer can limit the inputs of the pilot to make sure the aircraft does not pass these limits, in other words, the computer keeps the aircraft state within the normal flight envelope. This thesis looks mainly at the flight envelope for longitudinal flight, which during both design and operation is typically represented by the allowable load factor versus velocity, and is used for the flight envelope protection system. [13]

The nominal limits of this flight envelope, as shown by the black line on Fig. 1.1, are determined by the maximal operation velocity (V_{MO}), the maximum and minimum load factor (respectively, n_{max} and n_{min}), and the velocity related to the maximum angle of attack ($V_{\alpha_{max}}$). When approaching these limits, the control law can be slightly altered, such that the pilot perceives the aircraft as having a natural tendency to stay away from those limits. The point at which these changes occur can be indicated in the flight envelope by a smaller region inside the nominal envelope, called the safe flight envelope, indicated by the dashed red line in Fig. 1.1. All states inside of this safe flight envelope can be considered as “safe” since there is sufficient margin to the limits.

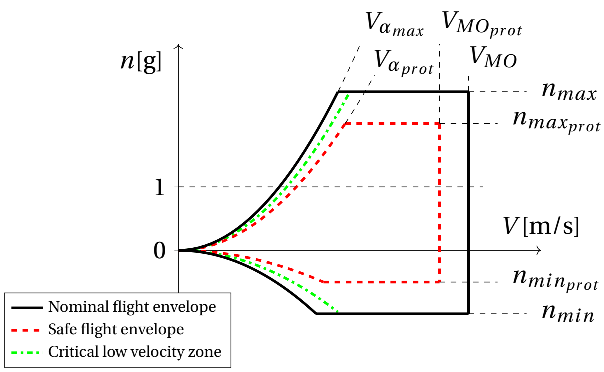


Figure 1.1: Flight Envelope: allowable load factor versus velocity

1

This flight envelope protection is possible when all computers and sensors are working. When a sensor fails, or a computer malfunctions, the aircraft can revert to a less protected state. In such a state, some flight envelope protections might be lost, increasing the risk of unusual attitudes, and allowing more extreme maneuvers to the pilot. The control law change at the limits of the safe flight envelope, and the different levels of protection of the nominal flight envelope are implemented on current fly-by-wire aircraft such as the Airbus A320 or A330. They are further elaborated in Chapter 2.

The entire control loop is summarized in Fig. 1.2, which illustrates the flight envelope protection setup: the flight control computers take both the input of the pilot, as well as the information of the flight envelope protection system. Based on these inputs, the inputs to the aircraft using the control surfaces are calculated. The information on the flight envelope is communicated to the pilot using both visual and auditory information.

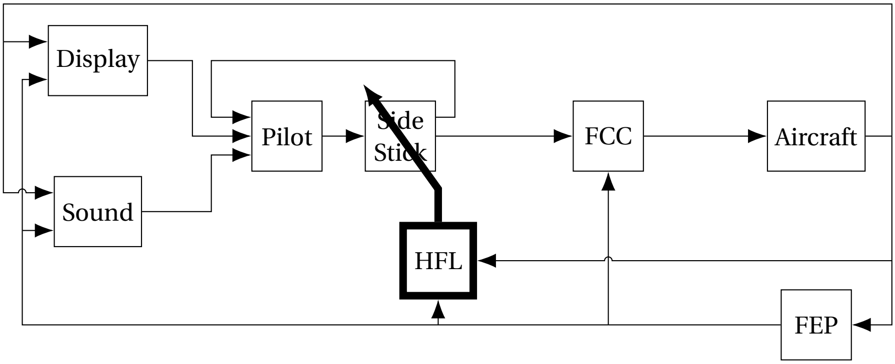


Figure 1.2: Pilot-aircraft control loop, combined with the haptic feedback as presented in this thesis in thick

It is, however, important to note that this information is not always clearly perceived by the pilots. Accidents have occurred, for example the crash of Air France flight 447 discussed before, where the lack of FEP and unawareness of the flight envelope limits might have been contributing factors. [7] It is therefore paramount to investigate whether more intuitive communication of this information is possible.

This thesis looks at the use of haptic feedback to provide the pilot with information on the flight envelope protection system. The implication of adding haptic feedback to the control loop is indicated in Fig. 1.2, using the thicker lines: an additional dependency of the side stick on the aircraft state and flight envelope protection system.

As the flight envelope protection system is directly linked to the distance of the aircraft state to the flight envelope limits, the information transmitted through the haptics will be the "relative distance of the current state to the limit". As such, when the aircraft state is clear of any of the flight envelope limits, the side stick will have nominal characteristics. When the aircraft state approaches the limits, the haptic feedback will become active together with the flight envelope protection system. In other words, the activation of the flight envelope protection can be observed by a possible change in control law *and* the haptic feedback, for which the haptic cues are elaborated in the next section.

1.2. LITERATURE ON HAPTICS FOR VEHICLE CONTROL

This section provides a brief overview of existing solutions which use haptic feedback to provide the human operator with information during the control of a vehicle. It provides the context of this thesis with some general applications, followed by some automotive and aerospace examples.

1.2.1. GENERAL APPLICATIONS

The first examples of haptic feedback use tactors, i.e., vibrating elements attached to some part of the body, to provide vibro-tactile feedback. The information transmitted by the tactors is mostly a warning and can be applied to almost any part of the body: fingers, arms, chest, legs, etc.

The literature involving tactors shows that it can be used to draw attention to a secondary task ([14–17]), spatial location of approaching traffic ([18]) and corresponding recommended action to avoid a collision ([19, 20]), act as an artificial horizon ([21–29]), and provide information on the state of the wing of an aircraft. [30, 31]

In summary, tactors are mostly used to provide the pilot with an alert of some system, or information on spatial orientation. They are not used to show the pilot information on the flight envelope limits, especially not on the proximity to these limits. Additionally, the tactors require the pilot to wear a specialist piece of equipment, either a vest or sleeves, which could be expensive, and personal to a pilot. If such parts are not worn correctly, the information might be encoded to a wrong part of the body resulting in wrong information. Combining all these possibilities and issues of tactile feedback, using only tactors was not deemed satisfactory for the intended application of this thesis.

Numerous examples exist where the control device is not just vibrating, yet the dynamical properties are actively changed. One example for the tele-operation of a UAV showed that the addition of artificial force can help the human controller avoiding hazardous areas. By providing the operator with forces to *avoid* certain areas, workload was reduced and safety increased. [32] Following this example, addition of forces on control device on the flight deck might be used to *avoid* areas outside the safe flight envelope. Artificial forces can also be used to *attract* a certain path, which was shown to be more effective for an abstract control task. [33] Such systems can be used to draw the attention of the pilot to a preferred region in the flight envelope.

Applications can have one path which is preferred, in the context of the thesis, one can think of a certain path through the flight envelope. When guiding the human operator along to that respective path, van Paassen et al. argue that such a design requires four choices: (i) the human-compatible reference path, (ii) the level of haptic support, i.e., feed-forward, (iii) the level of strength and strategy of haptic feedback, i.e., feed-back, and (iv) the overall level of haptic authority. [34]

1.2.2. AUTOMOTIVE APPLICATIONS

The driver of a car has similar objectives as a pilot: operate the car within the allowable limits the road. One simplified ‘driving envelope’ can define the allowable operating space by the side of the road and the distance to the car in front, the current state is the position car on the road. When operating the car within these limits, driving can be considered safe, and haptic feedback can be supplied to enhance safety and performance.

1

In order to protect the longitudinal element of the ‘driving envelope’, i.e., to avoid a head-on collision, haptic feedback can be provided through the gas pedal by increasing the stiffness when driving closer to the car in front. This was shown to improve car-following performance while reducing control activity. [35]

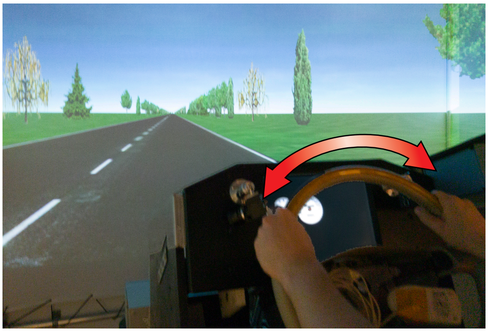


Figure 1.3: Example of haptic feedback applied to the steering wheel of a car in the HMI simulator at TU Delft

The lateral envelope can be protected by providing haptic feedback through the steering wheel as shown on Fig. 1.3, where vibrations can be used, so-called ‘motor-priming’, to provide a warning and direction similar to the vibrations shown before. [36] Active feedback which is more involving can be provided by using an offset force to indicate a required deflection, and changing the stiffness to indicate a criticality of the action. [37] This type of feedback can be used to provide support to either steer the car away from the boundaries, or steer the car to one specific path, comparable to the artificial forces discussed before. Within the automotive field, no clear preference is present and different techniques are tested. It was found that boundary-avoidance was susceptible to driver annoyance when the haptic system intervened too early, and steering towards a specific path might suffer from after-effects when no feedback is supplied. [38] Advantages and disadvantages for both types of feedback have to be kept in mind for designs in this thesis.

1.2.3. AEROSPACE APPLICATIONS

Within the aerospace domain, several haptic feedback designs have been investigated, where one design changed the control device position to communicate the autopilot commands to the pilot. This was preferred over a manual or fully-automated system. [39]

Most of the remaining research investigates whether the pilot can be supported in manual flying. As discussed before, two main groups can be distinguished: boundary-avoidance and path tracking. The latter group can be simplified as a system where both the autopilot and pilot operate the control devices, hence the aircraft. Such a ‘haptic flight director’ can improve pilot performance ([40]), and can be combined with guidance presented on a tunnel-in-the-sky display. [41] The direction of these forces can be changed: a pilot can be asked to follow the control device, i.e., exert no force, or can be asked to oppose the force, i.e. maintain position. Both improved control performance, yet the latter increased required physical effort. [42] These examples assume that there is a preferred path which is away from the boundaries. When the boundaries are exceeded, showing a preferred path to return the aircraft within its limits was found to be useful. [43]

The second group involves boundary-avoidance using haptic feedback. This was applied on a helicopter to provide the pilot with the limits on the engine using a visual indication and a soft-stop: a local step increase of force required to move the controls. It resulted in handling qualities benefits and reduced limit exceedances. [44, 45]

The controls in large passenger aircraft can be connected to a hydraulic system to adjust the control surfaces. This allows for larger forces, yet limits the control system by a maximum rate of change. When a limit on the rate of change is encountered, the pilot-vehicle system might develop an oscillatory response: a pilot-induced-oscillation. Haptic feedback has been used to prevent encountering such a rate boundary by increasing the static friction, or changing the natural frequency and damping. [46] Other designs increased the stiffness of the control device and lowered the gain on the pilot command when the hydraulic system ([47]), or, in the case of fly-by-wire, control law ([48]) was not able to keep up with the pilot command.

Older aircraft with reversible flight controls might still benefit from a retrofitted FEP system. This has been found to be useful, and as it acts directly on the cables connecting the control device and surfaces, the pilot can directly feel the system working. [49]

When a FEP is present, approaching the limits can be communicated to the pilot using an increased resistance force. This was shown to have a positive effect on flight safety. [50] Additionally, providing the pilot with a new visual display with information on the FEP can improve safety, yet might be difficult to add to the already visually loaded flight deck. [51] Another example involves haptic feedback that actively changes the reference point of the control input, and limits the deflection based on the remaining control space, complemented by a visual indication, showing promising results. [52]

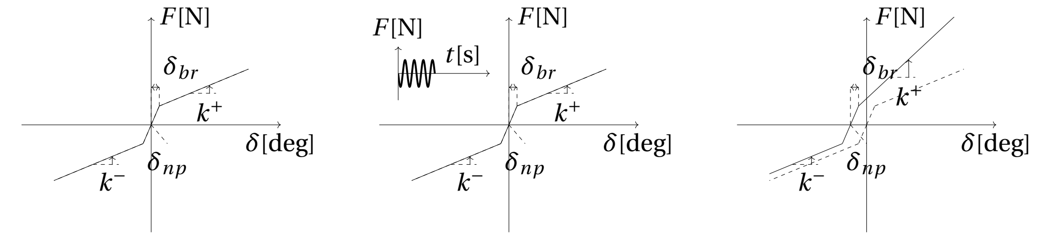
Figure 1.4: Example of haptic feedback applied to the side stick on the SIMONA flight deck at TU Delft

The examples in literature show that haptic feedback can be applied using multiple cues. Additionally, they show that there are a few examples which translate the limits of the aircraft to the pilot, and those examples do not provide a conclusive design rationale yet. It proves that there is still a lot to learn about haptic feedback for flight envelope protection. As such, an initial design has been setup and tested on a side stick shown on Fig. 1.4. [53, 54] This was, as the other designs presented here, showing promising results and proposed several points of improvement. This initial design, together with the lessons learned, formed the starting point of this thesis.

1.3. HAPTIC FEEDBACK DESIGN PARAMETERS

Many different applications, and matching definitions, of haptic feedback are possible. To clearly frame how this thesis looks at haptic feedback, the haptic profile is defined here as the amount of static force on the control device (F) required to move the control device to a certain deflection (δ). For most applications, for example the steering wheel in a car, the rudder pedals on the flight deck, as well as the side stick, the haptic profile resembles a linear or piece-wise linear relation as shown on Fig. 1.5a.

When no force is applied to a control device, it returns to a position called the neutral point (δ_{np}). From this position, the breakout deflection (δ_{br}) indicates a region with increased stiffness, as such, a threshold force is required to break the control device out of the neutral position. Next, the amount of force required for a given deflection is usually increasing linearly with the deflection, defined by the spring coefficient, up to a maximum allowed deflection (δ_{max}). The spring coefficient can have different values for both positive and negative deflections, respectively $k^+$and k^-.



(a) Default haptic profile: static force required to move the side stick

(b) Adding of stick shaker

(c) Increased stiffness for positive deflections and shifted neutral point

Figure 1.5: Haptic Profile: static force required to move the side stick

This conventional haptic profile provides the pilot with information of the input magnitude: larger inputs require larger forces. Following the examples from literature, additional haptic feedback is explored in this thesis by actively changing the haptic profile in two main ways: providing the pilot with vibro-tactile cues, and providing the pilot with force feedback. The first group, vibro-tactile cues, is a vertical shift of the haptic profile with a small effect in time. As such, to show what kind of vibrations are used, a time history of the vibration is shown next to the haptic profile on an inset graph, as on Fig. 1.5b. Such cues are typically used to indicate a critical region of the envelope. [36, 55]

The latter group, continuous force feedback, is a gradual change of the haptic profile, for example, changing the neutral point and stiffness of the side stick in one direction. This results in an altered haptic profile as shown on Fig. 1.5c. Such cues are typically used to indicate, respectively, required control inputs ([41, 56]), and unwanted deflections. [48]

The International Standarization Organization (ISO) defined that haptic feedback can be divided into both tactile and kinaesthetic feedback. [57] Since the cues shown here are considered to provide *both* tactile feedback through mechanical stimulation of vibro-tactile cues, and kinaesthetic feedback through torques on the body of the pilot induced by stiffness and neutral point changes, the more general term ‘haptic feedback’ is used to describe the type of feedback. These haptic cues will now be used throughout the thesis to provide pilots with feedback on the flight envelope protection system.

1.4. RESEARCH GOAL

The increased automation on current flight decks in the form of FEP, combined with the possibility of providing pilots with haptic feedback, presents a new research opportunity. Literature shows that haptic feedback can indeed be used to provide pilots with feedback on the vehicle/aircraft, nevertheless sources which provide the pilot with active feedback on the FEP are missing. Therefore, the main research goal for this thesis is given by:

Research goal

Within the current fly-by-wire flight deck, improve pilot situation awareness of the aircraft flight envelope protection system using haptic feedback.

Previous exploratory research by Ellerbroek et al. showed that a haptic feedback system for flight envelope protection can indeed be designed, yet that research lacks an in-detail description and a rigorous evaluation. [53] Therefore, the first task is to re-visit this design and to implement one of the main lessons learnt in that research: the addition of a discrete warning cue. Therefore the first research question of this thesis is stated by:

Research Question 1: Combining vibrations and guidance design

Does a haptic feedback design combining stiffness changes, neutral point shifts, stick shaker, and discrete cues improve pilot situation awareness?

Literature showed that information is best presented using multi-modal displays, i.e., using haptics *and* visuals. [58] The first iteration, the subject of Research Question 1, did not include a visual display and therefore the actions of the haptic support system might not always have been clear to the pilot. As such, providing a more transparent source of haptic information might be achieved when complementing it with a graphical, visual display. This is the topic of Research Question 2.

Research Question 2: Complementing visuals

What kind of visual display can be used to complement the haptic information?

Research Question 1 involves all haptic feedback cues elaborated in Section 1.3. Implementing a system which is capable of all cues might be difficult in terms of design or certification. A system which uses only a sub-set of those cues might be simpler to design/certify, for example a system using only vibrational cues, resulting in a system which only warns the pilot when approaching the limits. For this, a suitable cue has to be designed and it has to be evaluated whether such a simpler system may be equally useful. Both topics will be tackled with Research Question 3.

Research Question 3: Vibrations design

Does a haptic feedback design using only vibrations improve pilot situation awareness?

After a cueing system, a logical next system involves more active haptic feedback guiding the pilot near the limits. Such a system could use a change in stiffness to resist pilot inputs, and actively change the neutral point to indicate a required deflection. The investigation of such a guidance system is the topic of the last research question.

> Research Question 4: Guidance design
>
> Does a haptic feedback design combining stiffness changes and neutral point shifts improve pilot situation awareness?

1.5. OUTLINE

This thesis consists of seven chapters in two parts. Chapter two is published in a peer-reviewed journal, all other chapters have been published in the proceedings of peer-reviewed conferences. The details of these publications can be found at the beginning of each chapter. The chapters' content is equal to the publications, with small modifications for smoother transitions and more consistent terminology. As such, all chapters can be read independently.

After this introduction, the parts are structured to follow the research questions, shown in Fig. 1.6, and are elaborated in the following of this chapter. Part I presents the first iteration of the haptic feedback design following the initial research. Part II elaborates on the research to investigate specific aspects of the design. Finally, conclusions and recommendations are given in Chapter 8.

1.5.1. PART I: FIRST DESIGN ITERATION

The first part discusses the initial design, and applies the main lessons learnt from that evaluation. One main lesson learnt from the initial haptic feedback design: the pilots indicated that the transition into the FEP was not always clear and could perhaps better be indicated by just a tick-on-the-stick. [53] To have a clear overview of what the FEP can do, Chapter 2 starts with elaborating on these protections. Using this list, the discrete cue is incorporated into the initial design and all cues are elaborated in detail to fully disclose the working principles of the haptic feedback system.

To evaluate whether the system is effective in promoting awareness of the pilot on the flight envelope limits, an experiment and the corresponding results are shown in Chapter 3. This experiment invited eleven active Airbus pilots to fly approaches into Schiphol and Montpellier. In both airports, the pilots encountered one of two events, respectively icing, which makes the limits of the aircraft envelope shrink, and a windshear, the pilot has to maneuver the aircraft close to the flight envelope limits in the recovery.

1.5.2. PART II: EXPLORING THREE DESIGN IMPROVEMENTS

The initial experiment showed that pilots did not fully understand the haptic feedback, and that the scenarios provided pilots with much freedom, resulting in a large spread in data points. Hence, it was concluded that both the way the system is evaluated, as well as the system itself, were far from perfect. Therefore Part II investigates which improvements can be made to further improve the design of the haptic system and the sub-improvements are tested in smaller experiments.

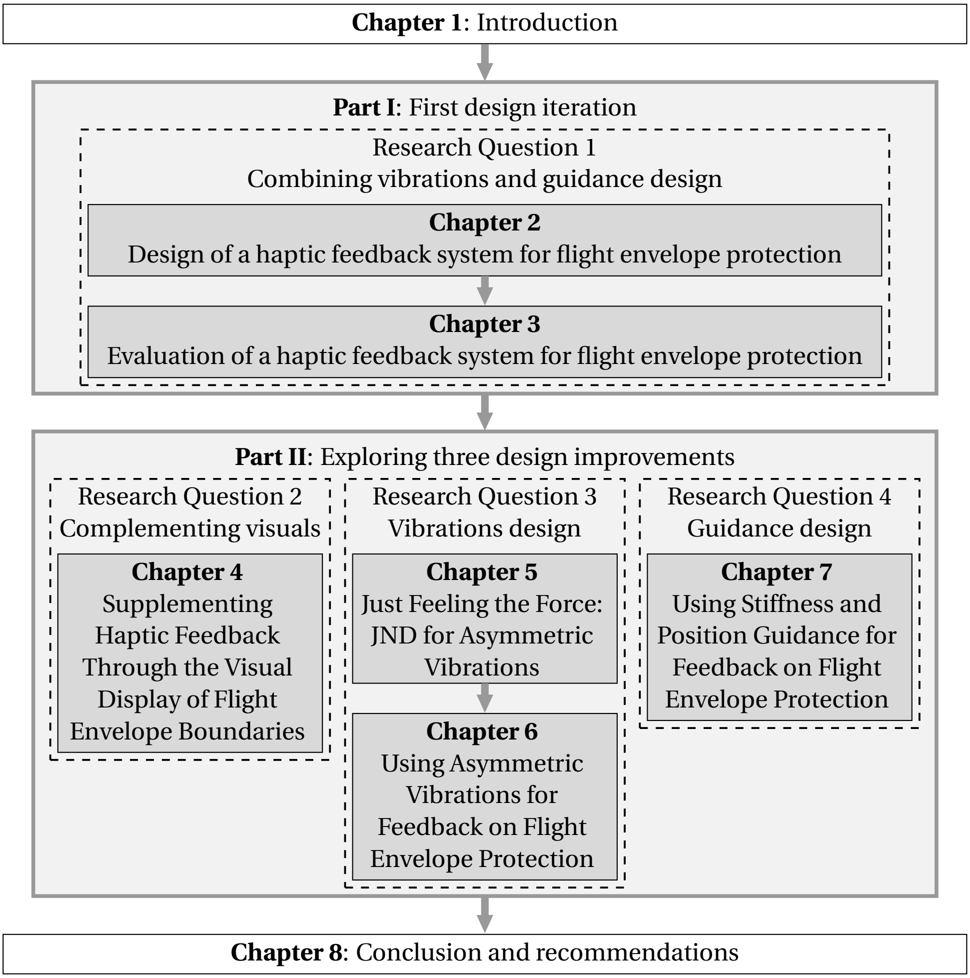


Figure 1.6: Structure of this thesis

In the evaluation of the first design iteration, the pilots indicated that the reason for triggering the haptic feedback was not always clear. Therefore, a visual display was designed to support the haptic feedback as shown in Chapter 4.

Additionally, the first evaluation showed that adding the discrete cue, i.e., a tick-on-the-stick, when the FEP becomes active, was appreciated by the pilots, perhaps even more as all the other cues. Nevertheless, the cue was intended to not only show the activation of the FEP, but also give information on which control input is required to move away from this protection. This directional information was not always clear to pilots, which warranted more research. As such, Chapter 5 investigates different signals to determine which has the clearest direction information and pin-point a threshold of minimal force required for pilot to be still able to feel that direction.

To determine whether the design can use *only* these new cues, or parts of the first design iteration is required, Chapter 6 evaluates this new design with a reduced experiment, using the lessons learned from the experiment setup of the first design iteration.

This last design evaluation did not show a clear benefit of adding haptic feedback in terms of averaged results, it did show a potential training benefit. To further explore this training benefit, another haptic feedback system involving active guidance feedback was designed. This guidance design is evaluated in Chapter 7, where its training effects are compared to the cueing design.

Conclusions on the different designs presented in this thesis, together with recommendations for future design and implementation, are provided in Chapter 8.

I

First design iteration

2

Design of a Haptic Feedback System for Flight Envelope Protection

Several modern aircraft use a passive control manipulator, a spring-damper system which generates command signals to the flight control computers in combination with a flight envelope protection system which limits pilot inputs when approaching the aircraft limits. This research project aims to increase pilot awareness of such protection systems through the use of force feedback on the control device, i.e., haptics. This chapter describes in detail how the haptic feedback works, and when it triggers; the next chapter will discuss the results of an experimental evaluation. With the current haptic design, pilots can get five cues: first, a discrete force cue when approaching the limits. Second, an increased spring coefficient for control deflections which bring the aircraft closer to its limits. Third, a stick shaker for low velocities. Fourth, if a low velocities condition requires an input, the stick is moved forward to the desired control input. And finally, the stick follows the automatic Airbus-like 'pitch up' command during an over-speed condition. This novel system is expected to help pilots correctly assess the situation and decide upon the right control action. It will be evaluated in two scenarios close to the flight envelope limits: a windshear and an icing event.

This chapter is published as:

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Authors	D. Van Baelen, J. Ellerbroek, M. M. van Paassen, and M. Mulder

2.1. INTRODUCTION

MODERN flight decks provide an abundance of information to pilots, primarily using the visual and aural communication channels. Examples of visual displays are the Primary Flight Display (PFD) for the most important aircraft states, and the Navigation Display (ND) for a planar, top-down overview of the environment. Aural signals are often used to provide urgent messages such as to warn pilots for excessive velocities, and to provide altitude read-outs and throttle back-commands on landing. [59]

But apart from these senses, pilots are able to perceive information in several other ways. This chapter will elaborate on the use of the pilots' haptic sense, by providing haptic feedback through the control device. As shown in Fig. 2.1, within the field of haptic research two main categories are identified: touch, stimuli to the skin, and kinaesthesis, stimuli to the receptors in the muscles, joints and tendons.[57, 60] The design discussed in this chapter uses both touch and kinaesthesis, hence the term haptic feedback is used.

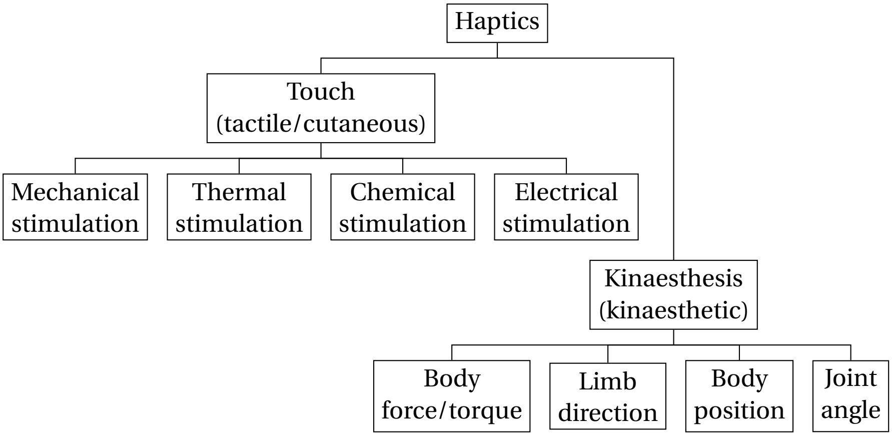


Figure 2.1: Components of haptics [57]

In most aircraft of the 20$^{\text{th}}$ century the control manipulator 'feel' provided information on, for instance, aerodynamic forces, buffeting when close to a stall, actuator saturation through hard stops of the controls, and other control-related phenomena. With the introduction of fly-by-wire, however, the forces on the control surfaces and the control devices were decoupled, eliminating this potentially very useful haptic information. [61]

A reason that haptic feedback on the aircraft limits was not integrated after the introduction of fly-by-wire systems in the 1980s and 1990s, was the rather bulky device required to implement the haptic forces. These old devices had issues regarding their size, weight, power and stability requirements, resulting in certification difficulties. Current-day devices have become much smaller and lighter while still able to provide reliable haptic feedback. [62] This offers the possibility to re-consider this type of feedback in fly-by-wire control systems. [63]

Together with the advances in control devices, automation on flight decks is rising resulting in a more supervisory role for the pilot, instead of direct manual control. Despite these advances, pilots are still often required to take over manual control of the aircraft in landing, takeoff, or during emergency scenarios. An example of the latter could be a computer or sensor malfunction which was the case for Air France flight 447. The crew, startled by unexpected high-altitude dynamics, lost situation awareness despite the information available from the visual and aural displays. Unaware of the loss of the usual flight envelope protections due to the malfunction, pilots stalled the aircraft. The accident report indicates that the stall warning, which was only aural, should be complemented. [7] The control manipulator, the Airbus A330 side stick, did neither provide the pilots with direct feedback on their control actions nor the aerodynamic stall buffets, i.e., it did not help them in properly identifying the situation as a stall. As this tragic example shows, when manual control is needed the lack of haptic information through the control device might contribute to a reduced situation awareness.

Combining the ever-increasing sophistication of automation on the flight deck, and the current generation of small and powerful control devices provides designers a new opportunity, namely to increase pilot awareness through haptic feedback. Some aircraft already include 'augmented forces' on the control device, which can be provided on *both* control devices (on a two-pilot flight deck) linked to the surfaces, or fly-by-wire control systems. An example of this is the "Q-feel force", which changes the stiffness of the controls with changing dynamic pressure/velocity in Boeing type aircraft. [64] Another example is a stick shaker or pusher, which warns pilots of moving closer to extreme aircraft states. [4] The control device can also be loaded with two passive springs to create a change in spring coefficient when pilots exert large control deflections irrespective of the aircraft state, such as in Airbus aircraft. Active control can be used to have an increased (artificial) spring force when rolling beyond the safe roll limit, irrespective of the control surfaces, as used in a Boeing 777. [55]

Although examples of haptic feedback implementations exist, there is limited research published in open literature to prove the benefits of such a system. Within the field of aerospace, Schmidt-Skipiol and Hecker used a passive spring or an active counterforce to communicate the distance to the flight envelope limits. The latter gave best tracking performance increase compared to the no-haptics condition. [50] A second example is the work by Stepanyan et al. that showed the limit on the available control space both visually and haptically. [52] For the haptics, they changed the input neutral point and the maximum deflection, which was used by the pilots to operate the aircraft at the limits. A soft-stop, i.e. a local step in the force required for a certain deflection, can be used to indicate the engine limitations in the collective of a helicopter. It was shown in simulations that such a system can reduce the workload of the pilot ([44, 65]), this was implemented in an experimental helicopter of the German Aerospace Center. [66] Tactile feedback through the use of tactors on a vest enabled improved spatial awareness and reduced spatial disorientation. [29]

These examples use haptic feedback to inform the pilot about the flight envelope limits. Note that research in supplying the pilot with such information is not limited to haptic only, new visual displays are investigated as well and show positive results. [51] Aside from information on the flight envelope limits, the haptic channel can additionally be used to supply guidance support, of which a haptic flight director showed great potential to increase the pilot tracking error and reduce workload. [67] Other fields do have more open domain research interest, for example in tele-operation: the control of an unmanned vehicle was supported by haptically showing the proximity to objects in its surroundings. It resulted in decreased workload and increased situation awareness for the given navigation task. [68] In the automotive field, haptics can be used on the gas pedal to show the proximity of a car in front, resulting in an increased performance while reducing input magnitudes ([35]); and to support curve negotiation. [37] Petermeijer et al. showed that automotive warning systems reduced the reaction time of the driver while have a potential to induce driver-annoyance, while guidance – for example to the center of the road – improved performance yet is subjective to after-effects. [38]

The aim of the current thesis is to investigate the use of haptic feedback to give the pilot more information on the augmentation with respect to the limits of the aircraft during manual control, within a modern fly-by-wire flight deck. In other words, the design presented in the following aims to provide feedback to the pilot on the proximity of the state to the flight envelope limits. Only longitudinal haptic feedback is considered here, lateral cues can be added in a future design using the same design ideas. This work builds on an initial study ([53]), which showed a potential benefit of such haptic feedback system. The goal of this chapter is to elaborate on a new iteration and give a thorough description on the *how* and *when* of the haptics, as well as the expected practical implications.

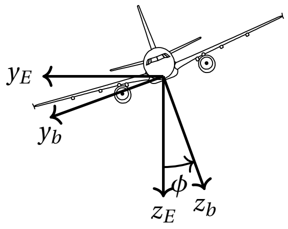
Section 2.2 will first discuss some basic flight dynamics and will introduce the control laws and flight envelope protection system present in fly-by-wire Airbus aircraft. Section 2.3 discusses the rationale of our haptic interface, designed to present some of the functions of these automated systems. We then discuss two operational scenarios where the flight envelope protection system will trigger, a windshear and an icing event, to explain in detail how our haptic interface works, Section 2.4. Finally, conclusions are given in Section 2.5.

2.2. Flight dynamics and control laws

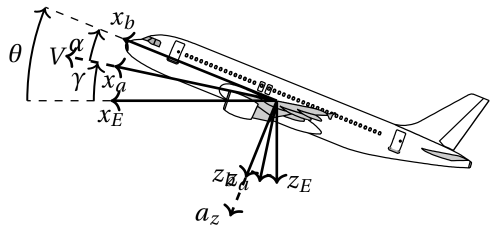
This section provides the background needed to understand the design rationale of our haptic interface. Subsection 2.2.1 covers some basic flight dynamics properties and variables. Readers familiar with aircraft flight dynamics can skip this subsection. As our haptic design focuses on supporting pilots in working with the complex Airbus-like control law and flight envelope protection systems, a brief recap of these systems is provided in Subsection 2.2.2. This recap discusses the (highly-coupled) protections, yet the level of detail is sufficient to support the design of the haptic feedback system in the following.

2.2.1. Flight Dynamics

This subsection explains a basic set of flight dynamics variables which are essential to understand the aircraft control laws and the application of the haptics. A full discussion on flight dynamics can be found in literature. [69] The bank angle (ϕ), indicating how much the aircraft wing is tilted with respect to the horizontal plane, is the most important lateral variable and is depicted in Fig. 2.2a. The relevant longitudinal angles are shown in Fig. 2.2b: the pitch angle (θ) depicts the angle of the nose of the airplane relative to the horizon, the flight path angle (γ) gives the elevation of the true velocity vector (V) with respect to the horizon, the angle of attack (α) is the angle of incidence of the air with the wing section. Accelerations are expressed in the aircraft body reference frame (index b); the vertical acceleration (a_z) is commonly expressed in load factor ($n = \frac{a_z}{g}$) and is also shown in Fig. 2.2b. Typical level cruise flight is performed with a load factor of one: lift is equal to weight. By pitching up, the load factor is increased, experienced as 'being pushed in the seat', and visa versa.



(a) View from the front



(b) View from the left

Figure 2.2: The aircraft with most important angles indicated (all positive)

Limits of the aircraft are typically expressed in a flight envelope. Different combinations of variables are possible, yet as Airbus pitch control laws are mostly load factor-dependent, this research considers only the relation between aircraft velocity (V) and load factor (n). This flight envelope is depicted by the solid black line in Fig. 2.3. The upper velocity limit (right-hand vertical line) is due to the maximum velocity (n_{max}) created by aerodynamic and vibration limits. Extreme load factor values are determined by static structural limits and indicated by the upper (n_{max}) and lower (n_{min}) horizontal lines. The lower velocity limits ($V_{\alpha_{max}}$), the left hand side of Fig. 2.3, follow a quadratic relation with velocity due to the lift equation shown in Equation 2.1, where ρ is the density of the air, S is the lifting surface of the wing, and C_L is the lift coefficient:

$$L = \frac{1}{2}\rho V^2 S C_L \tag{2.1}$$

The lift coefficient (C_L) depends on the wing shape and on the angle of attack: the higher α, the higher the lift coefficient, up to a maximum value (α_{max}) where this coefficient suddenly drops and a stall occurs.

2.2.2. AIRBUS CONTROL LAWS

To better understand when the haptic feedback is applied, it is important to understand how pilots control the aircraft. As this research focuses on control laws closely resembling an Airbus A320, the main control device used is discussed: the side stick. All information in the following is retrieved from the A320 Flight Crew Operation Manual (FCOM). [13]

The Airbus side stick is a passively loaded control device: the 'stick feel' is provided by springs and dampers. The device is not mechanically coupled to the control surfaces (ailerons, elevator), it produces an electrical signal to the Flight Control Computers (FCCs) as shown in Fig. 2.4. The latter are responsible for converting the side stick deflections to required control inputs and blending them with the autopilot control commands

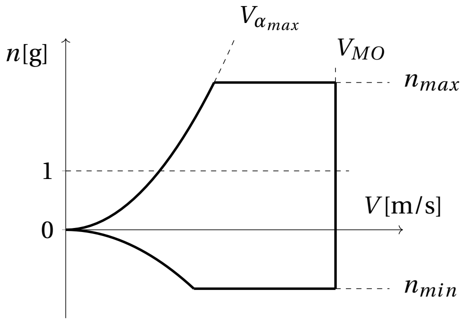


Figure 2.3: Flight envelope, allowable load factor (n) versus allowable velocity (V)

to control surface deflections. As such, the FCCs can *override* the pilot inputs and, in doing that, provide an additional layer of safety to keep the aircraft states inside the allowed flight envelope region. This process is called FEP and is applied for both lateral and longitudinal inputs as will be elaborated in the following.

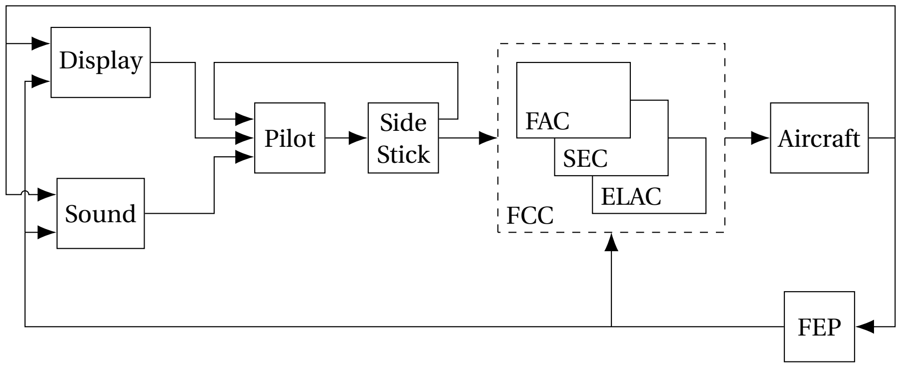


Figure 2.4: Block diagram representing the Airbus control loop

The FCCs consist of seven computers with three functions: 2 Elevator & Aileron Computers (ELACs), normal elevator and stabilizer control, constant aileron control; Spoilers & Elevator Computers (SECs): spoilers control, standby elevator and stabilizer control; 2 Flight Augmentation Computers (FACs): electrical rudder control. These computers are provided with information on the aircraft states by a number of systems and sensors: (i) Air Data and Inertial Reference Unit (ADIRU), (ii) Slat Flap Control Computer (SFCC), (iii) accelerometers, (iv) Landing Gear Control Interface Unit (LGCIU), (v) Radio Altimeter (RA) and (vi) Flight Management Guidance Computer (FMGC).

Five control laws with different levels of support are possible within the Airbus philosophy. This chapter will not discuss in detail when each of the control laws is active. The selection of control law is based on internal sensor validity checks for which more details can be found in the FCOM, Ref. [13]. Only a general description, together with the control laws, follows. We start with 'normal law' which provides the highest level of assistance to pilots, and then move to the configurations which provide less assistance ('alternate law with reduced protections' and 'alternate law without reduced protections'). The 'direct law' and 'mechanical backup' are included for the sake of completeness but will not be used in the sections that follow. A summary of the control laws can be found in Table 2.1, and all the protections in Table 2.2.

2

NORMAL LAW

When all systems are functioning nominally, the FCCs operate in normal law, the default control mode. The pilot longitudinal and lateral control inputs are both interpreted as 'command' signals for the FCCs, as will be discussed in the following. In addition, the FEP applies a number of protections, to prevent the aircraft from moving outside the – what is considered safe – flight envelope. Examples are the bank angle limitation, the load factor limitation, the pitch attitude protection, the high angle-of-attack protection, and the high-speed protection.

Table 2.1: Summary of Airbus Flight Control Laws

Direction	Normal Law	Alternate Law
Lateral	Bank rate demand maximum 15 °/ s	Bank direct stick-to-surface: clean maximum 30 °/ s otherwise 25 °/ s
Longitudinal	C^* control law Autotrim for changing speed or configuration Automatic pitch compensation for $\phi \leq \pm 33°$	Control law equal to NL

Lateral control The FCC interprets lateral stick deflections as commands to change the bank angle. From zero to 33° of bank, the side stick lateral deflection is a bank angle *rate* command, whereas the bank from 33° up to 67° is a bank *angle* command. The maximum bank angle rate achievable with full deflection is 15 °/ s. The FEP in the FCCs limits the maximum achievable bank to 67° which is the first hard envelope limit. If the bank angle exceeds 33°, positive bank stability is present such that the aircraft automatically rolls back to 33° when the side stick is not deflected. Hence, in case the pilot intends to execute a steep turn, a constant stick deflection is required. To assist the pilot during horizontal turns, for bank angles up to 33°, an automatic pitch command is added, such that the pilot does not need to maintain back pressure on the stick to compensate for the required increase in lift.

Additionally, the autopilot disconnects when the bank angle exceeds 45°, at which point the Flight Director (FD) bars (indication of the guidance by the FCC on the PFD) disappear. The bars return when the bank angle reduces below 40°. To prevent excessive Trimmable Horizontal Stabilizer (THS) deflections due to the manual or auto-trim functionality, the deflection is limited between the value on entering of the protection and 3.5° nose-down. Finally, limits for the bank angle depend on the longitudinal protections, which is elaborated in the following. A visual summary of the lateral protections can be found in Fig. 2.5. [13]

Table 2.2: Summary of Airbus Flight Envelope Protection

Variable	Normal Law	Alternate Law
Bank (ϕ)	THS limited between entry value and 3.5° nose-down Autopilot disconnects when $\phi > 45°$ FD bars disappear when $\phi > 45°$ FD bars return when $\phi < 40°$ Nominal maximum: 67° Maximum with α_{prot} active: 45° Maximum with $V > V_{MO}$: 40° Nominal protection: positive bank stability to ±33° Protection with $V > V_{MO}$: positive bank stability to 0°	Autopilot disconnects $\phi > 45°$ No other protections
Pitch (θ)	No limit for autopilot Nose-up maximum, flaps 0 till 3 30° Nose-up maximum, full flaps 25° Nose-down maximum −15° FD bars disappear $\theta > 25°$ or $\theta < -13°$ FD bars return $\theta < 22°$ or $\theta > -10°$	—
Angle of attack (α)	THS limited between entry value and 3.5° nose-down Autopilot disconnects when $\alpha > \alpha_{prot}$ Pilot input proportional in region: $\alpha_{prot} \to \alpha_{max}$ Protection deactivates: when 8° forward input or 0.5° forward for 0.5 s when $\alpha < \alpha_{max}$ Below 200ft, protection deactivates when pilot input is half of previous nose-up input or when $\alpha < \alpha_{prot} - 2$ When $\alpha > \alpha_{floor}$, thrust is set to TOGA[1]	—
Low velocity (V)	—	5 – 10kts above V_{SW}[2]: a nose-down command is inserted with bank angle compensation to keep $\to \alpha$ constant An aural “STALL” warning is provided with ‘appropriate margin from stall’
High velocity (V)	THS limited between entry value and 11° nose-up When $V > V_{MO}$[3]: autopilot disconnects pilot nose-down authority is reduced an automatic nose-up command is introduced command cannot be overruled by pilot	When $V > V_{MO}$: autopilot disconnects Nose-up command is inserted and can be overruled by pilot When $V > V_{MO} + 4$: and “Overspeed” warning sounds
Load factor (n_z)	THS limited between entry value and 3.5° nose-down when $n > 1.25$ Maximum, clean: 2.5 Maximum, with flaps/slats: 2 Minimum, clean: −1 Minimum, with flaps/slats: 0	Equal to normal law

[1] $\alpha_{floor} = 9.5°$ without flaps/slats (15° for configuration 1 and 2, 14° for 3, and 13° for full),
or when pilot inputs 14° pitch up with either pitch or angle of attack protection active.
[2] Speed margin according to Airbus documentation: “Based on the aircraft gross weight and slats/flaps configuration.”
[3] Airbus documentation is unclear on the exact activation point: “at/or above V_{MO}”

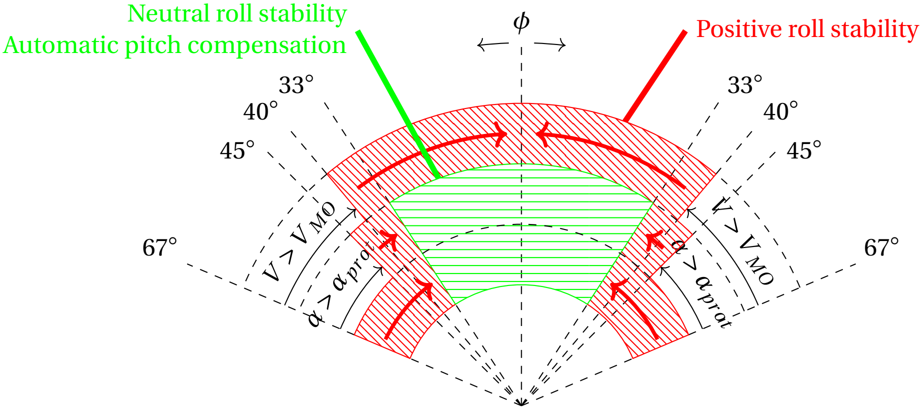


Figure 2.5: Lateral control in normal law, based on the A320 FCOM [13]

Longitudinal control For longitudinal control, Airbus uses the C^* control law which is a combination of both pitch rate (q) and load factor (n). [10–13] In the low speed regime, up to approximately 240kts, the pilot stick deflections are predominantly interpreted as pitch *rate* commands; in high speed regions, the stick deflections are mainly interpreted as load factor commands. [12] Due to this setup, there is no need for the pilot to trim the aircraft for changing velocity or configuration.

On top of the C^* control law, protections are present on the pitch angle, the angle of attack, the load factor, and high velocities. The limit on the pitch angle and load factor is without any buffer zone: when approaching the limit, the FCC gradually reduces the pitch rate/load factor until the maximum value is reached and no further control can be achieved. For the other limit, angle of attack, there is a zone from a protected value (α_{prot}) up to the maximum value (α_{max}) where the control device is no longer commanding the C^* control law, yet control device deflections are directly proportional to an angle of attack command above the protection value, i.e., proportional to $\alpha - \alpha_{prot}$. Additionally, the autopilot disconnects when entering the protected region, and the maximum achievable bank is reduced to 45° to prevent asymmetric stall. The throttle input is automatically set to Take Off/Go Around (TOGA) when the angle of attack increases beyond α_{floor} (9.5° without flaps/slats, 15° for configuration 1 and 2, 14° for 3, and 13° for full), or the control device deflection is larger than 14° nose up with pitch or angle of attack protection active.

The angle of attack protection deactivates when the pilot pushes the control device more than 8° forward, or when (s)he pushes at least 0.5s with a deflection of minimal 0.5° forward when the angle attack is below the maximum value. Below 200ft, the protection is also deactivated by when the pilot uses less than half of the previous nose-up input, or when the angle of attack is less than $\alpha_{prot} - 2°$.

For all three limits, the maximum value, and if applicable the size of the position control zone, depends on the particular flight conditions and the state of the aircraft. The pitch angle limits are between $-15°$ and 30° (25° for full flaps/slats), load factor must remain between $-1g$ and 2.5g without flaps/slats (0g and 2g for any other configuration), and the angle of attack must remain less than 12°, with a protection zone of 2°. The buffer zone for the angle of attack is shown on the PFD through the velocity indication,

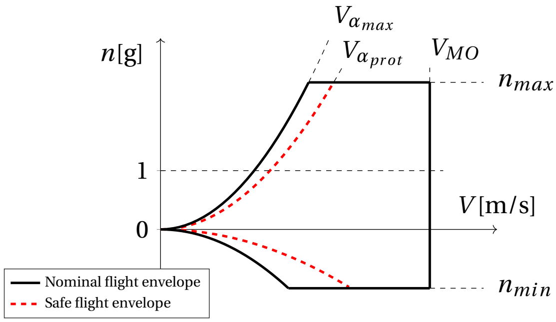


Figure 2.6: Flight envelope with A320 longitudinal Flight Envelope Protection limits indicated

whereas no indication for the load factor is available in the current Airbus setup on the primary display. Informing the pilot that this buffer is reached and that pilot inputs are being limited, could result in a more transparent system, increasing pilot awareness of the flight envelope limits. Note that the pitch limits do not apply to the autopilot, and that the FD bars disappear when the pitch increases above 25° nose up or below 13° nose down and return when the pitch is between 22° nose up and 10° nose down.

To prevent structural damage when controlling the aircraft at high velocities, a high-speed protection is present. This protection triggers at (or above, depending on the configuration) the minimum of both maximum operational velocity (V_{MO}) and maximum operational mach (M_{MO}), disconnects the autopilot, and activates an automatic nose-up command while reducing the nose-down stick authority to reduce the airspeed below the maximum, effectively creating an artificial high-speed stability. The pilot is warned of the overspeed condition by an aural message, yet the nose-up command is *not* communicated to the pilot. Enabling the pilot to know (or feel) how it is implemented can be an addition to improve pilot awareness of the flight envelope protection system. Note that the nose-up command cannot be overridden by the input of the pilot, even with full forward deflection. In order to ease returning to normal operational velocities and to avoid high structural loads during an overspeed, the positive bank stability shown in Fig. 2.5 rolls the aircraft back to 0° and the maximum bank angle is limited to 40°. These additional limitations are present until the velocity drops below the maximum velocity.

As for the lateral control, here the THS is limited to prevent excessive deflections. During the angle of attack protection and load factor values above 1.25g, the limits are the entry value and 3.5° nose-down. When the high velocity protection is active, maximum values are the entry value and 11° nose-up.

Fig. 2.3 already showed the nominal flight envelope. Here, we discussed the angle of attack (related to velocity through Equation 2.1), load factor and high velocity protections present in the A320 control laws. The angle of attack protection can be visualized on the flight envelope as shown with the red-dashed line on Fig. 2.6, where every state where no protection is active is defined as belonging to the safe flight envelope. As can be seen in the figure, the zone where a protection is active provides a buffer for the pilot when approaching the limits.

2

ALTERNATE LAW

In case of sensor or computer failures, the FCC reverts to control laws which provide less support for pilots. The first of these degraded control laws is the alternate law, with reduced protections, which triggers, for example, when a dual computer failure is detected.

Lateral control Lateral control becomes a direct stick-to-control-surface-position relationship with maximum roll rate of 30 °/ s for clean configuration and 25 °/ s otherwise. Hence, positive bank angle stability and bank angle protections are lost. Furthermore, if the autopilot is engaged, it disconnects at 45°, requiring the pilot to take over control.

Longitudinal control The longitudinal control law is not changed. One major change with respect to normal law, when considering safety, is the loss of the angle of attack and pitch protection. This includes the buffer zone described before, as well as the protection against excessive control inputs. Load factor protection is present equal to normal law.

Too large angle of attack angles can lead to an aircraft stall event, and pilots are trained to avoid this event in all circumstances. Most of the time the aircraft flies in normal law, and the aircraft simply cannot stall. But in the very rare situation that the normal law is deactivated and the degraded control laws become active, the angle of attack protection is lost. Pilots may fail to notice this control law degradation, and the corresponding loss of protection, which could lead to a stall. This possibly catastrophic event will be taken into consideration in our haptic interface design.

To assist the pilot in this control law, a region with low speed stability is introduced by Airbus. Dependent on the configuration, 5 to 10kts above the stall warning speed (V_{SW}) a nose-down signal is introduced. Additionally an aural “STALL” warning is added with, according to the Airbus documentation, ‘appropriate margin from stall’. Furthermore, during a turn, pitch compensation is present to maintain a constant angle of attack.

The high-speed stability from the normal law remains, yet the pilot is now able to overrule the imposed nose-up command. Autopilot disconnection occurs when the velocity exceeds V_{MO}, and at $V_{MO} + 4$ an aural “OVERSPEED” warning is present.

ALTERNATE LAW WITHOUT REDUCED VELOCITY PROTECTIONS

In some cases, for example when all three air data reference units fail, the control laws further degrade and have even less protections. Both lateral and longitudinal control laws remain equal to alternate law with the protections, except that the low- and high-speed stabilities are lost. The load factor limitation does remain available for the pilot.

DIRECT LAW

When all three inertial reference units fail, the RAs fail when the landing gear is down, or when flaps are selected while the LGCIUs disagree, the control law is reverted to direct law. In direct law, control surface deflections become equal to side stick inputs.

Lateral control Although direct stick-to-roll is low-level control, the FCC still aids the pilot inputting the right magnitude of inputs by scaling the control gains based on the configuration. Yaw damping and turn coordination are lost in this case, as is the maximum bank angle protection.

Longitudinal control Stick-to-pitch direct control is aided by scaling the control gains depending on the center of gravity location of the aircraft. In this control law, no protections are active and the pilot can therefore bring the aircraft outside the flight envelope limits.

MECHANICAL BACKUP

When a complete loss of electrical power occurs, the side stick is unusable due to the transducers used in the design, and the loss of the FCCs. Therefore a mechanical backup is available which is a very basic and crude control.

Lateral control Lateral control is achieved solely by operating the rudder pedals, without any direct bank control. Rolling is achieved due to the coupling of yaw and roll, but as this is a slow response and Airbus indicates in Chapter OP-20 of Ref. [70] to: "*Gently apply an input and wait for the response*". Care should be taken to not exaggerate the input as to not over-control the aircraft.

Longitudinal control The mechanical backup for the pitch control is by manually trimming the horizontal stabilizer. Again, this provides a slow control method and should be executed with caution.

Now that the basic flight dynamics are discussed, and the Airbus flight control philosophy has been summarized, we can move to the design of our haptic interface. That is, how can we use haptics to assist pilots in maintaining situation awareness of the state of the aircraft and the automation, especially in high workload situations when the aircraft operates close to the flight envelope limits?

2.3. HAPTIC DISPLAY DESIGN

This section describes the haptic display that is used to show the flight envelope boundaries to the pilot. First, the definition of haptic feedback in this research is shown, followed by the goal of the support system. Next, the information is used to elaborate on *how* and *when* haptic feedback is provided in the current design. Note that the values for all tuning parameters introduced in the following are summarized in Table 2.3.

2.3.1. HAPTIC FEEDBACK DEFINITIONS

Haptic feedback can be considered as a process that deliberately changes the feel of the control device. This research focuses on changing the haptic profile, i.e., the relation between the deflection of the control device (δ) and the amount of force required to do so (F). A default profile for many sticks (and other control manipulators such as rudder pedals) is a piece-wise linear relation as shown in Fig. 2.7. Here, δ_{np} is the position of the control device when no force is applied, referred to as the neutral point. The location of the break-out zone is given by $\pm\,\delta_{br}$, here the stick has a spring coefficient k_{br}. The breakout zone is included to haptically show pilots where the 'zero stick deflection' position lies. Outside this zone, k^+ and k^- are the spring coefficients for, respectively, positive and negative control device deflections. The default case for this design, as for the Airbus side stick[1], is a symmetric profile using a nominal stiffness (k_{nom}) for positive and negative deflections until a maximum deflection (δ_{max}). Such a haptic profile provides the pilot with information on the input magnitude: larger inputs require larger forces. Deviations from this default haptic profile can be used to provide the pilot with additional feedback through the control device. Although not considered here, haptic feedback can also be considered by changing the dynamic properties of the control device such as the natural frequency, damping coefficient, static friction (force required to move from a stand-still), dynamic friction (friction due to movement), or other non-linear phenomena. [57]

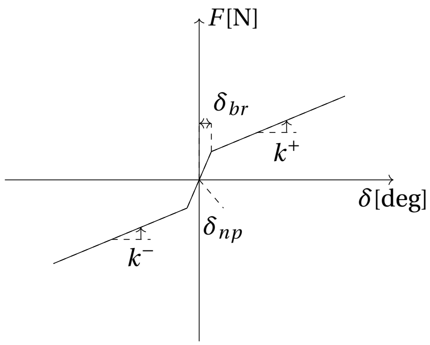


Figure 2.7: Nominal control device profile: required force exerted (F) versus stick deflection (δ)

Literature shows different ways of changing the haptic profile: in the automotive field there is a strong focus on using a forcing function which can be used both as a *warning* signal ([36, 71]), or as a *guidance* force. [35, 38]. Aerospace applications show examples which adds a soft-stop (a local step in the amount of force required), a hard-stop (a change in maximum deflection, [62]), forcing functions ([42]), changes in the stick neutral position ([52]), and changes in nominal stick stiffness. [46, 47] An example of haptic feedback in the current Airbus A320 flight deck is the detent present on the thrust levers: the controls 'clicks' in the important thrust positions (such as maximum continuous trust, of take off/go around setting) and requires a threshold force to move away from this position.

2.3.2. GOAL OF SUPPORT SYSTEM

We aim to use haptic cues to provide pilots with information on whether the aircraft approaches the limits of the FEP: increase situation awareness. In Subsection 2.2.2 we discussed how moving the aircraft outside the safe flight envelope, shown in Fig. 2.9, can lead to changes in the control law. For instance in normal law, when exceeding the protected angle of attack, the control laws change from C^* to α-command control. So in principle the fact which control law is active does provide some information on the proximity to the boundaries of the flight envelope. Nevertheless, pilots must *infer* this from the changing aircraft reaction to control inputs or from the velocity indication on the

[1] After publication it was note that the Airbus side stick has two spring coefficients: extreme deflections have an increased k^+ / k^-. This is included in the designs in Chapter 5, 6 and 7.

PFD when flying in normal law. To present this more clearly, the haptic support system will include the Airbus protection features expressed with haptic cues. In addition, we will explore how potential mitigation control strategies can be suggested by the haptics, e.g., by making clear what control actions are desired or undesired. The following haptic cues are added and will be discussed in detail in the indicated subsections:

1. A square pulse displaying the transition from in- to outside the safe flight envelope, i.e., crossing the red-dashed line indicating the safe flight envelope on Fig. 2.9 (Subsection 2.3.4).

2. Change in spring coefficient for positive or negative positions relative from the distance from the safe flight envelope to the limit, i.e., the distance between the red-dashed and the black line on Fig. 2.9 (Subsection 2.3.5).

3. Changing the neutral point to indicate the automatic control input by the FCC in case of overspeed, i.e., right of the high velocity protection line on Fig. 2.9 (Subsection 2.3.3).

4. Changing the neutral point to indicate a neutral stick position is not sufficient for low velocities, near the location of the inset on Fig. 2.9 (Subsection 2.3.3).

5. A stick shaker at critical low velocity, i.e., left of the green dash-dotted line on Fig. 2.9 (Subsection 2.3.4).

The result on the system architecture is a dependency of the control device properties on the aircraft states and FEP through the Haptic Feedback Law (HFL), shown on Fig. 2.8. Note that the HFL is not dependent on the current control device state: the haptic display shows *when* the limits are near, not the control device position *where*. Information on the limits is assumed to be calculated by an external model and are therefore not discussed in this chapter. For this research project, a proprietary Airbus A320 model created by the German Aerospace Center (DLR) has been made available. More information on the control laws, flight envelope and the corresponding protections can be found in Refs. [54, 72].

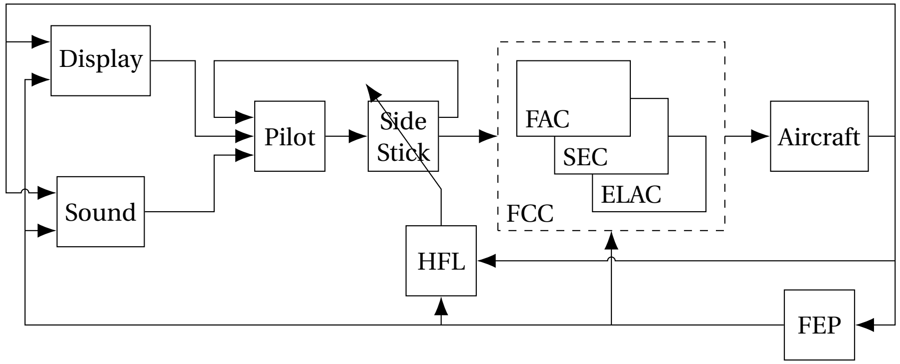


Figure 2.8: Block diagram representing the Airbus control loop combined with the Haptic Feedback Law (HFL)

2

This chapter discusses only longitudinal haptic feedback. Furthermore, it is assumed that the pilot is flying with hands on the controls, which is verified in conversations with pilots to be a common airline procedure below an altitude of 10,000ft, and in emergency situations. Additionally, Airbus specifies three phases in flight with different control modes: on the ground, during flare and in flight. [13] In this research, only 'flight mode' is considered. The transitioning modes during flare and on the ground, as well as lateral haptic feedback are left to a next iteration.

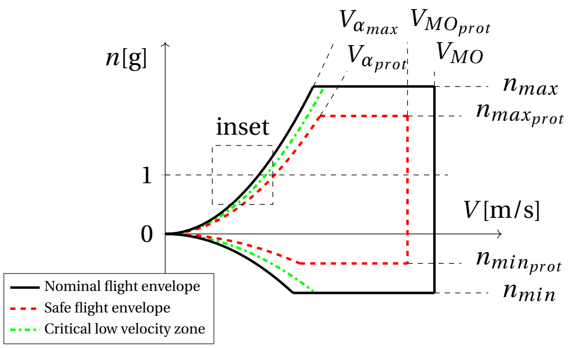


Figure 2.9: Flight envelope, load factor (n) versus velocity (V), inset for Fig. 2.11

Note that the flight envelope used for the design of the haptic display presented in Fig. 2.9, has three differences with respect to the flight envelope for Airbus control laws shown in Fig. 2.6. First, we decreased the upper aircraft velocity limit in the safe flight envelope, and provided a buffer of 20kts ($V_{MO_{prot}} = V_{MO} - 20$). Second, to complete the buffer zone towards the hard flight limits, we added a buffer on the load factor of 0.5g. Third, we implemented a critical low velocity zone, which will be communicated through the use of forcing functions.

In normal operations, the aircraft is operated within the safe flight envelope in the normal control law. In case of abnormal situations, as discussed in Subsection 2.2.2, the aircraft reverts to an alternate law in which fewer protections are active and the pilot has more control to move outside the flight envelope. In the current stage of our project, the haptic display is designed such that in both cases – normal and alternate law – the haptic settings are identical. The full haptic display can still be applied in alternate law because the intensities of the cues will be chosen such that pilots can always overrule the haptic signals: they have the final authority of the side stick. Hence in both conditions, in case the aircraft is maneuvered outside the safe flight envelope, the haptic cues are designed such that they should *support* the pilot in identifying the situation, and deciding on an effective mitigation strategy, to keep the aircraft safe.

The remainder of this section elaborates more on *how* and *when* the haptic cues are provided.

2.3.3. CHANGE THE POSITION OF THE NEUTRAL POINT

The position of the neutral point can be changed through manipulating the value of δ_{np}. If applied, the information provided by the haptic display is directly proportional to a required control command, and in principle the pilot can 'just follow the position'. Previous research showed that using such an approach increased tracking performance while reducing the physical effort. [42] If the pilot does not agree, however, (s)he can choose to override the cue, and keep the stick position fixed by actively counteracting, using co-contraction of the muscles. [37] Nevertheless, the shift in neutral position gives a clear message to the pilot on what (s)he should do. The effect of this change in neutral position on the profile can be seen in Fig. 2.10 by the shift of the entire graph to the right.

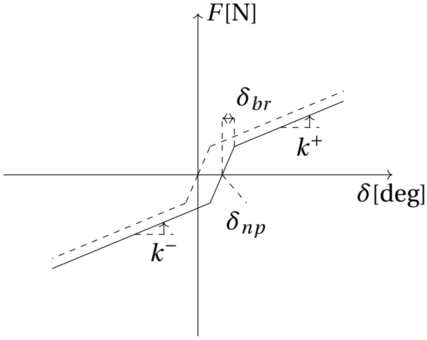


Figure 2.10: Haptic profile with a positive shift in the neutral point position

In the Airbus' philosophy, a zero stick deflection commands load factor of one. This is a safe and desired load factor for most of the flight, but in some cases a different load factor is needed to return to the safe flight envelope. To indicate this, the neutral point can be altered. Looking at the flight envelope in Fig. 2.9, two such regions can be identified: (i) in case of overspeed an active pull-up is required, and (ii) at g-loadings for low velocities since the maximum safe load factor is below one. The next sections therefore investigate this required load factor (n_{req}) for both situations respectively, followed by the translation of the required load factor to the required change in stick neutral position.

OVERSPEED

When an overspeed occurs, the speed has to be reduced actively by the pilot by either reducing the throttle, or by pitching up such that kinetic energy is exchanged for potential energy. The Airbus flight envelope protection system will implement a forced nose-up command (see Subsection 2.2.2), which could be translated to a change in neutral point. Nevertheless, the actual implementation of this signal is not known for this research and is approximated as described below. The main reason for this cue is to inform the pilot that maintaining the stick at zero deflection does *not* solve the flight envelope violation, and action needs to be taken. Note that here our research deviates from the A320 FEP: the nose-up command is not activated when crossing V_{MO}, it is already activated when crossing $V_{MO_{prot}}$.

For this research, the nose-up command, and therefore the magnitude of the neutral point shift, is governed by the change in load factor required to bring the positive acceleration to zero. It is determined by starting from the longitudinal equations of motion ([69]), where we assume engine thrust to be parallel to the x axis of the aircraft body frame:

$$T\cos(\alpha) - D - W\sin(\gamma) = m\frac{dV}{dt} \tag{2.2}$$

From all variables in this equation, the pilot can manipulate the aircraft flight path (γ), through moving the stick. Here, the neutral point is shifted to obtain a flight path angle such that there is no positive acceleration, $\frac{dV}{dt} = 0$. Since the aircraft is accelerating, the left part of Equation 2.2 is not zero and can be rewritten to obtain a steady flight path:

$$\gamma_{\text{steady}} = \arcsin\left(\frac{T\cos(\alpha) - D}{W}\right) \tag{2.3}$$

Thrust and drag cannot be measured directly, their effects can be measured through accelerometers, mounted on the aircraft body, which therefore must be rotated to the aerodynamic reference frame:[1]

$$\begin{aligned} T\cos(\alpha) - D &= ma_{x_a} + W\cdot\sin(\gamma) \\ &= m\left(a_{x_b}\cos(\beta)\cos(\alpha) + a_{y_b}\sin(\beta) + a_{z_b}\cos(\beta)\sin(\alpha)\right) + W\cdot\sin(\gamma) \end{aligned} \tag{2.4}$$

Combining Equation 2.3 with Equation 2.4 then yields the required change in flight path angle for zero acceleration ($\gamma_{\text{steady}} - \gamma$), all expressed in measured quantities.

As discussed above, the side stick gives load factor commands for high velocities and therefore also a relation between the change in flight path angle and load factor is required. By assuming that the steady state pitch rate is predominantly determined by a change in flight path, the required load factor can be expressed by the required flight path angle and a tuning factor ($\tau_{\text{overspeed}}$) which is chosen as a measure of the recovery speed: [73][2]

$$n_{\text{req}} = \frac{V}{g}\cdot q + 1 \approx \frac{V}{g}\cdot\dot{\gamma} + 1 = \frac{V}{g}\cdot\frac{\gamma_{\text{steady}} - \gamma}{\tau_{\text{overspeed}}} + 1 \tag{2.5}$$

G-LOADING FOR LOW VELOCITIES

As mentioned before, the stick neutral position commands a load factor of one. In case the aircraft velocity becomes too low – that is, too far to the left on Fig. 2.9, and zoomed in shown by Fig. 2.11 – returning to load factor ‘one’ is not sufficient to re-enter the safe flight envelope, and the pilot has to be informed that action is required.

This is done by shifting the stick neutral point. The prerequisites for this cue are that: the current safe load factor is below one (the green circle on Fig. 2.11) and the current load factor is above the safe load factor. Note that the current load factor is measured by sensors, and it is assumed that the aircraft (model) calculates the safe load factor. The required load factor to return to the safe flight envelope therefore *is* the safe load factor itself ($n_{max_{prot}}$).

[1] The term due to gravity was not included in the journal publication. After publication, it was found that the lack of this term resulted in an incorrect calculation of the required flight path angle when climbing/descending.

[2] The journal publication contained a mistake in the equation derivation and is correct for this thesis.

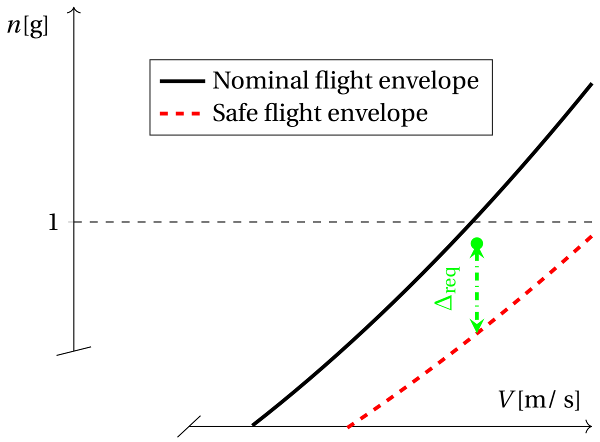


Figure 2.11: The amount of load factor change required when flying at low velocities, inset from Fig. 2.9

CHANGE IN NEUTRAL POINT IMPLEMENTATION

For the two cases discussed above, a required load factor is calculated, which needs to be shown to the pilot using a change in stick neutral deflection. Since zero stick deflection indicates a required load factor of one, the required shift in neutral point ($\Delta\delta_{\text{req}}$) given a required load factor (n_{req}) can be determined using:

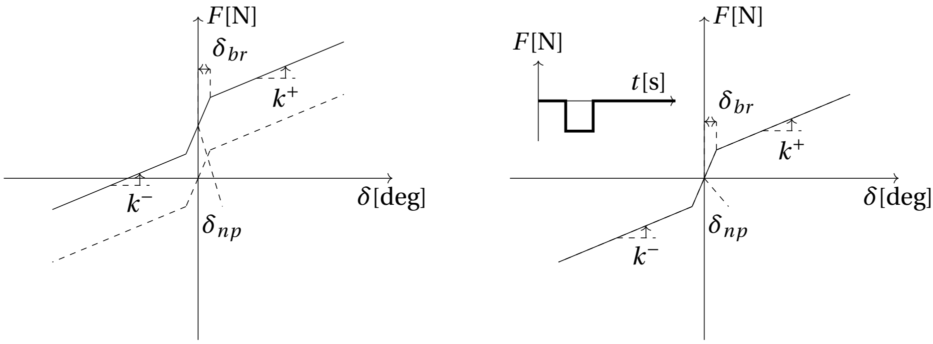
$$\Delta\delta_{\text{req}} = \frac{\delta_{\max}}{n_{\max} - 1}\left(n_{req} - n\right) \tag{2.6}$$

In case this required change in neutral point would be implemented immediately, abrupt changes in the control feel can be observed. The change in neutral point would then be perceived more as an 'alert', rather than a guidance cue. Therefore the required change in neutral point is ramped-in linearly using an iterative formula which can be easily implemented in software. With the previous neutral position ($\delta_{np_{\text{prev}}}$), the time difference with the previous step (Δt), and the rate ($\dot{\delta}$), the current neutral position (δ_{np}) is calculated using:

$$\delta_{np} = \min\left(\Delta\delta_{\text{req}}, \delta_{np_{\text{prev}}} + \Delta t \cdot \dot{\delta}\right) \tag{2.7}$$

2.3.4. ADD A FORCING FUNCTION TO THE DEVICE

When a forcing function is added to the control device, the whole force/position profile is shifted vertically up or down. Depending on the magnitude of the cue, and whether the pilot is holding the stick or not, it can change the control device deflection as shown in the illustrative example in Fig. 2.12a. In our design we intend to use this cue mainly to alert or warn the pilot, and not to impose a required control input. Hence, the forcing function should be of small period, or small amplitude. The effect is therefore short and not pre-defined in terms of deflection: the effect can be difficult to grasp in one snapshot of a haptic profile. As such, the time trace of the forcing function is visualized by an added graph as shown in Fig. 2.12b, where zero time is current, and times to the right represent past times. A pragmatic approach is used to evaluate whether the cue complies with the assumption of small period or amplitude. In the current design, two forcing functions are used: a discrete cue to communicate that the safe flight envelope is exited and a stick shaker to alert for low velocities.



(a) Shift due to a negative forcing function

(b) Added negative (pull) pulse

Figure 2.12: Haptic profiles showing the addition of a forcing function

Note that the addition of a forcing function and a pure change of neutral point both result in a change of position of the control device. Nevertheless, their driving principle is different: a forcing function does not have a predefined effect on the control position. The effect depends on the position of the control device in the haptic profile, and the pilot's arm stiffness. In contrast, a pure neutral point shift results in one desired control input, to guide a pilot through a maneuver.

DISCRETE CUE

Discrete cues are limited in time and can have a wide variety of shapes, ranging from a square block signal to a noise input. They can be a useful tool to warn the pilot of entering a certain region, while not giving a constant signal. The intent of this cue can be compared to a softstop: an indication of entering a region where caution is required. For example, a softstop can indicate a position *where* the maximum engine limits are exceeded. [44, 74] In contrast, a forcing function is added to the controls *when* the (protection) limit is exceeded. The forcing function is chosen in the design as it does not have a dependency on the state of the control device, as do all haptic cues used in the design.

One region which can be entered, with or without the intention of the pilot, is the protected region close to the edge of the flight envelope shown on Fig. 2.9 by the dashed line, corresponding to the buffers created on α, n, and V. An example where entering this zone can go unnoticed by the pilot, is when he/she is busy scanning the instruments, or involved in other tasks. Therefore, to provide a clear transition cue when exceeding the safe flight envelope, a warning cue in the form of a square pulse signal (width 0.1s, magnitude 10N, shown in Fig. 2.13a) is given. This shape and intensity of the forcing function was chosen based on a preliminary test with a single test-pilot, future research is needed for the further definition of this shape. By adding this cue, the pilot is triggered about the safe flight envelope departure and the attention is drawn to the event.

The direction of the cue should indicate the direction of the 'correct action' for the pilot to perform if (s)he intends to solve the limit violation. For this reason a stick forward cue ('pitch down' indication) is given for extreme positive load factors, high angles of attack for positive load factors, and low velocity violations. A stick backward cue ('pitch up' indication) is given when crossing all other boundaries.

STICK SHAKER

A periodic cue is a signal which repeats itself in time, and can be used as a persistent way to alert pilots of an imminent critical state. An example is the motor priming used by Navarro et al. ([36]) to warn drivers of a lane departure. Analogous to this event, in aerospace exceeding the maximum angle of attack should be avoided at all times. Hence, to bring extra attention to the proximity to stall, a second forcing function is added: a stick shaker following a sinusoidal forcing function with a frequency of 20Hz and 5N amplitude, shown in Fig. 2.13b. The frequency and amplitude is tuned to match the stick shaker present in other aircraft (such as Boeing [55]), and was initially designed to represent the aerodynamic buffeting on the control surfaces.

The stick shaker is activated when the aircraft velocity drops below half of the protected range (hence $\frac{V_{\alpha_{max}} - V_{\alpha_{prot}}}{2}$). In terms of the flight envelope, this means that close to the left-hand limits of the flight envelope, indicated on Fig. 2.9 with a stripe-dotted green line, the stick shaker activates. This cue is additional to the existing flight envelope protection as described in Subsection 2.2.2, yet is intended to clearly indicate to pilots that the aircraft is moving closer to the lower velocity limit.

(a) Stick push function

(b) Stick shaker

Figure 2.13: Continuous Forcing functions used

2.3.5. CHANGE IN SPRING COEFFICIENT

Previous research increased the spring stiffness to indicate that continued control inputs would result in a hazard, effectively reducing the occurrences of imminent pilot-induced oscillation ([46, 47]), signal a lagging adaptive controller ([75]), or indicate a helicopter main rotor setting below the limit. [74] In our design, a continued control input results in a hazard when it brings the aircraft closer to the limit.

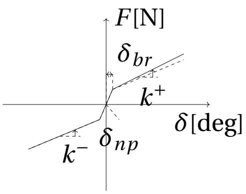
Looking at the flight envelope, it is not just *any* input that poses a hazard, it is *one direction* of input which worsens the situation. For example, when the aircraft is close to an overspeed condition, pushing the stick results in a state closer to the actual overspeed, pulling on the controls is a possible mitigation strategy. Therefore, to show the undesired input, a continuous single-sided spring cue is used resulting in a haptic profile as shown in Fig. 2.14c. In this figure, the positive (push) deflection requires more force indicating an unwanted input as in the examples above, a negative (pull) deflection is easier to obtain as the spring stiffness is equal to the nominal value. Note that a change in spring coefficient is only noticeable to pilots when they move the stick away from the neutral point, hence when the pilot is actively controlling. This haptic cue does not necessarily change the control input itself.

Similar to the further spring coefficient increase when the adaptive controller increases lags ([75]), increasing the spring coefficient can additionally be used to communicate the magnitude of the safe flight envelope excursion. As such, starting at the edge of the safe flight envelope, the red dashed line in Fig. 2.9, up to the the edge of the nominal flight envelope, the solid black line in Fig. 2.9, the stiffness is increased. For the load factor, the velocity and the angle of attack, we use v as generic symbol, the default stiffness is multiplied with a factor K_k, determined by the gain K_v and the severity of the violation:

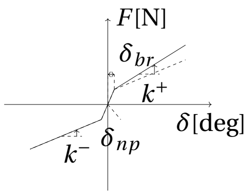
$$K_k = \begin{cases} 1 & \text{if } v < v_{prot} \\ 1 + K_v & \text{if if } v > v_{nom} \\ 1 + K_v \frac{v - v_{prot}}{v_{nom} - v_{prot}} & \text{else} \end{cases} \tag{2.8}$$

The severity is defined as the ratio of the violation of the safe flight envelope, $v - v_{prot}$, where v_{prot} is the value at the edge of the safe flight envelope, and the distance between the safe and nominal flight envelope, $v_{nom} - v_{prot}$, where v_{nom} is the value at the edge of the nominal flight envelope. To guarantee that the pilot has the final authority of the side stick, the stiffness does not increase when the state exceeds the nominal flight envelope. The haptic display is defined to trigger on the maximum (α_{max}) and protected (α_{prot}) angle of attack instead of the lower velocity, nevertheless these variables are related through Equation 2.1.

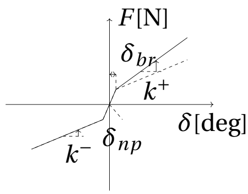
To illustrate the working principle in the overspeed condition mentioned before, Fig. 2.14 shows three instances where the velocity is outside the safe flight envelope. Fig. 2.14a represents a situation where the severity is 0.2: the velocity is slightly over $V_{MO_{prot}}$. If the situation gradually evolves, an increased velocity results in Fig. 2.14b which shows an increased single-sided stiffness with a severity of 0.5. Finally Fig. 2.14c shows a condition at or above V_{MO} where the spring stiffness is maximal, severity is one.



(a) k^+ for severity 0.2



(b) k^+ for severity 0.5



(c) k^+ for severity 1.0

Figure 2.14: Haptic profiles showing progressively increasing positive spring stiffness (k)

The direction of the stiffness cue is inversed from the discrete cue. That is, the stick feels 'stiffer' for *backwards* movement in cases of extreme positive load factors, high angles of attack for positive load factors, and low velocity violations. All other violations of the safe flight envelope lead to increased stiffness for *forward* movements. As such, the direction of the stiffness cue informs pilots of control actions which bring the aircraft closer to its limits, the discrete cue informs which action can resolve the current situation.

As the stiffness changes with continuous variables, no sudden changes in stiffness should occur. Nevertheless, if it occurs, a large change in stiffness could be observed by pilots as a forcing function, an alert, not a continuous guidance cue. Therefore, to guarantee a smooth change in stiffness, the change is ramped-in linearly, similar to Equation 2.7.

Table 2.3: Summary of design parameters for control device and haptic settings

K_α	K_n	$K_{V_{MO}}$	k_{nom}	δ_{max}	k_{br}	δ_{br}	$\tau_{overspeed}$
3	2	2	1 N/deg	18 deg	50 N/deg	0.05 deg	15

2.4. OPERATIONAL TEST SCENARIOS

Two relevant operational scenarios will be discussed in this section, which were chosen because we expect that our haptic interface can provide pilots intuitive and useful information to deal with these events, both scenarios are based on Ref. [54]. The first example describes a case in which pilots are required to maneuver close to the edges of the flight envelope limits: a wind shear. The second example shows how pilots can use the system when the flight envelope is shrinking, and the envelope limits approach the current aircraft status, ultimately limiting pilots in their control: icing.

For both scenarios we will discuss the origin of the event, the required (or: desired) actions to be taken by the pilot, and how we expect that the new haptic system supports the pilot in deciding and performing the necessary actions. In addition, Subsection 2.4.3 discusses some possible undesired actions, as a brief introduction to what our experimental depend measures may look like.

2.4.1. WIND SHEAR: AIRCRAFT OPERATES NEAR THE LIMITS

A wind shear is a meteorological phenomenon in which locally wind velocities are rapidly changing. Such event can be caused by multiple sources such as strong surface winds, weather fronts, and convective storms. Severe wind shears can occur when a large cylinder of air suddenly “drops” towards the earth due to convective weather conditions, sometimes referred to as microbursts. [76] When this cylinder plunges on the earth surface, the air spreads out as illustrated in Fig. 2.15, with the numbers in circles corresponding to those used in the text below, and figures that follow. If an aircraft flies through the windfield, the headwind initially causes its airspeed to increase as in 2. When the pilots do not recognize the windshear and fail to take action, the downwind that follows will push the aircraft towards the ground 3 and 4. The next tailwind drastically reduces the velocity 5. Near the final stage of the recovery, the aircraft is flying with high throttle settings and almost level flight, a potential problem is an overspeed 6. At the end of this event, the pilots hopefully are able to return to normal flight 7. All things considered, windshear forms a severe risk to the safety of the flight, especially during take-off or landing when already close to the ground. [77] Throughout the recovery of a severe windshear, is vital that pilots use all available aircraft performance to climb irrespective of forward velocity, with one catch: the aircraft should not be stalled.

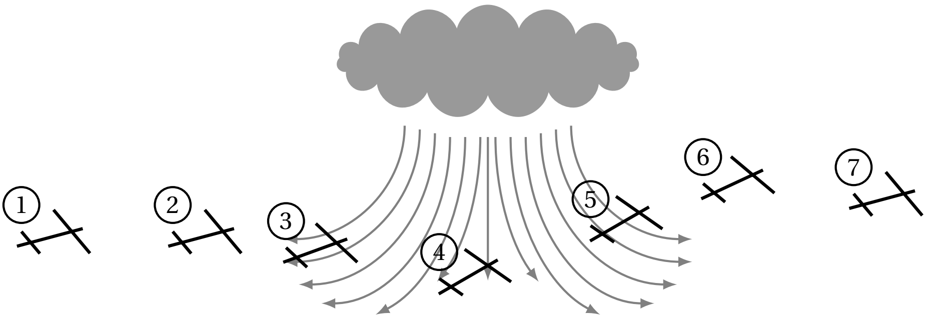


Figure 2.15: Weather structure during wind shear

If this event occurs with the autopilot active, most actions are handled automatically while the pilot maintains a close watch on the autopilot actions. Here we focus on manual flight control, and the autopilot is assumed to be turned off. The pilots must perform a set of actions, put forward by the manufacturer as described in the FCOM. [13]

The initial warning for the pilot of the oncoming event is a visual and an aural warning: a red "WINDSHEAR" message on the PFD and a synthetic voice which announces "Windshear" three times. At this point the FCOM states that the pilots must take the following six actions:

A Do not change configuration (flaps, slats, gear) until out of the windshear,

B Throttle levers at go around position,

C Initial pitch attitude of 17.5°,

D Increase pitch if necessary to minimize loss of height above terrain,

E Closely monitor flight path and speed, and

F Recover smoothly to normal climb out of shear.

The first step is a straightforward command, to make sure that no time is lost before starting the recovery. Next, one must assure that maximum energy is available, step B, followed by an initial pitch attitude to start increasing altitude, step C. Then, steps D and E are crucial to the safety of the aircraft: here we see a trade-off between on the one hand reducing altitude loss and on the other hand maintaining sufficient airspeed. In case of an extreme wind shear, this recovery procedure might require pilots to move dangerously close to the limits of the flight envelope, namely at very low velocities as to use all available energy to climb out of the shear. The final step, F, assures that, when clear of the dangerous winds yet still with high throttle settings, the aircraft velocity does not exceed the upper limit.

Throughout the procedure, pilots are likely to work under high workload levels and could develop a mental state of "cognitive tunnelling", heavily monitoring the loss of height. [78] A support to improve the attention division of the pilot is of crucial importance and we show below that our haptic interface can enable this.

The trajectory in the flight envelope of the seven selected time frames is shown in Fig. 2.16. For each frame, the left column of Fig. 2.17 shows the aircraft flight envelopes, with the current aircraft state shown using a circle. The center column shows the corresponding PFDs, with velocity (left), altitude (right), and attitude (center). The right column of Fig. 2.17 shows the haptic profile. These frames are used here to show how the haptic interface is working during operations. For example, the first of these frames is the starting point when the windshear-warning becomes active, the corresponding flight envelope, PFD and haptic profile can be seen in, respectively, Fig. 2.17a, 2.17b and 2.17c.

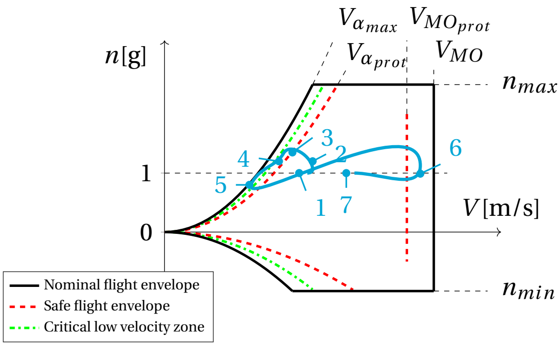


Figure 2.16: Trajectory through the flight envelope during windshear recovery with frames indicated in Fig. 2.15

After the warning is given, our haptic interface is expected to help in the following steps (corresponding to the list of actions stipulated by the FCOM):

C. The pilot must pitch-up the aircraft and this increases the load factor somewhat (Frame 2). If this maneuver is executed too fast, the pilot is informed of the g-loading limit through the load factor protection cues.

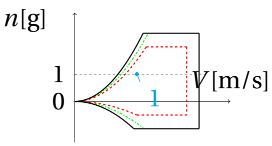
D. During this step as much energy as possible should be used to climb, and the haptic system is expected to help pilots to operate at or close to the flight envelope limits. The initial cue of approaching limits is the discrete cue, corresponding to Frame 3.

E. As the pilot has to divide attention over two elements of the PFD (the velocity and altitude indicators) and possible cognitive tunneling may develop on the vertical speed, the haptic system is expected to serve as a velocity monitoring aid. This can be achieved by both the continuous spring cue and the change in neutral position for low velocities, as illustrated in Frames 4 and 5 in Fig. 2.17, respectively. Additionally, we expect pilots to use the stick shaker as a possible control aid to “ride the stick shaker”: adjusting the input such that the stick shaker remains on the verge of activation.

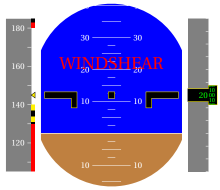
F. When approaching the upper limit on velocity, the high velocity cues alert the pilot of imminent limit violation with an extra control aid by where the pilot can follow the stick backwards position, shown in Frame 6 in Fig. 2.17.

In general, for each of the steps the discrete haptic pulse cue (Frame 3) is expected to first *alert* the pilot that a flight envelope limit is approaching, and then the continuous spring cue (Frame 4) follows to clearly communicate the distance left to the ultimate flight envelope boundaries.

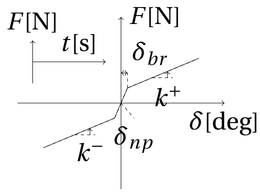
2



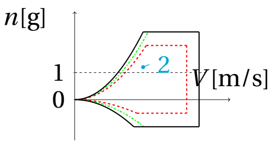
(a) Flight envelope for Frame 1



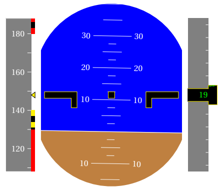
(b) PFD for Frame 1



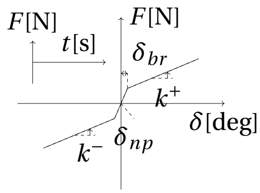
(c) Haptic profile for Frame 1



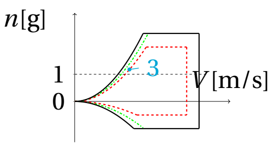
(d) Flight envelope for Frame 2



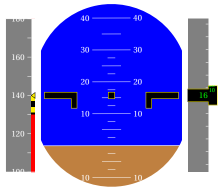
(e) PFD for Frame 2



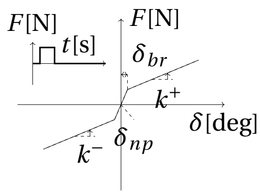
(f) Haptic profile for Frame 2



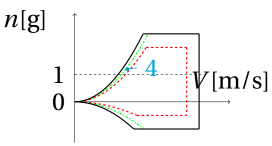
(g) Flight envelope for Frame 3



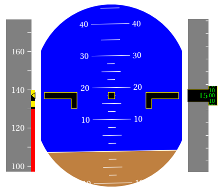
(h) PFD for Frame 3



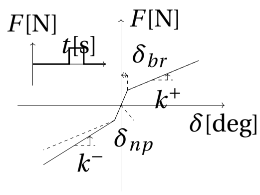
(i) Haptic profile for Frame 3



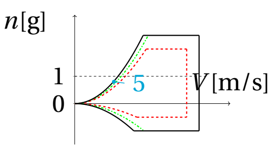
(j) Flight envelope for Frame 4



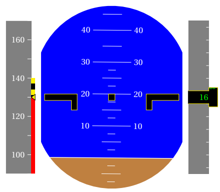
(k) PFD for Frame 4



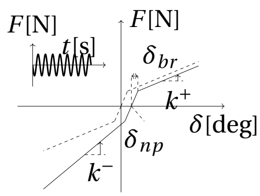
(l) Haptic profile for Frame 4



(m) Flight envelope for Frame 5

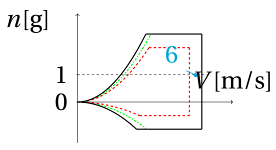


(n) PFD for Frame 5

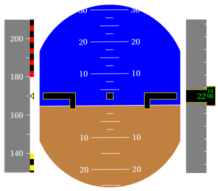


(o) Haptic profile for Frame 5

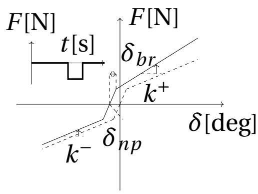
Figure 2.17: Flight envelopes, PFDs, and haptic profiles for the windshear recovery according to the frames from Fig. 2.15



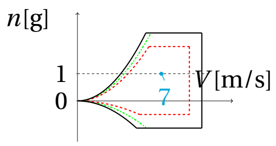
(a) Flight envelope for Frame 6



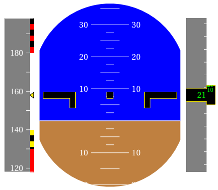
(b) PFD for Frame 6



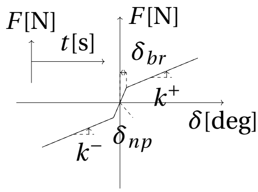
(c) Haptic profile for Frame 6



(d) Flight envelope for Frame 7



(e) PFD for Frame 7



(f) Haptic profile for Frame 7

Figure 2.17: (continued)

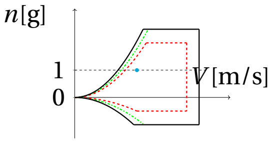
2.4.2. ICING: LIMITS MOVE TOWARDS THE AIRCRAFT

The second scenario we will use to evaluate our haptic interface is an extreme form of ice formation on the aircraft wings. Especially when flying through cold humid air, the risk of such an event is severe. [79] The effect of ice formation is a degradation of the aircraft aerodynamic performance, resulting in a reduced lift from the wings, and with that an increase in the aircraft minimum velocity. Here, it is assumed that the FEP has an updating algorithm which is presented with icing implementation in Ref. [54]. The decrease in minimal velocity highlights the main difference with the previous scenario: in this case the flight envelope *shrinks*, the flight envelope limits 'approach the pilot', and (s)he must identify this situation properly and act on it.

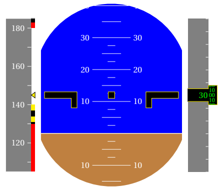
An example case of such an event is during a manual instrument landing in which the landing is performed in the clouds. If extreme ice accumulation is present, or when the de-icing system is not working properly, the ice formation is inherently a slow yet detrimental process. It is very likely that, for considerable time, pilots may not be aware of the deteriorating aerodynamic properties.

In principle, pilots can notice the degradation of the aerodynamic properties due to icing through two clues. First, the increase in drag requires a higher throttle setting, and second, the decrease of lift requires a higher angle of attack.

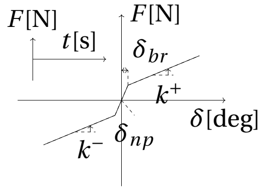
Especially when the pilot is flying with the auto-thrust active, the increase in throttle setting can be more difficult to notice and, as Airbus aircraft by default do not have an angle of attack indicator, pilots might be unaware of the creeping danger. Nevertheless, the haptic feedback system uses information on the angle of attack sensor, and therefore the pilot will get new information without adding another element on the, already comprehensive, visual display.



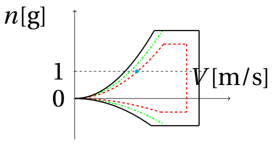
(a) Flight envelope for Frame 1



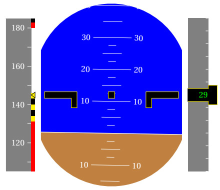
(b) PFD for Frame 1



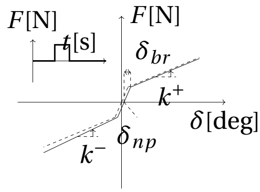
(c) Haptic profile for Frame 1



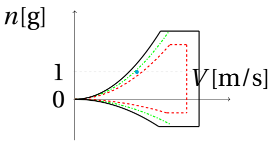
(d) Flight envelope for Frame 2



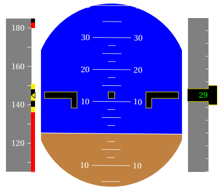
(e) PFD for Frame 2



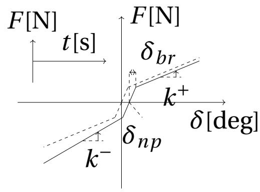
(f) Haptic profile for Frame 2



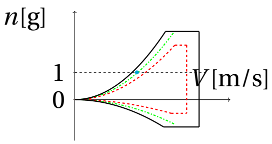
(g) Flight envelope for Frame 3



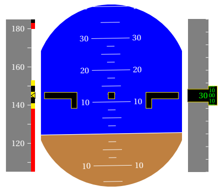
(h) PFD for Frame 3



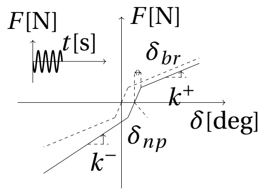
(i) Haptic profile for Frame 3



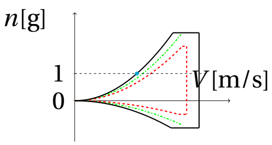
(j) Flight envelope for Frame 4



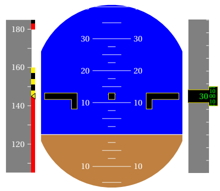
(k) PFD for Frame 4



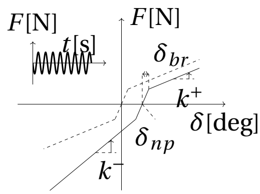
(l) Haptic profile for Frame 4



(m) Flight envelope for Frame 5



(n) PFD for Frame 5



(o) Haptic profile for Frame 5

Figure 2.18: Flight envelopes, PFDs, and haptic profiles for an icing event illustrating shrinking of the flight envelope

To illustrate how the state is developing and how the haptic feedback is supplying flight envelope information, Fig. 2.18 shows five frames of an icing event in which the flight envelope is shrinking. The left column shows the aircraft flight envelopes, with the current aircraft state shown using a circle. The center column shows the corresponding PFDs, with velocity (left), altitude (right), and attitude (center). The right column shows the haptic profile. Starting from the nominal condition in Frame 1, icing forms and the minimal velocity is increasing as stated before. If the pilots do not react to this, the first signal from the haptic display is the discrete cue when exiting the safe flight envelope as in Frame 2. At this point, the pilots should become aware that something is going on. Additionally, they have received the correct action by the direction of the cue: reduce the angle of attack. When the pilot would keep controlling in the low velocity region, the increased spring coefficient for negative deflections (pull) in Frame 3 indicates them that pulling should be executed with caution. Crossing the stick shaker activation threshold gives a clear cue that a stall is imminent, shown by Frame 4. Finally, if the pilot still did not react, the state in Frame 5 is at the upper angle of attack limit where the stiffness is maximum, the stick shaker is active, and the neutral point shift is most observable, all cues which inform the pilot of the proximity of the flight envelope to the state.

2.4.3. POSSIBLE UNDESIRED ACTIONS

The previous sections discussed the intended use of the proposed haptic feedback system. We now look at possible undesired actions, which are discussed using the concepts of misuse, disuse and abuse as proposed by Parasuraman. [80]

Misuse is the use of the automation for an unintended goal, typically due to overreliance on the system. In the case of the haptic feedback system, overrelience can result in a lack of scanning the instruments: the pilot might expect the haptic feedback to signal an approaching limit and focus on other tasks besides the primary flight duty. As the feedback system is reliant on sensor measurements, if these sensors fail, the haptic system might not trigger whereas a scan of the instruments might show the erroneous measurement. In an evaluation experiment, presence of overreliance on the haptic feedback system might give different results in the scenarios discussed above: in case of windshear the pilot is actively maneuvering the aircraft closer to the limits and more likely to be aware of closing limit, in case of icing the limits move to the current state and in case of overreliance this event can surprise the pilots.

Disuse is the deliberate *not* using of the automation available, commonly caused by a distrust in the system due to a significant false alarm rate. Looking at the haptic feedback system while assuming that it functions as intended (no false positives), pilots might still consider the haptic feedback as false when it would be perceived as out of tune with respect to the magnitude of the flight envelope protection zones. For instance, the haptic feedback might signal a limit as close, whereas the pilot experiences it not as such. In that case, the haptic feedback might be considered as distracting when controlling the airplane, in a worse case, the pilots can feel that they are fighting the haptic feedback system. An evaluation of the system therefore has to check that the workload of the pilots does not increase, and that pilot actions and haptic feedback are in line.

Abuse is the automation of functions by designers without due regard for the consequences for human performance. In the haptic feedback design, part of the design parameters (for example the magnitude of the discrete cue) are heuristically tuned using one test pilot. Due to this heuristic tuning, the haptic feedback might be experienced by some pilots as intrusive. As such, an evaluation has to investigate whether the current setup does not increase workload, and allows the pilot to keep performing the nominal mission.

This provides a set of criteria for the haptic display of flight envelope limits: the haptic feedback system should not increase workload and should not hinder the primary pilot tasks. Furthermore, it should be investigated that overrelience is not present, and that pilots are not fighting with the system. Additionally, performance and safety metrics of pilots flying both windshear and icing scenario's should improve. In conclusion, we expect that the new haptic display presented in this chapter increases the knowledge of the pilot on the edges of the flight envelope and helps identifying abnormal situations. This hypothesis is tested with an experimental evaluation: the subject of the next chapter.

2.5. CONCLUSION

This chapter describes the design of a haptic feedback system, i.e., using force feedback through the control device, to provide intuitive information on the state of the aircraft relative to the Flight Envelope Protection. The system (i) informs the pilot about an approaching limit using a discrete cue, (ii) indicates a non-desired control direction using the spring coefficient, (iii) warns the pilot of a dangerously low velocity using a stick shaker, (iv) shows a desired control input during an over-speed event by moving the control device, and (v) indicates the required control input at low velocities when a stick neutral position is not sufficient by moving the control device.

3

Evaluation of a Haptic Feedback System for Flight Envelope Protection

Flight envelope protection systems in modern fly-by-wire aircraft support pilots in staying within the safe flight envelope, however the actions of these systems may not always be clear to pilots. To support situation awareness, the aircraft proximity to the limits of its flight envelope can be communicated using haptic feedback, through providing forces on the control device. The haptic feedback design was discussed in detail in the previous chapter; this chapter reports on its experimental evaluation. Professional airline pilots were invited to fly an airliner model similar to an Airbus A320 in a research flight simulator. A windshear and an icing scenario were flown using a full and degraded flight control law, with the haptic feedback system turned on and off. Results show that the haptic feedback does not lead to significant changes in performance or safety metrics. It also does not interfere with normal pilot control actions. Pilots did express a clear preference for the haptic system, however. Recommendations for future work include more research in haptic feedback tuning, the addition of visual support to complement the haptic cues, and the redesign of the scenarios.

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3.1. INTRODUCTION

MODERN flight decks provide an abundance of information to pilots, using mainly the visual and aural communication channels. Examples of visual displays are the PFD for the most important aircraft states, and the ND for a planar, top-down overview of the aircraft trajectory and flight plan. Aural signals are used to provide urgent messages, such as to warn pilots for excessive aircraft velocities, and to provide altitude read-outs and throttle back-commands on landing. [59]

But apart from these senses, pilots are able to perceive information in several other ways. This chapter will elaborate on the use of the pilots' haptic sense, by providing haptic feedback through the control device. As shown in Fig. 3.1, within the field of haptic research two main categories are identified: (i) touch, stimuli to the skin, and (ii) kinaesthesis, stimuli to the receptors in the muscles, joints and tendons. [57, 60] The design used in this chapter uses both touch and kinaesthesis, hence the term haptic feedback is used.

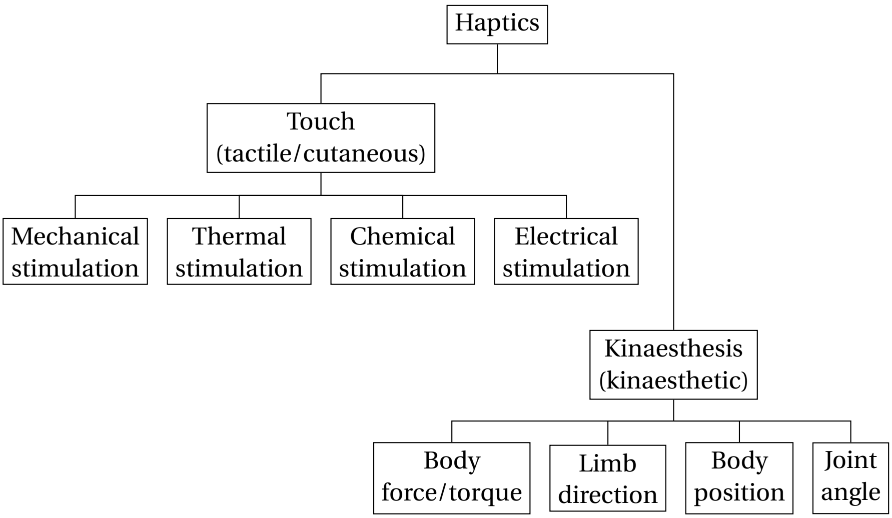


Figure 3.1: Components of haptics [57]

In most 20th century aircraft, the control manipulator 'feel' provided information on for instance aerodynamic forces, buffeting when close to a stall, control surface limits through hard stops of the controls, and other control-related phenomena. With the introduction of fly-by-wire, however, the forces on the control surfaces and the control devices were decoupled, eliminating the potentially useful haptic information channel. [61]

A reason that haptic feedback on the aircraft limits was not integrated after the introduction of fly-by-wire systems in the 1980s and 1990s, was the rather bulky device required to implement the haptic forces. These old devices had issues regarding their size, weight, power and stability requirements resulting in certification difficulties. Current-day devices have become much smaller and lighter, while still able to provide reliable haptic feedback. [62] This offers the possibility to re-consider this type of feedback in fly-by-wire control systems. [63]

Together with the advances in control devices automation on flight decks is rising, leading to a more supervisory role for the pilot, instead of direct manual control. Despite these advances, pilots are still often required to take over manual control of the aircraft in landing, takeoff, or during emergency scenarios. An example of the latter could be a computer or sensor malfunction, which was the case for Air France flight 447. Here the crew, startled by unexpected high-altitude dynamics, lost situation awareness, despite the information available from the visual and aural displays. Unaware of the loss of the usual flight envelope protections due to the malfunction, pilots stalled the aircraft. The accident report indicates that the stall warning, which was only aural, should be complemented. [7] The control manipulator, the Airbus A330 side stick, did neither provide the pilots with direct feedback on their control actions, nor the aerodynamic stall buffets. The passive stick did not help them in properly identifying the situation as a stall. As this tragic example shows, when manual control is required the lack of haptic information through the control device might contribute to a reduced situation awareness.

Combining the ever-increasing sophistication of automation on the flight deck, and the current generation of small and powerful control devices provides designers a new opportunity, namely to increase pilot awareness through haptic feedback. Some aircraft already include 'augmented forces' on the control device, which can be provided on *both* control devices (on a two-pilot flight deck) linked to the surfaces, or fly-by-wire control systems. An example of this is the "Q-feel force", which changes the stiffness of the controls with changing dynamic pressure/velocity in Boeing type aircraft. [64] Another example is a stick shaker or pusher, which warns pilots of moving closer to extreme aircraft states. [4] The control device can also be loaded with two passive springs to create a change in experienced stiffness when pilots exert large control deflections irrespective of the aircraft state, such as in Airbus aircraft. Active control can be used to have an increased (artificial) spring force when rolling the aircraft beyond the safe roll limit, irrespective of the control surfaces, as used on a Boeing 777. [55]

Although examples of haptic feedback implementations exist, there is limited research published in open literature to prove the benefits of such a system. Within aeronautics, Schmidt-Skipiol and Hecker used either a passive spring or an active counterforce to communicate the distance to the flight envelope limits, with the latter yielding better performance. [50] A second example is the work by Stepanyan et al. that showed the limit on the available control space both visually and haptically. [52] For the haptics, the input neutral point and maximum deflection were manipulated, to be used by pilots to operate close to the aircraft limits. A soft-stop, i.e., a local step in the force required for a certain deflection, can be used to indicate the engine limitations in the collective of a helicopter, which was shown in simulations to reduce pilot workload ([44, 65]), and is implemented in an experimental helicopter of the German Aerospace Center. [66] Tactile feedback through the use of tactors on a vest enabled improved spatial awareness and reduced spatial disorientation. [29] These examples all use haptic feedback to inform the pilot about the flight envelope limits. Note that research in supplying the pilot with such information is not limited to haptic only, new visual displays are investigated as well and show positive results. [51] Aside from information on the flight envelope limits, the haptic channel can be used to supply guidance support, of which a haptic flight director showed potential to increase pilot control performance while reducing workload. [67]

Other fields do have more open domain research interest, for example in automotive. Here, haptics were successfully applied on the gas pedal, to show the proximity of a lead car, with better performance while reducing driver input magnitudes. [81] Haptics for the steering wheel are currently being developed, to support curve negotiation. Implementations as either a 'warning system' (to reduce the driver reaction time) or 'guidance system' (to keep the car on the road) exist. [38] In tele-operation, the control of an unmanned aerial vehicle was supported by haptically showing the proximity to objects in its surroundings, leading to safer flight and increased operator awareness. [32]

The aim of the current thesis is to investigate the use of haptic feedback to give pilots more information on the aircraft FEP limits during manual control, within the modern fly-by-wire flight deck. In other words, the haptic feedback aims to provide feedback to the pilot on the proximity of the aircraft state to the limits adhered by the FEP system. The full design and rationale is described in detail in the previous chapter. This chapter presents the evaluation of this new design using two operational scenarios flown by commercial airline pilots. This design only involves longitudinal haptic feedback, lateral cues can be added in the future.

Section 3.2 will first provide a brief description of the control laws and elaborate the cues which can be perceived using the haptic feedback. Section 3.3 presents the experimental setup, designed to test two operational scenarios: windshear and icing. Results are shown in Section 3.4 and discussed in Section 3.5. Recommendations are given in Section 3.6, followed by conclusions in Section 3.7.

3.2. HAPTIC DISPLAY

The haptic feedback design rationale, full implementations details, and the Airbus A320 control structure on which it is based, are extensively discussed in the previous chapter. This section provides the essential information on the control laws, Subsection 3.2.1, and haptic feedback design, Subsection 3.2.2, to understand the working principles and provided information during the experiment, discussed in Section 3.3.

3.2.1. AIRBUS A320 CONTROL STRUCTURE

Modern day Airbus aircraft, such as the A320 and the A330, employ a fly-by-wire system. This means that there is no mechanical connection between the control surfaces and the control device, yet the latter acts as an interface between the pilot and the FCCs. The FCCs augment the pilot control input with a control law, to move the control surfaces with hydraulic actuators. The FCCs also include a Flight Envelope Protection (FEP) system, which can limit pilot inputs, such that no flight envelope limits are violated.

Longitudinal control in a Fly-By-Wire (FBW) Airbus, when all sensors are functioning, is the normal law. It uses C^*-control, a combination of both pitch rate (q) and load factor (n). [10–13] On top of this control law, a hard envelope limit is defined which protects pilots from exceeding pre-defined limits on angle of attack (α), load factor (n), and maximum velocity (V_{MO}). This protection is shown in Fig. 3.2, where the nominal flight envelope is the extreme limit which can not be exceeded, and the safe flight envelope is the point where protections start acting. The envelope is defined by the maximum (n_{max}) and minimum (n_{min}) load factor, their protection limits ($n_{max_{prot}}$ and $n_{min_{prot}}$, respectively), the maximum operation velocity (V_{MO}, and protection $V_{MO_{prot}}$), and minimum velocity ($V_{\alpha_{max}}$, and protection $V_{\alpha_{prot}}$).

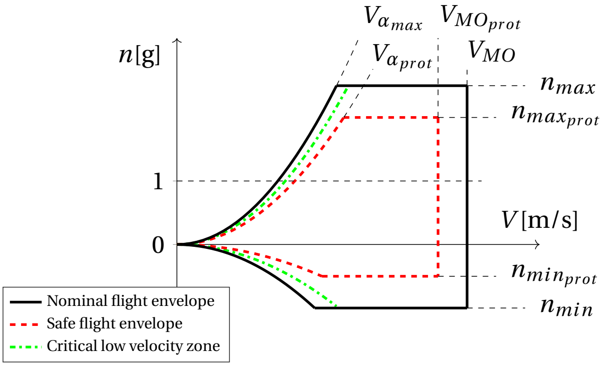


Figure 3.2: Flight envelope, load factor (n) versus velocity (V)

When multiple FCCs fail, or when a sensor failure occurs, control is reverted to a degraded control law. In this research, besides the normal law, the Airbus alternate law without reduced protections is considered. In this law the same protections apply as before, only the angle of attack protection is lost, and therefore, while in alternate law, the aircraft can be stalled.

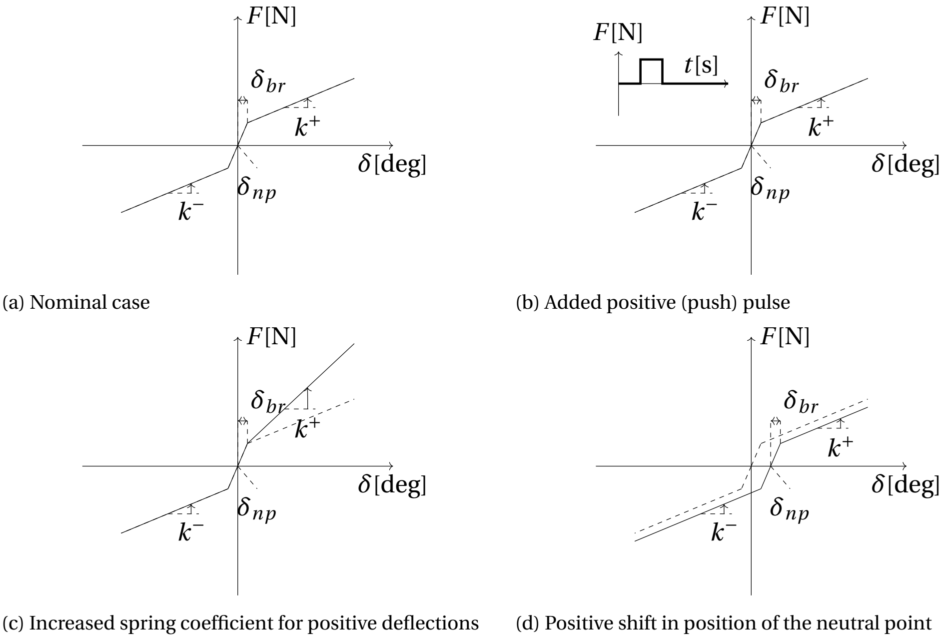
These control laws and envelope protections were implemented in a proprietary model by the German Aerospace Center (DLR) which is made available for this research, see Ref. [54, 72]. Although this model in not in the public domain, the principles behind the haptic feedback can be extrapolated to any model which provides flight envelope information. Note that the model does not include the automatic 'pitch-up' command during high speed conditions, which raises the aircraft nose when its velocity is too high.

3.2.2. HAPTIC FEEDBACK DESIGN

For this research, haptic feedback is provided using two methods: (i) by *changing the haptic profile* of the control device, and (ii) by *adding deterministic forcing function signals* to the control device. The haptic profile is defined here as the amount of force required (F) to achieve a certain deflection of the control device (δ). A typical nominal haptic profile is illustrated in Fig. 3.3a: a breakout center (δ_{br}) with an increased spring coefficient (k_{br}), followed by symmetric spring behaviour (k_{nom}) until maximum deflection (δ_{max}). Such a haptic profile provides the pilot with information on the input magnitude: larger inputs require larger forces. By changing this haptic profile, certain deflections require pilots to exert a different force input, which informs them about (non-)desired inputs.

The goal of the haptic feedback is to communicate the FEP limits in an intuitive way. When presenting the evaluation scenarios in Section 3.3, we will discuss how we expect pilots to use the following five cues:

1. When the aircraft leaves the safe flight envelope (anywhere outside the red dashed line in Fig. 3.2), a discrete, unit pulse *forcing function is added* to the stick resulting in a perceived 'tick on the stick'. This is illustrated on the haptic profile with the inset graph in Fig. 3.3b.



(a) Nominal case

(b) Added positive (push) pulse

(c) Increased spring coefficient for positive deflections

(d) Positive shift in position of the neutral point

Figure 3.3: Control device profiles

2. For aircraft velocities close to the lower velocity limit V_{prot}, a stick shaker (i.e., a sinusoidal forcing function) activates, to communicate the increasing risk of stalling the aircraft.

3. To communicate the relative distance to the limit, the *spring coefficient increases* when moving from the safe flight envelope to the actual limit (the black line on Fig. 3.2). Maximum spring coefficients are determined by the tuning parameters K_α, K_n and $K_{V_{MO}}$ for angle of attack, load factor and maximum velocity, respectively, as discussed in our design chapter, Chapter 2. The increased spring coefficient results in a situation where pilots must apply a larger force to move the stick in a particular direction, illustrated for positive (push) deflections in Fig. 3.3c.

4. When the aircraft has a critically low velocity, and bringing the stick back to its neutral position is not sufficient to return to the safe flight envelope, the required stick deflection is communicated to the pilot by *a change in neutral point* of the stick, as illustrated in Fig. 3.3d.

5. During an overspeed situation, the automatic ‘pitch up’ command is communicated to the pilot by a change in neutral point of the stick, similar to Fig. 3.3d, but now using a negative neutral point position. This command is discussed in the previous chapter and is defined by one tuning parameter ($\tau_{overspeed}$).

All implementation details are provided in the design chapter, Chapter 2. For example, there we discussed that both the discrete and periodical forcing functions are empirically tuned to be noticed by pilots, without interfering with actual control inputs. We also discussed two scenarios with intended use, and potential disuse/abuse/misuse of the haptic feedback. The goal of this chapter is to show the results of these scenarios when flown by professional pilots in a human-in-the-loop experiment evaluation, discussed next.

3.3. Method

An experiment was performed to test the haptic feedback system. Professional airline pilots were instructed to fly standard approaches, in which emergency situations were introduced.

3.3.1. Independent variables

The experiment had three independent variables. First, the haptic feedback was either present (HF), or not (NH). Second, two levels of protection in the control laws were used: a control law resembling the the default Airbus normal law (NL) where all protections are present, and one resembling the Airbus degraded alternate law (AL) where a stall is possible (see Subsection 3.2.1 for more details). Third, two scenarios were used: windshear (WS) and icing (IC), as will be discussed in detail below.

A factorial $2x2x2$ design resulted in eight experiment conditions. However, experimenting with the first participants revealed that the flight dynamics simulation model did not work well during the icing scenario in normal law, and it was decided to abandon these two conditions. The experiment was continued with the remaining six conditions for all remaining participants. Each of the six conditions was flown by each participant, in both a training and measurement phase. The order of the conditions for each participant was determined using a latin-square.

3.3.2. Participants and Instructions

Participants (all males) were commercial airline pilots with a current Airbus license (either A330 or A320); their experience is shown in Table 3.1. Pilots did the experiment alone, no other crew members were either present or simulated. Instructions were to fly as they would in the actual aircraft, and to voice their thoughts as much as possible. Additionally, the pilots were told that each run would stop at 50ft of altitude, irrespective of any other events or their performance. Because all participants (and experimenter) were native Dutch speakers, the questionnaires introduced below were all provided in Dutch; they have been translated to English for this publication.

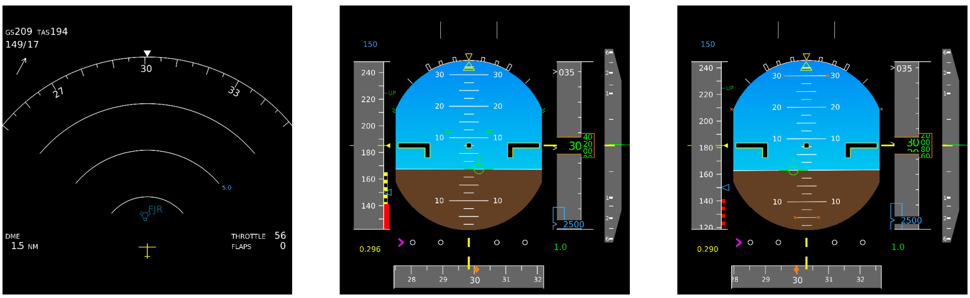
3.3.3. Apparatus

The experiment was performed in the Research Facility for SImulation, MOtion and NAvigation (SIMONA) at Delft University of Technology. It is a full-motion capable, near 180° outside field-of-view, generic flight deck, used in the first officer position of which an inside-picture is shown in Fig. 3.4. Since the pilot was seated in the first officer position, the display to the front-left was the ND showing a top-down view, Fig. 3.5a. The display right in front of the pilot was the PFD showing the critical flight states, Fig. 3.5b for normal and Fig. 3.5c for alternate law.

Table 3.1: Experiment participants

Participant	Age	Flight hours	Airbus flight hours
1	45	13,500	500
2	47	15,000	4,500
3	57	17,000	2,000
4	41	10,000	6,000
5	56	14,000	7,500
6	30	4,800	4,600
7	27	5,200	5,000
8	49	14,000	7,000
9	34	5,000	4,000
10	29	3,000	1,900
11	26	2,250	2,100
Mean	40.1	9,431.8	4,100
Std. Dev.	11.5	5,466.6	2,258.8

Figure 3.4: Inside view of the SIMONA flight deck (picture by Thierry Schut)



(a) ND

(b) PFD for normal law

(c) PFD for alternate law

Figure 3.5: Flight deck display setup

A control-loaded, two degrees-of-freedom electrical Moog FCS Ecol-8000, with a haptic profile resembling a conventional Airbus side stick was the main control manipulator. The nominal control device settings, and the haptic feedback settings for this experiment, all defined in the previous chapter, are given in Table 3.2. Forcing functions used were a discrete unit pulse function (duration 0.1s, magnitude 10N) when exiting the safe flight envelope, and a stick shaker for low velocities as a sinusoid (frequency 20Hz, magnitude 5N). Furthermore, a Boeing 777 center console with throttles and flap-lever provided engine and high-lift device inputs, and a Boeing 737 Mode Control Panel (Airbus terminology: Flight Control Unit) was the interface with the heading/velocity/altitude references on the displays.

3

Table 3.2: Control device and haptic settings in the experiment

Parameter	Value
K_α	3 -
K_n	2 -
$K_{V_{MO}}$	2 -
k_{nom}	1 N/ deg
δ_{max}	18 deg
k_{br}	50 N/ deg
δ_{br}	0.05 deg
$\tau_{overspeed}$	15 s

3.3.4. EXPERIMENT SCENARIOS

The haptic feedback system is designed to communicate the 'proximity of the flight envelope limits' to the pilot. It was expected that it supports pilots by providing both a control aid when maneuvering close to the limits, as well a warning aid when moving (unknowingly) to the limits. To investigate these two potential use cases, two experiment scenarios were designed: (i) a situation where the pilot is forced to maneuver close to the aircraft limits: a windshear event; and (ii) a situation where the flight envelope shrinks, and the limits slowly move to the normal maneuvering range of pilots: icing.

For both scenarios, a training and evaluation design was extensively discussed and prepared with the help of an experienced A330 captain (and instructor). They are elaborated in the following; we also discuss how we expected pilots to use the system.

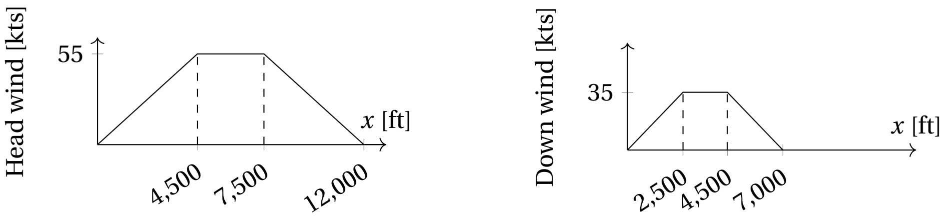
WINDSHEAR

A wind shear is a meteorological phenomenon where wind velocities are locally rapidly changing, and can be caused by a large cylinder of air suddenly "droping" towards the earth. During such a wind shear event, the pilot has to control the aircraft as close to the stall limit as possible, to prevent further height loss. This can be a dangerous situation especially when it occurs when flying close to the ground, such as on final approach. When a windshear is detected by the aircraft sensors, this is announced using visual and aural warnings.

Following these warnings, pilots must apply the windshear recovery procedure as stipulated by the aircraft manufacturer. For Airbus aircraft, the procedure is shown in Section B.5 and includes the following items ([13]):

1. Do not change configuration (flaps/slats/gear),
2. Set thrust levers at go-around position,
3. Set pitch initially at 17.5°,
4. Increase pitch to eliminate descent rate,
5. Closely monitor flight path and speed, and
6. Recover smoothly when clear of the windshear.

As can be seen in this checklist, the pilot might need to increase the aircraft pitch angle to extreme values if a severe windshear occurs and thereby the aircraft can possibly reach the limits of the flight envelope. This latter property makes this scenario of great interest for our evaluation. Following the FAA training manual, the windshear in this experiment was modeled by both a head-on and top-down component as shown in Fig. 3.6, where x represents the along track distance traveled from the trigger point. [76]



(a) Headwind component (b) Downwind component

Figure 3.6: Windshear component distribution

Training Phase To make sure the pilots became sufficiently familiar with the windshear procedure, it was first trained using an approach to Nice (France). A full approach was flown since it improved the immersive feeling of the simulation. The flight path, with the approach chart shown on Section B.3, was an agile GNSS approach starting at an altitude of 2,500ft, velocity of 190kts, heading 310, and 2NM South-East of point SOVEX. From there, the pilot had to fly along the navigation points in the right order, with speeds and altitudes as indicated on the chart:

1. NANAX: minimal 2,000ft, maximum 150kts
2. MN410: at 1,500ft, maximum 145kts
3. MAP22: descent to 1,000ft after this point, maximum 145kts

Between waypoints MN410 and MAP22, and when the velocity and altitude were 'stable' as judged by the experimenter, the windshear was initiated and the pilot had to execute the recovery procedure. The missed approach procedure consisted of turning South, climbing to 2,000ft, 185kts and reporting to Air Traffic Control (ATC).

Measurement Phase In this phase a tear-drop approach was flown into Montpellier, to runway 12L. A tear-drop was chosen to increase pilot workload, as it requires a rather accurate timing of the maneuvers. The approach started at 3,000ft altitude, 180kts, heading 300, 1.6NM South-East of the airfield, and the pilot had to perform a procedure as indicated on the approach chart in Section B.4:

1. Fly overhead the airfield while descending to 2,500ft,
2. Follow radial 332 outbound of the FJR VOR,
3. Slow down to 150kts,
4. At 7.0NM radial distance from FJR, make a left turn to heading 121,
5. Perform the turn using a 'rate one turn' (2 minutes per 360°), using the rule-of-thumb: "roll angle equals speed divided by 10, plus seven" ([82]), and
6. On completion of the turn, maintain heading/velocity/altitude and await ATC instructions.

When the turn to heading 121 was completed, and when the velocity and altitude were 'stable' as judged by the experimenter, the windshear is initiated. The missed approach consisted of maintaining runway heading 121, climbing to 2,500ft, and informing ATC.

Intended Use In our design chapter, we proposed that the haptic feedback system would help in informing the pilot on extreme inputs which result in an aircraft state close to the limits during the initial stage of the windshear recovery procedure. Next, when the pilot has to increase pitch to climb, the initial discrete cue can help the pilot being aware of the envelope limit. The stick shaker can be used to operate the aircraft near the limits by 'riding the stick shaker': adjusting the input such that the stick shaker remains on the verge of activation. Additionally, at the end of the recovery, with high throttle settings, the pilot can follow the pitch-up cue to understand the high-speed protection and can feel that the distance to the limit is decreasing with the increased local stiffness. In summary, the haptic feedback system was expected to help in alerting the pilot that the aircraft is approaching the flight envelope by means of the discrete cue, and to communicate the distance left to the ultimate flight envelope boundaries using the increasing spring stiffness.

ICING

When flying through cold, humid air, there is a risk that ice starts forming on the leading edges of the aircraft and degrades its aerodynamic performance. [79] This can result in reduced lift from the wings, increasing the minimum velocity and reducing pilot control authority. If this is not anticipated by the pilot, icing can result in a loss of control.

The aircraft model included a simulation of the effect of icing on the aerodynamic parameters, which was used to test this scenario. For both the training and measurement runs, the simulation was initialized slightly off the instrument approach path to a runway. The instructions for the pilots in this scenario were to follow the localizer/glide slope, to fly as slow as possible due to heavy traffic, until an altitude of 50ft where the simulation automatically stops. It was the pilots' responsibility to decide what the slowest velocity was, and the information they had was the minimum velocity indicated on the PFD and felt through the haptics (if enabled).

Training Phase During training, an Instrument Landing System (ILS) approach to Rotterdam (EHRD) for runway 24 was performed. The approach started at 2,500ft, 140kts, 15.4NM radial distance from touch down point, slightly left of the localizer, and below the glide slope. From this point on, the pilot had to intercept the localizer and glide slope as indicated on Section B.1. Approximately 60s after the start of the run, the aircraft was stabilized on the localizer/glide slope and icing was gradually ramped in. The stable approach after 60s was checked visually by the experimenter, and was indeed the case for all runs and for all pilots.

Measurement Phase Here, a similar instrument approach was flown into Amsterdam (EHAM) for runway 36C. The approach started at 3,000ft, 150kts, 10.3NM radial distance from touch down point, slightly right of the localizer, and below the glide slope. The pilot was again asked to intercept the localizer and glide slope as indicated on Section B.2 and the icing initiation point is approximately 100s after the start of the run.

Wind variation During the approach, there were stable and variable wind components. The stable wind was different for each of the runs the pilots performed: values can be found in Table 3.3. As the runway in use for Rotterdam is 24 (heading West South-West, actual heading 237), and for Amsterdam is 36C (heading North, actual heading 003), all wind instances gave a headwind with a slight crosswind. The four wind states were distributed using a (four-by-four) Latin square, which was repeated every four pilots.

Table 3.3: Wind components during the icing scenario

Wind realization	Stable heading [°]	Stable intensity [kts]	Variable heading [°]
Training set 1	272	7	262
Training set 2	259	11	249
Training set 3	214	11	224
Training set 4	201	7	211
Measurement set 1	321	13	331
Measurement set 2	332	11	342
Measurement set 3	027	11	017
Measurement set 4	038	13	028

Variable horizontal wind (w_{var}) was added to the experiment to mask the change in aircraft aerodynamic properties, and to increase pilot workload. It was modeled with a sinusoidal shape, Equation 3.1, where I is the amplitude, $T_{duration}$ the duration of one period, and $T_{trigger}$ the time between the end of one shape and the start of the next. When $t > (T_{trigger} + T_{duration})$, time was reset to zero, and the parameters were re-initialized. It was converted to North-East components using the direction specified in Table 3.3.

$$w_{var} = \begin{cases} 0 & \text{if } t < T_{trigger} \\ \frac{I}{2.0} \cdot \left(1.0 - \cos\left(2 \cdot \pi \cdot \frac{(t - T_{trigger})}{T_{duration}}\right)\right) & \text{if } T_{trigger} \leq t \leq \left(T_{trigger} + T_{duration}\right) \\ \text{reset properties and time} & \text{else} \end{cases} \tag{3.1}$$

3

Parameters were re-initialized to prevent recognition of the variable wind, and taken from a random distribution. I was taken from a Weibull distribution with $\lambda = 4.9$ and $k = 2.3$, $T_{duration}$ from a Weibull with parameters $\lambda = 9.0$ and $k = 5.5$, and $T_{trigger}$ from a normal distribution with $\mu = 6.5$ and $\sigma = 1.0$. To enable reproducibility of the results, and equal variable wind over the participants, one realization of the stochastic process is made for each of the eight cases listed in Table 3.3.

Intended Use The haptic feedback system was expected to help pilots in identifying the performance degradation, especially in a manual control situation, by the progressing severity of the haptic cues: an initial tick when the protection value is exceeded, a changing neutral point since the load factor corresponding to the protection can be below one, an increasing stiffness with the flight envelope boundary approaching, and a stick shaker when crossing the respective activation velocity.

3.3.5. SECONDARY TASK: ATC REQUESTS

As a secondary task, and used as an objective measure for pilot workload, pilots were instructed to listen and, if required, respond to ATC requests throughout the simulations. Each of the ATC requests is characterized by three variables: a callsign, a command, and a trigger time. All callsigns used had the company name of which the pilot is an employee. At the start of the experiment day, each pilot was asked what his preferred flight number is, and if no preference, flight number '107' was used. Two other flight numbers were used: 685 and 713, which resulted in three possible combinations of callsigns.

The commands issued by ATC were requests on state information. These could be: 'report altitude', 'report speed', or 'report heading', which are variables easily retrievable from the PFD. Of course, these requests had to be answered only for the correct callsign.

To prevent recognition and anticipation of the requests, random realizations were made of the above; one realization was coupled to one condition. Using a uniform distribution, a callsign and a command was selected. Next the trigger time was determined by a normal distribution (μ = 20s and σ = 2.5s) indicating the time after the previous command. At the trigger time, the command was presented to the pilots. The eight realizations made of this random process resulted in a slightly different number of ATC calls made during each condition, as shown in Table 3.4.

To exclude any effects of the experimenter, messages were produced with a text-to-speech generator: the 'festival' library by The University of Edinburgh. [83] This latter was setup to provide the requests with a synthetic American-English, female voice.

3.3.6. EXPERIMENT ORDER

None of the participating pilots had any experience with haptic feedback on the side stick (since current Airbus aircraft do not provide this), nor with the particular behaviour of this aircraft model. Therefore, even before training a familiarization phase was required to

Table 3.4: Number of ATC calls per run

	IC		WS			
	AL		AL		NL	
Condition	HF	NH	HF	NH	HF	NH
Total ATC calls during training	32	30	30	31	31	31
ATC calls to participant during training	12	9	6	13	14	12
Total ATC calls during measurement	31	30	29	31	31	30
ATC calls to participant during measurement	8	12	13	16	17	8

provide pilots with sufficient time to get used to the haptics, aircraft model, and simulator. We discuss the familiarization, and the setup of the training and measurement runs in the following.

FAMILIARIZATION

After a briefing on the simulator safety procedures, controls and displays, the aircraft model was introduced to the pilots by requiring them to fly a traffic pattern to a final approach at Schiphol (EHAM), see Fig. 3.7. Pilots were asked to follow the instructions as indicated, unless company policy deviates. This to focus on the model familiarization, not procedures. The traffic pattern was flown three times in visual approach weather conditions: twice in normal law without wind, and once in alternate law with variable wind similar to the winds used in the icing scenario.

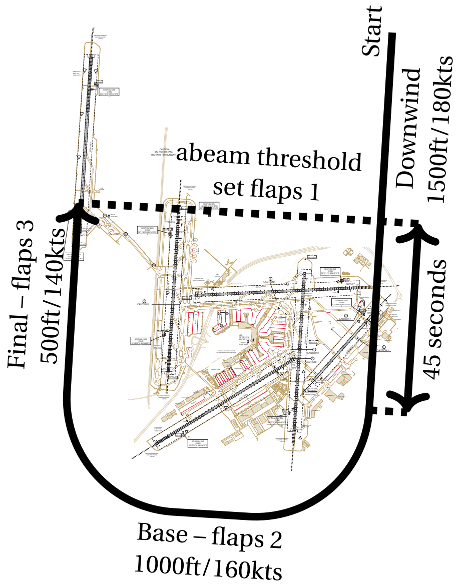


Figure 3.7: Traffic pattern flown to runway 36L at Schiphol (Schiphol layout from AIP [84])

After the model familiarization, the pilots were offered the opportunity to *feel* the design rationale behind the haptic feedback design. This was done by presenting both the flight envelope (computer implementation of Fig. 3.2), haptic profile (computer implementation of Fig. 3.3), and the PFD (Fig. 3.5b) to the pilot. In this static setup, no aircraft model was used, yet the flight envelope state was changed directly (hence changing the velocity and load factor) and all cues of the haptic design were elaborated in detail.

Following the static demonstration, the pilots *flew* the haptic feedback design using the full simulation model. Pilots were asked to fly a set of maneuvers (stall, overspeed, high load factor, climbing stall) three times. This was flown once in normal law without haptics, such that pilots could see how the aircraft reacts. Next the manoeuvres were repeated in normal law, with haptic feedback enabled, such that pilots could feel the feedback. Finally, it was flown once more in alternate law, with haptics enabled. After this last set of maneuvers, the pilot was asked to pitch to 5° nose down, followed by closing his eyes and pitching up as far as possible while not crossing the envelope limits. The rationale behind the latter was to see whether the pilot could indeed feel the limits of the aircraft. If (s)he stalled the aircraft, the haptic cues were not understood, if the pilot was able to keep pitching up while not exceeding the limits, the pilot understands how the haptic support communicates the limits. Each pilot was able to pitch-up the aircraft while not stalling the aircraft, indicating that at this stage in the evaluation the haptic feedback was indeed understood. After this familiarization phase, a lunch break was provided.

TRAINING AND MEASUREMENTS RUNS

The training and measurement runs used the six conditions as described above. These were flown in a randomized fashion, using a latin-square distribution. The pilot had to respond to ATC requests during the run, as explained before. After each run, pilots were asked to give a Rating Scale Mental Effort (RSME) rating ([85]), and fill-in the post-run situation awareness questionnaire (both are discussed below). Once the task was completed, the appropriate performance score was communicated to the pilot (discussed with the dependent measures). After all runs were finished, pilots were asked to complete a post-experiment questionnaire, which contained a number of questions on how they experienced the haptic feedback system (discussed below).

As mentioned to the pilots in the briefing, each experiment run was stopped at 50ft above the ground. This limitation was added because the aircraft model did not include a wheels-on-ground reaction model.

3.3.7. DEPENDENT MEASURES

The dependent measures are split into objective and subjective measures.

OBJECTIVE MEASURES

The objective measures were directly retrieved from the experiment data and focused on performance, safety and workload.

First, pilot performance depends on the scenarios flown. During windshear recovery, performance was defined by the altitude lost, the difference between the altitude at which the windshear was initiated, and the lowest altitude flown during the recovery. During icing, performance was defined as the root-mean-square of the position deviation from the ILS glide slope/localizer, starting at the initiation of the icing event until the end of the simulation.

Second, safety was defined as the remaining margins to the limits during the wind-shear recovery or icing event, using three sub-metrics based on angle of attack: (i) to determine *how close* the pilot operated to the limits, the 5% closest distance to the limit ($\alpha - \alpha_{max}$) was taken and the average is calculated, (ii) in order to see *how long* the pilot operated near the limits, the amount of time spent in the protected zone was calculated (hence time where $\alpha > \alpha_{prot}$), and (iii) to differentiate between short, close encounters with the limit, and sustained flight in the neighbourhood of the limit, a combination of distance and time was calculated by the integral of the angle of attack in the protected zone (hence $\int \left(\alpha - \alpha_{prot}\right) \mathrm{d}t$). A visual summary of the safety margins is shown in Fig. 3.8.

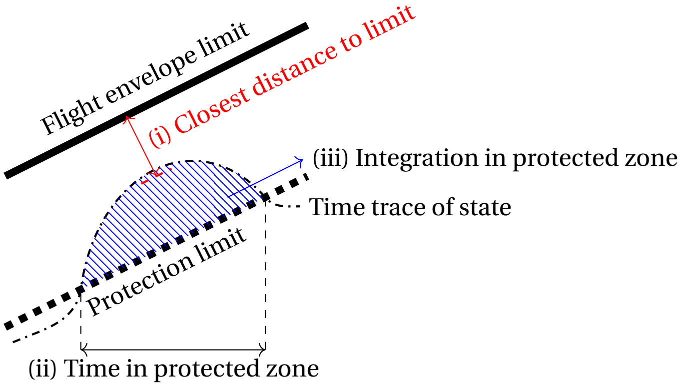


Figure 3.8: Safety metrics indicated on time trace

Related research often reveals a trade-off relation between performance and safety, referred to as risk homeostasis: the perceived level of risk is kept constant with increasing support. [86] An example is the increase in driving speed when being supplied with haptic feedback for lane keeping in an automotive study. [87]. In this experiment, risk homeostasis was considered to be present when performance would increase, while safety margins would degrade.

The third metric used to evaluate the system was an objective measure for workload: the performance with respect to the secondary task introduced above (responding to ATC requests). When workload due to the primary flying task was high, responses to the ATC requests were expected to be less accurate, and vice versa. Note that this follows the aviation order of priority: '*aviate, navigate, communicate*'.

In addition to these system evaluation metrics, a design evaluation metric was introduced to validate one of the design assumptions. As mentioned in the design section, it still remains to be seen whether the forcing functions used for the haptic feedback, cueing the pilot about approaching the FEP, would interfere with nominal pilot inputs. Therefore, the ratio of force exerted by the haptic feedback system (F_{haptic}) was compared with the total force exerted on the control device (human F_{human} and haptic feedback F_{haptic}) as shown by Equation 3.2. Here the integration is approximated by the summation of the discrete simulator states.

$$r_{\text{haptic}} = \frac{\int |F_{haptic}|\, dt}{\int \left(|F_{human}| + |F_{haptic}|\right) dt} \approx \frac{\sum |F_{haptic}| \cdot dt}{\sum \left(|F_{human}| + |F_{haptic}|\right) \cdot dt} = \frac{\sum |F_{haptic}|}{\sum \left(|F_{human}| + |F_{haptic}|\right)} \tag{3.2}$$

Subjective measures

The subjective metrics included workload, situation awareness, and pilot experience. Workload was measured after each run using the RSME which presented the participants with a scale ranging from zero to 150 to indicate how mentally demanding the last run was. To aid the participants with choosing a score, several verbal indications are added (for example ‘a little effort’, or ‘great effort’) at validated locations along the scale. [85]

Situation awareness was measured by presenting the participants with two questions after each run: ‘Did you have the feeling you were in control of the situation?’ and ‘Did you have the feeling you missed critical information?’. Both questions had a linear ratio scale (0–100) ranging from left ‘Never’ (0), to right ‘Always’ (100).

Finally, to ask participants for their experience with the haptic feedback system, and to streamline the debriefing, every pilot was asked to fill in a questionnaire after the experiment. It proposed thirteen statements, see Table A.1, using five point Likert-scales where the extreme and middle points are labeled.

3.3.8. Hypotheses

The haptic feedback system aims to improve pilot situation awareness with respect to the flight envelope limits and protections. To determine whether this goal is achieved, the following hypotheses were tested on the ‘measurement phase’-data described above:

1. With haptics enabled, risk homeostasis is present, that is, performance metrics will improve while safety margins reduce.
2. With haptics enabled, the pilot awareness of the aircraft critical flight states improves, as indicated by better scores for the situation awareness questions asked after each run, and in the debriefing questionnaire.
3. With haptics enabled, pilot workload, in terms of both the secondary task performance and RSME ratings, decreases.
4. The haptic feedback is equally effective when maneuvering the aircraft towards the edges of the flight envelope, the windshear scenario, as compared to a shrinking flight envelope, the icing scenario.
5. The haptic feedback is equally effective in both normal and alternate law in terms of performance and safety.
6. The haptic feedback does not interfere with nominal pilot behavior (executing normal tasks such as navigation and communication).

In the following, the results are shown and thereafter discussed to see whether we can find evidence in the experiment data to reject any of the proposed hypotheses.

3.4. RESULTS

In the experiment, some irregularities with the aircraft model came up which will be discussed first. In the next subsection, it will be illustrated how a pilot used the haptic support system, using typical time histories. A full description of all experimental results is split in objective measures, presented in Subsection 3.4.3, subjective measures in Subsection 3.4.4, and pilot answers to the questionnaire, Subsection 3.4.5.

3.4.1. SIMULATION OBSERVATIONS

Throughout the experiment campaign, four unexpected events are noted. The first two were simulation-related, the latter two were pilot-related.

First, a problem with the control law simulation occurred which resulted in oscillating aircraft responses (sometimes enlarged by pilot control inputs) in the runs indicated in Table 3.5 with an ‘x’. The effects were mostly a worse performance; when the oscillation occurred close to the flight envelope limits, also the safety margins reduced. To avoid any misinterpretation of our data, these runs were all excluded from further analysis.

This first category of events is a consequence of using the flight dynamics (and control laws) model in regions close to the flight envelope limits, for which these models were originally not developed. This can be regarded as an inevitable problem for our research, as good and validated models of aircraft operating close to their limits are scarce and difficult to obtain.

Table 3.5: Unexpected events: ‘x’ indicates control law oscillation, ‘i’ indicates too low icing, ‘c’ indicates crash

	WS				IC	
	NL		AL		AL	
Participant	NH	HF	NH	HF	NH	HF
1	0	x	x	0	i	i
2	0	x	0	0	0	0
3	0	0	0	0	0	x
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	x	0[1]	0	0
7	0	0	0	0	0	0
8	0	0	0	0	c	0
9	0	x	x	x	0	0
10	0	0	0	0	0	0
11	0	x	0	0[1]	0	0
comparisons	7		8		8	

[1] Angle of attack increased above protection value and pilots were informed by the haptic feedback.

Second, during the measurements for the first participant, it was found that the icing severity was too small. Hence, the icing level was increased for all participants that followed. All data on the icing conditions for Participant 1 were discarded, indicated in Table 3.5 with an ‘i’.

Third, after dropping below the glide slope in the icing condition without haptic feedback, Participant 8 tried to climb again but stalled the aircraft, resulting in a crash. This is indicated in Table 3.5 with a ‘c’.

Fourth, in the windshear scenario with haptic feedback, Participants 6 and 11 slowed the aircraft down *without* increasing the flap setting. The resulted in an angle of attack above the protection value and therefore the haptic feedback informed them as such. On the haptic cue, the pilots noted the low velocity and adjusted the flap setting. These events did not have any influence on the performance nor safety margin metrics. They are a good example of other unintended use of the haptic feedback system.

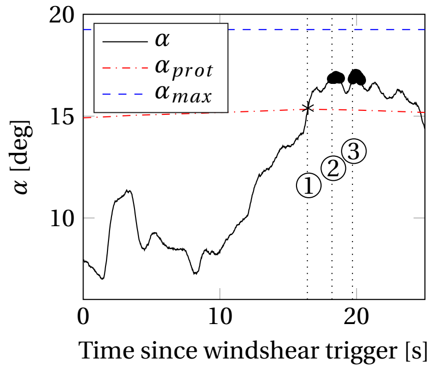
In the evaluation of the results, discussed below, our main focus will be to investigate the effects of activating the haptic feedback *within* a scenario, (windshear or icing) using one control law (normal or alternate law). That is, it will be investigated for each of the three conditions what the effects will be of activating the haptic feedback, and we will compare the ‘no haptics’ versus ‘haptics’ runs pair-wise. Since these comparisons could be affected by any of the first three simulation events mentioned above, all comparisons with ‘issues’ will be discarded. For example, Participant 2 encountered a control law oscillation with the windshear scenario, using normal law when provided with haptic feedback, as such data for this participant on windshear in normal law are not presented below. The other data points for this participant are shown in all figures and analysis.

When excluding all runs with simulation or pilot issues, a total of 7, 8 and 8 comparisons can be made for the windshear+NL, windshear+AL and icing+AL conditions, respectively. Note that any of the comparisons is statistically questionable, as the experiment runs are inevitably dependent, and any data do not come from independent samples. One should further note that, in making a comparison with just 8 samples, applying conservative statistics means that at least 7 of these comparisons should have the same sign for the comparison to be significant at the 0.05 level. Hence, with the limited number of pilots participating, most comparisons will be statistically insignificant.

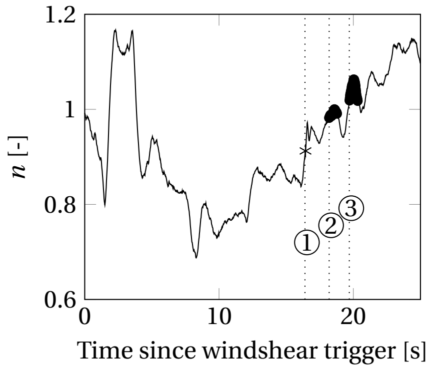
3.4.2. Time trace

Time histories for Participant 3 are shown, in the windshear scenario, flown in alternate law with the haptics enabled (WSALHF). Time traces for angle of attack, load factor, side stick deflection, force exerted on the control device, pitch angle and velocity can be found in Fig. 3.9, which all start at the time of the windshear warning which is initiated approximately 250s into this flight. Three time frames are distinguished, defined in the text below. Combining the control device deflection and force, Fig. 3.10 shows the changes in the haptic profile, for the same three time frames.

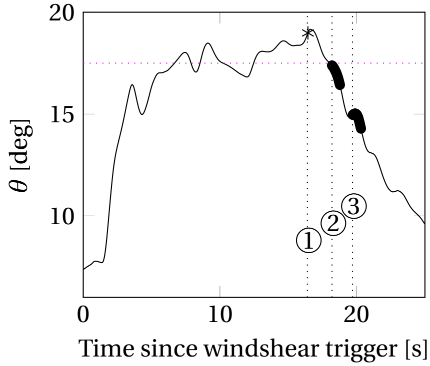
At the start of the windshear recovery procedure, the pilot observed the aircraft states, and pulled the stick (Fig. 3.9e) to increase the pitch angle to approximately 17.5°, Fig. 3.9c. The pilot then maintained that pitch angle using slight variations in input. At Frame 1, Fig. 3.10a, the pilot encountered the protections and was informed as such with a discrete haptic tick (indicated with the star ($*$) symbol). Nevertheless, to stop the aircraft from descending, the pilot maintained the pitch angle. When the stick shaker was activated at Frame 2 (indicated with the solid dots), the pilot reduced his inputs and pushed slightly on the side stick until the stick shaker de-activated. Following the de-activation, the pilot intended to move the side stick backwards again, yet encountered once again the stick



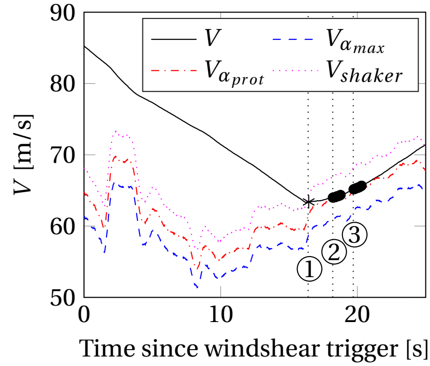
(a) Angle of attack



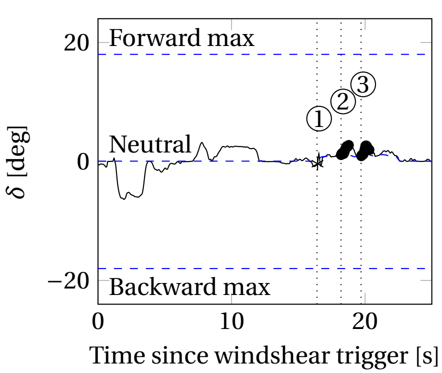
(b) Load factor



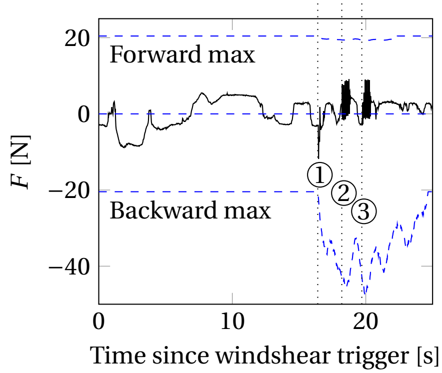
(c) Aircraft pitch angle



(d) Aircraft velocity



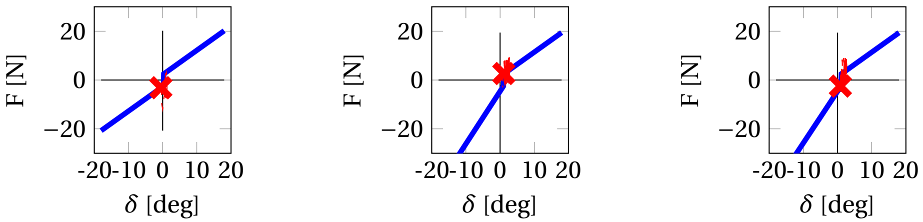
(e) Side stick deflection



(f) Pilot force on the side stick

Figure 3.9: Time traces for Participant 3 in condition WSALHF, thrust was set to full after 6.4s

shaker (solid dots), Frame 3, and had to push the side stick, as shown in Fig. 3.10c. Note that the way the pilot used the haptic feedback system in this example, effectively 'riding the stick shaker, is as expected.



(a) Haptic profile for Frame 1 (b) Haptic profile for Frame 2 (c) Haptic profile for Frame 3

Figure 3.10: Haptic profile during windshear recovery of Participant 3 in condition WSALHF. The current state is indicated with a cross, and a preview of the control device of 1.5s, frame numbers correspond to Fig. 3.9

3.4.3. OBJECTIVE MEASURES

The objective measures are determined based on the time traces of the experiment. Here the performance for both scenarios is shown, followed by the metrics for safety margins, secondary task scores, and an analysis of the forces applied by the haptic feedback system. In all figures, individual pilot data are shown with and without the haptic feedback enabled, for both the training and measurement phases. Although the metrics for the measurement phase is leading in the evaluation of the hypotheses, the training data is additionally shown due to the lack of data points in the measurement phase, and to show initial pilot behavior.

To facilitate quick reading, we counted and show the number of times the dependent measure increased more than 5% (↑), decreased more than 5% (↓), or remained equal (=), for each individual pilot. These indications should be considered with care, however, as the 5% threshold is arbitrary, and as mentioned above statistically the comparisons cannot be regarded as independent.

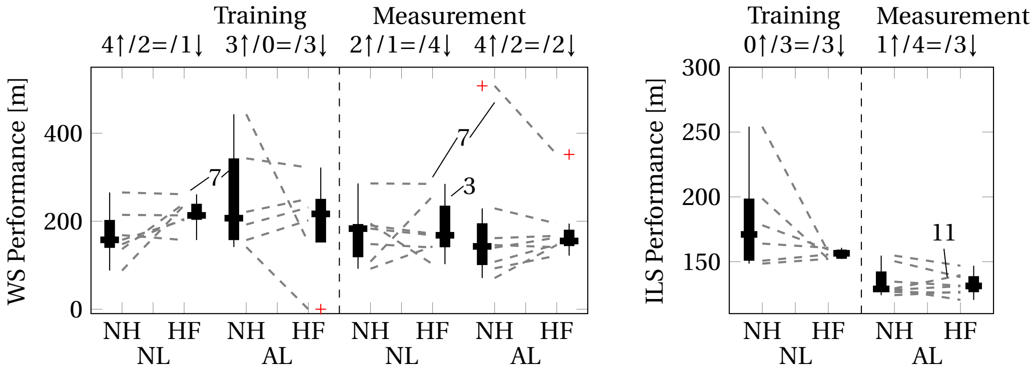
The data for each condition is summarized in a boxplot, where the median is indicated with a horizontal line, outliers with a cross. It will be the medians that are central in our analysis, as these indicate what the ‘average pilot’ would do with the haptics enabled.

PERFORMANCE

Performance in the windshear scenarios, Fig. 3.11a, and icing scenarios, Fig. 3.11b, do not indicate any visible trend in the median of the measurement phase data. Some larger differences are present between participants: each participant has a certain performance-level indifferent from the control law, or haptics state used. But overall one can safely say that performance during the measurement phase is not affected by the haptics system.

The trends which are present in the measurement phase, are more prominently present in the training phase: during the windshear scenario, enabling the haptic for normal law seems to worsen performance with normal law, whereas in alternate law the performance doesn’t change. The icing scenario clearly shows an improvement when haptic feedback is enabled during training.

Aside from the general trend, some participants do stand out: for Participant 3, the haptics-enabled run in normal law during the measurement phase was one of the final runs, and a sign of fatigue showed: his initial reaction after the windshear warning was a reverted control input; using his captain (left-hand) seat-routine he closed the throttles and pitched down, resulting in a low performance. Participant 7 shows consistently the



(a) Windshear (b) Icing

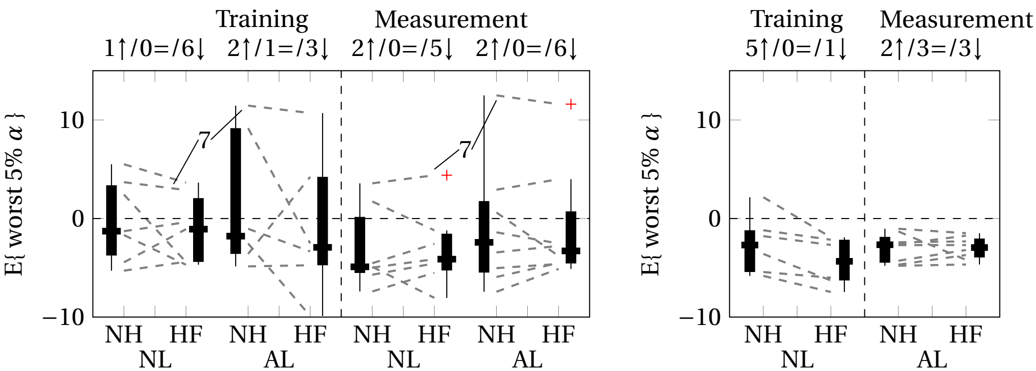
Figure 3.11: Performance scores, lower values indicate improved performance

lowest performance for windshear. During the debriefing, he indicated that he prioritized the windshear over the stall warning and haptic cues by maintaining a pitch-up command despite the visual/aural/haptic low velocity warnings.

On the icing plot in Fig. 3.11b, Participant 11 is the only participant who has a noticeable decrease of performance when enabling the haptic feedback, no confounding factors (such as the control law or fatigue) have been identified. Nevertheless, the pilot was not paying much attention to the velocity/altitude causing a larger deviation from the glide path and resulted in considerable effort to rejoin the glide slope.

SAFETY

Objective metrics for safety margins are defined in relation to pilot behavior at or near the limits. The first metric, presented in Fig. 3.12, looks at the 5% highest values for angle of attack near the windshear or during icing, and takes the average of these data as the evaluation criterion. More negative numbers means more distance to the limit, hence a larger safety margin.

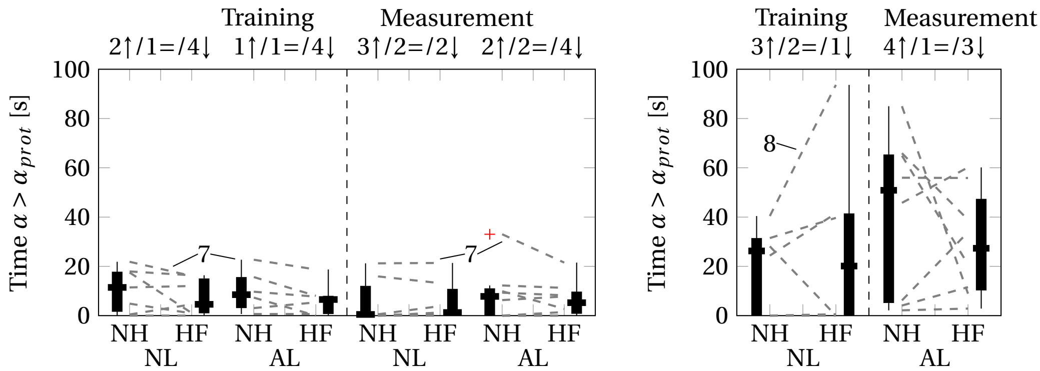


(a) Windshear (b) Icing

Figure 3.12: Safety metric: Closest distance to the limit, positive values indicate (aural) stall warning

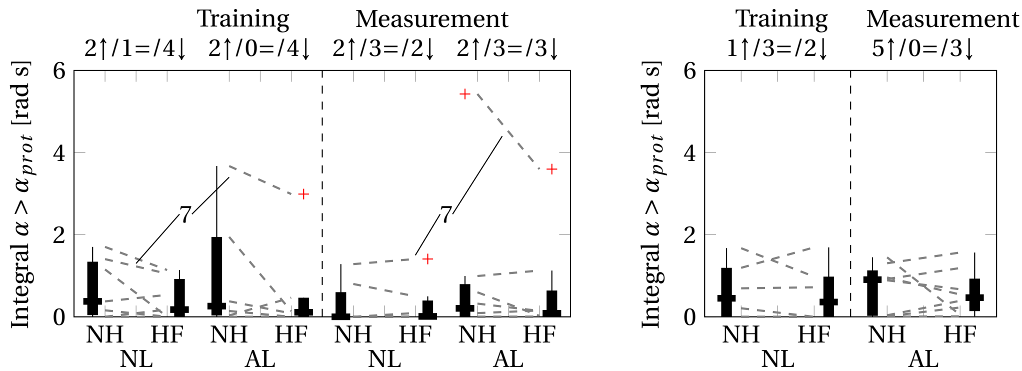
Similar to the performance in windshear, and now also for icing, no trend is present in the measurement data, yet considerable differences between participants are observable. The windshear scenarios clearly show the control strategy of Participant 7: by ignoring the high angle of attack warnings, worse safety margins are obtained. The training data of windshear shows a similar lack of trends, for icing, a slight improvement is present following performance.

Fig. 3.13 shows the time outside the safe flight envelope. For the windshear data, during both training and measurement, the median time spend outside is marginally lower when enabling haptic feedback. In the case of icing, although the median is slightly decreasing, more participants have an increase of this metric.



(a) Windshear (b) Icing

Figure 3.13: Safety: time where angle of attack is above protection value



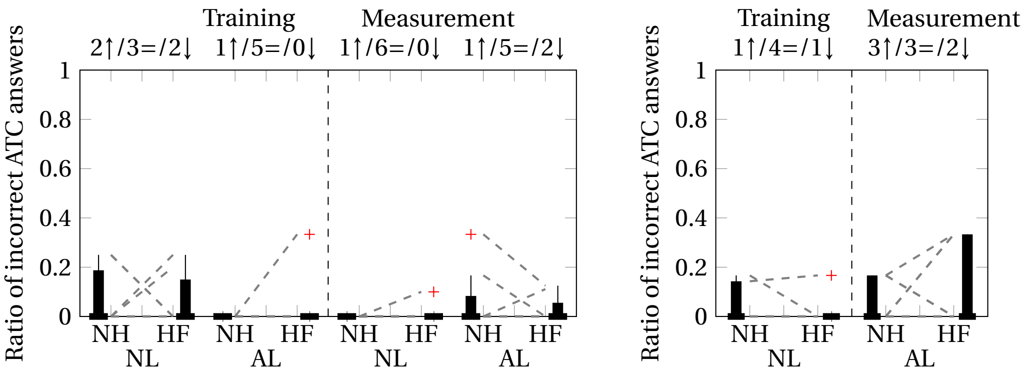
(a) Windshear (b) Icing

Figure 3.14: Safety metric: integral of α in protected zone

The integral of angle of attack in the protected zone for both scenarios is shown in Fig. 3.14 and shows no clear trends, yet does show the performance level per participant. Similar observation for windshear can be made as with the previous safety margin metric: the control strategy by Participant 7 results in the worst obtained metrics. During the training for icing, Participant 8 maintained a velocity around the haptic feedback triggering point. This results in small, but sustained, excursions of the safe flight envelope.

SECONDARY TASK

During each run, the answers of the pilots to the requests of ATC were recorded. The ratio of incorrect answers is shown in Fig. 3.15. It shows that the pilots in each case were triggered by the ATC command, and gave correct answers. No statistical significant results are obtained. A trend might be visible, yet keep in mind that the number of calls addressed to the participant (see Table 3.4), was not the same for all conditions.



(a) Windshear (b) Icing

Figure 3.15: Secondary task: ratio of incorrect responses to ATC

DESIGN EVALUATION

For each of the conditions where haptic feedback is provided, Fig. 3.16 shows the amount of force exerted on the side stick by the feedback system, relative to the total force exerted. It includes all flights shown in Table 3.5, except for those where a problem with the control law occurred. The figure indicates that, in general, the haptic feedback system exerts a small portion of the total force: the medians are between 0.3% and 2.6%.

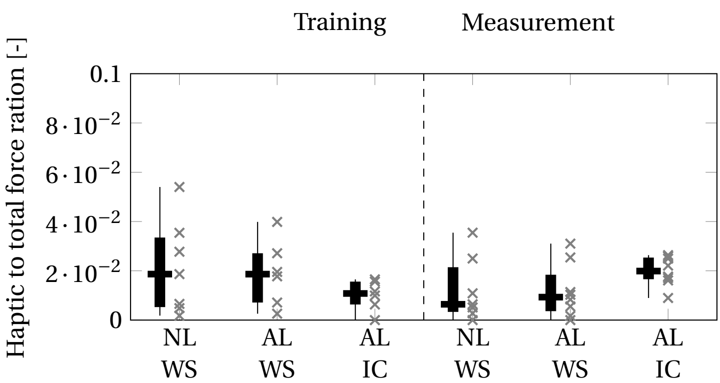
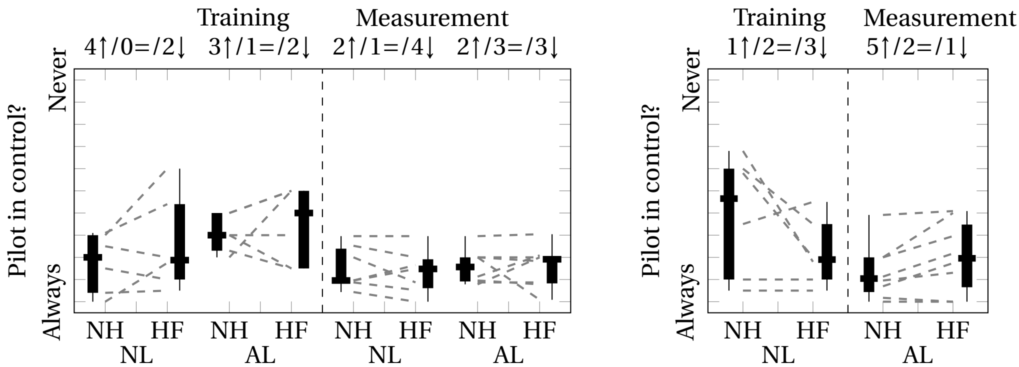


Figure 3.16: Ratio of force exerted by haptic feedback system

3.4.4. SUBJECTIVE MEASURES

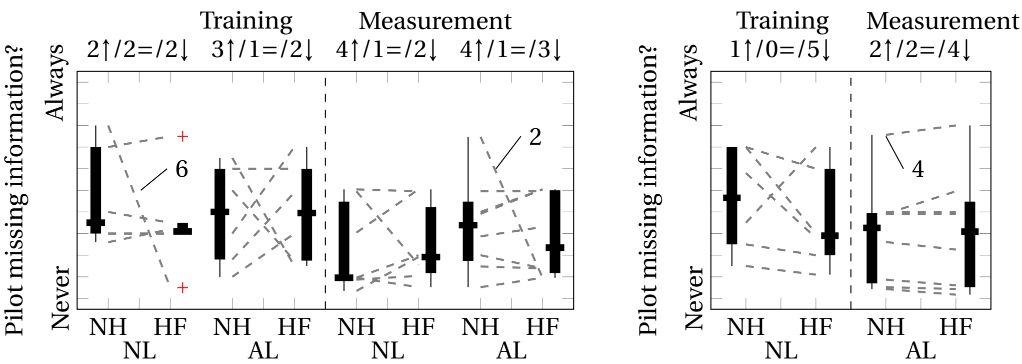
After each run, participants were asked to provide a number of ratings, these include a measure of how well they were in control, Fig. 3.17, a measure on whether they had all the critical information they needed, Fig. 3.18, and a rating for their mental workload, Fig. 3.19. As for the previous results, no statistically significant trends show.



(a) Windshear (b) Icing

Figure 3.17: Subjective situation awareness: is the pilot in control?

When asked whether the pilot was in control, enabling the haptics in the windshear scenarios does not seem to influence most pilots: scores remain equal and the number of pilots indicating higher/lower is almost the same. In contrast, switching on the haptics in the icing scenario improved the feeling of being in control during training, yet lowers the perceived level of being in control during the measurement phase: five participants indicated feeling less in control. This hints that haptics can be used to provide pilots with information during training, yet is less helping when accustomed to the task and dynamics.

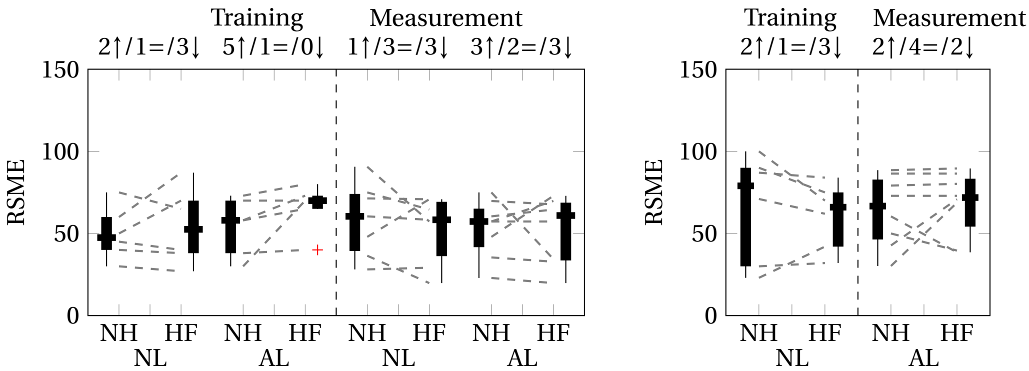


(a) Windshear (b) Icing

Figure 3.18: Subjective situation awareness: is the pilot missing information?

The information missing according to the pilot, Fig. 3.18, has again no clear trends. During windshear, in Fig. 3.18a, two participants stand out: Participant 6 during training, and Participant 2 during measurement. Participant 6, in normal law during training, had the no-haptics run, followed by the haptic-enabled run, this sharp improvement of this metric indicates that the haptic feedback added information for this pilot. Participant 2 during the measurement phase experienced the run with haptic had less information missing, leading also him to conclude that the haptics provided the information required as it was not available on the display anymore. In the icing condition, Participant 4 consistently missed information on the icing level.

Multiple pilots, such as Participant 3 and 5 during the icing scenario, indicated that the triggering data of the haptics (mostly α_{prot} and $V_{MO_{prot}}$ for this case) were not clear, especially in alternate law as that triggering data is not available on the PFD. Therefore, they were not able to properly understand the haptic cues and indicated an increased amount of information missing: the reason for the haptic cues.



(a) Windshear

(b) Icing

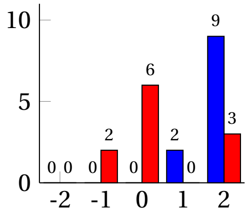
Figure 3.19: Workload: RSME

Mental effort required to operate the aircraft for each condition is shown in Fig. 3.19. These figures show once more that each participant has a personal base line, and little variation is present between condition. Even more, including the between-participant variability on the box-plots indicates that very little spread is present around the median scores.

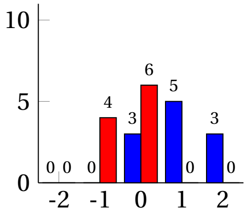
3.4.5. POST-EXPERIMENT QUESTIONNAIRE

After the final run, the participants were asked to complete a questionnaire which queried them about their experience with the system. It involved thirteen questions shown in Table A.1, and the answers are shown in Fig. 3.21. Note that in this figure, the horizontal axes are defined in such a way that the right-hand side of the subfigures indicate ratings which are favorable towards the haptics system enabled, and the left-hand side less favorable ratings.

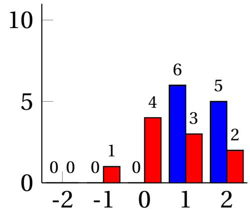
The questions contain one entry for each pilot (hence eleven in total) for the windshear scenarios, and ten answers for the icing scenario since one pilot did not want to complete the questions for the icing scenario as he did not recognize it as such an event. Statistical analysis between both scenarios is performed using a Wilcoxon Signed Rank test with continuity correction.



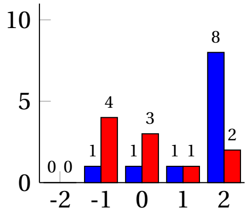
(a) What is your general feeling on the haptic feedback as an information cue about the flight envelope?
-2) Negative 0) Neutral 2) Positive



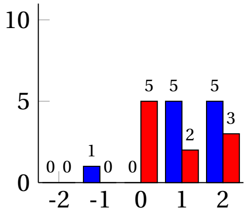
(b) The haptic interface affected my workload.
-2) More 0) Neutral 2) Less



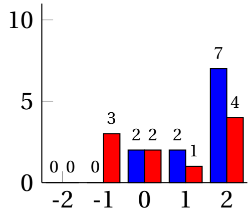
(c) If a critical event occurs, the haptic interface helps to mitigate the consequences.
-2) Disagree 0) Neutral 2) Agree



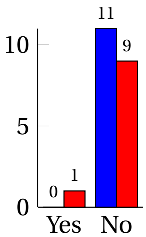
(d) The haptic interface distracts me.
-2) Agree 0) Neutral 2) Disagree



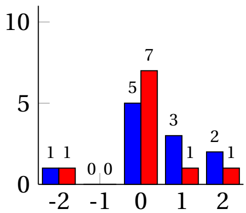
(e) The haptic interface changes the likelihood of human error.
-2) Increased 0) Neutral 2) Decreased



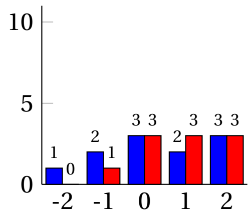
(f) I was fighting the haptic interface.
-2) Always 0) Sometimes 2) Never



(g) Do you expect any adverse impact on outcomes when using this technology?



(h) Using the haptic system, my knowledge on the edges of the aircraft performance changed.
-2) Less 0) Neutral 2) More



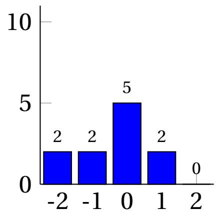
(i) The haptic interface changed my behavior.
-2) Agree 0) Neutral 2) Disagree

Figure 3.20: Results of the post-experiment questionnaire (1); blue indicate answers for windshear, red for icing

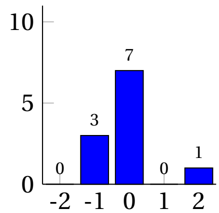
The first question, Fig. 3.20a, asked pilots what their general idea on the haptic system is. For the windshear scenario, the ratings are statistically significant more towards the positive side, whereas for the icing scenario the results are more centered around neutral ($V = 28$, $p = 0.021$).

Another set of questions was asked to investigate the expected consequence of using the system according to the pilots. With a statistical significant difference from the icing answers, the pilots answered in case of windshear that with haptics their workload was less (Fig. 3.20b, $V = 0$, $p = 0.011$), the system has the ability to help mitigate consequences of critical events (Fig. 3.20c, $V = 15$, $p = 0.057$), and did not distract them (Fig. 3.20d, $V = 1.5$, $p = 0.040$). For the icing scenario, the haptic system gave a neutral to increased workload, a more neutral opinion for the system to mitigate consequences of critical events, and a larger distraction. In both scenarios, pilots expect the possibility of human error to decrease (Fig. 3.20e), in general were not fighting the haptics (Fig. 3.20f), and expected no adverse impact (Fig. 3.20g). Overall, a neutral to positive change on their knowledge on the edges of the flight envelope was observed (Fig. 3.20h), which should be kept in mind when considering the goal of the design. Pilots did not provide a uniform answer to whether they changed their behavior (Fig. 3.20i).

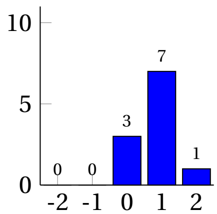
In order to evaluate whether the simulation was adequately representing an actual Airbus aircraft, four questions on realism were asked see Fig. 3.21. The displays and weather implementation were positively received, whereas the aircraft dynamics did lack realism. The realism of the controls, in Fig. 3.21b, is more important as the experiment considers the design of the controls itself. Most pilots perceived the (nominal) feeling of the controls to be acceptable.



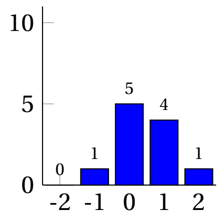
(a) How would you grade the A320 dynamics?
-2) Unrealistic 0) Acceptable 2) Perfect



(b) How would you grade the controls?
-2) Unrealistic 0) Acceptable 2) Perfect



(c) How would you grade the displays?
-2) Unrealistic 0) Acceptable 2) Perfect



(d) How would you grade the weather?
-2) Unrealistic 0) Acceptable 2) Perfect

Figure 3.21: Results of the post-experiment questionnaire (2)

3.5. DISCUSSION

The discussion is split in the objective, subjective and post-run criteria. We conclude with the overall haptic feedback system evaluation.

3.5.1. OBJECTIVE MEASURES

Statistical analysis of results for the objective performance metrics indicated there was no significant difference beteen the scenarios, nor for the different control laws. Nevertheless, in the icing scenario the haptic feedback system did lead to an improvement in terms of performance during training. Note that this scenario is only evaluated for alternate law, in which case the display shows minimal velocity, and no velocity protections. With the addition of the haptic feedback angle of attack information is added, as the haptics use the protection angle of attack to trigger the discrete cue. This improvement of performance could be caused by this inclusion of angle of attack information, and not directly in the way of communicating it. Hence, one can only conclude that showing angle of attack information can be beneficial for the performance.

From the safety margins in the icing scenario, no significant differences appear, yet the medians of the integral of the angle of attack and the time outside the safe flight envelope tend to indicate that more margin is kept. As for the performance metric, this tendency is most likely caused by the inclusion of the angle of attack data, not present on the PFD. An extra argument that the information presented by the haptics is required, is the occurrence of a crash in the haptics-disabled run of Participant 8.

Safety margins for windshear showed no statistically significant results, nevertheless, enabling haptics in alternate law tends decrease the time spent above the protection value of angle of attack and decrease the integral of angle of attack outside the safe flight envelope. The latter indicates that pilots, on average and not statistically confirmed, moved less into the protected zone when given the (haptic) protection information.

Combining both scenarios in alternate law show no indication for risk homeostasis: performance is not improving and slightly more margin is kept to the limits. This indicates that the current data does not support our first hypothesis

In normal law, pilots can see the velocity corresponding to the angle of attack protection on the display, but do not move closer to the limits. This can indicate that the perceived level of risk is not changed by adding the haptic feedback, and pilots are still relying on the information on the displays. A possible reason for not using the haptic feedback information could be a lack of experience with the haptic system while having ample experience with the visual system, or a dislike for the haptic feedback information channel. The first can be mitigated by re-evaluating the training, probably a longer training with the haptic system is needed. From the questionnaire, discussed below, we inferred that pilots do not disapprove on the system. Nevertheless, to avoid dislike of the system, the limits used by the haptics can be perhaps more clearly communicated to the pilot on the display. An example for this is the overspeed protection ($V_{MO} - 20$kts) used by the haptics, yet not visible on the PFD.

Results for both the performance and safety metrics show a large differences in metrics between participants: the metric per participant is in most cases of similar value, irrespective of control law used or status of the haptic feedback system. This shows that the largest variation is the participant, not the intervention used. Hence, the hypotheses stating that the haptic feedback is equally effective in normal and alternate law, and also equally effective when moving towards the flight envelope limit as compared to the limit approaching by itself, are comparing two conditions between which no significant differences are found. Therefore these hypotheses cannot be rejected.

The ratio of correct answers to ATC did not show any difference over the conditions. Therefore this secondary task cannot confirm that the workload of the pilot changes. It did show that the addition of haptic feedback still allowed pilots to aviate, navigate the approaches, and communicate with ATC. Hence, these data supports the hypothesis that the haptic feedback does not interfere with nominal behavior.

Finally, the design evaluation parameter showed that on average 0.3 % to 2.6% of the force on the side stick is delivered by the haptic feedback system. The metric which is used here, takes into account all absolute forces by the haptic feedback system imposed on the side stick. For example, a sustained stick shaker could inflate this metric since it is a high frequency oscillation yet it provides no actual input. As this example shows, we can consider this metric to be a worst possible case. Therefore the metric indicates that the haptic feedback system is indeed 'cueing' the pilot on the limits, and not imposing any input, following our intended design goal.

3.5.2. SUBJECTIVE MEASURES

The subjective measure for situation awareness involved two questions: "Is the pilot in control?" and "Is the pilot missing information?". As stated, pilots indicated that they feel more in control during the training phase, yet slightly less in control in the icing event. Following the debriefings with the pilots, this is traced back to the mis-match of the visual display, showing the aircraft minimum velocity, and the haptic system giving information on the angle of attack. The latter was largely influenced by the icing, caused the haptic cues to be triggered at much higher velocities. During training this helped the pilots to be aware that something was going on. Nevertheless, when more accustomed to the model and task, those cues did not match the information on the visual display, and pilots found this situation to be unclear, resulting in a reduced feeling of being in control during the measurement phase.

Looking at whether pilots were missing information, our participants did not seem to experience that they had more information available in the scenarios with haptics. The objective results before did indicate that in the windshear scenario, when using alternate law, they moved slightly less into the protected flight envelope, and they performed better with the icing scenario, which could only be caused by the added information from the haptics. Nevertheless, this was not experienced as such by the pilots. To make the haptic feedback more clear, it should either be redesigned, or the information should be more clearly presented, for example, using multiple modalities.. [58]

Ideally, a system improving situation awareness should give the pilot the feeling of always being in control and never missing information, as is the hypothesis for this system. Nevertheless, the answers to the questions after each run do not confirm that the haptic display increases the situation awareness of the pilots.

Looking at the results for the workload, a grouping per subject is present, again indicating that the intervention used is not the major variation. This information is currently not sufficient to reject the hypothesis on decreasing workload.

3.5.3. Post-run questionnaire

The questionnaire asking the pilots for their experience with the system, showed a clear difference between both scenarios (already rejecting Hypothesis 4). For the windshear scenario, pilots clearly experienced the haptic feedback system as positive, whereas more neutral for the icing scenario, which corroborates the metrics discussed before and the answers in the following.

With respect to the windshear scenario, although the objective and subjective metrics before did not show this, the pilots after the experiment did experience a decrease in workload, supporting Hypothesis 3. Although most pilots do not indicate a change, some indicate that their knowledge on the flight envelope improved. Additionally, pilots indicate that the haptics help to solve problems and it deceases the human error possibility. This implies that the pilots expect the haptic feedback system to transfer some knowledge about the situation, partly supporting Hypothesis 2. Nevertheless, as stated in the results, this unexpected answer of the pilots on the knowledge on the boundaries should be further investigated, more elaborate interviews with the pilots might indicate points of improvement.

Pilots did not provide a clear answer whether the haptic feedback changed their behavior. This might be caused by the way the question is posed, the intention of the question was to query 'a change in nominal behavior', yet the pilots might have interpreted this to 'a change in their behavior to incorporate the haptics in their loop'. As such, depending on how the question is interpreted, different answers are possible. Nevertheless, as the haptics were not experienced as distracting, nor did pilots report to 'fight' them, the pilot's answers support the hypothesis that it does not change nominal behavior.

No clear preference for the haptic feedback system was present for icing. Pilots indicated that the haptics slightly increased their workload, distracted some of them, and made them 'fight' the system sometimes. This can be partially explained by (i) the icing scenario might have been slightly unclear: one pilot did not recognized the situation as icing, and (ii) a biased comparison of available information (as no angle of attack indication present in no haptics case). The latter is confirmed by the debriefing: pilots remarked that the haptic cues were sometimes unclear. When a haptic cue was provided, it was not always supported by an item on the display. An example of this is the haptic cue for angle of attack, while the visual display does not show this, leading to a clear recommendation for follow-up designs.

In the debriefing, some pilots remarked that from all haptic cues provided, they especially liked the discrete cue provided when crossing one of the protection values. Although it was intended to communicate a direction to move away from this protection, pilots did note that this direction was not always clear. It therefore served as a clear trigger that something is going on and they have to be vigilant. The discussion also showed that pilots experienced the other cues as useful, yet less salient.

From all the post-run questions, one which clearly stands out in favor of this new system is the answer to the expected negative outcomes: this clearly shows that pilots do not expect an immediate negative result. Combining this with their general feeling about the system, and the debriefing, shows that almost all the pilots are in favor of haptic feedback for flight envelope protection. Some did even make a remark along the lines: 'Why is this system not implemented yet?'.

3.5.4. SIMULATION EVALUATION

The four questions concerning the level of reality of the simulation indicated that pilots did perceive the displays and weather to be adequate. For the latter, mostly the occurrence of icing was problematic. Concerning the model, there was a significantly lower drag present compared to the actual aircraft, and, noted in the objective results, some oscillations occurred due to the flight control law in the proprietary model. This model behavior might have resulted in a more conservative control strategy of the pilots, making the difference due to the haptic feedback less prominent.

Considering this research investigates haptic feedback through the control device, one of the most important realism questions was the realism of the nominal feeling which was experienced as acceptable, slightly leaning to an off-nominal feeling. The major point of improvement is the default stiffness of the control device. In an actual aircraft, the default control stiffness is higher, making our simulation more responsive. Nevertheless, as the pilot received time to get acquainted to the controls, this probably had only minor influence on the results.

3.5.5. OVERALL SYSTEM EVALUATION

As some of the hypotheses could be evaluated by both objective and subjective measures, this subsection summarizes the results for all of them. Hypothesis 1 proposed that risk homeostatis is present and is fully based on the objective results. Those results tend to show that risk homeostasis is not present as pilots do spent slightly less time in the protected zone for the haptics-enabled windshear condition with alternate law and during the icing condition. Therefore this first hypothesis is not supported by the data.

The pilot awareness of the aircraft critical flight states does not seem to increase nor decrease based on the subjective questions asked after each run, nevertheless, in the debriefing questionnaire the pilot's answers indicate that they have an increased perceived situation awareness. Therefore, the current data partly supports Hypothesis 2 for an increased situation awareness.

Workload was measured objectively with the ratio of correct answers to ATC and subjectively with a RSME evaluation, giving no difference when enabling haptics. Looking at the post-run questionnaire, the icing scenario showed an increase in workload due to the unclear cues, yet in the windshear scenario it was deemed that workload decreased. Hence, Hypothesis 3 is not supported with the current design because of the lack of evidence.

To support Hypothesis 4, no differences should be found between the windshear and the icing scenario. Mainly the post-run questionnaire indicates that the current haptic feedback design is not equally effective for both scenarios. This might be due to both the remaining simulation problems, as well as unclear reason of the haptic feedback in the icing scenario as stated by the pilots.

It was shown for both scenarios that the visual displays in alternate law did not show the pilots the protection zones, whereas the haptic feedback system did. As such a skewed comparison was performed. In alternate law for windshear, the pilots tend to operate less in the protected zone with haptic feedback enabled. Nevertheless this trend was not visible for normal law. As such the effect for both control laws was different and Hypothesis 5 is not supported.

As pilots were able to aviate, navigate and communicate throughout all runs, the haptic feedback system does not interfere with nominal behavior and Hypothesis 6 is supported. The results shown above give the indication that the haptic feedback system in the current design does not lead to the expected result in terms of our hypotheses. Nevertheless, all pilots indicated that they see the potential benefit of such a system.

Chapter 2 discussed possible use, misuse, disuse and abuse following the principles proposed by Parasuraman and Riley. [80] Misuse is the use of automation for an unintended goal, which in this experiment would be shown by overreliance on the system. As explained in the simulator events, two participants started a windshear run with decelerating without the proper flap setting. This brought them close to the limit, and were informed as such by the haptic feedback. This could be considered as a lack of scanning the instruments when haptic feedback is available, yet it happened only once for these two participants. This leads us to conclude that there is no consistent overreliance on the haptic feedback system.

Disuse is deliberately not using the haptic feedback, commonly caused by a distrust in the system. Some participants commented, as discussed before, that the haptic cues were not always clear in the icing scenario. Although the safety margins increased for the icing scenario indicating intended use of the haptic feedback, this scenario might be at risk of disuse as the limits are not visible on the visual display.

Finally, abuse by designers would result in a system that provides pure guidance due to the large cues, instead of the intended goal of informing the pilot of the limits. The design evaluation metric showed that only a small portion of the input was imposed by the haptic feedback system, leaving the control actions solely to the pilot. This metric therefore proves that our intended design goal, without abuse, was achieved.

3.6. RECOMMENDATIONS

From this haptic feedback system evaluation, several points of improvement can be listed. One of the most straightforward recommendations for a next iteration of a haptic feedback system is the inclusion of more participants. Due to simulator and pilot availability, this evaluation included the results of eleven participants, where several runs had to be excluded due to a control law issue. Future evaluations can always benefit from more participants to capture smaller differences and reduce the dependency of the results on one individual.

Another recommendation to tackle the lack of differences is to re-consider the scenarios. Currently, the windshear scenario asked pilots to operate the aircraft as close to the angle of attack limit as possible, the icing scenario tried to operate at the same boundary. Providing pilots with a scenario in which they have *more freedom in their solution*, could result in more prominent use of the haptic cues. Nevertheless, this makes analysis more complex as one single evaluation metric might not be available for a wide range of solutions. On the other hand, *restricting the operating space* might make the initial conditions more uniform over all participants, enabling simpler evaluation. Doing so might reduce the reality and make the simulation less immersive, reducing the validity of the scenarios.

The simulation environment itself can be improved by resolving the oscillatory response, and by improving the default stiffness to better resemble the existing A320 side stick. Furthermore, inclusion of angle of attack state and limit data proved to be useful in the icing scenario, therefore it is recommended to provide this information to pilots. Note that the limit data requires information on the current flight envelope, yet this can be obtained using update algorithms. [88]

During the debriefing, some pilots indicated a preference for the discrete cue that indicates crossing a protection value. A next design iteration might therefore explore the use of discrete signal as it proved to be useful in the automotive field. [36] Additionally, to improve acceptance of the haptic feedback itself, the haptic display can be augmented by a visual display as multi-modal information proved to be more clear. [58]

Finally, as the current system does not interfere with nominal pilot behavior, it should be investigated whether haptic feedback for flight envelope protection can be combined with haptic feedback for tracking tasks, such as during an instrument landing. [41]

3.7. CONCLUSION

To increase pilot situation awareness about flight envelope limits we investigated haptic feedback – force feedback through the control device. Our haptic interface communicates the proximity to the flight envelope limits using several cues, and was evaluated in the SIMONA research simulator by eleven professional Airbus pilots. The results showed no significant changes in performance and safety margins for any of the conditions or control laws used. Nevertheless, all metrics showed that the haptic feedback did not hinder them to perform their tasks. Finally, the debriefing indicates that some pilots experienced an increased situation awareness, and most pilots see a potential benefit of implementing the haptic feedback system on a modern fly-by-wire flight deck.

II

Design improvements

4

Supplementing Haptic Feedback Through the Visual Display of Flight Envelope Boundaries

This chapter describes the design and evaluation of a visual display in supplementing haptic feedback on the side stick as a way to communicate flight envelope boundaries to pilots. The design adds indications for the limits in airspeed, load factor, angle of attack and angle of bank to a standard Airbus Primary Flight Display (PFD). The indications not only show the limits of the flight envelope, but also indicate magnitude and direction of the haptic cues. Fifteen professional Airbus pilots and one Airbus simulator instructor participated in an experiment in the SIMONA Research Simulator at Delft University of Technology. Several approaches in three different scenarios were flown in alternate law with the old and new PFD, while haptic feedback was always enabled. Although the time spent outside the flight envelope is slightly reduced, performance with the new display was not improved significantly. Subjective results indicate a preference, however, for the new display and an increased understanding of the haptic feedback. Further research is recommended to focus on improving the design by removing unused indications and setting up an experiment with a bank scenario that allows the use of operational bank limits rather than artificially reduced limits.

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4.1. INTRODUCTION

AVIATION is one of the safest forms of transport, yet there are still improvements to be made. In the last decade, loss of control in-flight (LOC-I) has been the primary cause of fatal commercial jet airplane accidents. [89] There are multiple slightly different definitions of LOC-I, but a common factor is that it involves flying outside the flight envelope with the potential of making it impossible for the pilot to control the aircraft. [90] Modern fly-by-wire (FBW) aircraft can be protected from such flight envelope excursions, but when automation fails, the pilots find themselves in a stressful situation and do not always know what to do to keep the aircraft within the envelope. An example of such an occurrence is Air Asia flight 8501 in 2014. [91] Due to a fault in the Rudder Travel Limiter Unit (RTLU) of the Airbus A320 and subsequent actions by the crew, the aircraft switched from normal to alternate control law, losing most of its protections and disconnecting the autopilot. The RTLU fault made the aircraft bank to 54°. Startled by this, the crew responded incorrectly, banking the aircraft to even more extreme angles and eventually pulling the aircraft into an unrecoverable prolonged stall. All 162 people on board perished when the aircraft crashed into the Java Sea. This and other incidents like Air France 447 ([7]) show that once protections are lost, pilots lack clear cues on their position with respect to the flight envelope and how to return to the envelope if they exceed it.

Chapter 2 presented that haptic feedback can be used as a way to communicate information to human operators and has shown that haptic cues might close this information gap and decrease LOC-I incidents. Nevertheless, Chapter 3 found that pilots were unsure as to what triggered the haptic feedback and what corrective action to take. It was recommended that a visual representation of the haptic cuing and flight envelope is developed to help pilots understand what the haptic feedback is telling them. In combination with haptic feedback, this may assist pilots in recognizing the edges of the flight envelope and acting accordingly. Research on an unmanned aerial vehicle collision avoidance system indeed suggests an increase in user acceptance when adding visualizations to a haptic system. [92]

Several research projects have looked at the design of displays that can show (more) flight envelope information. The primary flight display (PFD) seems to be the preferred location to integrate such information, although some projects designed stand-alone displays. A common factor in most existing solutions is the separation of output and input space, showing either the limits of the envelope ([54, 93–95]) or the limits in control inputs that would otherwise bring the aircraft outside that envelope. [96] No previous research is known on an aircraft display specifically integrating the limits on the input and output space together with information on associated haptic feedback.

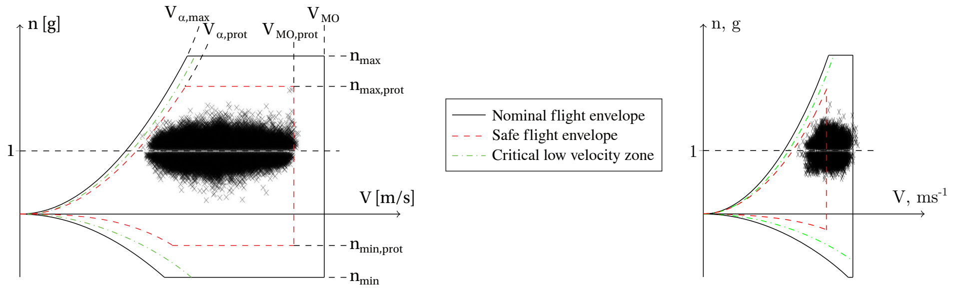
This study builds on the foundations of the aforementioned research by investigating the design of a display that integrates the input and output space, while also showing the force and direction cues of the haptic feedback. The chapter starts with background information on flight envelopes and haptic feedback in Section 4.2. Section 4.3 presents the display design and explains the rationale behind it. The display was tested in a human-in-the-loop simulator experiment involving 16 professional pilots as explained in Section 4.4, to asses the added value of said display. Section 4.5 lists the results of the experiment, which are then discussed in Section 4.6 together with some recommendations for further research. Finally, Section 4.7 concludes this chapter.

4.2. Background

A basic understanding of the flight envelope is required to grasp the working of the haptic feedback and consequential display design choices. This section provides a short introduction to these concepts, together with a couple of implementation details that are specific to this research.

4.2.1. Flight envelope

The longitudinal performance limits of an aircraft are often captured in a flight envelope that relates velocity (V) to load factor (n). A common flight envelope shape is depicted by the solid line in Fig. 4.1. The upper velocity limit is dictated by the maximum velocity V_{MO} that can be attained by the aircraft respecting aerodynamic and vibration limits. Structural limits, indicated by horizontal lines, put a minimum n_{min} and maximum n_{max} on the load factor, independent of airspeed. At low speeds, a quadratic relation limits the minimum velocity $V_{\alpha_{max}}$. Flying below $V_{\alpha_{max}}$ at a too high load factor will stall the aircraft. With extended flaps, both $V_{\alpha_{max}}$ and V_{MO} decrease, leading to a much smaller flight envelope (Fig. 4.1b). Airbus in addition moves the lower and upper load factor limits to 0 and 2g respectively when the slats and flaps are extended ([13]), but the model from this experiment keeps the load factor limits at -1 and 2.5g in order to match the haptic feedback.



(a) Flaps clean

(b) Flaps 3

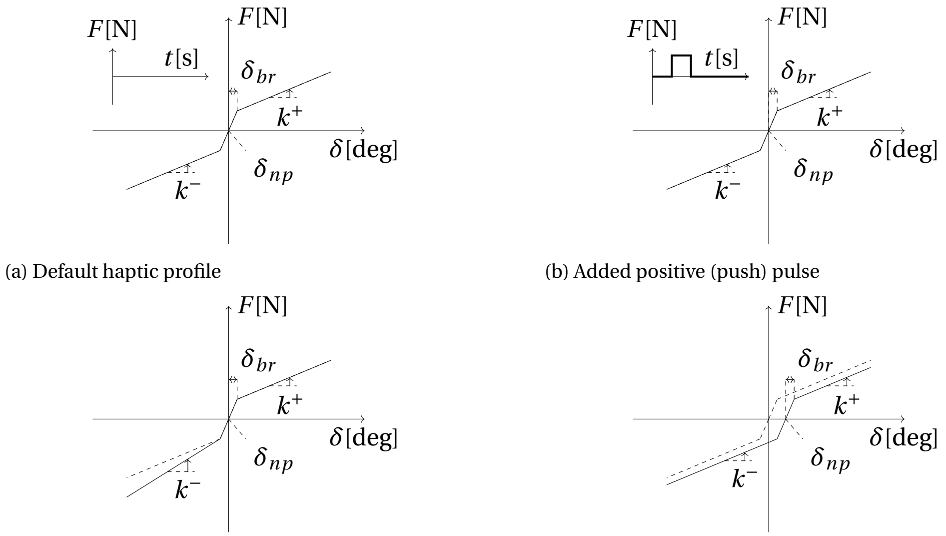
Figure 4.1: Typical flight envelopes with velocity (V) versus load factor (n); [97] augmented with load factor data for 10,066 A320 flights; [98] the actual envelopes depend on the aircraft's configuration and loading

Safety margins are added to the flight envelope to create a so-called safe flight envelope, indicated by the red dashed line in Fig. 4.1. The associated *protection* margins are chosen such that pilots have sufficient time to steer the aircraft away from the boundaries after being alerted of leaving the safe flight envelope. The load factor margins are 0.5 g, lower speed margins vary along the envelope, and high-speed margin is fixed at 20 kts below V_{MO}. Another margin can be distinguished near the lower velocity indicated by the dashed green line, and showing critically low velocity close to a stall.

The envelopes in Fig. 4.1 are overlaid with maximum and minimum load factors encountered in 10,066 Airbus A320 flights. [98] Note that the envelopes shown here are for illustration purposes only and do not precisely match the actual envelope corresponding to those flights. In flaps up, aircraft in general stay well away from the boundaries, nevertheless some flights do get close to the limits of the safe flight envelope. On the contrary, with the significantly smaller flight envelope corresponding to a flaps 3 configuration, the majority seems to operate outside the safe flight envelope. This can be explained by the fact that the fixed 20kts overspeed margin of the safe flight envelope is not used in real-life operations.

4.2.2. HAPTIC FEEDBACK

The working principles of the haptic feedback system are best explained using the haptic profile, shown in Fig. 4.2a, which gives the stick deflection δ and the force required F. Break-out zone δ_{br} and associated spring coefficient k_{br} give the pilot a haptic feeling of the neutral point δ_{np}. Outside this break-out zone the spring coefficients are related to the negative (k^-) or positive (k^+) deflection of the stick. The full description can be found in Chapter 2. While only longitudinal haptic feedback was considered, lateral feedback based on the same principles, has since been implemented and both were used in the present research.



(a) Default haptic profile

(b) Added positive (push) pulse

(c) Increased spring coefficient for negative deflections

(d) Positive shift in neutral point

Figure 4.2: Control device profiles

The system can be summarized with five haptic cues to communicate the flight envelope to the pilot. First, when the aircraft leaves the safe flight envelope, a discrete force cue warns the pilot, depicted by the in-set graph in Fig. 4.2b. Second, continuing to steer the aircraft out of the safe flight envelope, results in a progressively increased stiffness as shown by the asymmetric profile on Fig. 4.2c. Third, when zero stick input is insufficient to return to the safe flight envelope for low velocities, the neutral point moves as shown on Fig. 4.2d. Fourth, a stick shaker activates when crossing the critical lower velocity indicated on the flight envelope in Fig. 4.1 by the dashed green line. Fifth, the neutral point of the stick during an overspeed situation shifts backwards to indicate the automatic pitch up command.

4.3. Display design

The haptic feedback system from Subsection 4.2.2 was tested with professional pilots in the Chapter 3, resulting in a recommendation to investigate the addition of a display to visualize the haptic cues. Combining haptic feedback with a visual display could fulfill the important principle of multiple resources when presenting information. [99] To address the shortcomings of existing displays, such as the lack of integration of input and output space, a new display was designed. It should show the pilots which envelope limit is triggering the haptics, where the aircraft is with respect to the (safe) flight envelope and what forces are acting on the stick. This section first elaborates on the principle behind a design that fulfills all of these requirements and then explains the look and feel of the various new display elements.

4.3.1. Design principle

In order to support the haptic system, the indications on the display have to match with the forces felt through the side stick in both magnitude and direction. From the cues discussed in Subsection 4.2.2, the discrete cue and changing stiffness can be visualized by an ordinary spring (upper part of Fig. 4.3) that is positioned next to the side stick. When the aircraft approaches the edge of the safe flight envelope as discussed in Subsection 4.2.1 the spring moves towards the stick. Upon leaving the safe flight envelope the free end of the spring – visualized by the left-most vertical line – barely touches the stick. At this point the haptic feedback gives a discrete tick on the stick to grab the pilot's attention. When the aircraft gets further into the protection zone, the spring is progressively compressed, its width increases and so does the force exerted by the spring. This force acts in the direction opposite to the movement of the stick, making it harder for the pilot to maintain a stick input in that direction. If the compression is relaxed, the spring lengthens again while its thickness and force decrease. Like any spring, the force is only felt when the spring starts getting compressed. The maximum compression is reached when the two vertical lines touch each other. Beyond that maximum the spring coefficient does not change any further.

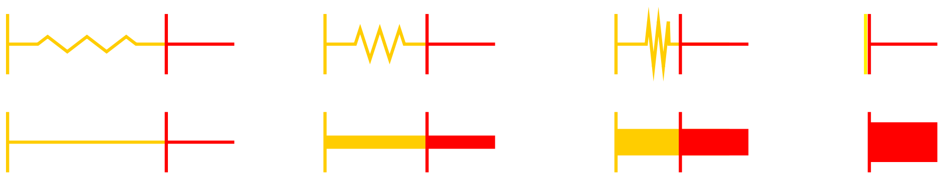


Figure 4.3: Spring (top) and piston (bottom) symbols with increasing levels of compression

To ease implementation in the display, improve clarity and reduce clutter, the spring can instead be visualized in the form of a piston cylinder whose thickness is similar to the width of the spring (lower part of Fig. 4.3). Apart from visualizing the 'feel' from the haptics in both magnitude and direction, these indications also show the pilot in which direction he should provide control inputs to alleviate the required force and return the aircraft to the safe flight envelope. All of this is known to help pilots understand and consequently appreciate haptic feedback better. [92]

The other cues from the haptic system are not explicitly visualized. The stick shaker is a trigger to bring the pilot's attention to low speed rather than an actual limit, so no extra indication is added. The neutral position shift is neither explicitly visualized, as it comes in combination with an increased stick stiffness and thus another visual indication.

The piston analogy is used throughout the enhanced display. The symbols and colors are kept uniform over the various indications to adhere to Wicken's design principle of consistency. [99] In line with industry recommended color coding, yellow is used to indicate the protection limit, beyond which the aircraft is outside the safe but still within the nominal flight envelope. [100] The actual flight envelope limits are indicated in red.

In order to help pilots quickly determine what flight parameter is driving the haptic feedback on their control inputs, the various axes (bank, load factor, angle of attack and airspeed) are displayed separately. Where possible the new indications are placed on parts of the display that are already showing the related parameter(s) according to the proximity compatibility principle. [99] Fig. 4.4 shows the PFD with all of the flight envelope indications in place. The various elements are discussed in greater detail below.

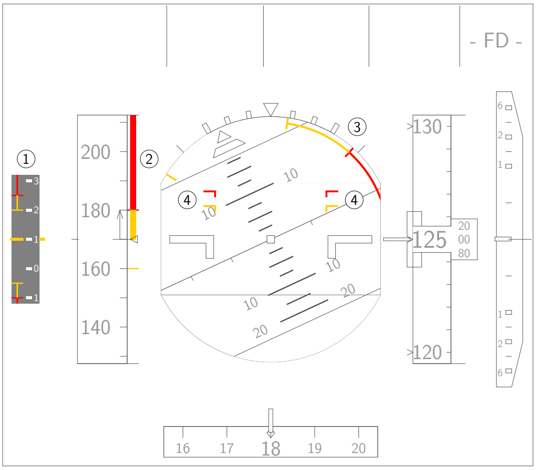


Figure 4.4: Wireframe view of the Airbus A320 PFD with additional load factor indicator (1) and flight envelope limits for airspeed (2), bank angle (3) and angle of attack (4)

4.3.2. NOVEL DISPLAY INDICATIONS

This section elaborates on the new display elements implemented within the PFD.

LOAD FACTOR

The first addition is a load factor indicator to the left of the airspeed tape (Fig. 4.5). The new indicator consists of a tape showing the load factor currently acting on the aircraft. Similar to the speed and altitude tapes, the indicator is of the inside-out style: the aircraft is fixed and the reference scale is moving. The reference scale has major tick marks every 1g and minor tick marks every 0.5g. The flight envelope limits are indicated by horizontal lines that attach to vertical lines running away from the fixed reference line. The flight envelope limit is indicated in red, while the safe flight envelope limit is shown in yellow. When the aircraft leaves the safe flight envelope, the thickness of the vertical line on the associated side increases linearly according to the piston principle. The horizontal yellow and red lines stay fixed at their positions on the moving scale to provide a quick indication of the distances to the flight envelope boundaries. An example of an excessive load factor maneuver is shown in the sequence of Fig. 4.5. The big red line at the top of the rightmost figure gives a clear 'pitch down' cue to the pilot. Approaching and crossing the lower limit exhibits a similar but mirrored sequence on the lower part of the scale.

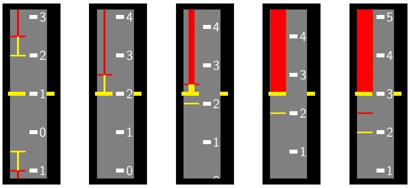


Figure 4.5: Load factor indicator progressively reaching and eventually exceeding the upper limit

AIRSPEED

The haptic system provides speed cues on the pitch axis of the side stick, because pitching up or down is an effective method to control airspeed (next to controlling the throttle). In order to make it clear to the pilots that the pitch cue is actually a speed cue, an indication is added to the speed tape rather than the pitch ladder (Fig. 4.4). For the overspeed protection, the standard overspeed barber pole at $V_{MO}$is replaced by a protection and maximum limit indication similar to that of the load factor. The protection is always 20kts below the maximum speed. Once the aircraft crosses the protection limit, a gentle nose up command is encouraged by the haptics.

A similar indication on the lower side of the speed tape corresponds to the low speed part of the flight envelope, where the haptics will eventually encourage a nose down command. Midway between the yellow and red limit, the stick shaker will activate to alert the pilot of an impeding stall.

One potential issue with the above described representation is that the nose has to go up for the speed to go down and vice versa. The way the speed tape is oriented, leads to indications that are not adhering to the principle of the moving part. [99] A big red line at the top of the speed tape might be interpreted as a nose down cue while the proper thing to do is to pull the nose up. The other indications (bank, load factor and angle of attack) do give cues in the correct direction. However, since the speed tape on the A320's current PFD already has an indication for overspeed that is similar in direction to this new piston-symbol, it can be considered an acceptable design.

BANK ANGLE

For the bank angle protection, the piston-like indications are added below the bank indicator scale (Fig. 4.4). The limits move with the horizon – in-line with the inside-out design of the PFD – while the reference aircraft symbol stays fixed. When the aircraft approaches a bank limit, this gives the pilot the sensation that the limits move towards the center of the display from the side that the aircraft is banking to. According to Wickens' principle of the moving part this helps pilots interpret the direction of the limit that matches the directional cue given by the side stick. [99] In the example from Fig. 4.4, the pilot should roll left to lower the bank angle.

ANGLE OF ATTACK

An indication for margin to stall angle of attack (AoA) is added to the PFD as shown in Fig. 4.6. The distance from the 'whisker' indications to the fixed aircraft symbol equals the margin of the current AoA to the stall AoA, similar to Boeing's pitch limit indication (PLI). [101] At the red whiskers, the aircraft is flying at its maximum AoA. A vertical line in the center of the display grows in width analogous to the piston indication from the design principle. To put additional emphasis on the importance of unloading the wing by pitching down, the lower end of the piston progressively changes to an arrow as it grows wider. The indications do not rotate with bank, to ensure that the indications are always visible and always match a pitch down command. The whiskers are placed beside the pitch ladder to not obstruct the ladder.

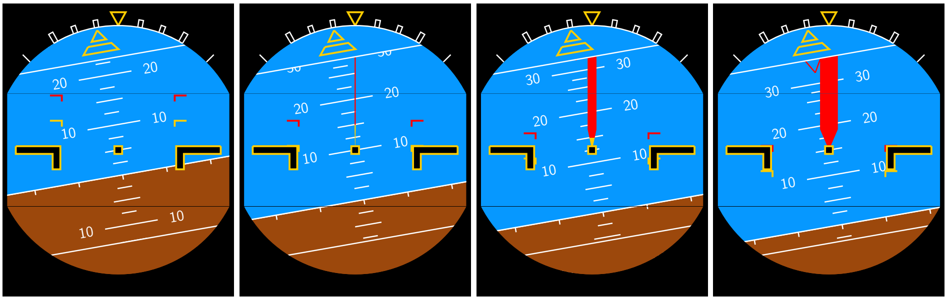


Figure 4.6: AoA indicators relative to the fixed aircraft symbol progressively reaching the AoA limit

4.3.3. TYPICAL WINDSHEAR RECOVERY

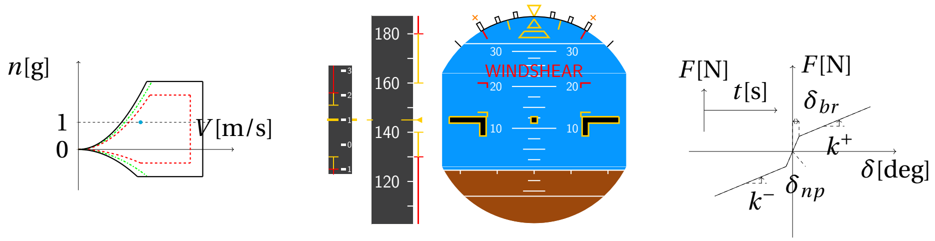
To illustrate the synergy between the flight envelope, display and haptic feedback, Fig. 4.7 shows the display indications during a typical windshear escape procedure side-by-side with the flight envelope and haptic profiles. The series of four frames follows the actions a pilot would typically perform.

Frame 1: The windshear is triggered, indicated by a red windshear text on the PFD and a synthetic voice repeating 'windshear' three times. The pilot initiates the windshear procedure by applying full thrust and pitching the aircraft to 17.5° of pitch. [13]

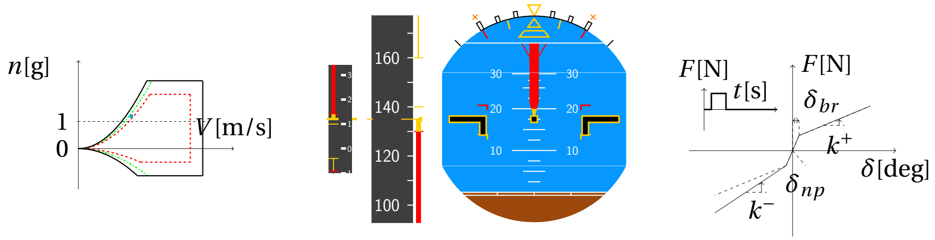
Frame 2: The pilot receives a tick on the stick's pitch axis, as well as an increased stick-back stiffness, to alert him that the speed is decreasing outside the safe flight envelope. On the speed tape this is shown by the current speed protruding into the yellow part of the low-speed piston. At the same time, the load factor indication shows that the aircraft is above the safe load factor limit for the current airspeed. And finally the angle of attack indication on the pitch scale starts growing in width, as the angle of attack approaches its maximum.

Frame 3: When the aircraft continues the deceleration, the stick shaker is enabled as an additional low velocity warning. The aircraft is now very close to a stall and the big red arrow on the pitch ladder of the PFD urges the pilot to push the nose down. This is felt in the stick by an increased stiffness on the nose-up side. Additionally the neutral point of the stick is shifted forward to help the pilot lower the nose.

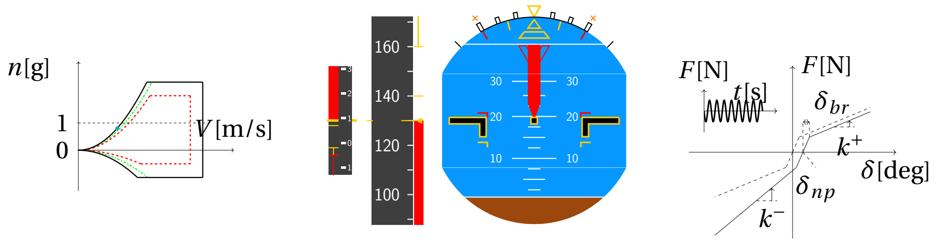
Frame 4: After the initial windshear recovery, the aircraft is now accelerating. When approaching the maximum velocity limit as shown here, a tick warns the pilot of an imminent excursion and the stick moves backwards to help the pilot bleed of airspeed. The spring stiffness of the stick is increased to inform the pilot of the distance to the ultimate flight envelope limit, as visualized by the widening of the piston on the speed tape.



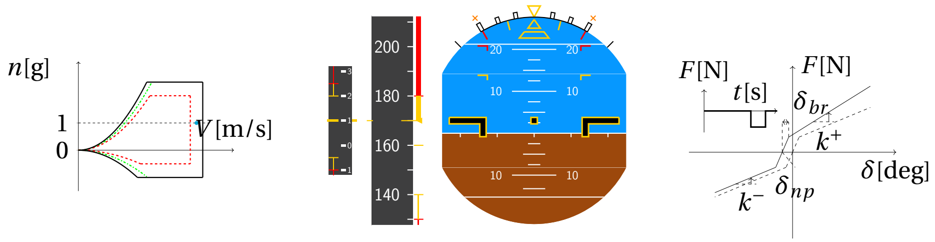
(a) Flight envelope for frame 1 (b) PFD+ for frame 1 (c) Haptic profile for frame 1



(d) Flight envelope for frame 2 (e) PFD+ for frame 2 (f) Haptic profile for frame 2



(g) Flight envelope for frame 3 (h) PFD+ for frame 3 (i) Haptic profile for frame 3



(j) Flight envelope for frame 4 (k) PFD+ for frame 4 (l) Haptic profile for frame 4

Figure 4.7: Typical windshear recovery procedure. The left column shows the flight envelope, the center column shows an excerpt of the PFD and the right column shows the associated haptic pitch profile

4.4. METHOD

Since pilots are expected to interact with the display, its design was tested in a human-in-the-loop simulator experiment. The goal of the experiment was to evaluate the interaction of pilots with the display, see what it does to their control strategy and whether it improves their subjective perception of the haptic feedback.

4.4.1. PARTICIPANTS

Fifteen professional Airbus pilots, all male, from four airlines and one male Airbus A320 synthetic flight instructor (SFI) participated in the experiment. The experience of all participants is shown in Table 4.1. They were divided over two groups (A and B) that experienced a different display order. Four pilots previously participated in our haptic feedback evaluation, namely A5, A6, B1 and B6. It is worth noting that the second officers – while not certified to operate the aircraft below 20,000ft – did receive a complete flight training and all had first officer Boeing experience from previous positions. Of the pilots, 14 had experienced windshear on a real aircraft, of which nine in an Airbus. All pilots had received upset recovery and prevention training (UPRT) and had experienced alternate law in simulator training.

Table 4.1: Participants in the experiment

Pilot	Age	Flight hours	Airbus flight hours	Position	Type rating
A1	52	13,500	2,000[2]	SFI	A320
A2	48	13,500	700	First officer	A330
A3	27	2,800	2,300	First officer	A320
A4	56	10,000	6,000	Captain	A330
A5[1]	57	9,500	9,000	Captain	A320
A6[1]	47	15,000	1,500	Captain	A330
A7	28	1,200	600	Second officer	A330
A8	25	2,300	200	Second officer	A330
B1[1]	48	16,000	5,000	Captain	A330
B2	50	16,000	5,000	Captain	A330
B3	43	12,500	7,500	Captain	A320
B4	30	3,000	400	Second officer	A330
B5	49	13,000	2,000	Captain	A330
B6[1]	31	5,500	5,300	Captain	A320
B7	47	13,950	3,300	Captain	A330
B8	39	8,787	6,178	Captain	A320
Mean	42	9,784	3,561		
Std. dev.	11	5,235	2,758		

[1] Pilot participated in previous haptic feedback research.
[2] These are simulator hours. Participant is a former Boeing pilot and current SFI for the Airbus A320.

4.4.2. APPARATUS

The experiment took place in the Research Facility for SImulation, MOtion and NAvigation (SIMONA) at Delft University of Technology. The simulator's exterior and interior are shown in Fig. 4.8 and 4.9 respectively. SIMONA is a six degrees of freedom motion simulator with a full fledged flight deck shell. The interior can be configured to resemble any modern glass cockpit transport aircraft. For this particular experiment the motion system was not used.

Figure 4.8: Exterior of SIMONA at TU Delft

Figure 4.9: Interior of SIMONA at TU Delft

An electrically controlled Moog FCS Ecol-8000 side stick with force feedback capabilities as described in Chapter 3 was located on the right hand side of the pilot, who was seated in the right seat. The pedals were not used. A Boeing 777 pedestal with throttle quadrant and flaps lever, and a Boeing 737 Mode Control Panel (Flight Control Unit in Airbus terminology) complemented the interior. The outside visuals were provided by FlightGear[1] and showed the airport infrastructure, terrain and important buildings at the airport. A proprietary A320 flight dynamics model including control laws from the German Aerospace Center (DLR) was used as the simulated aircraft. Since the model did not include a landing gear, all flights were automatically stopped upon reaching 50ft above ground level (AGL).

The entire simulation was run using the Delft University Environment for Communication and Activation (DUECA) software. DUECA is a framework written in C++ allowing for easy real-time distributed simulations. [102] The PFD and ND were drawn using OpenGL (see Fig. 4.15) and very closely resembled the real Airbus displays.

4.4.3. PROCEDURE

All participants engaged in the procedure outlined in Table 4.2. They were divided over two groups, with an equal distribution of aircraft types. Group A first used the original PFD and then the new PFD, denoted as PFD+, while the order was reversed for group B. The complete experiment took circa five hours per pilot.

1. **Briefing** – At the start of the day, the pilots received a short introduction, signed a consent form and were asked to fill in a pre-experiment questionnaire on their flying and previous research experience.

   Inside the simulator, the pilots were seated in the right seat. After a safety briefing, the various controls and standard displays were explained, as some of them were

[1] Open source flight simulator available at `http://flightgear.org`

Table 4.2: Experiment procedure

<table>
<tr><th></th><th>45 min</th><th>40 min</th><th>30 min</th><th>30 min</th><th>60 min</th><th>60 min</th><th>20 min</th></tr>
<tr><td>Group A</td><td rowspan="2">Briefing</td><td rowspan="2">Famili - arization</td><td rowspan="2">Training flights</td><td rowspan="2">Lunch</td><td>PFD flights</td><td>PFD+ flights</td><td rowspan="2">Debriefing</td></tr>
<tr><td>Group B</td><td>PFD+ flights</td><td>PFD flights</td></tr>
</table>

not completely resembling their Airbus counterparts. For instructional purposes, the original PFD was temporarily moved to the left screen – the normal location of the ND – while the right screen showed the haptic profile and the flight envelope.

Without the model in the loop, hence by the simulator operator changing the state of the aircraft directly, all haptic cues were explained. The pilots were asked to close their eyes while experiencing all cues once again to check whether they had understood the explanation of the various cues. Next, the PFD+ was shown and all cues were thoroughly presented and experienced once again.

2. **Familiarization** – For familiarization with the model and controls, a simple right-hand circuit to runway 36L at Amsterdam Airport Schiphol (EHAM) was flown twice with the baseline PFD. Note that this is a non-standard approach and therefore no instrument landing system or precision approach path indicator was provided.

   Next, the pilots performed the following exercises over the North Sea to experience the haptic cues:

   (a) Pilot induced stall by maintaining altitude with idle throttle.

   (b) Overspeed by full throttle and pitching down.

   (c) Nose-dive followed by a strong back stick input to reach the high-g region.

   (d) Rolling to the left and right.

   (e) Pitching up as far as possible with closed eyes, while keeping the aircraft at the onset of stall.

   Upon completion of these exercises, the same circuit as before was flown once more, this time with the PFD+. The haptics were left unchanged with respect to the previous circuit. After one circuit the same manoeuvres were flown over the North Sea as before, apart from the closed-eyes exercise.

3. **Training** – The training phase was setup to more closely resemble operational flights and prepared the pilot for the actual measurement flights. Four approaches were flown towards runway 16R of Seattle Airport (KSEA), for which the layout is shown in Fig. 4.10. The baseline PFD was used on the first two approaches, while the novel PFD+ was present on the latter two approaches. The conditions per flight are shown in Table 4.3. After each flight, the pilots were asked to fill in a questionnaire, identical to those used in the measurement runs.

4. **Measurement runs** – For the measurement runs, the pilots were divided into two groups. Group A flew the first set of measurements with the old PFD, followed by the PFD+, Group B vice versa.

Table 4.3: Training phase flights

Run	Airport	Scenario	Display
1	KSEA	Windshear	PFD
2	KSEA	Runway sidestep	PFD
3	KSEA	Runway sidestep	PFD+
4	KSEA	Windshear	PFD+

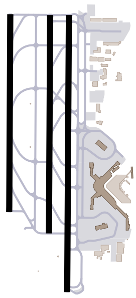


Figure 4.10: Airport diagram of KSEA [103]

At the start of each block of six measurement runs, a go-around scenario was flown into KSEA with the PFD variant corresponding to that block of flights. This 'refreshment' run was used to give the participants a chance to re-familiarize themselves with the model, haptic feedback and when applicable PFD+ after a (lunch) break.

Thereafter, the six measurement runs were flown. Each ended with a questionnaire, followed by the presentation of a score. The airports and scenarios for these flights were assigned according to a balanced Latin square distribution. After the six flights, the pilots were asked to fill in another questionnaire about the complete set of six flights.

5. **Debriefing** – At the end of the experiment the pilots received one more questionnaire about their overall experience throughout the day as well as the realism of the simulator. Once the questionnaire had been filled in, the pilots were debriefed. The research question was revealed to them and any open questions that could not be answered before in order to not influence the experiment outcome were discussed at this point.

4.4.4. SECONDARY TASK

Apart from flying the approach, the pilots were given a secondary task in the form of ATC calls that they had to reply to. Each pilot's callsign reflected the company that the pilot was employed at: '{Company} 107'. To ensure the pilots had to pay attention to the ATC calls, two other aircraft from the same company were introduced with flight numbers 685 and 713. ATC could ask to 'report heading', 'report speed' and 'report altitude'. Random realizations were made for each condition, to ensure that all pilots received the same

ATC commands in the same condition. A callsign and command were selected from a uniform distribution. These were then triggered at a delay after the previous command, determined by a normal distribution ($\mu = 20$s and $\sigma = 2.5$s). The texts were read out loud by a female American-English accent from the Festival[1] text-to-speech generation library, developed by the University of Edinburgh.

4.4.5. INDEPENDENT VARIABLES

Three independent variables were used in the experiment: the airport (two levels), the scenario (three levels) and the display (two levels). In total there were therefore 12 different conditions. To reduce variance in the data, all pilots experienced the same conditions. However, to mitigate order effects, a randomized balanced Latin square was used. The airport and scenario were varied constantly, while the display variant was fixed during a series of six consecutive flights in order to prevent pilots from having to re-adapt to the available cues all the time.

AIRPORT

Approaches were varied between runway 26L at Hartsfield–Jackson Atlanta International Airport (KATL) and runway 09L at London Heathrow (EGLL). Both airports have runways on either side of the terminals, with comparable spacing (KATL: 1340 m, EGLL: 1420 m) and more or less adjacent thresholds. The layouts can be found in Fig. 4.11 and 4.12. An instrument landing system (ILS) was available on the approach runway, with corresponding indications on the PFD. The pilots were provided with approach charts including a schematic of the runway layouts.

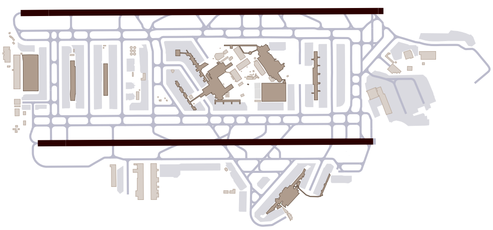


Figure 4.11: Airport diagram of EGLL [103]

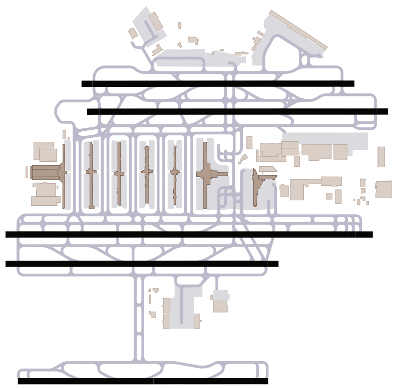


Figure 4.12: Airport diagram of KATL [103]

Each flight started circa 12 NM from the airport in trimmed flaps-up condition at 215 kts and an intercept heading of circa 45°, towards the final approach fix (FAF) on the localizer. At EGLL the starting position was circa 3 NM right of the localizer, while it was circa 4 NM left of the localizer at KATL. Fig. 4.13 shows a typical trajectory towards EGLL.

[1] Available at `http://www.cstr.ed.ac.uk/projects/festival/`

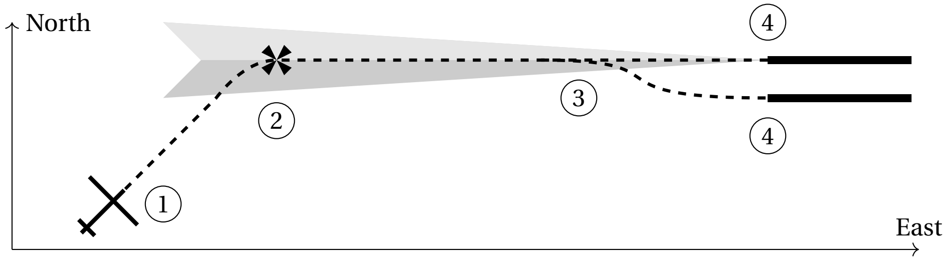


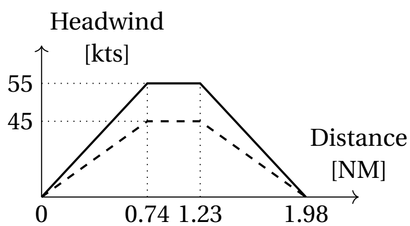
Figure 4.13: Flight plan for EGLL (not to scale). Start (1), localizer interception at FAF (2), scenario triggering point (3) and end of flight (4)

4

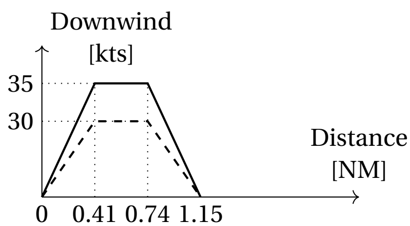
SCENARIO

The pilots were presented with three scenarios. These were automatically triggered upon descending through a pre-determined altitude given in Table 4.4. In all scenarios, a stable and variable wind was introduced according to the distribution used in Chapter 3. This wind was identical for all pilots.

1. **Windshear** – The windshear was implemented using the standard take-off wind model from the FAA with wind components as shown in Fig. 4.14. [76] An approach windshear model was not used because it was found not to ensure that the aircraft would fly near the limits of the flight envelope. In the training runs, the strength of the windshear was reduced while keeping the same distances, as indicated by the dashed lines in Fig. 4.14.



(a) Headwind component



(b) Downwind component

Figure 4.14: Windshear model, based on Ref. [76]; the dashed profile was used in the training runs

In accordance with the FCOM procedure, the pilots were told to not change the configuration of the aircraft, apply full thrust, pitch up to an initial attitude of 17.5° and adjust pitch as necessary to control altitude loss. [13] The lack of Speed Reference System (SRS) pitch guidance upon windshear encounter was explicitly briefed. When out of the shear pilots were asked to climb to the missed approach altitude at which the simulation was halted.

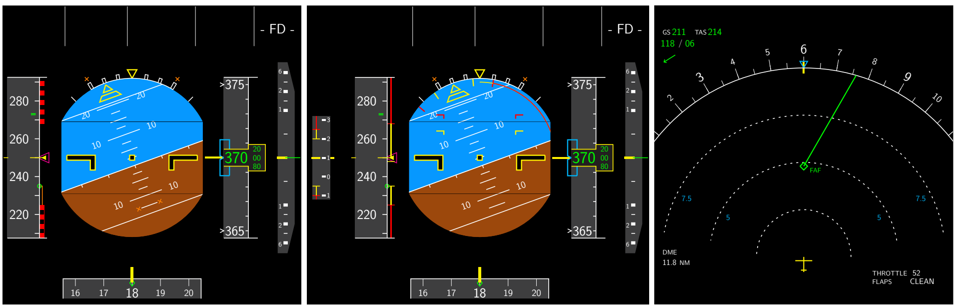
2. **Runway sidestep** – ATC would make either of the following calls, depending on the airport: '{Company} 107, sidestep right to runway 09 right, cleared to land' (EGLL) or '{Company} 107, sidestep left to runway 27 right, cleared to land' (KATL). Pilots were briefed to try to line up with the new runway as quickly as possible without using extreme bank angles.
3. **Go-around** – When ATC made the following call '{Company} 107, go-around', pilots were supposed to perform the go-around procedure by climbing to the missed approach altitude with a climb rate of 2000 ft/min at runway heading.

Table 4.4: Scenario triggering altitudes

Scenario	Airport	Triggering altitude			
		ASL [ft]		AGL [ft]	
		PFD	PFD+	PFD	PFD+
Windshear	EGLL	1500	1500	1420	1420
	KATL	2500	2500	1475	1475
	KSEA	1700	1650	1270	1220
Sidestep	EGLL	1200	1200	1120	1120
	KATL	2100	2100	1075	1075
	KSEA	1500	1500	1070	1070
Go-around	EGLL	800	1000	720	920
	KATL	1700	1900	675	875
	KSEA	1200	1300	770	870

DISPLAY

Two variants of the PFD were used in the experiment (Fig. 4.15): the original PFD was a replica of the PFD on the real A320, while the new PFD+ had several new indications as discussed in Section 4.3. The A320-like ND was the same throughout the experiment and always showed the final approach fix and runway threshold as waypoints (Fig. 4.15c). This display also showed the current throttle and flap settings to compensate for the absence of their normal indicators in the simulator.



(a) PFD (b) PFD+ (c) ND

Figure 4.15: Displays used in the experiment

4.4.6. CONTROL VARIABLES

The aircraft model and haptic feedback settings were the same in all flights. The aircraft had a total mass of 64,841.7 kg and was in clean configuration at the start of each flight. All flights took place in alternate law. In terms of haptic feedback, the protection and maximum limits in roll were set to 15° and 30° respectively on all flights. These are considerably smaller than the 33° and 67° used by Airbus ([13]) and have been chosen to ensure that pilots would actually encounter the (artificial) limits, as pilots do not bank beyond circa 30° in normal operation. To ease recognition of these adjusted limits, the crosses on the PFD's bank scale that normally indicate the limit at 67° were moved to 30° for the experiment. Pilots were briefed on these stricter limits, but also asked to fly like they would normally do.

4.4.7. DEPENDENT MEASURES

Objective and subjective measures are used to assess the display in terms of performance, safety and pilot appreciation.

OBJECTIVE MEASURES

Data from the simulator were automatically logged at a rate of 100Hz. All objective measures were afterwards computed from this data, except for the secondary task score which was indicated on paper during the run.

- Control activity – Root mean square of the stick deflection angle in degrees.
- Margins to flight envelope limits – Both the flight envelope limits and aircraft states were measured in terms of airspeed, angle of attack, load factor and roll angle. The flight envelope margin was computed off-line.
- Performance scores, dependent on the scenario, were used for two reasons. First and foremost to assess whether the pilot's performance changed in the experiment and second to communicate to the pilots in order to encourage them to improve themselves throughout the experiment. The scores were defined as follows:
  - Windshear – Total altitude loss in feet from start of windshear till lowest point during recovery.
  - Sidestep – Smallest distance in nautical mile to the threshold of the new runway at which the aircraft was more than 300ft offset to either side of the localizer of that runway.
  - Go-around – Ratio of time during climb at which vertical speed was between 1500 and 2500ft/min, measured from 100ft above the trigger altitude till 100ft below the missed approach altitude.
- Workload through a secondary task: ratio of correct responses to ATC requests.

SUBJECTIVE MEASURES

Subjective measures were collected through questionnaires at various times throughout the experiment.

- After each flight:
  - Workload through a RSME questionnaire. [85]
  - Situation awareness through two questions on a linear scale ranging from 'Never' (0) to 'Always' (100):
    1. *Did you have the feeling you were in control?*
    2. *Did you have the feeling you missed essential information?*
  - Usefulness of each haptic axis (pitch and roll) and – when flying with the PFD+ – each new display element in helping the pilot to stay within the limits of the flight envelope through a five-point Likert scale question per item labeled as *not at all, slightly, moderately, very* and *extremely*.
- After both consecutive sets of six flights:
  - System acceptance through Van der Laan rating ([104]) and Modified Cooper-Harper rating. [105]
  - Five-point Likert scale questions on three statements, with labels at the minimum (*disagree*), middle (*neutral*) and maximum (*agree*).
  - Questions on usefulness of individual haptic and display properties in helping the pilot to stay within the flight envelope limits. Five-point Likert scale labeled as *not at all, slightly, moderately, very* and *extremely*.
  - Open question on what haptic cue(s) and/or display element(s) to add to the system, if any.
  - Open question on what haptic cue(s) and/or display element(s) to remove from the system, if any.
- At the end of the experiment:
  - Question on the pilot's display preference (PFD or PFD+) in combination with the haptic system.
  - Five-point Likert scale statements on the haptics, display and experiment with a minimum (*disagree*), middle (*neutral*) and maximum (*agree*) label.
  - Five-point Likert scale question on the safety effect of the system, with a minimum (*unsafer*), middle (*unchanged*) and maximum (*safer*) label.
  - Five-point Likert scale questions on the realism of various simulation aspects with a minimum (*unrealistic*), middle (*acceptable*) and maximum (*perfect*) label.

Apart from the questionnaires, pilots were actively encouraged to verbally communicate any questions, remarks and thoughts throughout the day. Since all pilots were native Dutch, all questionnaires and instructions were in Dutch.

4.4.8. HYPOTHESES

Based on the dependent measures, the following hypotheses are formulated:

H1 **Workload** – Workload in terms of control activity is expected to be lower with the PFD+ compared to the original display since the pilot can anticipate the limits. With a lower workload for the primary task, secondary task performance is expected to increase.

H2 **Performance** – In a similar fashion it is also predicted that the addition of a visual display will improve the overall performance of pilots flying with haptic feedback.

H3 **Safety** – Safety metrics are expected to follow risk homeostasis theory (a trade-off between performance and perceived level of risk). [86] However, it is assumed that pilots consider the edge of the safe flight envelope as the maximum allowable risk. It is therefore hypothesized that the margins to the ultimate flight envelope limits will be larger when flying with the PFD+. Additionally, pilots can anticipate the limits in contrast to the haptic *feedback*.

H4 **Pilot appreciation** – On a subjective level, pilots are expected to show greater appreciation for haptic feedback when combined with the PFD+ as the display should help them understand the haptic cues that they receive, one of the issues raised by pilots in the previous haptic system evaluation.

H5 **Indicator usefulness** – It is expected that the load factor display brings the least improvement compared to the old display as the respective limits are mostly encountered in combination with other limits. The angle of attack indication is expected to be most useful as it provides critical information that is currently not directly communicated to the pilot.

4.5. RESULTS

Several events warranted the selection of data, as some flights could not be used for the main analysis. Subsection 4.5.1 elaborates on this selection. The results are then split in objective results as shown in Subsection 4.5.2 and subjective results in Subsection 4.5.3 that stem from the questionnaires. Whenever statistical tests are performed, these are Wilcoxon signed-rank tests with a 95% confidence interval, unless explicitly stated otherwise.

4.5.1. DATA SELECTION

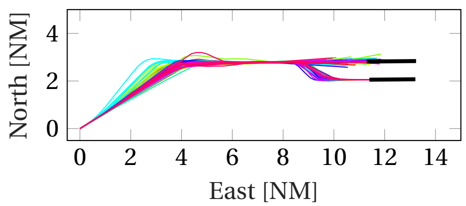
Sixteen pilots participated in the experiment, each flying 12 measurement conditions. Some flights in which a simulator hiccup, before reaching the scenario trigger point, prevented proper execution were restarted. Two pilots crashed their aircraft during the measurement flights by not recovering from a stall upon windshear occurrence. Pilot B2 crashed on the first measured windshear, while pilot B5 crashed on his second windshear. Both where flying with the PFD+ when they crashed and had already experienced two successful windshears in the training flights. B2 indicated after the flight that he did not follow the procedure from the FCOM, but relied on the AoA indication on the PFD+. B5 did not provide an explanation but showed similar behavior. Those flights have been started over without telling the pilots that they would encounter the same condition again. One other PFD+ flight was re-started when the pilot (A5) entered a stall while turning to final, before reaching the scenario trigger point. According to his own analysis he lost his concentration. The crashed and canceled flights are excluded from the results, unless explicitly mentioned.

4.5.2. OBJECTIVE RESULTS

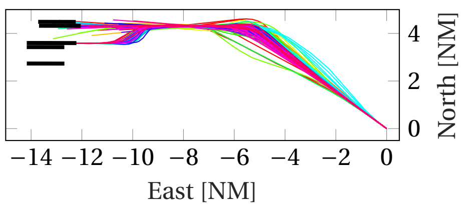
All flown tracks for both airports are shown in Fig. 4.16. The freedom of the pilots to choose their flight path is clearly visible. Some pilots steered away from the localizer to give themselves a smaller intercept angle, while other pilots steered towards the localizer to overfly the FAF while lined up with the runway. While the intercept angle varied per pilot, this was found to be constant irrespective of the display. Furthermore, in the go-around and windshear scenarios many pilots did not maintain runway heading even though that was instructed. Pilots also utilized various flap extension strategies leading to vastly different approaches in terms of airspeed and corresponding flight envelope limits.

This freedom comes with several challenges for the analysis of the data. For a fair comparison, each flight is therefore cut into two sections based on the following criteria:

- **Approach** (APP) – From the start of the flight until the triggering of the scenario, performed in every flight.
- **Windshear** (WS) – From the onset of the windshear until the aircraft is stable at the missed approach altitude.
- **Runway sidestep** (RW) – From sending the command to the text-to-speech generator till reaching 50ft AGL.
- **Go-around** (GA) – From sending the command to the text-to-speech generator till stable at missed approach altitude.



(a) EGLL



(b) KATL

Figure 4.16: Flight tracks of all flights combined, colored per pilot

Looking at all the other variables in the data, three more points should be raised. First, not all pilots managed to fly the approach speed of 140kt when the windshear was triggered. Notably pilots A1 and A5 had much higher velocities, generally this corresponds to a smaller loss of altitude. These pilots were consistently flying fast, irregardless of the display variant (Fig. 4.17). In both groups the airspeed is (slightly) lower in the second series of flights. Second, two flights stand out with a very high AoA of up to 29°. The pilots of both flights provided full back stick upon encountering the windshear. One of the pilots explained that he inadvertently thought he was flying in normal law. Third, flap extension time is different per pilot, leading to different performance during the initial approach phase.

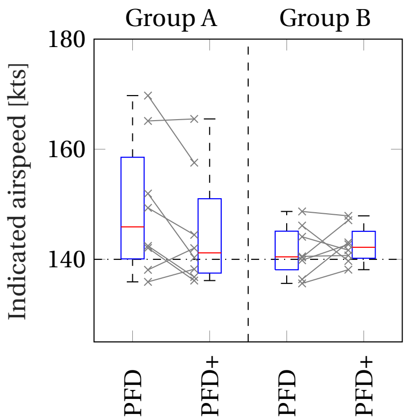


Figure 4.17: Mean indicated airspeed per pilot at start of windshear (V_{APP} = 140 kt)

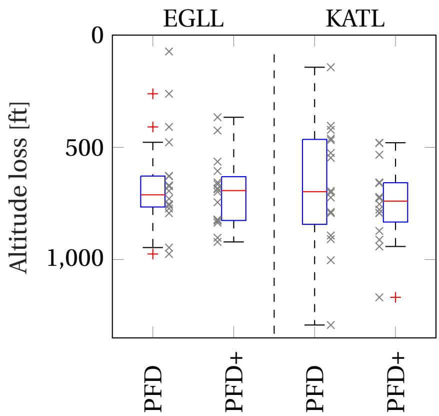


Figure 4.18: Mean windshear altitude loss per pilot

TYPICAL DATA

Fig. 4.19 shows data for all of the protected variables on a typical flight for the windshear scenario. The flap adjustments are clearly reflected in the maximum speed limits, as well as in the maximum permitted AoA. When turning onto the localizer, the pilot exceeded the 15° roll limit activating the haptic feedback on the roll axis. During the windshear, the pilot was in the AoA protection zone for circa five seconds, and exceeded the maximum AoA limit very briefly. Finally, a small airspeed violation can be seen on the climb out to the missed approach altitude when the pilot did not retract the flaps upon acceleration.

PERFORMANCE

Overall there seems to be little effect of the display on the performance scores, but there are some differences between the two airports. Especially in the windshear scenario at KATL, the PFD shows a much larger spread than the PFD+ (Fig. 4.18), which is not observed at EGLL. The other scenarios only showed marginal effects and thus their data is not visualised here for brevity. At EGLL the PFD+ leads to a slightly lower sidestep score, while at KATL the PFD+ has a higher score. Finally the go-around also shows a small difference, with more low scores at KATL than at EGLL. Wilcoxon signed-ranks tests show no significant differences for any of the performance scores. Windshear at EGLL (Z = -0.724, p = 0.469) and KATL (Z = -1.293, p = 0.196), sidestep at EGLL (Z = -1.028, p = 0.304) and KATL (Z = -0.159, p = 0.874) and finally the go-around at EGLL (Z = -0.035, p = 0.972) and KATL (Z = -0.175, p = 0.861).

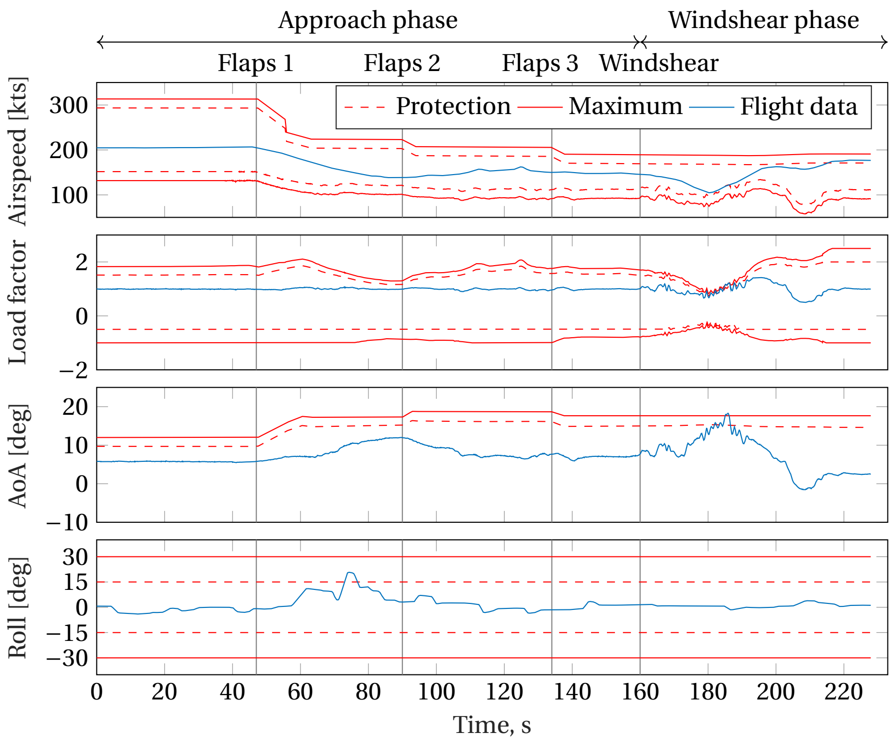


Figure 4.19: Typical flight data: Pilot A2 flying a windshear scenario at EGLL with the PFD+

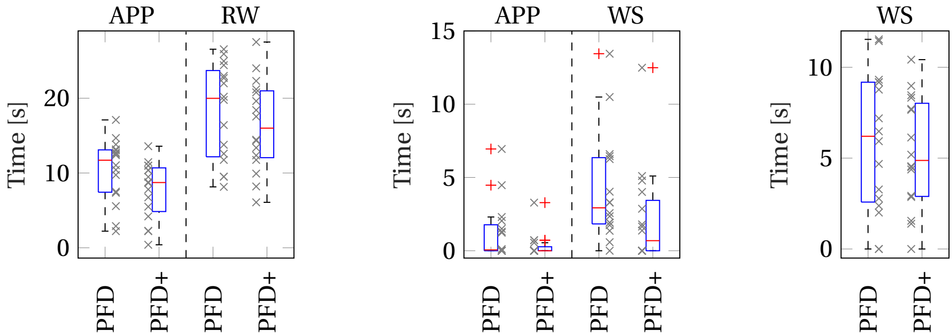
4

SECONDARY TASK

Combining the flights of all pilots, there were 734 ATC calls that required a reply. Just 22 of those were not or incorrectly answered. Further analysis shows that the vast majority of ATC requests that were missed occurred while the aural windshear or stall warnings were active, or when the pilot was already transmitting a message, and not the result of workload differences. The ratio of correct replies is therefore not a useful workload measure in this experiment.

TIME OUTSIDE THE SAFE FLIGHT ENVELOPE

The mean time spent outside the various limits of the safe flight envelope is shown in Fig. 4.20, where only flight phases are shown for which there was more than one excursion in the entire experiment. Roll protection limit excursions ($\phi > 15°$) mostly occurred during the localizer interception and in the runway sidestep. Only during one windshear the roll protection was very briefly activated, while it was never activated in the go-around phase. Fig. 4.20a shows that in both approach and sidestep the excursions were slightly shorter with the new display. A Wilcoxon's signed-rank test shows that the change in approach is significant (Z = -3.206, $p < 0.01$) while in the sidestep it is not (Z = -1.034, p = 0.301). For the maximum roll limit ($\phi > 30°$), there were too few violations to run a similar analysis.



(a) Roll (b) Overspeed (c) Angle of attack

Figure 4.20: Mean times in protection per pilot; flight phases in which one or zero excursions into the protection limits were registered are not shown

Speed excursions were primarily seen during windshear and approach (Fig. 4.20b). In approach these excursions were generally caused by a decreasing maximum speed upon flap extension. When climbing out of the windshear, flaps were often retracted too late while the airspeed increased rapidly. In windshear, pilots seem to spend less time in the high speed protection with the PFD+, but this decrease is not significant (Z = -1.619, p = 0.105). A similar, but significant, effect is seen during approach (Z = -2.521, p = 0.012). In the sidestep and go-around there were too few overspeed moments for any statistical analysis. The maximum speed was only exceeded once, during a windshear with the original PFD.

As expected, the angle of attack limits are almost only exceeded during the windshear. Fig. 4.20c shows the time spent above the protection limit. Only one pilot (A1) never exceeded the AoA protection limit. There was a small decrease in time with the PFD+ that is not significant (Z = -0.795, p = 0.427).

CONTROL ACTIVITY

The root mean square (RMS) control deflections of the side stick are given in Fig. 4.21 and 4.22 for, respectively, pitch and roll. Control activity is highest in the pitch axis during the windshear scenario. In the roll axis, most control activity is seen during the sidestep and to a lesser extent during the approach phase. There are no significant differences between the two displays, even though pitch control activity appears slightly higher in windshear with the PFD+ (Z = -0.879, p = 0.379), while roll control activity seems slightly lower in the sidestep (Z = -0.465, p = 0.642).

4.5.3. SUBJECTIVE RESULTS

Apart from objective data, subjective results were collected through a series of questionnaires. The results are discussed per questionnaire, starting with the questionnaire that was presented after each single flight. Followed by the questionnaire that wrapped up a series of six flights with a single display configuration and finally the questionnaire that was posed at the end of the experiment.

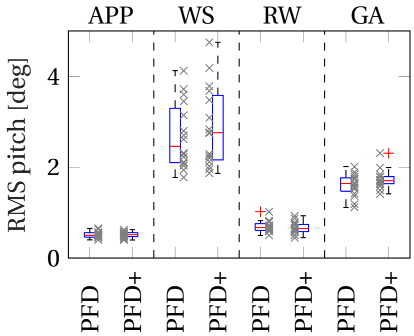


Figure 4.21: Mean RMS pitch input per pilot

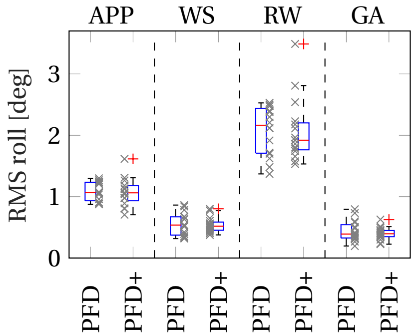


Figure 4.22: Mean RMS roll input per pilot

4

POST-RUN QUESTIONNAIRE

A short questionnaire after each single run allows to see how the display and haptics are experienced in the three scenarios. Fig. 4.23 shows the answers to the question *'Did you have the feeling you missed any essential information?'*. Wilcoxon signed-ranks tests indicate that the display had a significant effect on both the lack of information in the windshear scenario (Z = -2.691, p = 0.007) and sidestep scenario (Z = -2.121, p = 0.034). The go-around scenario showed no significant results (Z = -0.756, p = 0.450). In the windshear scenario, 11 of the 16 pilots indicated a lower score on the lack of essential information question when using the PFD+, while for three pilots the display version did not make any difference. Especially the angle of attack indication was said to be missed on the original PFD.

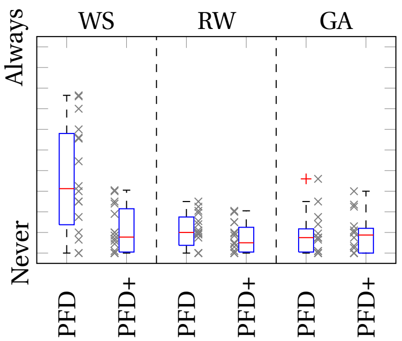


Figure 4.23: Post-run question:
Did you have the feeling you missed any essential information?

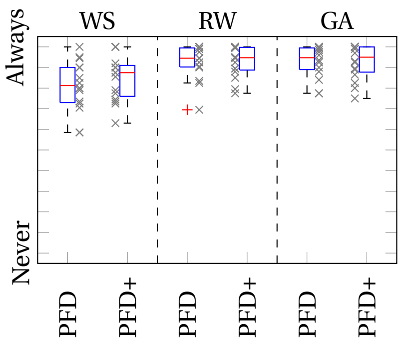


Figure 4.24: Post-run question:
Did you have the feeling you were in control?

No significant difference between displays is observed for any of the scenarios in the control metric regarding the question *'Did you have the feeling you were in control?'* (Fig. 4.24). During the windshear pilots feel slightly more in control with the new display, in correspondence with the indicated lack of information. Ten pilots indicated an improvement with the PFD+ in windshear, five pilots a decrease and one pilot was indifferent to the display variant. Overall most pilots had the feeling they were less in control in the windshear scenario than in the other scenarios.

In terms of subjective workload, the RSME scores, averaged over the two flights per scenario, show that the pilots perceived the highest effort in the windshear scenario (Fig. 4.25). The effort in the sidestep scenario is less and comparable to that in the go-around scenario. There are no statistically significant differences observed between the two displays.

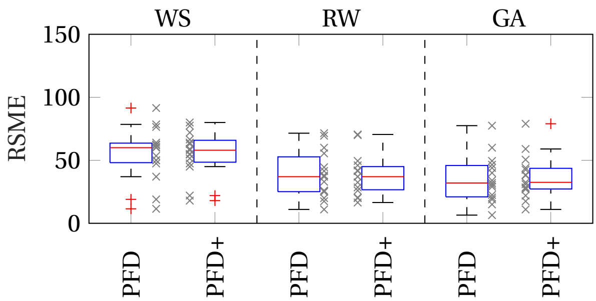
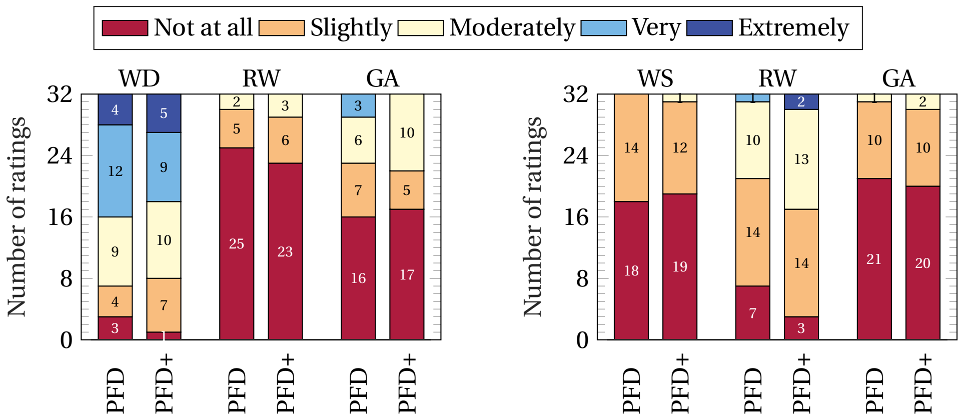


Figure 4.25: Mean RSME scores per pilot

When asked about the usefulness of the haptic feedback on the pitch and roll axis of the stick, it can be seen that the pilots considered the haptic pitch cues most helpful in the windshear scenario (Fig. 4.26). Haptic feedback in pitch did not help in the sidestep scenario but provided some help in the go-around scenario. Roll feedback was scored as somewhat helpful during the sidestep, but much less so than the pitch cues in windshear. In the other scenarios roll cues were not so helpful. For both axes there is no significant change in subjective haptic usefulness between the two display variants.



(a) Pitch

(b) Roll

Figure 4.26: Subjective usefulness ratings of the haptic axes in helping to stay inside the flight envelope limits

Results of a similar usefulness questionnaire regarding the various display indications are shown in Fig. 4.27. It reveals that pilots consider the airspeed indication useful in all scenarios, but especially in windshear. The AoA indication is even more useful in the windshear scenario and for some pilots also in the go-around. The indication of bank is somewhat helpful during the sidestep scenario but not in the other scenarios. And finally the load factor indication is almost never useful according to the pilots, who often mentioned that they did not look at it at all.

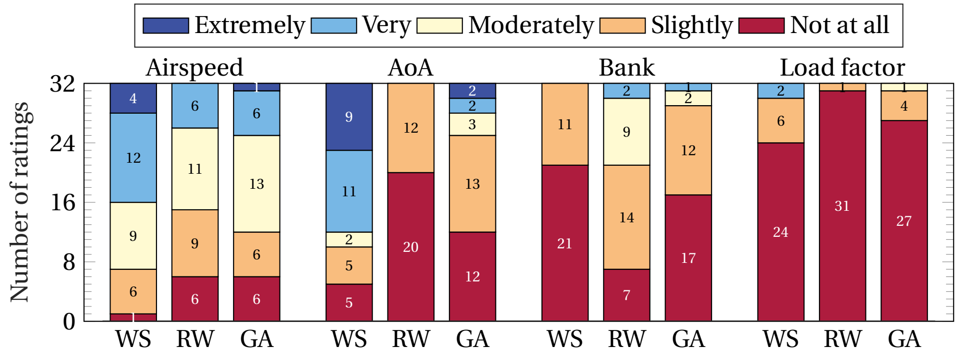
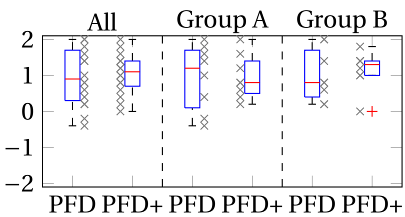


Figure 4.27: Subjective usefulness ratings of display elements in helping to stay inside the flight envelope limits

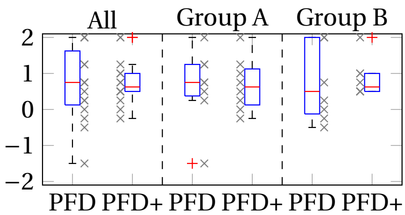
POST BLOCK QUESTIONNAIRE

The Van der Laan ratings, that were collected after six consecutive flights with one of the display options, are shown in Fig. 4.28 after being averaged per category. [104] The ratings show a small insignificant positive effect of the PFD+ on usefulness (Fig. 4.28a). No such difference is observed in the acceptance of the system (Fig. 4.28b). Nevertheless the spread did reduce in both categories when the PFD+ was used. When splitting the two groups of pilots, the mean of the usefulness rating of the first batch of six flights appeared to be higher than that of the second batch, irrespective of the display order. Apparently the pilots considered the system less useful once they had practiced more with it. The mean of the acceptance rating did not change much between the first and second batch, but group B shows a greatly reduced spread with the PFD+, whereas group A does not. One pilot from group A gave the lowest rating of all pilots on both usefulness and acceptance when flying the PFD. His ratings were significantly higher with PFD+. As shown in Fig. 4.28c, only two pilots gave the system a negative usefulness rating, both when flying with the PFD. The PFD ratings show a strong correlation between usefulness and acceptance with a Pearson correlation coefficient $\rho = 0.877$, while the correlation is weaker with the PFD+ ($\rho = 0.757$).

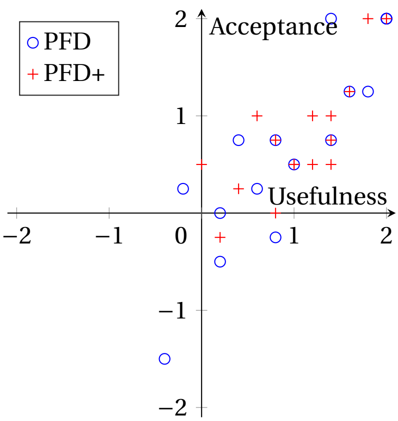
To get a better understanding of what might have lowered their ratings, the pilots were asked what they would remove from the haptic system, if anything at all. No differences were observed between the two displays, with the exception of the neutral point shift at high speed. Two pilots would like to remove this cue with the PFD, but not with the PFD+. The neutral point shifts in general were not noticed by the pilots unless they explicitly paid attention. One pilot attributed this to his ‘flying with my finger tips’. Furthermore, four pilots that would like to see the tick removed were annoyed by the strict limits in bank. They also considered the tick in pitch a nuisance when extending the flaps brought them above the 20 kts margin towards the maximum speed limit while still below the maximum flap extension speed. The tick itself was said to have the potential of a good attention grabber, as long as the limits are set to realistic values.



(a) Usefulness



(b) Acceptance



(c) Correlation

Figure 4.28: Van der Laan Ratings

The same question was asked regarding the display indications, assuming that the haptics would not change. The load factor is the only indication that should be removed according to a majority of 11 pilots (four from group A, seven from group B), with the other indications receiving at most three nominations in total for removal.

The Modified Cooper-Harper (MCH) ratings in Fig. 4.29 show little differences between the old and new PFD, except that the spread is less with the new display and there are less ratings of 4 and worse. When looking at the PFD+ ratings for each group separately, it can be observed that the rating is 3 on average for group A, while it is 2 on average for group B. To get from a 2 to a 3 or vice versa, one must answer differently on the question '*Does the system support efficient decision making?*' A MCH rating of 1 or 2 indicates that this question was answered with '*yes*', while a rating of 3 or more can only be chosen when the question is answered with '*no*'.

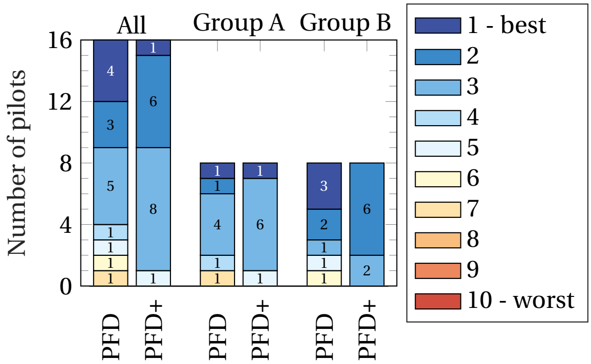


Figure 4.29: Modified Cooper-Harper ratings

Asking about the usefulness of the various haptic cues in preventing envelope excursions, all cues except for the stick shaker are considered more useful with the PFD+ (Fig. 4.30). The increasing stiffness and shifts of neutral point stand out with considerably higher ratings. The tick is slightly more useful with the PFD+, while the stick shaker is considered slightly less useful. The number of '*not at all*' ratings for the tick and neutral point shifts correspond to the similar number of pilots that indicated that these should be removed from the system.

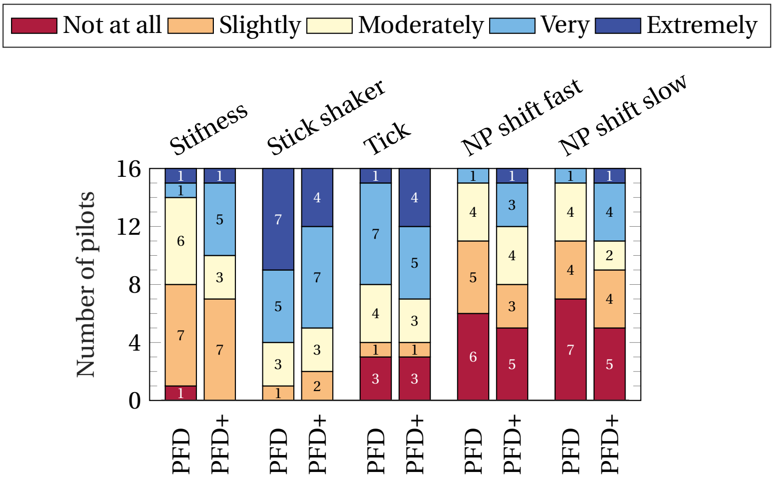


Figure 4.30: Usefulness of haptic feedback cues

The same question was asked about the various elements of the display indications (Fig. 4.31). The indication of the protected limit (beyond which the safe flight envelope is exited) is considered just slightly more useful than the indication of the maximum flight envelope limit. Despite a slight inclination towards useful there is no clear consensus between the pilots on whether the thickening of the indication is a useful aid in preventing envelope excursions.

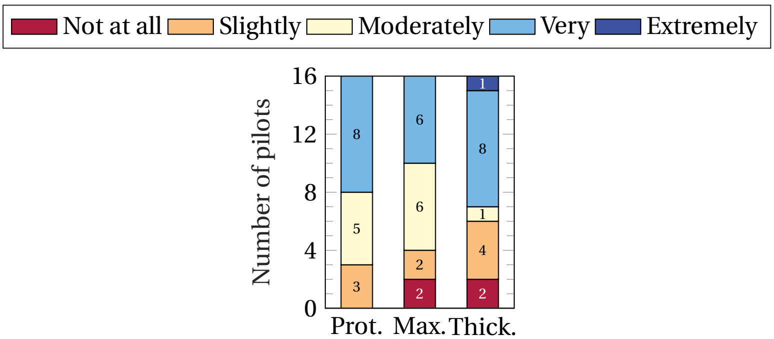


Figure 4.31: Usefulness of display cues

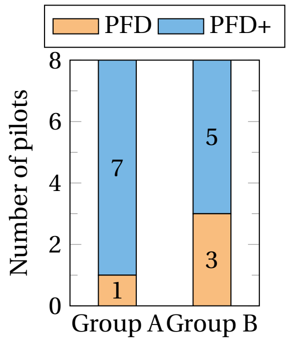


Figure 4.32: Preferred display

4

POST EXPERIMENT QUESTIONNAIRE

At the end of the experiments, the pilots had to fill in one final questionnaire. When asked which system had their preference, most pilots in both groups indicated that they would like to see the haptics combined with the PFD+ (Fig. 4.32). In group B the preference is less pronounced than in group A, but there is still a small majority in favor of the PFD+ over the original PFD.

Apart from this binary question, several statements were posed to get a better understanding of how the pilots experienced the system and the experiment itself. The results are shown in Fig. 4.33. From the figure a slight positive effect of the PFD+ on understanding the haptic cues can be observed. With the PFD, which lacked an indication for the overspeed protection at 20kts below V_{MO}, numerous pilots experienced ticks in the stick that they could not explain. Pilots also indicated to be able to return faster to the safe flight envelope upon exceeding the envelope when using the PFD+. Almost all pilots were of the opinion that their understanding of the haptics and display increased throughout the experiment; the so-called 'learning effect'. Nevertheless, a small majority of pilots thought the system does not require lots of training. The vast majority of pilots is of the opinion that the system would help prevent critical situations and if such situations do occur that the system would help solve them. In fact, almost all pilots thought implementation of such a system would have a positive effect on safety; only one pilot thought safety would be unchanged. Finally, there is no consensus on whether the display is too distracting. Pilots that said it was distracting, often attributed this to the strict bank angle limits leading to – when being accustomed to normal bank limits – premature warnings on the bank scale.

In terms of simulation fidelity, all aspects of the experiment are considered acceptable or better by the vast majority of pilots (Fig. 4.34). Two '*unrealistic*' ratings on flight dynamics and weather were given by pilot A7, who also gave the lowest rating of all pilots on the side stick and ND. The other '*unrealistic*' rating for weather was by pilot A8. There were considerable comments on the flight dynamics model, primarily about the thrust setting not matching that of a real Airbus and a too high sensitivity in pitch, which were also primary complaints in our earlier research. In terms of weather, some pilots thought the windshears were too strong compared to their usual training scenarios and

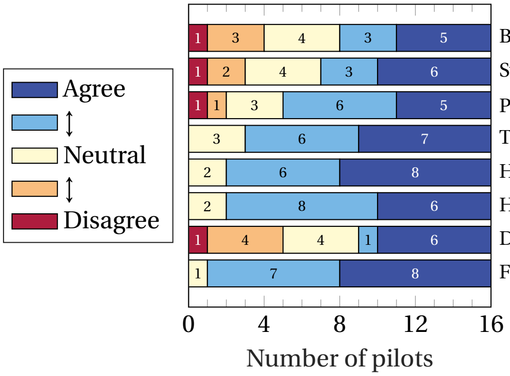


Figure 4.33: Subjective post experiment ratings

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some attributed the effect of wind on the aircraft to the weather system. The projected environment (terrain, airport and sky) was rated acceptable or better by all pilots.

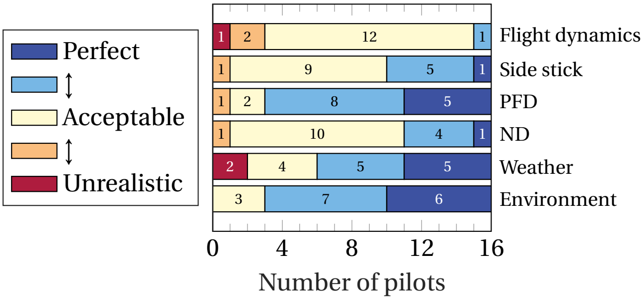

Figure 4.34: Subjective simulation ratings

When taking a closer look at the two – for this experiment – most important simulation elements, the side stick and the PFD, it is clear that both are sufficiently realistic. The nominal feeling of the side stick was considered at least acceptable by all but one pilot. Several pilots commented that the pitch and roll axes are more separated in the real stick, allowing for separate inputs in either axis. With the simulated stick it was said to be difficult to only apply pitch inputs without inadvertent roll input.

Pilots were in general also very positive about the realism of the PFD, saying it resembled the real instrument very well. Most criticism was about the nervousness of the speed trend vector and occasional disappearance of the flight path vector (FPV). The FPV only disappeared during the training sessions at KSEA when the aircraft was flying a heading of exactly 180°. This was only discovered on the third experiment day and was therefore left unfixed for the remainder of the experiment. The ND scored mostly acceptable or better, although some pilots missed the track indication from the real aircraft to help them line up with the runway.

4.6. Discussion

Previous research has indicated that adding visualizations to haptic feedback improves user acceptance and possibly also performance and safety metrics. [92] The current experiment indeed shows a slight improvement in acceptance and safety with the newly designed display. It does not, however, show an increase in performance. The following discussion is split in parts that follow the hypotheses. It concludes with the experiment setup and an overall system evaluation.

4.6.1. Workload

There were only some small changes observed in control activity both in positive and negative direction, depending on the scenario. All changes lacked statistical significance. The secondary task, replying to ATC requests, actually turned out to be unusable for workload analysis due to the small number of ATC requests. A comparable result was seen in Chapter 3, therefore future research should consider using different secondary tasks to aid the measurement of workload. The subjective RSME rating, however, showed no change in workload either, nor did any of the pilots hint on a change in workload in the debriefing. Thus, it is reasonably safe to conclude that the PFD+ does not lead to a change in workload, rejecting hypothesis H1. The fact that there is no increase in workload makes the PFD+ an acceptable addition in terms of workload.

4.6.2. Performance

Concerning the go-around scenario, several pilots indicated that it was 'unusual' to maintain 2000ft/min on go-around so they sometimes forgot to pay attention to the vertical speed. Another possible cause of the low scores for this scenario is the standard procedure to start reducing the rate of climb some 10% below the target altitude, while the score was based on the climb rate up to 100ft (ca. 5%) below the missed approach altitude.

While the performance measures in the sidestep and go-around scenarios were not expected to see significant improvements with the PFD+, there were strong expectations that the AoA indication would lead to better windshear performance. In theory it allows pilots to fly at the maximum performance of the aircraft, reducing the altitude lost during recovery. This is, however, not reflected in the results. A possible explanation is that the indication persuaded pilots to pitch up further than the standard 17.5° dictated by procedures. A larger pitch angle makes it harder to recover the aircraft once stalled. Limiting the indication to a fixed maximum – similar to Boeing's pitch limit indicator (PLI, [101]) – to prevent excessive pitch (pilot following symbol) may diminish this problem. Another potential source of poor performance was the ambiguity of the AoA indicator's reference. Aligning the 'whiskers' such that they touch the upper side of the fixed aircraft symbol when the angle of attack margin is zero would solve this ambiguity, while also making it easier to 'ride' on the limit. Concluding, the new display seems to neither significantly improve, nor deteriorate performance. Hypothesis H2 is thus also rejected.

4.6.3. Safety

During windshear, pilots flying the PFD+ spent slightly less time outside the safe flight envelope at high AoA and airspeeds. The decrease in time in overspeed protection during the approach phase clearly shows that the stringent 20kts high speed margin, only visible to pilots with the PFD+, changed pilot behavior when clearly communicated. Similar behaviour was seen in roll. While the time spent in roll protection also significantly reduced, the artificially strict bank limits may have had a big impact on pilot behavior in roll. In order to ensure the pilots would enter the roll protection, the bank angle limits in the experiment were artificially reduced compared to the real aircraft. Many pilots indicated this was unrealistic and perceived the roll cues in the haptic system and display as a nuisance since they activated while flying at a bank angle perfectly acceptable in normal operation. A different scenario setup may allow for the standard bank angle limits to be used. Nevertheless pilots did respect the bank limits more when shown on the PFD+. The hypothesis H3 that the margin to the flight envelope boundaries would become larger with the PFD+ can, however, not be accepted due to a lack of statistically significant differences. There does seem to be a small effect of the display that warrants further research.

While the objective effect on safety was rather limited, a large share of the pilots does expect that the system would improve safety when implemented. The data do not provide an answer on whether that can be attributed to the haptics, the display or the combination of both. Chapter 3 does suggest that the haptic system by itself is already seen as a safety improvement so the effect of the display may be limited here.

4.6.4. PILOT APPRECIATION

Overall, most pilots preferred the PFD+ over the old PFD, suggesting an improved acceptance of the haptic system in combination with the new display. This is confirmed by the increased usefulness of the various haptic cues with the PFD+. Still, Van der Laan and MCH ratings did not indicate a significant change in appreciation of the system as a whole. A possible explanation for this is that the haptic feedback, which was always enabled, was a more prominently present novelty for the pilots and thus had a bigger impact on their system-wide ratings than the display. Testing a baseline condition, with no haptic feedback, would show the effect of just the haptic feedback. Previous evaluations of the haptic feedback did include such a condition, but did not use the Van der Laan and MCH rating scales. Based on the preceding, hypothesis H4 cannot be unequivocally accepted.

4.6.5. DISPLAY INDICATIONS

As hypothesized, the load factor indication was considered the least useful indication by the pilots. They often indicated that they did not look at it at all for mainly two reasons. Firstly, it is simply not needed, because whenever the load factor limits are reached there is always another limit crossed (in the conditions from the experiment that is indeed true). The other reason is that the indication is added to the left of the speed tape, where in the actual Airbus there is nothing. The new indication was therefore not included in the scanning pattern. It is worth noting that several pilots considered the addition of a load factor indication 'extremely useful' during the briefing at the start of the experiment, but then changed their opinion after flying with it. More training may improve this, but combining all results it is expected that a load factor indication brings no extra benefit over the other indications. In future research the load factor indication can be removed to reduce visual load and to make the display fit in the standard Airbus display size.

The AoA indication on the other hand was much more appreciated by the pilots. The only pilot that said to remove it, does like to see the AoA and load factor indications in certain critical situations, like windshear or terrain avoidance maneuvers. Although it did not bring the expected performance benefit, it gave pilots the feeling that they were better informed about the state of the aircraft. It is probably also the reason why the stick shaker is considered less useful with the PFD+, as stall information is now also communicated through the AoA indication. Hypothesis H5 is thus accepted.

4.6.6. EXPERIMENT

Looking back at the experiment itself, the use of two pilot groups with different display orders was a valid choice, as some dependent measures showed a stark contrast between the two groups. This can probably be primarily attributed to the learning effect. Haptic feedback was new for almost all pilots and those that did fly with it before did so over a year earlier. Even though the pilots received considerate training, they were clearly still getting more accustomed to both the simulator and researched systems as the experiment progressed. Subjective results may have also been affected by the fact that the pilots did not fly a baseline condition with haptic feedback disabled and the original PFD. This could have helped determine whether any changes are caused by the haptic feedback itself, or the display.

In the aim for realistic scenarios, pilots were given a lot of freedom which lead to challenges in the data analysis. It could help to limit this freedom in future experiments. For example by showing the route on the ND all the way from the start, instead of from a distant waypoint onward. Using the autopilot to bring the aircraft to a pre-determined state and hand-over control to the pilot on the onset of an event may also help and is an accepted method in flight training. [106] As with any simulator experiment, the simulator itself may also have influenced the results. To minimize the impact of differences between the real aircraft and the simulation, pilots were given considerable time to familiarize themselves. Together with this research's focus on the PFD and side stick, both rated as sufficiently realistic by the pilots, the differences with respect to the real aircraft are considered acceptable with insignificant influence on the outcome.

Finally the lack of motion may have influenced pilot behavior. Especially in stall conditions, pilots are known to over-react when they do not feel the load factor. [107] Displaying the load factor was expected to make up for this lack of information. However, as discussed before, pilots did not pay much attention to the load factor indicator so this can not be assumed to be an adequate replacement. An experiment involving haptic feedback, PFD+ and motion cueing should be conducted to see whether motion has any effect.

4.6.7. OVERALL SYSTEM EVALUATION

Wrapping up, the PFD+ brings no big improvements nor any large deteriorations. Since pilots seem to like the display, albeit with a couple of modifications, the integration of input and output space seems to be a feasible solution. The display appears to fulfill its main design goal: increasing the understanding and appreciation of haptic feedback as a way to communicate flight envelope boundaries. Particularly in approach scenarios, in which a substantial number of LOC-I accidents in recent years occurred during cruise. Testing the haptics and display in a cruise situation where the pilots suddenly find themselves in alternate law could show the potential of the system in a wider range of flight phases.

4.7. CONCLUSION

This study looked into the effect of providing a visual display as a complement to haptic feedback in communicating flight envelope boundaries. The resulting display design is unique for displaying not only the limits of the flight envelope or the limits of the control inputs, but combining both in one display. In addition, the display shows the direction and force of the haptic feedback that is applied to the side stick. To accomplish this, the standard A320 PFD has been enhanced with new indications for angle of attack, airspeed, bank angle and load factor. The display was evaluated by inviting 16 professional Airbus pilots to TU Delft's SIMONA research simulator, where they flew two approaches in each of three different scenarios with both the original and modified PFD.

Unlike hypothesized, the design presented in this article did not yield significant differences in performance compared to the original PFD. Small but significant changes were observed in the time spent outside the safe flight envelope regarding roll angle and airspeed, hinting on a potential safety improvement. On the subjective front, the display proved to result in a small increase in pilot appreciation of haptic feedback. The display increased the pilots' understanding of what the haptics were trying to communicate and helped pilots stay within the limits of the safe flight envelope.

In conclusion, the proposed display can help increase pilot appreciation of haptic feedback. The combined system can lead to an improvement in aviation safety by reducing LOC-I accidents. Future research should focus on improving the display and experiment design. The unused load factor indication should be removed to reduce clutter. In contrast, especially the AoA indication appears to be useful, but also lead to a number of crashes when pilots followed it too closely. Further research is therefore suggested to improve this particular indication and reduce its ambiguity. It is also recommended to test the display with the actual bank limits, instead of the reduced ones used in this research.

5

JUST FEELING THE FORCE: JND FOR ASYMMETRIC VIBRATIONS

Previous research showed that haptic feedback, in the form of asymmetric vibrations, can be used to provide a cue and a direction to the operator in a laboratory setting. Nevertheless, it is unclear how these vibrations should be designed for pilots controlling their aircraft using a side stick, in terms of shape, amplitude, frequency, or background force. This chapter aims to determine the magnitude and shape for which vibrations can still be perceived as directional cues, for one fixed frequency based on literature. The threshold magnitude of two forcing function shapes (triangular and sawtooth) was determined for both pulling and pushing cues in a just-noticeable-difference experiment. Participants were asked to report the direction at varying input magnitudes while exerting different offset force levels on the stick at different stick positions. Results confirmed all hypotheses: they indicated a lower perception threshold for the asymmetric sawtooth shaped vibration compared to a triangular shaped; higher offset force decreased the threshold in the opposite direction; and stick position had no effect on the obtained thresholds. Based on the experiment we advise for this stick geometry to use sawtooth vibrations with an amplitude higher than 0.094 Nm.

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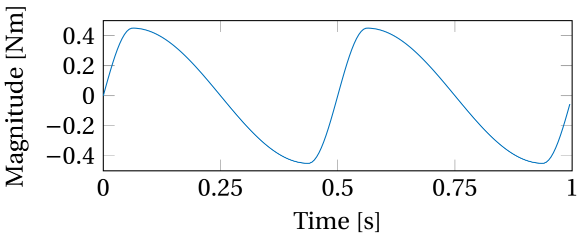
Conference	IEEE International Conference on Human-Machine Systems, Rome (Italy), 2020
Authors	D. Van Baelen, J. Ellerbroek, M. M. van Paassen, D. A. Abbink, and M. Mulder

5.1. INTRODUCTION

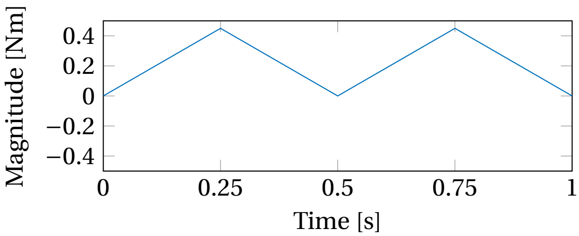
HUMAN-MACHINE interface environments, such as the flight deck of an aircraft, provide an abundance of visual and auditory information. Haptic feedback, i.e., force feedback through the control device, presents a different and direct way of communicating with the operator, but is still little used. Within haptics, support ranges from simple 'attention'-demanding cues to haptic shared control mixing automation and human input. [108] Haptic shared control involves an automated system actively moving the control device, which could be unwanted when an operator is accurately controlling a vehicle near its limits. Vibrations, on the other hand, provide a cue to the operator without imposing a control input which makes them useful for accurate control.

Literature on vibrations shows two similar and parallel lines of research. In the first line, operators are only perceiving the signal and not actively controlling; the second line of research looks at applications involving active control. An example of the first line of research, Tappeiner et al. investigated an asymmetric vibrations applied to an operator holding a magnetic flotor. [109] The vibration was asymmetric *in time*: the 'rise time' differs from the 'fall time', see Fig. 5.1a. Their analysis showed that such a system can indeed be used to provide directional cues, yet requires more research when the operator is actively using the control device.

5



(a) Asymmetric-in-*time* and symmetric-in-*amplitude* vibration [109]



(b) Symmetric-in-*time* and asymmetric-in-*amplitude* vibration [71]

Figure 5.1: Asymmetric vibrations studied in this work

An example of the second line where operators are perceiving and also actively controlling, is a haptic lane departure systems when driving a car. Navarro et al. used pulse inputs when a lane departure was imminent and showed that participants were more inclined to follow these commands as they act as a 'motor priming' element. [36] Huang et al. investigated three variations: the forcing function shape (square, triangular pulses), amplitude (large/small) and frequency (20/10/3 Hz). The analysis of lane departures showed that a signal with small amplitude, a square shape and mid-frequency was the best compromise for practical applications. [71] These two examples show the use of vibrations which are asymmetric *in amplitude*: the upper and lower parts of the oscillation are not equal as shown on Fig. 5.1b. Note that next to these two groups of vibrations, asymmetric-in-amplitude and asymmetric-in-time, multiple other vibrations exist, yet this chapter limits itself to these two groups.

Although the last two examples show that providing a directional force cue to an actively-controlling operator is feasible, it can happen that the operator experiences the *asymmetric* amplitude as a *symmetric* vibration with a shift in mean force, losing the directional information. Hence both the asymmetric-in-time and asymmetric-in-amplitude vibrations required more investigation to transfer them from a laboratory setting to an application.

The work presented in this chapter is part of a project which applies haptic cues for increasing pilot awareness when controlling aircraft close to the flight envelope limits. [97, 110] First evaluations of our haptic flight envelope protection system indicate that pilots preferred rather simple cues which indicate that the aircraft is close to the flight envelope limits through a discrete 'tick on the stick'. Ideally, such a 'tick on the stick' would not interfere with pilot control actions (as he or she may be operating close to the flight envelope boundaries), so its magnitude should be small. But not too small, because then pilots may not perceive it at all. One of the downsides of the vibrations we used was that these did not provide advice about which direction to steer, unlike the haptic shared control forces, while this direction is valuable information when operating an aircraft near the limits.

When a pilot is flying, the side stick can be at different positions where the vibrations might have a different effect due the grip of the side stick or other bio-mechanical effects. Additionally, the side stick in consideration has a centering stiffness, which requires a force of the pilot at a certain deflection. This offset force might influence the effect of the vibrations following Weber's law: higher offset forces lower the perceivability. [111]

As we want to investigate the use of vibrations on a typical side stick manipulator to transmit both a triggering and directional cue, the goal of this research is to find the asymmetric vibration shape, its advised magnitude, and whether it depends on the side stick position or force exerted on the side stick. Therefore, we will determine the minimum amplitude which two shapes of asymmetric vibrations require such that pilots are able to distinguish a direction while actively exerting a force on the control device: the Just Noticeable Difference (JND) for an asymmetric vibration.

This chapter is structured as follows. Section 5.2 discusses the forcing functions design rationale. Section 5.3 describes an experiment set-up to obtain the JNDs in asymmetric vibrations. Results are shown in Section 5.4 and discussed in Section 5.5. The chapter ends with conclusions in Section 5.7.

5.2. Design of Asymmetric Vibrations

All forcing functions used in this chapter are intended to indicate a *direction*, which requires an *asymmetry*. This asymmetry can be either in time or in amplitude. An asymmetry in time shows itself as the difference in rise and fall time as can be seen on Fig. 5.1a. It results in a side stick which is accelerating more in one direction. Asymmetry in amplitude is a difference in the magnitude to one side as shown on Fig. 5.1b. Using such a function makes the side stick move mostly to one side.

Aside from the forcing function, the actions of the pilot need to be considered too. The closest control task found in literature is a lane keeping task for which the use of asymmetric-in-amplitude forcing functions was considered. [36, 71] Nevertheless, the literature available on asymmetric-in-time forcing functions shows that these can be of interest and hence a combination of asymmetry in time *and* in amplitude is used in this research and specified here.

Before the actual forcing functions can be discussed, one more component needs to be addressed, the link between the forcing function and the pilot: the side stick dynamics. Whereas some literature might not fully specify the dynamics involved, initial implementations of forcing functions found that the side stick dynamics can have a large impact on the perceivable forces and available functions. As such, this system is first discussed in Subsection 5.2.1, followed by the forcing function specification in Subsection 5.2.2.

5.2.1. SIDE STICK DYNAMICS

Stick dynamics are governed by a simple mass-spring damper system, representing a side stick used on the flight deck of commercial aircraft (with inertia, $m_{ss} = 0.2\text{kgm}^2$, spring stiffness, $k_{ss} = 35.68\text{Nm/ rad}$, damping $b_{ss} = 0.4\text{Nm/ rads}$). Limb dynamics are modelled by a spring-mass-damper system, representing the inertia of the lumped neuro-muscular system and the damping/spring dynamics of the skin combined with limbs (with inertia, $m_l = 0.07\text{kgm}^2$, spring stiffness, $k_l = 400\text{Nm/ rad}$, and damping $b_l = 12\text{Nm/ rads}$). [112] These are combined in a lumped system as shown in Fig. 5.2.

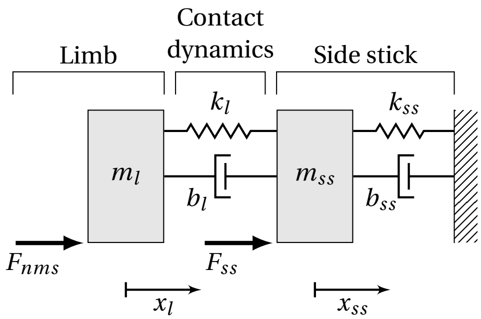


Figure 5.2: Schematic representation of the lumped limb and stick dynamics

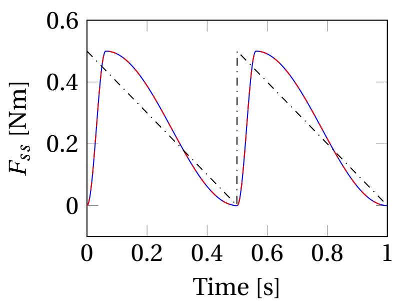
The lumped system state-space matrices are shown in Equation 5.1 and Equation 5.2. It contains four states (side stick position and velocity x_{ss} and $\dot{x}_{ss}$, and the limb position and velocity x_l and $\dot{x}_l$), two inputs (neuro-muscular force F_{nms}, and force on the side stick F_{ss}), and three outputs (side stick position, limb position, and the contact force F_c which is the combination of the side stick and contact dynamics).

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-k_{ss}-k_l}{m_{ss}} & \frac{-b_{ss}-b_l}{m_{ss}} & \frac{k_l}{m_{ss}} & \frac{b_l}{m_{ss}} \\ 0 & 0 & 0 & 1 \\ \frac{k_l}{m_l} & \frac{b_l}{m_l} & \frac{-k_l}{m_l} & \frac{-b_l}{m_l} \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} 0 & 0 \\ \frac{1}{m_{ss}} & 0 \\ 0 & 0 \\ 0 & \frac{1}{m_l} \end{bmatrix} \tag{5.1}$$

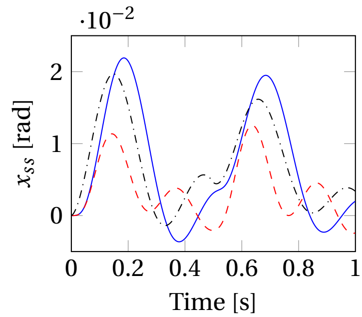
$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ k_l & b_l & -k_l & -b_l \end{bmatrix} \quad \text{and} \quad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{5.2}$$

To investigate effects of the side stick dynamics, and the importance of specifying all parameters in scientific publications, an asymmetric sinusoid as described by Tappeiner et al. is applied (amplitude 0.25Nm, frequency 2Hz, offset 0.25Nm, asymmetry −1.5) to the system described before, and a system where the side stick stiffness is doubled ($k_{ss_2} = 2 \cdot k_{ss} = 71.36$Nm/rad). The forcing functions for both systems are shown in Fig. 5.3a. From the resulting limb position, Fig. 5.3b, it can be seen that it is approximately *halved* when doubling the stick stiffness. The contact force, Fig. 5.3c, shows that equal magnitudes are obtained, yet frequency content differs.

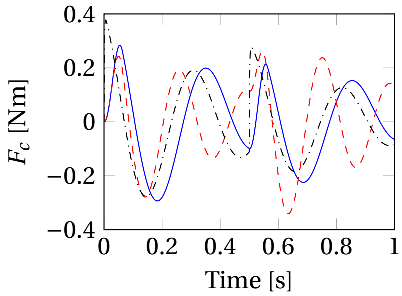
A full analysis of the effects of side stick dynamics on the resulting observations to the pilot is beyond the scope of this thesis. Clearly, they play an important role in the design of haptic feedback systems. The side stick properties used in remainder of the chapter are as described with the first system.



(a) Vibrations used (F_{ss})



(b) Side stick position (x_{ss})



(c) Contact force (F_c)

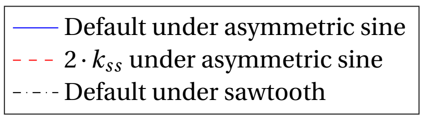


Figure 5.3: System responses to an asymmetric input

5.2.2. VIBRATION SPECIFICATION

With the side stick defined, we continue with the forcing function design. The effects of both asymmetric-in-amplitude and -in-time have shown to be beneficial for perceiving direction, and a combination of these two asymmetric dimensions could perhaps be used. An example is the input illustrated in Fig. 5.3a, which is asymmetric-in-time due to the difference in rise and fall time, *and* asymmetric-in-amplitude due to the positive offset resulting in only positive added forces.

The frequency of the signal, as well as the level of (a)symmetry, is heuristically determined by changing the settings in the simulator and striving for best noticeable direction by the experimenter. The final settings are a frequency of 2Hz and an asymmetry of -1.5, following the definitions used by Tappeiner et al. Next, the dynamics of the side stick are taken into account to further simplify the forcing function design: a forcing function with a sawtooth-shape was found to have a similar effect as the (slightly more complex) asymmetric sinusoid. This is illustrated in Fig. 5.3 (black and blue lines).

Fig. 5.3a shows that the asymmetric sinusoid is a smooth function, and the sawtooth contains a discrete step at each start of an 'oscillation'. Nevertheless, the dynamics of the side stick filter this input, as can be seen in the resulting limb position (Fig. 5.3b) and contact force (Fig. 5.3c) where the results with both forcing functions are very similar. Hence, in the remainder of this chapter, the sawtooth-shaped forcing function is used. To compare it with a signal that is only asymmetric in amplitude, we will compare it with a triangular pulse (see Fig. 5.1b) used in automotive applications.

5

5.3. METHOD

The experiment was approved by the Human Research Ethics Committee, and all participants signed an informed consent form. Eight participants took part in the experiment, with ages ranging from 23 to 51 years (mean 30 and standard deviation 8.9). None of the participants reported a medical condition that limited sense or use in the hand they used to hold the side stick. There were both left- and right-handed participants. Handedness should not be a determining factor, as pilots on the flight deck are controlling either as pilot-in-command (left seat, side stick at their left) or co-pilot (right seat, side stick at their right) position, regardless of their preferred hand.

5.3.1. APPARATUS

TU Delft's Human-Machine Laboratory was used as shown in Fig. 5.4, which features a custom-made, hydraulically driven side stick (of which the dynamic properties are easily changed), located at the right-hand side. To the left, a throttle quadrant is present, of which a toggle-button is used to let the participant input a direction after each trial. In front of the participant, a display as shown in Fig. 5.5 is placed to request an input on the side stick, a timer, an indication of the buttons, and a stop bar when a staircase is finished. The stick properties are tuned to match an Airbus-type stick ($m_{ss} = 0.2\text{kgm}^2$, $k_{ss} = 35.68\text{Nm/rad}$, $b_{ss} = 0.4\text{Nm/rads}$); this ensures that results are transferable to our main application. [97]

Figure 5.4: Simulator inside view showing the throttle quadrant (left), screen (front), and side stick (right)

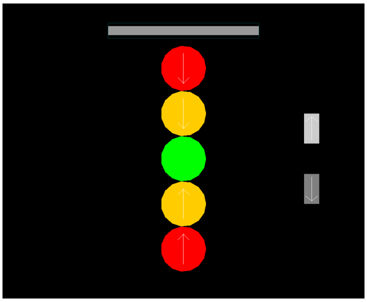


Figure 5.5: Display provided to the participants; the traffic light indicates the required input change by the participant and is shown in the 'start'-phase, the right arrows show which direction is selected during the 'wait for input'-phase, and the top bar indicates the time in one run

5.3.2. INDEPENDENT VARIABLES

The goal of this experiment is to obtain a threshold magnitude of the forcing function for which a pilot can indicate the direction while actively controlling the side stick. Therefore the participants are asked to exert a force on the side stick equal to the force required to deflect the Airbus side stick 0.1rad in pitch (3.57Nm). The deflection is chosen as pilots in our previous experiment were, even in emergency scenarios, controlling mostly within 0.1rad deflection. [110] As the forcing function should be felt when the pilot is pulling, pushing, or not actively using the side stick, the experiment is performed when the pilot is exerting negative (NEG, −3.57Nm), positive (POS, 3.57Nm), and no force (NO, 0Nm) on the side stick.

Previous research has shown that operators manipulating a side stick are more sensitive to differences in forces compared to positions, therefore the main analysis will be at one position (FORW, 0.1rad forward) and with the three force levels. [113, 114] To validate this assumption, one forcing function is additionally tested at zero neutral position (MID) with no force and with back force resulting in −0.1rad deflecting (AFT). If the assumption is indeed valid that the threshold is mainly determined by our sensitivity to force and far less by position, the comparison of the results should show similar thresholds.

As discussed already in Subsection 5.2.2, two forcing functions are selected to determine their respective threshold: a sawtooth (SAW) and a triangle (TRIANGLE) shape with a frequency of 2Hz. Only the former is used to analyse the assumption on the position and force interaction.

This makes in total 8 conditions (2 forcing functions × 3 force levels at 0.1rad, and the sawtooth function at the middle position with no force and −0.1rad).

5.3.3. PROCEDURE

Several 'trials' are performed where a single forcing function is presented. Trials consist of three phases, see Fig. 5.6. In the first phase the 'traffic light' display is shown, Fig. 5.5 helping participants apply the proper offset force. After a full second of proper offset force, the run phase is started, during which the vibration signal is applied. An end phase without vibration, of 0.5s closes off the trial. Participants can then, with their left hand on the toggle button, indicate in which direction the vibration input was felt.

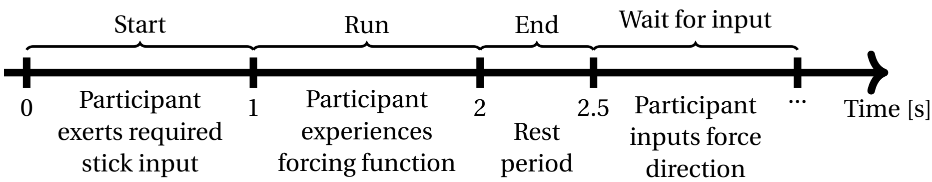


Figure 5.6: Summary of the phases in one trial

A staircase procedure is performed: after the participant experiences a cue, he/she is asked whether a change was observed, i.e., one 'trial'. The magnitude of the cue is decreased on a correct answer, and increased on an incorrect one. [115] The starting magnitude is so large that all participants start with a correct answer; the decrease in magnitude converges to the limit where the participant is able to sense a change. To improve staircase accuracy, following the first incorrect answer the amplitude increases on each incorrect answer and decreases following two consecutive correct answers.

The event of switching from a correct to an incorrect answer, and vice versa, for a staircase is called a *reversal*. Step sizes are determined by how many reversals have passed, the decrease is 30% for the first three reversals, 15% afterwards; the increase is 60% for the first three reversals, 30% afterwards, where the percentages are calculated based on the current magnitude. A staircase is completed when seven reversals are encountered.

Our experiment differs with respect to a 'standard' staircase application: for every condition mentioned with the independent condition, *two* staircases are performed in parallel. One staircase looks for the threshold where a participant can correctly indicate a direction for *positive* forcing functions (representing a pushing cue), one staircase looks for the *negative* threshold (pulling cue). The trials presented to the participant are a mix of the two staircases. Whether the direction of the next cue is positive or negative, is randomly chosen from a binomial distribution. Random directions are selected until *both* staircases had seven or more reversals.

The entire experiment for one participant lasts about 1.5 hours. After an initial safety and experiment briefing, a training is performed in which the participant is given feedback on his/her answer. This training is at least four runs with the sawtooth function and four with the triangle shape, and is concluded when the participant feels confident with the procedure. Following this, the above-mentioned eight conditions are executed following a randomized Latin-square design, ensuring that all transitions of conditions are distributed over the participants, where one condition lasts about five minutes. Between each condition a small break is held, and after four conditions a larger break is added.

5.3.4. DEPENDENT MEASURES

Each condition results in two threshold values for the forcing function force amplitude. These are calculated by averaging the last four reversals of a single staircase. In the following, a pushing/positive threshold is coded with 'UP', a pulling/negative threshold 'DOWN'.

Statistical analysis is performed using the R-programming language, for which the 'PMCMR' and 'PMCMRplus' packages are loaded. The package manuals provide references to the theoretical background such as the method, and the definition of the p-value and test statistics (χ^2 and V).[1]

5.3.5. HYPOTHESES

We want to determine the most effective asymmetric vibration shape, its advised magnitude, and whether it depends on the side stick position or force exerted on the side stick. Following this aim, the results of the JND experiment are expected to follow four hypotheses:

1. The threshold force where a direction can be indicated of the sawtooth-shaped forcing function is lower compared to the triangle-shaped one. This is due to the sawtooth-shaped being asymmetric in both time and amplitude, whereas the triangle is only asymmetric in amplitude.

2. The threshold force where a direction can be indicated of any forcing function is lower in the opposite direction from the force exerted by the participant. This because opposite direction from the force exerted has a lower background force, hence following Weber's law.

3. The threshold force where a direction can be indicated is lowest, and equal for pulling and pushing cues, when exerting no force on the side stick. As background forces are equal, this follows again from Weber's law.

4. The threshold force where a direction can be indicated is primarily dependent on the force applied by the pilot, not by the position measured. Following the perception research where operations were found to be more sensitive to differences in forces compared to positions.

[1] Available using respectively `https://cran.r-project.org/web/packages/PMCMR/PMCMR.pdf` and `https://cran.r-project.org/web/packages/PMCMRplus/PMCMRplus.pdf`.

5.4. RESULTS

An example of the result of a single staircase is shown in Fig. 5.7. The structure of the staircase is especially visible in the negative one: initially each correct answer decreases the amplitude. After the first incorrect answer, two consecutive correct answers are needed to decrease again. Note that after the fourth reversal, the step size is decreased.

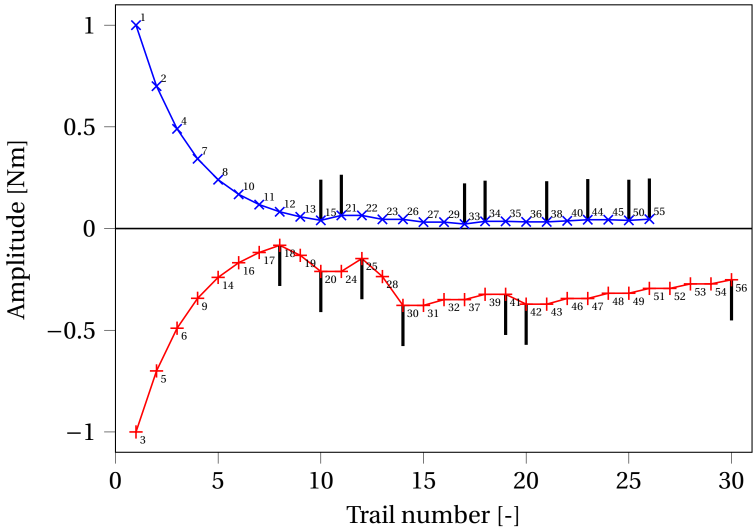


Figure 5.7: Example staircase-procedure (Participant 3), when applying a backward force on the stick and using a triangular pulse; numbers next to the points indicate the trials' sequence, vertical lines indicate reversals

The resulting JND levels for all participants over all conditions are illustrated in Fig. 5.8. Note that the coding of the conditions is as given in Subsection 5.3.2. Some general trends can be observed: first, the spread in JND values for TRIANGLE are much higher as compared to those from SAW. Second, the JND values for TRIANGLE are higher. Third, differences in JND for pushing and pulling forces (UP versus DOWN) while varying the force applied by the participant (POS/NO/NEG) seem to be present for both forcing functions, yet are more visible for TRIANGLE. Fourth, the absolute maximum median JND value found for SAW is 0.094Nm.

Statistical analysis of all forward-positioned cues (FORW) using a Friedman Rank Sum Test showed that there are significant changes between conditions ($\chi^2(11) = 63.1$, $p < 0.001$). Further investigation in the differences was performed with pairwise comparisons using Conover's test, for which the Bonferroni corrected p-values are shown in Table 5.1.

Finally, a statistical analysis to investigate the position effect was performed: a paired Wilcoxon test was used to compared the JND values found for forward position with no force (SAW/FORW/NO) with middle position (SAW/MID/NO), separately for the pushing and pulling forces, as well as for forward position with backwards force (SAW/FORW/NEG) and backwards position (SAW/AFT/NEG). These tests show that there is no statistically significant change (for all $p > 0.37$). In more detail, comparing no force forward and

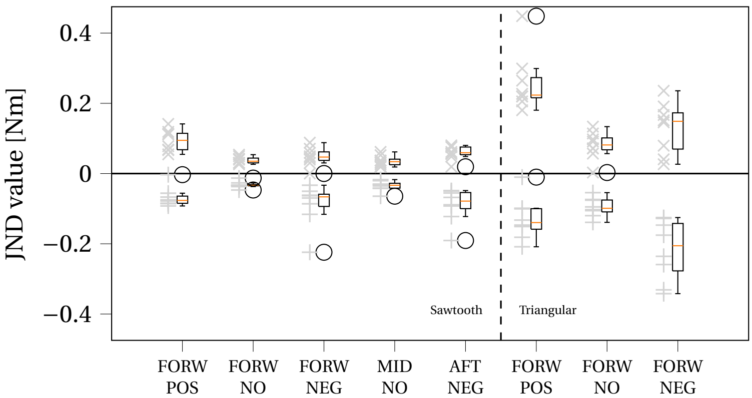


Figure 5.8: Boxplots of the JND values obtained for all conditions, circles indicate outliers, crosses indicate points for pushing cues, plus-signs for pulling cues

mid positions for pushing cues gives $V = 23$ and $p = 0.55$, for pulling $V = 24$ and $p = 0.46$; with the participant pulling on the side stick and comparing forward and aft positions for pushing cues $V = 11$ and $p = 0.38$, for pulling $V = 18$ and $p = 1$.

5.5. DISCUSSION

Considering the first hypothesis, a comparison needs to be made between the sawtooth and the triangle signals. Especially comparing the p-values indicated in Table 5.1 by subscripts 1, equal conditions (same force applied, and same forcing function direction) can be compared. These tests show that there is a clear difference between both forcing functions except for the NO/UP and POS/DOWN conditions. The differences can also be seen from Fig. 5.8: a decrease for the sawtooth-shape can be verified, together with a decrease in variation. This supports the hypothesis of decrease in threshold force when using the sawtooth-shape function instead of the triangle-shape.

For the second hypothesis, we consider the individual conditions (forcing function TRIANGLE or SAW, force level POS or NEG) and compare the UP and DOWN values. From Fig. 5.8, there seems to be a difference present for the triangular-shaped forcing function: a positive force by the participant (POS) results in a higher positive JND and visa versa; for the sawtooth-shaped functions this is less evident. This supports the second hypothesis: participants are more sensitive to forcing functions in the opposite direction of the force applied. Studying the p-values indicated by subscripts 2 in Table 5.1 this observation is not supported, however, with statistical significance. Because of the small sample size and the less powerful non-parametric statistical tests, the lack of statistical significance is not considered sufficient to reject the hypothesis either.

The third hypothesis requires no (statistically significant) change between the UP and DOWN thresholds when the participant is applying no force on the side stick (NO). Looking at the FORW/NO conditions for both forcing functions gives a visual confirmation that this is the case. The p-values indicated by subscripts 3 in Table 5.1 confirm this with clear statistical significance, hence supporting the third hypothesis.

The fourth and last hypothesis compares the results of the sawtooth-shaped forcing function for different positions. Visually comparing the results for the no load at forward and mid positions, and negative load at forward and aft positions, only small changes are observed. This is confirmed by the Wilcoxon tests, which showed no statistical significance. Hence all evidence supports this hypothesis: a participant is more sensitive to the amount of force applied compared to the position of the side stick.

Regarding the experiment, some other observations are worth sharing. First of all, we only had a rather small sample, with just eight participants affecting the statistical significance of our results. Second, whereas the side stick properties were designed to resemble Airbus sticks as close as possible – to allow for quick implementation in practice, our participants were not real pilots. However, there is no reason to believe that pilot JNDs will be different than the 'average' human, and we can assume that better averages can be found with a higher number of participants.

These results can be directly used on the side stick on the flight deck of an Airbus A320 and A330, and can be extrapolated to cars and other vehicles which are controlled using a side stick. Additionally, the methodology can be used to determine similar properties for a control column, used in some other aircraft types, as well as other control devices.

Note that our participants only focused on the force they had to exert on the side stick as well on the direction they perceived. In the intended application, pilots are actively operating the aircraft with a more specific task, for example flying an approach. Pilots are not fully focused on what he/she feels through the haptic feedback and the resulting threshold force is higher. When implementing a forcing function as researched in this experiment, a safety factor should be applied to make sure the pilot is feeling the force. A more time-consuming approach to circumvent this issue is a new experiment where the participants' focus is actively drawn away from the haptic feedback, yet a similar threshold task is performed in parallel.

An issue surfaced during this experiment, which is applying two parallel staircases: one participant's strategy was to input 'forward' whenever a pushing force was felt, and in *any* other case, whether nothing was felt, or the cue was not clear, a 'backward' input was given. This resulted in a good approximation of the threshold in the forward direction, whereas the backward direction approaches zero without any reversals. As the threshold values determined by the reversals assume a stochastic element in both staircases, results became invalid, the participant was removed and another one invited. To circumvent this problem, one can instruct participants to 'indicate direction, if not sure pick random input'.

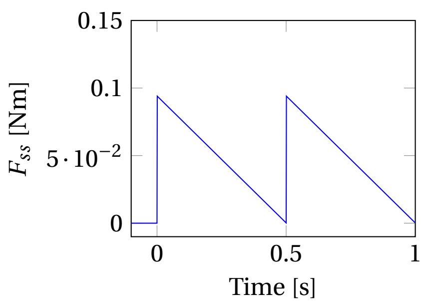
Table 5.1: p-values for post-hoc pairwise comparisons using Conover's test, Bonferroni correction applied, rounded to two digits; subscripts explained in text

			SAW						TRIANGLE				
			NEG		NO		POS		NEG		NO		POS
			DOWN	UP	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	UP	DOWN
SAW	NEG	UP	1.00_2										
	NO	DOWN	0.07^{*}	1.00									
		UP	0.26	1.00	1.00_3								
	POS	DOWN	1.00	1.00	0.14	0.47							
		UP	1.00	0.47	0.01^{***}	0.04^{**}	1.00_2						
TRIANGLE	NEG	DOWN	0.00_1^{***}	0.00^{***}	0.00^{***}	0.00^{***}	0.00^{***}	0.03^{**}					
		UP	1.00	0.01_1^{***}	0.00^{***}	0.00^{***}	1.00	1.00	1.00_2				
	NO	DOWN	1.00	0.05^{**}	0.00_1^{***}	0.00^{***}	1.00	1.00	0.26	1.00			
		UP	1.00	1.00	0.07^{*}	0.26_1	1.00	1.00	0.00^{***}	1.00	1.00_3		
	POS	DOWN	1.00	0.01^{**}	0.00^{***}	0.00^{***}	1.00_1	1.00	0.84	1.00	1.00	1.00	
		UP	0.00^{***}	0.00^{***}	0.00^{***}	0.00^{***}	0.00^{***}	0.00_1^{***}	1.00	0.35	0.05^{**}	0.00^{***}	0.19_2

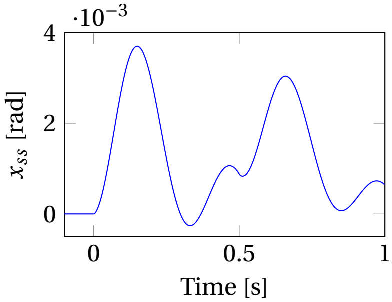
* indicates $p < 0.1$
** indicates $p < 0.05$
*** indicates $p < 0.01$

5.6. INFLUENCE OF THE ASYMMETRIC VIBRATION

To see the effect of the asymmetric vibration, the off-line analysis performed at the start of this chapter is re-visited with the signal properties as identified in the experiment. As such, a sawtooth-shaped vibration with an amplitude of 0.094Nm and a frequency of 2Hz, shown in Fig. 5.9a, is applied to the lumped limb and stick dynamics.



(a) Vibration used (F_{ss})



(b) Side stick position (x_{ss})

Figure 5.9: System responses to the asymmetric input identified in the experiment

Fig. 5.9b shows that the resulting deflection remains below 0.004rad. The effect of this position is different for each controlled system. The side stick on the flight-deck, in our intended application, requests a load factor change of 1.5g when deflecting the side stick fully at 0.28rad (16°). [61] Therefore the deflection of the vibration results in a requested change in load factor of 0.022g, comparable to mild gusts. Additionally, this is comparable to the load factor experienced when performing a turn with a bank angle of 0.2rad (12°). Most airlines limit the bank during normal operations for passenger comfort to 0.52rad (30°), which is a turn with 1.15g, hence our vibrations stays well within the limits of passenger comfort. Nonetheless, since the vibrations are intended as a cue for the pilot, not a control action, more investigation is needed to reduce the effect of those vibrations on the vehicle dynamics.

5.7. CONCLUSIONS

We investigated the perceivability of asymmetric haptic force cues designed to indicate *direction*. Results show that a sawtooth-shaped signal has a lower threshold and is recommended for future implementation. When participants applied different levels of force on the stick, data trends indicate a lower threshold for cues *opposing* the applied force; a non-significant effect, however. In case no force is applied on the stick, the threshold is equal in for/aft directions. Our participants were more sensitive to forces as compared to positions. The findings allow us to design asymmetric-in-amplitude *and* -in-time vibrations, which provide pilots with a clear direction cue, even when actively controlling their aircraft. This will be used in future developments of a haptic flight envelope protection system.

6

EVALUATING ASYMMETRIC VIBRATIONS FOR FEEDBACK ON FLIGHT ENVELOPE PROTECTION

The evaluation of the first design in Chapter 3 showed that the pilots appreciated the discrete cues when the flight envelope protection systems becomes active, yet it lacks a clear direction. Therefore, Chapter 5 investigated what vibration shape and magnitude is required to communicate a clear direction. This chapter evaluates a haptic feedback design using those vibrations with real pilots in a fixed-base simulator. The evaluation involved 24 active PPL/LAPL pilots who flew a challenging vertical profile and encountered a windshear. We used a counterbalanced design to evaluate pilot behavior with and without the haptic feedback. It was expected that this haptic feedback design helped in performing a safer recovery. Results indicated no difference in the tested metrics, except for a slight increase in acceptance when providing haptic feedback. Subsequent analysis revealed a strong learning effect in the first four runs, despite the initial training. The 12 pilots that experienced haptic feedback first seemed to have a steeper learning rate than the other pilots. Additionally, when the haptic feedback was no longer provided, there was no indication of negative after effects. This suggests a potential beneficial effect of the haptic feedback on training, but further experiments are needed to elucidate such effects.

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6.1. INTRODUCTION

INTERNATIONAL aviation safety boards, such as the European Union Aviation Safety Agency EASA and the International Air Transport Association IATA, identify loss of control in flight as the key risk area, resulting in most fatalities within aviation. [2, 3] A safety issue contributing to such a loss of control is identified as the inadequate monitoring of the main flight parameters and automation modes. To ensure and improve current safety levels, loss of control events should be prevented at all times, especially looking at the expected growth of the aviation industry.

Improving the information presented to pilots is expected to help reducing the loss of control occurrences. The most straightforward measure would be to change the flight deck displays, through showing the flight-critical states on, e.g., the PFD. This display can be augmented with information on the limits of the aircraft, i.e., the flight envelope, which can improve safety by reducing the risk of violations of those limits. [51] Research on improving pilot understanding of the current status of their automation shows promising designs, yet a simple indication like a cross was not conclusively shown to be effective. [116, 117] On the other hand, once the limits are exceeded, for example in a stall, the information on the PFD can be augmented with recovery guidance which delivers performance improvements as shown in three simulator evaluations. [118]

Apart from the visual channel, pilots can also perceive information through the sense of touch. An example is the haptic interface, which provides force feedback through the control device. This form of information can have a significant positive effect when a pilot is guided along the approach path. [41, 67] Additionally it can be used to show a set of predicted controllability limits, which was shown to be used by pilots in an experiment. [52] Furthermore, our previous research showed that haptic feedback can be used to show the pilot information on the FEP system which can limit the input of the pilot to ensure that aircraft is flying within acceptable limits. [97] The evaluation of this feedback system showed a potential benefit, yet lacked conclusive data. It did indicate that not all haptic feedback cues used were equally effective. [110]

This chapter presents a further design of the haptic feedback system for FEP, which uses asymmetric vibrations to show the activation of the FEP *and* indicate a clear direction to move away from the limit. This design is simpler than our previous one, in that it lacks situation dependent changes in device stiffness, but providing pilots with direction specific ‘ticks’ on the stick is expected to be equally effective.

This chapter first discusses the new haptic design iteration in Section 6.2. To evaluate this new design, Section 6.3 presents an experiment where the pilots are required to operate the aircraft at the limits. In Section 6.4 and 6.5, results of the experiment are described and discussed. Finally, the conclusions are shown in Section 6.6.

6.2. HAPTIC DISPLAY

The haptic feedback design is based on the control structure similar to an Airbus A320. Full details are given in our earlier work on the design of a haptic feedback system, see Ref. [97], only the most important elements will be explained in this section. Using an Airbus-like control law structure, the working principles of the new haptic feedback design are elaborated.

6.2.1. AIRBUS A320 CONTROL STRUCTURE

Modern-day Airbus aircraft, like the A320 and the A330, all employ a FBW system. This means that there is no mechanical connection between the control surfaces and the control device. The latter acts as an interface for the pilot to provide inputs to the FCCs which then command the control surfaces with hydraulic actuators. This allows a Flight Envelope Protection (FEP) system to be used, which can check and, if necessary, limit pilot inputs, to ensure that no flight envelope limits are violated.

Longitudinal control in a FBW Airbus, when all sensors are functioning (under so called "normal law"), is provided using C^*-control, which is a combination of both pitch rate (q) and load factor (n). [10–13] On top of this control law, a hard envelope limit is employed which protects the pilot from exceeding limits on angle of attack (α), load factor (n), and maximum velocity (V_{MO}). This protection is depicted in Fig. 6.1, where the nominal flight envelope is the extreme limit which can not be exceeded, the safe flight envelope is the point where protections start acting. The envelope is constructed by the maximum (n_{max}) and minimum (n_{min}) load factor, their protection limits ($n_{max_{prot}}$ and $n_{min_{prot}}$, respectively), the maximum operation velocity (V_{MO}, and protection $V_{MO_{prot}}$), and minimum velocity ($V_{\alpha_{max}}$, and protection $V_{\alpha_{prot}}$).

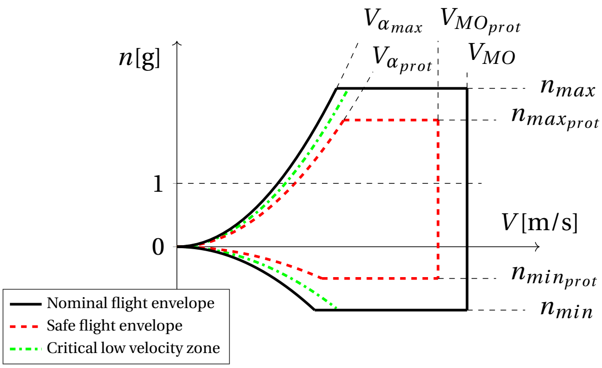


Figure 6.1: Flight envelope, velocity (V) versus load factor (n)

When multiple FCCs fails, or when a sensor failure occurs, the control is reverted to a degraded control law. In this research, we will consider a control law close to the Airbus alternate law without reduced protections, where the same protections apply as before, only the angle of attack protection is lost. Hence, in alternate law the aircraft can be stalled, yet allowing the pilot more extreme control actions.

Lateral control in normal law is a bank (ϕ) rate command from −33° till +33° of bank. Beyond these limits, positive roll stability is achieved such that the aircraft rolls back to the protection value (ϕ_{prot}) of ±33°. The maximum achievable bank, with full lateral side stick deflection is ±66° of bank. In alternate law, lateral control reduces to a pure rate command, irrespective of the actual bank angle. More details on the control laws and degraded control laws can be found in Ref. [97].

Given that for both longitudinal and lateral control, a degradation of the control law results in a different effect for a given control input, a clear indication of both the limits and the active protections of the flight envelope is required. Nevertheless, accidents did occur where pilots were not aware of what control law was active, and what protections were engaged. [7] As such, a clear and intuitive way of presenting this information can be found in haptic feedback and a new design is proposed in the following.

6.2.2. HAPTIC FEEDBACK DESIGN

The design rationale of the haptic feedback presented in this chapter is based on the results of an evaluation with a previous design. We found that the majority of pilots appreciated a discrete cue when leaving the safe flight envelope, therefore additionally indicating when the FEP starts acting as indicated above. Furthermore, the stick shaker close to a stall, was considered to be very valuable. Although the other haptic cues used in the initial design – such as the increased stiffness of the side stick, the change of the position to which the stick returns when no force is applied – were appreciated, these were not received as well as the discrete indications. [110]

Looking at the flight deck implementation of a haptic feedback system with variable stiffness and changing neutral point, the verification, validation and certification procedure might present a huge hurdle to overcome. On the other hand, adding a 'simpler' discrete cue might be easier to implement as similar systems already exist, such as a stick shaker in Boeing aircraft, or an indication of angle of attack by a soft stop in the Gulfstream G500/G600 [1]. [55] Additionally, the discrete cue might be incorporated in the grip of the side stick such that it can be retro-fitted to current passive side sticks. Combining the preference by the pilots, and the potential market, we considered it to be worthwhile to investigate whether a haptic feedback system using *only* discrete cues might already yield an improvement.

6

Although the discrete cues were the preferred way of communication, it was not always clear to pilots in our previous experiment what *direction* of control input was required. This is no surprise, since the discrete cues were not optimised to indicate direction, but it was a good incentive for us to investigate whether discrete cues *can* indicate direction. Therefore, an investigation into a number of forcing functions was performed in Chapter 5.

This analysis indicated that a sawtooth-shaped forcing function had best performance. The experiment showed the minimal required amplitude where the subjects could just indicate a direction, which was determined to be 0.094Nm. As the subjects only focused on the side stick and the perceived direction, the minimal amplitude for use on the flight deck is expected to be larger. For the present experiment the amplitude is multiplied with a 'safety factor' of three. The resulting forcing function has a sawtooth-shape with amplitude (I_0) 0.282Nm, frequency 2Hz, lasts for one second, and is shown in Fig. 6.2. Although it has a discrete start, combining the forcing function with the actual side stick-dynamics results in a smooth experience on the stick as shown in Chapter 5.

Like the discrete cue evaluated in the previous experiment, this discrete cue is provided to the pilots when the aircraft leaves the safe flight envelope and the FEP becomes active, and the direction of the cue is the required direction to avoid the approaching limit. As such, a positive roll (i.e., to the right) cue is provided when $\phi < -\phi_{prot}$, a negative roll (left) cue is provided when $\phi > \phi_{prot}$. A positive pitch (push) cue is provide when

[1] https://www.baesystems.com/en-us/feature/an-active-role, accessed June 6th 2019.

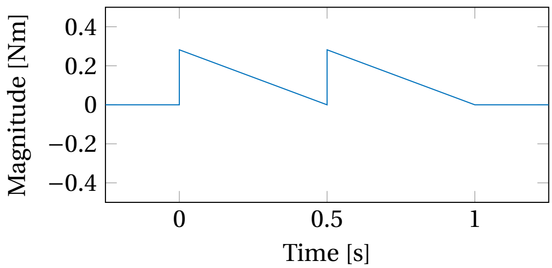


Figure 6.2: Sawtooth-shaped forcing function used

one or multiple of the following conditions are met: (i) $\alpha > \alpha_{prot}$ or (ii) $n > n_{max_{prot}}$. A negative pitch (pull) cue is provided when at least one condition is met of the following: (i) $V > V_{MO_{prot}}$, (ii) $n < n_{min_{prot}}$, or (iii) $\alpha < \alpha_{min_{prot}}$.

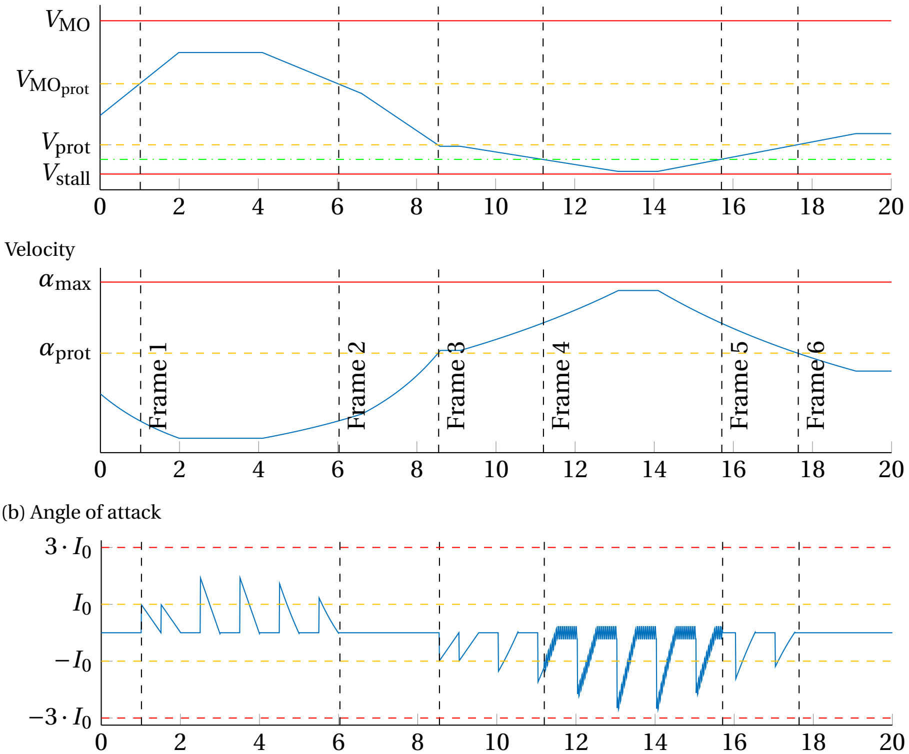
To inform the pilot that (s)he remains outside the safe flight envelope, a single tick is repeated every second as long as the safe flight envelope limits are exceeded. Additionally, the amplitude of the tick is used to transmit the proximity of the current aircraft state to the outer flight envelope. For a generic variable ν, the intensity starts at the protection state (ν_{prot}) with default value I_0, and increases to a multiple of the initial value determined by the gain K_I (2 in this setup) at the outer flight envelope (ν_{nom}) using:

$$\mathrm{I} = \mathrm{I}_0 \cdot \left(1 + K_I \cdot \frac{\nu - \nu_{prot}}{\nu_{nom} - \nu_{prot}}\right) \tag{6.1}$$

To clarify the expected working principle of the haptic feedback system, Fig. 6.3 shows the time trace of an illustrative example: Fig. 6.3a, 6.3b and 6.3c show, respectively, the time traces of the velocity, angle of attack and resulting force supplied to the control device, i.e., the haptic feedback.

At the start of the example, the aircraft accelerates to a value just below its maximum velocity. When the protection velocity is exceeded at Frame 1, as shown on Fig. 6.3a, the two initial ticks are supplied to the side stick visible on Fig. 6.3c. These initial discrete cues have a set intensity of I_0 and are positive/backwards: indicating a pulling action is required. While remaining in the upper velocity protection, the ticks are repeated every second, and the intensity is adjusted to reflect the relative distance from the protection limit to the ultimate flight envelope limit. Upon decelerating the flight state leaves the upper velocity protection in Frame 2, the ticks are stopped and the nominal side stick feeling is resumed.

When the angle of attack increases above the protection value at Frame 3 shown on Fig. 6.3b, two more ticks are provided on the side stick as illustrated on Fig. 6.3c. Note that the direction of the tick is opposite from the previous: these ticks at intensity I_0 are negative/forward, indicating that the current problem can be resolved by pushing. By decelerating more, the velocity drops below the green dash-dotted line on Fig. 6.3a, i.e., halfway between the lower protection and lower flight envelope velocity, at Frame 4. At that point, the stick shaker is activated as shown by the added oscillations on the force to the side stick on Fig. 6.3c. The intensity of the discrete cues is again adjusted to reflect the relative distance to the ultimate flight envelope. Increasing the velocity/lowering



(a) Velocity

(b) Angle of attack

(c) Haptic feedback: force supplied to the side stick

Figure 6.3: Illustrative example of haptic feedback triggering on changing states

the angle of attack, stops the stick shaker at Frame 5 and the discrete ticks at Frame 6, resuming nominal side stick feeling again.

Using the haptic feedback cues presented here, it is expected that the pilot is better informed on the flight envelope limits and protection zones, yet this needs to be proven by a system evaluation as proposed in the following.

6.3. METHOD

To evaluate the haptic interface design as proposed in the previous section, an experiment was performed.

6.3.1. PARTICIPANTS & INSTRUCTIONS TO PARTICIPANTS

For this experiment, 24 pilots (1 female, 23 male) with a current Private Pilot License (PPL) or Light Aircraft Pilot License (LAPL) license were invited. As these pilots are not necessarily active Airbus pilots, they were reminded that the aircraft model used has a mass of 64,000kg and has to be handled with more care than a general aviation aircraft. Additionally, they were instructed to always stay within the nominal limits of the flight envelope (black line on Fig. 6.1) which was shown on the PFD using the indications proposed in Ref. [119]. It was mentioned that each run would stop at 50ft above ground level irrespective of any other event/performance due to limitations of the simulation.

Table 6.1: Participants in the experiment

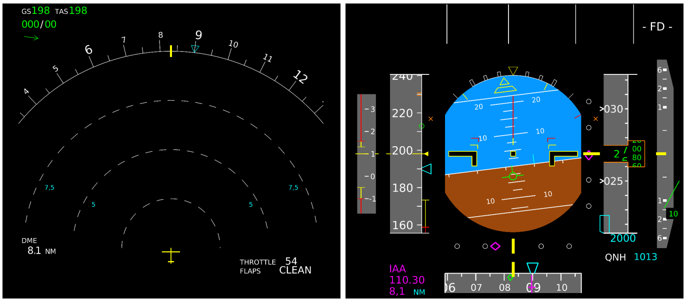
Participant	Age	Flight hours	License
1	34	116	PPL
2	36	106	PPL
3	25	80	LAPL
4	38	150	PPL
5	49	205	PPL / E-IR
6	56	130	PPL
7	40	630	PPL
8	26	152	PPL
9	48	350	PPL
10	47	160	PPL
11	24	500	PPL
12	69	800	PPL
13	66	900	PPL
14	45	120	PPL
15	46	250	LAPL
16	55	190	PPL
17	48	500	PPL
18	47	552	PPL / IR
19	50	400	PPL
20	60	170	PPL
21	33	240	PPL
22	41	80	PPL
23	53	600	PPL / E-IR
24	42	330	PPL
Mean	44.9	321.3	-
Std.Dev.	11.9	237.1	-

IR Instrument Rating
E-IR Enroute-Instrument Rating

6.3.2. EXPERIMENTAL SETUP

The experiment was performed in the Human Machine Interaction (HMI) research simulator of Delft University of Technology. It is a fixed-base, near 180° outside field-of-view, used in the first officer position of which an inside-view is shown in Fig. 6.4. Since the pilot was sitting in the first officer position, the display to his front-left was the ND showing a top-down overview of the situation, shown in Fig. 6.5a, combined with a basic engine N1-indication and slats/flaps indication. The display right in front of the pilot was the PFD showing the critical flight states, shown in Fig. 6.5b, which included display indications used to show *why* and *when* the haptic feedback was active. [119] Next to the visual information, auditory warnings were presented when the angle of attack was above the maximum value, and when the velocity was above the maximum velocity.

Figure 6.4: Inside view of the HMI flight deck



(a) ND (b) PFD

Figure 6.5: Flight deck display setup used in the experiment

A custom-made, hydraulically driven side stick with programmable dynamic properties is located at the right-hand side and was configured to Airbus side stick properties. [61] To the left, a throttle quadrant is present which could be used to control the throttle and high lift device settings. Centrally placed, a Boeing 737 Mode Control Panel (Airbus terminology: Flight Control Unit (FCU)) enabled the interface with the heading, velocity and altitude references on the displays. Outside visuals were generated using FlightGear[1] and showed the airport infrastructure, terrain and important buildings at the airport. A proprietary A320-like flight dynamics model with control laws, from the German Aerospace Center (DLR), was used as the simulated aircraft. [120]

The nominal control device settings for this experiment, including mass (m), spring coefficient (k), damping coefficient (b) and maximum deflection (δ_{max}), for both longitudinal and lateral side stick axes are given in Table 6.2, no breakout was used as it was not present in Chapter 5.[2] Forcing functions used in the experiment were: (i) a sawtooth shape of intensity 0.282Nm, duration 1s and frequency 2Hz when exiting the safe flight envelope, (ii) a sawtooth shape with varying intensity proportional to the relative distance of the protection and flight envelope limit, duration 0.5s and frequency 2Hz when remaining outside the safe flight envelope and (iii) a stick shaker for low velocities as a sinusoid with frequency of 20Hz and magnitude 0.426Nm.

[1] Open source flight simulator available at `http://flightgear.org`
[2] Our conference publication incorrectly provided breakout properties.

Table 6.2: Control device in the experiment

Property	Value
m	0.2 kg m^2
$k_{lon_{nom}}$	36.3 Nm/rad
b_{lon}	0.4 Nm s/rad
$\delta_{lon_{max}}$	0.279 rad
$k_{lat_{nom}}$	21.8 Nm/rad
b_{lat}	0.4 Nm s/rad
$\delta_{lat_{max}}$	0.314 rad

6.3.3. Experiment Scenarios

The haptic feedback system was designed to communicate the ‘proximity of the flight envelope limits’ to the pilot and therefore requires an evaluation at these limits. In previous work, this was achieved by presenting the pilots with a scenario as realistic as possible, by initializing the simulation right before the pilot would intercept the glide slope and localizer. An event was triggered after following the glide slope/localizer for several minutes. The analysis showed that, due to variation in performing this initial part of the simulation, the aircraft states (velocity/altitude/heading) presented to each pilot when the events were triggered, were not equal, which resulted in a large spread in the data. These results indicated that for the experiment it would be beneficial to better control the conditions under which the system is tested. [110, 119] Therefore, in the present experiment the required flight trajectory was more stringently prescribed, as discussed below. This ensured more uniform conditions when the emergency scenario was encountered.

Flight path

Each run was started when the aircraft was flying 140kts (72.0mps) at 2500ft (762m) with flaps setting 3, overhead the threshold of runway 23 of Zoersel (Belgium) and aligned with the respective runway. This location was chosen as it has no special terrain features close-by, and the runway was not visible from the starting position as illustrated on Fig. 6.7a. Additionally, the auto-throttle was set to 140kts and activated, reducing the variability of the initial aircraft state when the event was triggered, which should provide more consistent results. From this position, pilots were presented with visual markers (squares of 60m by 60m) on the outside display to fly a flight profile consisting out of six ‘hills’, for which an example path is presented in Fig. 6.6 and is visualized as illustrated by Fig. 6.7.

One hill was 2.27NM (4200m) long and followed a saw-shaped trajectory with one of three possible amplitudes: 150ft (45.72m), 300ft (91.44m) or 500ft (152.4m). The flight path started with a horizontal segment of 0.41NM (750m) and one hill of the smallest amplitude as run-in. This was followed by a randomized order of hills such that each hill amplitude occurred twice in the flight path. Each flight ended with a horizontal segment of 0.54NM (1000m) as run-out. This setup of hills was chosen as it was expected that it allowed the results to be evaluated for each hill separately. Eight different realizations of the randomization were obtained to present pilots with variability in the scenarios. The resulting trajectories are all shown in Section C.1.

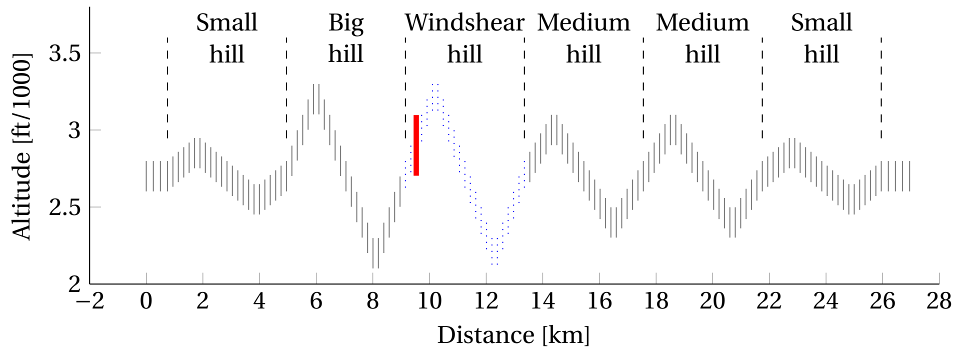
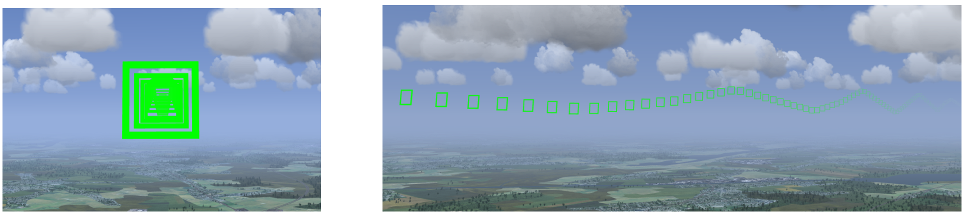


Figure 6.6: Flight path side-view, solid black vertical lines indicate “fly-through gates” shown on the outside visual; the thick red line indicates the trigger point of the windshear (not shown on the outside visual); the dotted blue lines lines indicate the windshear section used in our evaluation



(a) View at start of run

(b) Perspective view on flight path (viewing angle is for illustrative purpose only, never encountered during flight)

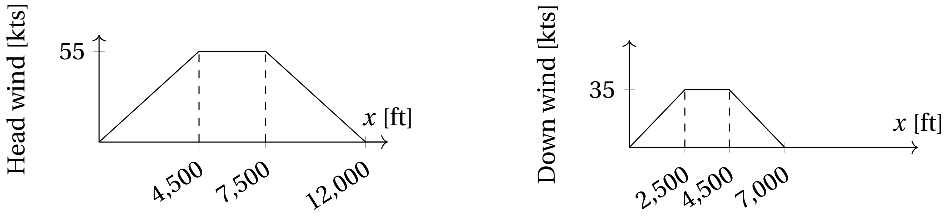
Figure 6.7: Example of the outside visual flight path visualization

EMERGENCY SCENARIO

As the pilots of the experiments mentioned before did express the potential added value of the haptic feedback system in a windshear event, this event was re-used for this research. A wind shear is a meteorological phenomenon where wind velocities are locally rapidly changing, and can be caused by a large cylinder of air suddenly “droping” towards the earth. During such a wind shear event, downdrafts can push the aircraft dangerously close to the ground. [76] To recover from this event, the pilot has to fly as close to the stall limit as possible to prevent further height loss and maximise aircraft performance.

The windshear was *always* started when the aircraft moves through the visual marker of the large amplitude hill at an altitude of 2900ft (883.92m). Each flight path contained two large hills, only one of them was selected at random to contain the windshear trigger point. The windshear itself was modeled by both a head-on and top-down component as shown in Fig. 6.8. [76] Once the windshear was initiated, the visual and aural warning triggered, and the pilot had to apply the windshear recovery procedure as stipulated in Section B.6, which was based on the Airbus Flight Crew Operating Manual. [13]

When providing only windshear as the emergency scenario, pilots might anticipate this event, even in the first run. To prevent this, two more checklists for an emergency were presented to the pilots: the actions required for a single engine stall (Section B.7), and for a sudden center of gravity shift (Section B.8). Note that the checklists presented in Fig. B.6 and B.7 are heavily modified from the FCOM, and the checklist for the sudden center of gravity shift is non-existing in the FCOM.



(a) Headwind component

(b) Downwind component

Figure 6.8: Windshear component distribution

6.3.4. EXPERIMENT DESIGN

In order to provide pilots with sufficient familiarity with the simulator and the haptics, a familiarization phase was performed, followed by measurement runs.

FAMILIARIZATION

After a briefing on the simulator safety procedures, controls and displays, the pilots *felt* the design rationale behind the haptic feedback design. This was done by presenting the flight envelope (an image similar to Fig. 6.1), the haptic feedback (a time trace of the forcing function on the side stick), and the PFD (Fig. 6.5b) to the pilot. In this setup, no aircraft model was used, yet the flight envelope state was changed directly (hence changing the velocity and load factor) and all visual, auditory and haptic cues were presented and experienced by the participant.

Next the model was introduced to the pilot by flying a traffic pattern twice to a final approach at Schiphol (EHAM) as shown on Fig. 6.9 without the haptic feedback, hence focusing on familiarization with the model. Pilots were instructed to follow the instructions as indicated. Some pilots did encounter a stall and/or an overspeed condition during these first runs. If the pilots did not hit one or both limits by their own exploration, they were asked to deliberately explore those boundaries to ensure that all pilots encountered these before the measurement runs.

MEASUREMENTS

The measurement phase contained eight realizations of the flight path presented above. They were flown in a randomized fashion, distributed over all participants using a Latin-square distribution. The participants were divided in two groups: one group performed four runs with haptic feedback, followed by a break, and four runs without haptic feedback, the other group had reversed order of the haptic feedback: first off, then on.

After each run, pilots were asked to indicate their workload using a RSME rating ([85]), complete a post-run situation awareness questionnaire, and indicate how helpful the display and haptic (if supplied) elements were. They also provided a misery scale rating tracking effect of motion sickness. [121] Once this was completed, pilots were informed on how much time they spent inside the flight envelope, which they had to maximise.

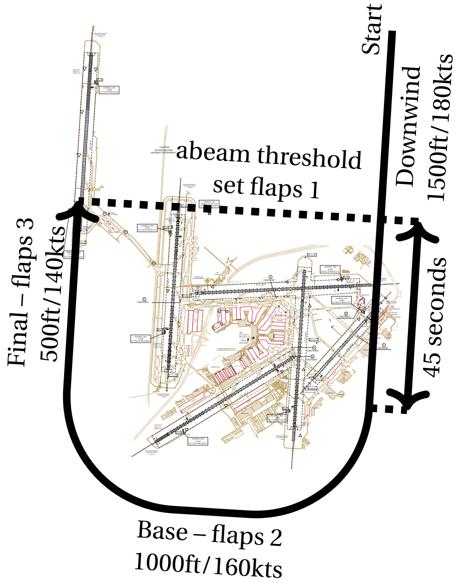


Figure 6.9: Traffic pattern flown to runway 36L at Schiphol (Schiphol layout from AIP [84])

Table 6.3: Experimental design

Block	1				2			
Run	1	2	3	4	5	6	7	8
HFG	HF				NH			
HSG	NH				HF			

After one block of four runs, the pilots were asked to complete a questionnaire with a modified Cooper-Harper rating scale ([122]), and a Van der Laan-rating scale. [104] After the experiment was completed, pilots were asked to complete a post-experiment questionnaire, which contained a number of questions with Likert-scales on how they experienced the haptic feedback system.

6.3.5. INDEPENDENT VARIABLES

The experiment had two independent variables. First, the haptic feedback was within-participant either present (Haptic Feedback, HF), or not (No Haptics, NH). Second, participants were divided in two between-participants groups: the Haptics First Group (HFG) receives haptic feedback for four runs, followed by no haptic feedback, the Haptics Second Group (HSG) vice versa as shown in Table 6.3. Participants with an odd number in Table 6.1 were placed in the HFG, all even-numbered participants were part of the HSG.

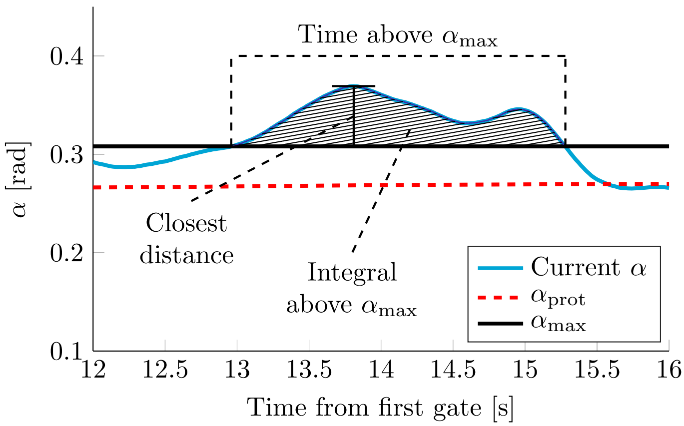


Figure 6.10: Time trace of velocity with safety metrics indicated

6.3.6. Dependent Measures

The dependent measures of the experiment are split into objective and subjective.

Objective measures

The objective measures were retrieved from the windshear recovery procedure, and focus on performance and safety. To show why metrics were chosen, a time excerpt of a windshear recovery is shown in Fig. 6.10. Another example is further elaborated in the results section, for now it is sufficient to understand that this shows a participant hunting for the best performance of the aircraft close to the maximum angle of attack.

Looking at the example, one can argue that a safe flight is performed when the aircraft state is within the flight envelope limits, indicated with the solid black line representing α_{max}. Although participants were instructed to stay within the limits at all times, at certain moments in time the pilot could control the airplane beyond these limits. A first performance metric therefore was considered to be the *time spent outside the flight envelope limits.*

Time by itself only informs about the length of the limit violations, it does not take into account the severity/safety: two different limit violations might be of equal time, yet one just slightly over the limit while another one is in a deep stall. As such, a safety metric combining both the time and the magnitude of the violation was the *integral of the variable over the flight envelope limit.*

The example also shows that a participant can operate the aircraft within the limits, yet they can either stay well clear of the limits, or push the system by flying very close to the limits. A straightforward metric to determine this safety definition was the *closest obtained distance of the state relative to the flight envelope limit*: it indicates how close to the limits the participant dared to control the airplane.

Next to this performance, and two safety metrics, one more performance metric on the overall windshear recovery procedure was available: the *total amount of altitude lost during the recovery.* Although not communicated to the participants, the maximum altitude lost from the windshear initiation to the end of the windshear recovery is an indication of how much of the available aircraft performance was utilized by the participants.

Previous research showed that the perceived level of risk was mostly kept constant with increasing support, i.e., risk homeostasis, as exampled by a haptic feedback system in an automotive study. [86, 87] For the current experiment, risk homeostasis was defined by improved performance combined with a degradation of objective safety metrics, as pilots obtained better awareness of the risk involved when supplied with haptic feedback.

SUBJECTIVE MEASURES

Subjective measures were obtained by asking the pilot for an opinion, or experience. The categories and measures are:

- Workload: after each run, the pilot was asked to provide a RSME [85]
- Situation awareness questions: after each run, the pilot was asked to answer two questions on a linear scale (0–100) ranging 'Never' left (0), and 'Always' right (100):
    1. Did you have the feeling you were in control of the situation?
    2. Did you have the feeling you missed critical information?
- Usefulness:
    1. Pilots were asked after each run to rate the usefulness of all display and haptic elements
    2. After a block of 4 runs, pilots were asked to provide a modified Cooper-Harper rating
    3. After a block of 4 runs, pilots were asked to fill a Van Der Laan-questionnaire
- Pilot experience: after the experiment, the pilot was asked to fill in a questionnaire regarding the experience with the haptic feedback system. It used a five point Likert-scale where the all points are labeled.

6

6.3.7. HYPOTHESES

From the experiment, we expected the following when the pilot was provided with haptic feedback:

1. Risk homeostasis is present during the windshear recovery, therefore:
    - Performance of the pilots improve.
    - Objective safety metrics decrease.
2. Subjective workload ratings decrease.
3. Pilots will have an increased (subjective) situation awareness:
    - Have an improved feeling of being in control.
    - Have a reduced feeling of missing information.
4. Modified Cooper-Harper ratings improve.
5. Van Der Laan-rating scales improve.

6.4. RESULTS

To see how a pilot can use the haptic feedback system, Subsection 6.4.1 shows a time trace of a windshear recovery. Next, the objective and subjective measures are discussed in, respectively, Subsection 6.4.2 and 6.4.3. Answers to the debriefing questionnaires are shown in Subsection 6.4.4. All flown trajectories for all flight paths used are included in Section C.1, together with data from one additional participant: a very experienced commercial airline pilot, whose data was included to check the performance of the 24 less experienced pilots.

When presenting data using box plots, medians are indicated using a horizontal thick line, outliers are indicated using plus-signs; all individual data points are presented next to the boxes using crosses. Furthermore, statistical analysis is performed in R ([123]) and a significance level of 0.05 is used. When comparing the means of the haptic versus no haptic feedback conditions (HF vs NH), or within one group on different runs, a Friedman test is performed. Within single runs and between groups, results are compared using the Wilcoxon Rank Sum test.

6.4.1. TIME TRACE

Fig. 6.11 illustrates all windshear recoveries from Participant 23, and shows that they all follow a similar pattern in terms of altitude. The black line indicates a situation where the pilot made use of the haptic feedback, as shown on Fig. 6.12. During the windshear recovery, the goal is to stay as close to the limit as possible, while not surpassing it during the highly dynamic recovery phase.

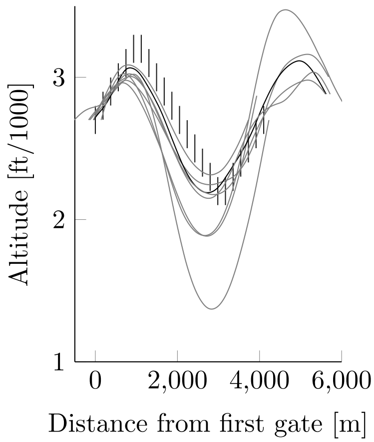
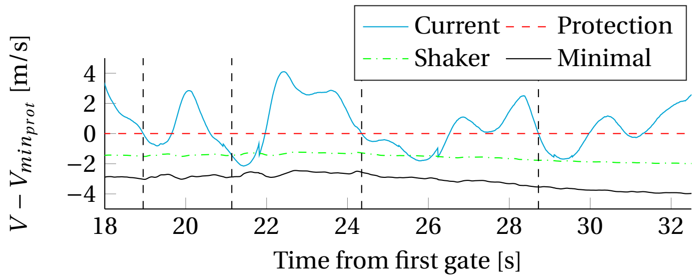
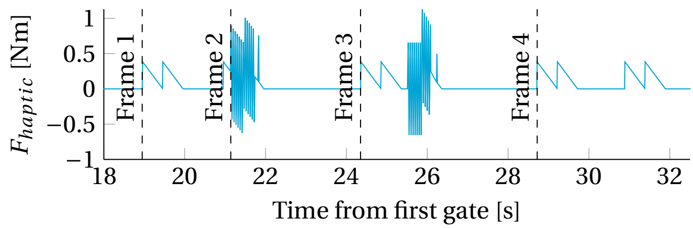


Figure 6.11: Windshear recoveries flown by Participant 23, Run 3 indicated in black, vertical lines represent gates on the outside visual

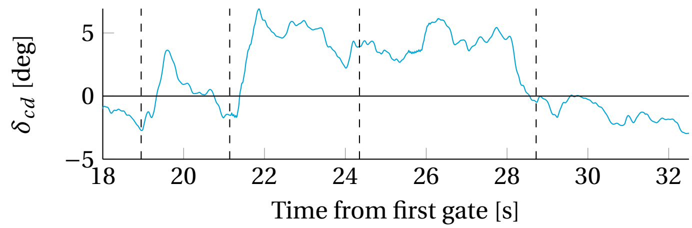
During the recovery performed in this example, shown on Fig. 6.12, at Frame 1 the haptic feedback (Fig. 6.12b) informs the pilot of the approaching limit (Fig. 6.12a), the pilot reacts by reducing the input (Fig. 6.12), even pushing the side stick. When clear of the limit, a more negative input is given again, resulting in a quick encounter of the stick shaker at Frame 2. The pilot reacts by pushing hard on the side stick and succeeds in increasing the aircraft velocity. In the dynamic situation, the wind is changing and the state of the aircraft is moving closer to the limit even though a positive/push input is provided. In Frame 3, the pilot is informed of the protection zone, yet decides not to act on it yet, only at the subsequent stick shaker, the positive input is increased and the state moves out of the protection zone. After Frame 4, two more occurrences of the initial tick occur on which the pilot reduces input slightly.



(a) Velocity relative to the minimal protection velocity



(b) Haptic feedback: force on the side stick



(c) Control device deflection, i.e., input from the side stick to the FCC

Figure 6.12: Example of Participant 23 using the haptic feedback during the windshear recovery in Run 3

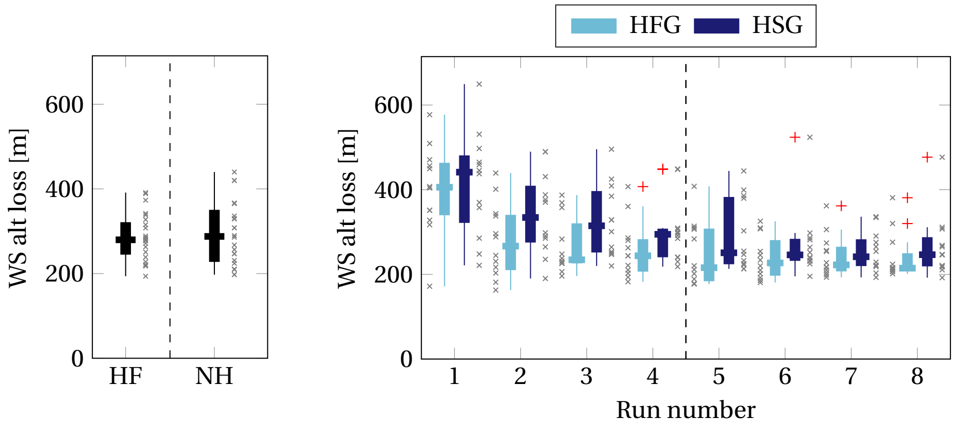
This case exemplifies that pilots *can* make use of the haptic feedback, yet the metrics presented below should indicate *how* pilots use them. It will be further explored what the possible consequences are on the results in the discussion.

6.4.2. OBJECTIVE MEASURES

Objective measures are retrieved from the simulation states and discussed next.

ALTITUDE LOST DURING RECOVERY

For the windshear recovery, the difference in altitude between the windshear trigger point and the lowest point encountered during the windshear is calculated and averaged over the four runs in one block (following the block/run structure in Table 6.3). The results in Fig. 6.13a show that there is no difference in performance when comparing the HF and NH conditions, which is confirmed by the results of a Friedman test that indicated no statistical significance. This result is found despite the fact that the final runs with haptic feedback appeared better compared to the runs without haptic feedback during execution of the experiment.



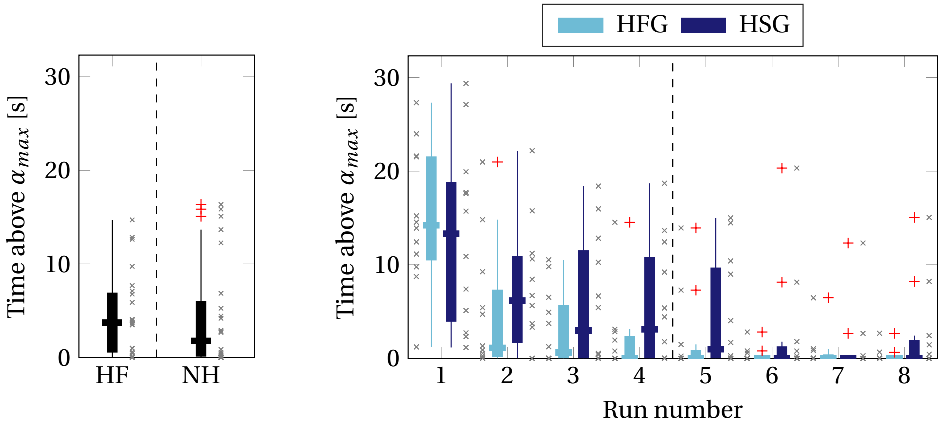
(a) Initial analysis (b) Individual runs

Figure 6.13: Altitude lost during windshear recovery

To find out why no effect of the haptic feedback was found, the windshear performance is plotted for each individual run in Fig. 6.13b. This shows that, irrespective of whether haptic feedback is supplied or not, a strong learning effect is present during the first runs, resulting in unchanged means, as shown in Fig. 6.13a. Additionally, it shows that the median of the haptic first group (HFG) reduces faster compared to the haptic second group (HSG). To investigate this learning effect present, statistical analysis is performed to compare Runs 1 and 4, indicating a statistical difference for the HFG ($\chi^2 = 8.33$, $p < 0.01$) and near statistical significance for the HSG ($\chi^2 = 3$, $p = 0.08$). Using a Wilcoxon Rank Sum, no statistical significance at Run 4 is found between both groups ($W = 42$, $p = 0.09$), although the plot show a small difference in median. Friedman analysis on Runs 4 and 8 did not show a significant difference in means for both groups. In other words, there seems to be no further improvement in performance over the final four runs.

TIME ABOVE MAXIMUM ANGLE OF ATTACK

Pilots were instructed to stay within the flight envelope limits at all times. Although time spent outside the flight envelope should ideally be zero, the means for both blocks shown on Fig. 6.14a indicates that this was not always the case. Similar to the performance in terms of altitude lost during the recovery, this performance metric does not have a visual or statistical difference when providing haptic feedback.



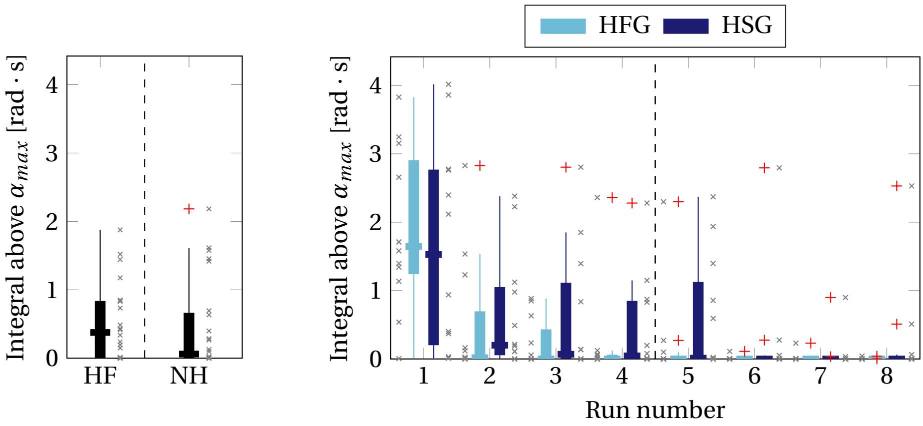
(a) Initial analysis (b) Individual runs

Figure 6.14: Time with angle of attack above maximum value during windshear recovery

As also seen with that previous metric, this metric shows a quicker improvement of the performance metric in terms of each run as shown on Fig. 6.14b. There again is a visual and statistical difference between Runs 1 and 4 for both groups (HFG: $\chi^2 = 12$, $p < 0.001$, HSG: $\chi^2 = 8.33$, $p < 0.005$). Although visually the HSG appears to spend more time above the maximum angle of attack, no statistical significance using the Wilcoxon Rank Sum was found between the results of Run 4 for both groups, possibly due to the fact that numerous data-points are at zero. Nevertheless, the median of the HFG approaches zero from Run 2, whereas the median of the HSG has a median clearly above zero even at Run 4. Statistical analysis showed no difference between Runs 4 and 8 for the HFG, yet the HSG has a 'near' statistically significant difference ($\chi^2 = 3.57$, $p = 0.059$).

INTEGRAL ABOVE MAXIMUM ANGLE OF ATTACK

Safety during the windshear recovery is further evaluated using the integral of the angle of attack above the maximum value allowed by the flight envelope, with the per block averaged results in Fig. 6.15a. As before, no difference is observed (visually or statistically), yet Fig. 6.15b shows a difference between Runs 1 and 4 (for both groups $\chi^2 = 12$, $p < 0.001$). Although no statistical difference is found between both groups at Run 4, a statistical significant difference is found between Runs 4 and 8 for the HFG ($\chi^2 = 5$, $p < 0.05$) as all participants have near zero metric, and near statistical difference for the HSG ($\chi^2 = 3.57$, $p = 0.059$) although the visual change appears to be quite large.



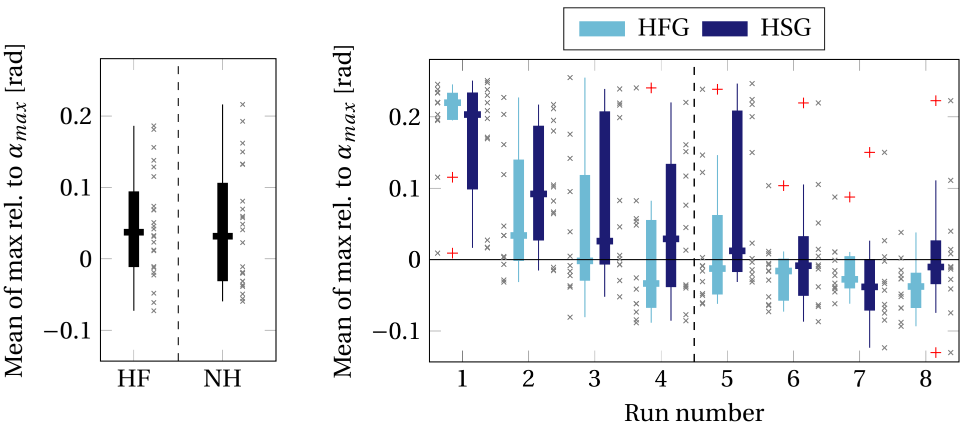
(a) Initial analysis

(b) Individual runs

Figure 6.15: Integral of angle of attack above maximum value during windshear recovery

HIGHEST ANGLE OF ATTACK

The second safety metric is the closest point to the maximum angle of attack, for which the per-block means are shown on Fig. 6.16a. These again show no difference. Focusing on the individual runs in Fig. 6.16b, Friedman tests show a significant difference between Runs 1 and 4 for both groups (HFG: $\chi^2 = 8.33$, $p < 0.01$, HSG: $\chi^2 = 12$, $p < 0.001$).



(a) Initial analysis

(b) Individual runs

Figure 6.16: Highest angle of attack obtained during the windshear recovery, relative to the maximum angle of attack (positive values result in a stall warning)

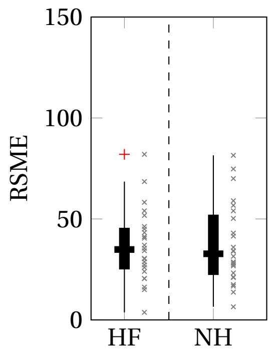
While a Wilcoxon test comparing the results of both groups at Run 4 did not show statistical significance, one has to observe one critical difference: the mean of the HSG (hence without haptic feedback) is above zero, meaning that at least half of the participants reached angles of attack above the maximum. For the HFG, the median is below zero, indicating that at least half of the participants in the HFG did not exceed the maximum angle of attack. Looking at the evolution of the metrics after the break, the HFG seems to slightly improve yet this is not supported by statistical significance. On the other hand, the HSG does have a 'near' statistically significant difference from Runs 4 to 8 ($\chi^2 = 3$, $p = 0.083$). In addition, it is clear that the spread of all data reduces and the median approaches zero when providing haptic feedback.

6.4.3. SUBJECTIVE MEASURES

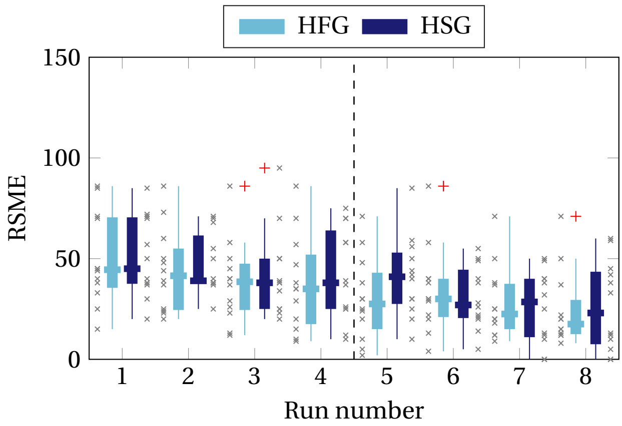
The subjective measures are obtained after each run, those are the Rating Scale Mental Effort (RSME) and a situation awareness scale, and metrics obtained after a block of four runs, which are a Van Der Laan and MCH rating.

RSME

After each run, participants were asked to fill a RSME on a calibrated scale ranging from zero to 150, indicating how much mental load was required for the task. Results per block are shown in Fig. 6.17a, and similarly to the objective measures, have no difference (both visually and statistically). Results per run in Fig. 6.17b clearly show a learning effect: an improvement is present from the initial towards the final run. Both groups show a similar trend, and no statistical differences between groups are observed within one run.



(a) Initial analysis



(b) Individual runs

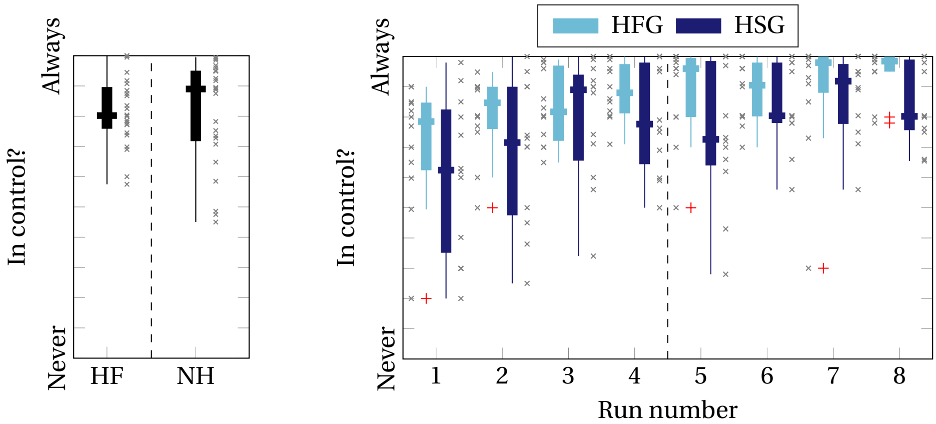
Figure 6.17: Rating Scale Mental Effort (subjective workload)

SUBJECTIVE SITUATION AWARENESS

Situation awareness is subjectively measured by asking the pilot whether (s)he has the feeling of being in control (Fig. 6.18) and the feeling of missing information (Fig. 6.19). Ideally, a pilot always has the feeling of being in control and is never missing information. Looking at the plot for block in Fig. 6.18a and Fig. 6.19a, no differences between conditions can be seen, and no statistical difference was found after testing.

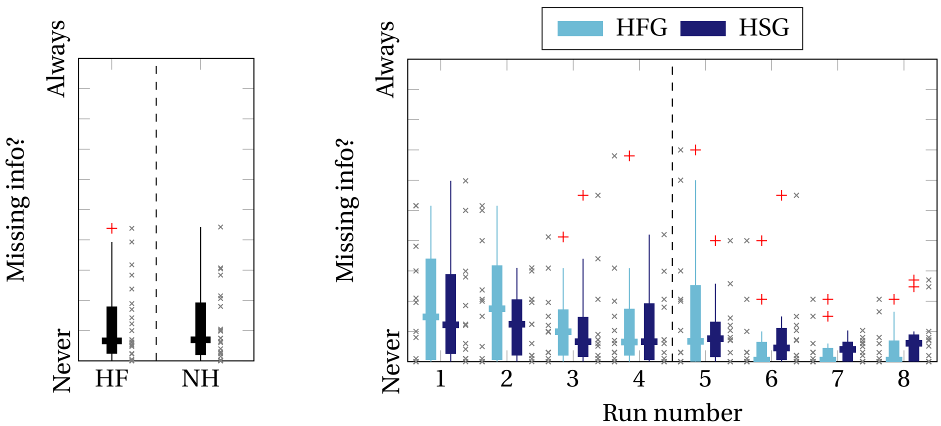
When looking at the individual runs (Fig. 6.18b and Fig. 6.19b), no clear visual differences can be seen between groups in terms of trend or final value. Statistical analysis showed a significant difference for the HFG with the feeling of being in control of Run 4 compared to Run 8 ($\chi^2 = 2.78$, $p < 0.1$).

An additional interesting point can be the transition from Run 4 to Run 5: going from receiving haptic feedback to no feedback (HFG) increases the feeling of missing information, and when enabling the haptic feedback reduces the feeling of being in control (HSG). Nevertheless, this is not supported by statistical significance using a Friedman test for both sub-scales.



(a) Initial analysis (b) Individual runs

Figure 6.18: Did the pilot have the feeling of being in control?



(a) Initial analysis (b) Individual runs

Figure 6.19: Did the pilot have the feeling (s)he was missing information?

MCH ratings

After a set of four runs with or without haptic feedback, a questionnaire queries the pilots for more high level feedback on the way of presenting the flight envelope limits. Two typical scales are used and shown here. First of all, a Modified Cooper-Harper rating scale is presented for which the results are shown in Fig. 6.20. Keep in mind that the scale ranges from ten to one, where one is the best score. Additionally, the horizontal lines on the figure indicate the tipping point for the questions on the decision tree. Both the figure and statistical tests did not show a difference between groups for either haptic feedback or no haptic feedback. Equally so, the figure and Friedman test did not show an in-between participant difference for the haptic feedback.

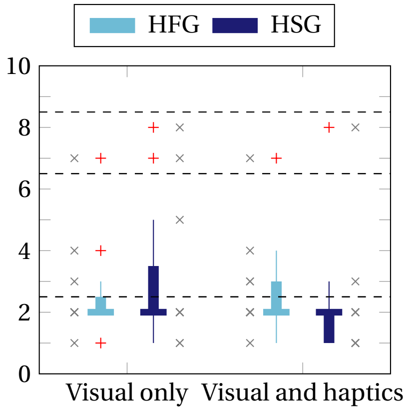
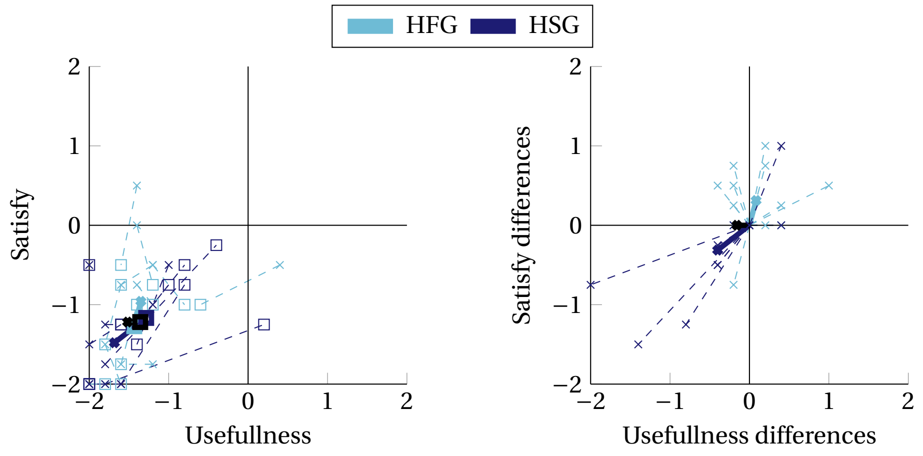


Figure 6.20: Modified Cooper-Harper rating

Van Der Laan ratings

Secondly, a Van Der Laan-questionnaire asks nine questions to score the system on usefulness and satisfaction, keep in mind that due to the definition of the questionnaire, a perfectly useful and satisfying system would score minus two on both scales. Fig. 6.21 shows the results for the analysis, Fig. 6.21a shows the raw scores for both groups and indicates that both with and without haptic feedback, the system is well received in terms of usefulness and satisfaction.

Fig. 6.21b shows the differences of the system with haptic feedback, relative to the no haptic feedback case. Looking at the mean of all participants, only a small improvement in usefulness is obtained. More intriguing is the mean of each group separately indicated with the bold lines. This indicates that the participants who started without haptic feedback experience the system with haptic feedback to be more useful and more satisfying. On the contrary, participants who started with haptic feedback experienced the conditions without haptic feedback as more useful and satisfying. As such, an order effect of presenting the haptic feedback is present.



(a) Raw data

(b) Change in rating of the haptic feedback enabled condition relative to no haptic feedback

Figure 6.21: Van Der Laan-ratings; black bold indicates population mean, coloured bold indicate group means; squares represent the score after a block without haptic feedback, crosses with haptic feedback

6.4.4. DEBRIEFING QUESTIONNAIRES

In order to have a structured debriefing session when all runs are completed, a questionnaire with 19 questions was presented to the pilots. The first and foremost question presented pilots a simple choice: do you prefer to fly with or without haptic feedback? Results to this first question are shown in Fig. 6.22, which follows the order effect stated before with the Van Der Laan-questionnaires: the vast majority of the HSG prefers the haptic feedback, the participants in the other group are divided: half of them prefer the haptic feedback. Most other debriefing questions used a five point Likert-scale for which questions and results are shown in Fig. 6.23.

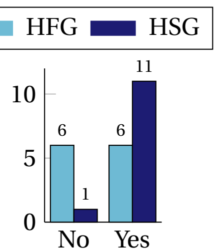
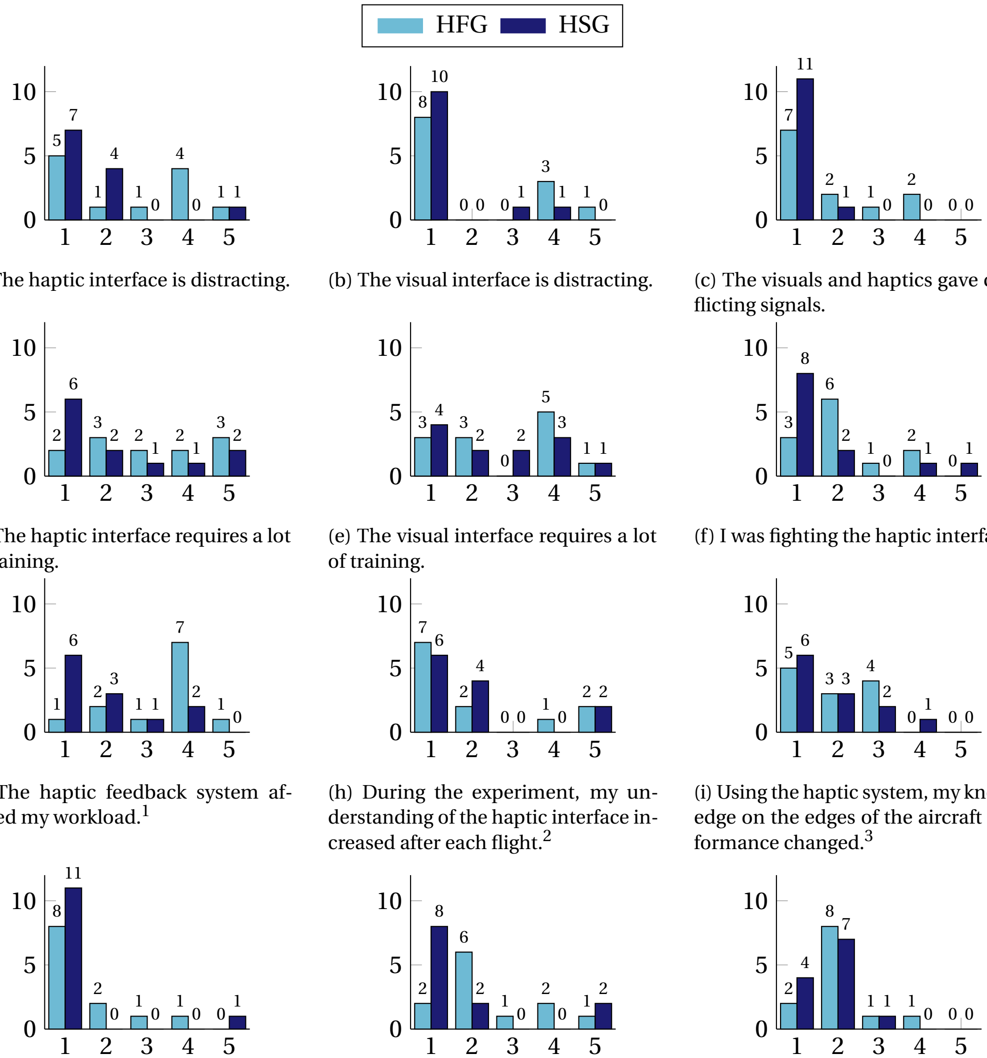


Figure 6.22: Do you prefer to fly with the haptic feedback system?

Pilots indicate that the haptic and visual display are not distracting (respectively Fig. 6.23a and 6.23b), yet are indecisive on whether a lot of training is needed (Fig. 6.23d and 6.23e). Shown on Fig. 6.23c, they do indicate that the combination of visual and haptic feedback did not give conflicting signals (as they were designed for in Ref. [119]).



(a) The haptic interface is distracting.

(b) The visual interface is distracting.

(c) The visuals and haptics gave conflicting signals.

(d) The haptic interface requires a lot of training.

(e) The visual interface requires a lot of training.

(f) I was fighting the haptic interface.

(g) The haptic feedback system affected my workload.[1]

(h) During the experiment, my understanding of the haptic interface increased after each flight.[2]

(i) Using the haptic system, my knowledge on the edges of the aircraft performance changed.[3]

(j) The haptic interface helps in preventing critical situations.[2]

(k) If a critical situation occurs, the haptics helps in resolving it.[2]

(l) When implementing this system on an aircraft, what would be the effect on safety?[4]

Figure 6.23: Debriefing Likert-scale questions. Possible answers (unless specified otherwise) were: 1) Disagree 2) Slightly disagree 3) Disagree nor agree 4) Slightly agree 5) Agree

[1]Possible answers:	1) Decreased	2) Marginal decrease	3) Did not change	4) Marginal increase	5) Increased
[2]Possible answers:	1) Agree	2) Slightly agree	3) Disagree nor agree	4) Slightly disagree	5) Disagree
[3]Possible answers:	1) Increased	2) Marginal increase	3) Did not change	4) Marginal decrease	5) Decreased
[4]Possible answers:	1) Much safer	2) Safer	3) Safer nor unsafer	4) Unsafer	5) Much unsafer

6

Focusing on the haptic feedback, most pilots felt that they were not fighting the haptic feedback (Fig. 6.23f), nevertheless they are indecisive on whether the workload was changed (Fig. 6.23g). For this latter question, note the order effect: the HFG mostly indicates a marginal increase in workload, whereas the HSG indicates a decrease in workload. The majority of the pilots indicate that there is a learning effect present over the run (Fig. 6.23h), and they agree that their knowledge on the edges of the flight envelope did increase using the haptic feedback (Fig. 6.23i).

As mentioned in the Introduction section, upset prevention is one of the major fields to improve in aviation, and our participating pilots agree that this haptic feedback system can help to achieve this (Fig. 6.23j). When in an upset condition, the majority of our participants think the haptic feedback system might help, yet their answer is not as convincing (Fig. 6.23k). The final Likert-type question asked the pilot for the effect when implementing this haptic feedback on an aircraft, Fig. 6.23l shows that a clear majority of the pilots believe that implementing this system can improve safety.

The final questions, asked for further textual elaboration on any of the previous questions, asked for comments on the reality of the simulation and possible final comments. These comments include:

- *I was not looking at instruments anymore with the haptic feedback, instead I reacted naturally to the cues by looking outside and monitor to the behavior of the airplane.*
- *I used the haptic feedback to double check whether my input was correct. If it was correct, I increased the input.*
- *The initial tick made me look for the problem.*
- *With the haptic feedback, I made more subtle movements and anticipated more.*
- *The haptic feedback indicates the problem, the visual display gives the space left (criticality).*
- *Too much information for a pilot in combination with visible/audible.*
- *When using all warning system extra training is recommended to process everything correctly.*
- *I think my performance improved solely due to experience with the simulator and the scenarios.*
- *Audible warnings are best for VFR pilots together with minimal visual information, and a stick shaker for stall.*

6.5. DISCUSSION

Five hypotheses were formulated, all related to the comparison between the conditions with (HF) and without (NH) haptic feedback. First, risk homeostasis was expected to be present in the form of improving performance metrics while objective safety metrics decreased. Results showed no difference between the haptic enabled/disabled conditions for both metrics, hence this hypothesis is not supported by the data.

Second, workload was expected to decrease which did not show in both the RSME or the debriefing questionnaire, again not supporting the hypothesis.

Third, enabling haptic feedback should improve situation awareness which is not supported by the two situation awareness-related questions proposed to the pilots after every run. Pilots did indicate in the debriefing, however, that the haptic feedback increased their knowledge of the flight envelope, and that it helps in preventing and resolving critical situations. So even though this hypothesis is not supported by the data, there are subjective indicators that haptic feedback improved pilot situation awareness.

Fourth, although handling qualities as observed with a Modified Cooper-Harper rating were expected to improve, the results obtained do not support this hypothesis.

Finally, Van Der Laan-questionnaires indicate an overall positive acceptance of the system both with and without the haptic feedback. When enabling haptic feedback, the acceptance rating when averaged over all participants improves as expected in the hypothesis, hence supporting this last hypothesis. In summary, all hypotheses except the last one are not supported by the data.

Discussions with the participants showed that the majority believes that a haptic feedback system in the current form could be a useful tool in combination with a fly-by-wire flight deck. This is supported by the answers to the debriefing questionnaire which indicate that the majority of the participating pilots prefers the system with haptic feedback, irrespective of whether haptic feedback was introduced in block one or two. Furthermore, pilots indicated that the system is not distracting, matches other (visual/aural) interfaces, and improves knowledge and prevention of critical situations. Summarizing, pilots expect aviation to be safer when using this haptic feedback system.

A reason for the non-effect on the hypotheses can be found in the design of the experiment: participants are divided in two groups where one group received haptic feedback for the first block of four runs (HFG) and the other groups received haptic feedback in the second block (HSG). The intended goal of this division was to perform a balanced comparison where the order effect due to unfamiliarity and training is eliminated. Nevertheless, the results of the individual runs already show that although all participants received a basic explanation of the interfaces (visual/haptic/aural) and a basic training with the model, the subsequent task and procedure used in the measurement runs was of such difficulty that all participants showed a major learning effect.

This learning effect is also confirmed by some of the comments made by the participants after the experiment: they indicate that it was a lot to process from the start. As a result, a large order effect is present which cannot be compensated by the balanced experiment design, hence making a comparison of the per block averaged metrics useless. Additionally, the flight path presented on the outside visual is a challenging profile and is not a realistic profile which can be flow in the real aircraft with passengers (within six minutes the load factor varied between 0.45g and 1.6g). The goal of this profile is to ensure that the initial condition for the windshear is always equal, which was achieved, yet probably induced more artefacts because of a training effect.

Despite this unexpected learning effect among all participants, the resulting metrics per run do show an interesting behaviour: when supplying the participants with haptic feedback from the start, the learning effect appears to be stronger. This is visible in all performance and safety metrics, as well as the subjective situation awareness (specifically the feeling of being in control), indicating that the haptic feedback might help in more quickly developing a proper strategy to handle the windshear recovery procedure. In addition, the first run without haptic feedback for the HFG does not show any regression, which indicates that there is no reliance on the haptic feedback for the developed strategy.

Participants in the HSG, hence those who do not receive haptic feedback from the start, improve their performance over the first runs. Nevertheless, the spread of the metrics only matches the results of the HFG after one run with haptic feedback. This suggests that the haptic feedback can help to further improve an already developed strategy.

The final remarks are based on the analysis performed and observations made in this chapter. Further analysis should be performed to investigate the learning effect by fitting learning curves through the data of each participant and comparing their characteristic properties. [124] Furthermore, a re-design of the experiment setup is required to match a transfer-of-training experiment which involves a training phase (comparable to the first block in this experiment), followed by a test phase where the (haptic feedback) support is removed (comparable to the first run without haptic feedback for HFG), and a generalization run where the participants are performing a different, but comparable task, to investigate whether either a skill was learned or participants relied on a pure feedforward technique. [125]

In summary, the experiment did not show the expected change in metrics when enabling the haptic feedback. Nevertheless, an interesting effect of the haptic feedback on learning during training is found, which should be further investigated.

6.6. CONCLUSION

This chapter presents a further design of a haptic feedback system, which uses force feedback through the control device to inform pilots on the flight envelope limits and protections of modern fly-by-wire aircraft. The new design uses forcing functions which are *asymmetric in both time and amplitude*, to inform pilots of an approaching limit *as well* as of the direction of the corrective action.

The system is evaluated by 24 PPL/LAPL pilots who flew a flight trajectory shown on the outside visual and encountered a windshear during each run. To counter-balance the learning effect, the participants are divided in two groups: one group performed a block of four flights with haptic feedback, followed by a block of four flights without, the other groups vice versa. It was expected that the data would show that enabling haptic feedback during this windshear recovery allowed the pilots to have an increased performance while having a reduced (objective) safety margin, i.e., risk homeostasis, and that pilot acceptance and handling ratings of the system haptic feedback would increase when providing haptic feedback.

Results did not show those expected results: most metrics were unchanged when switching the haptic feedback, only the acceptance scale (Van Der Laan-questionnaire) improved slightly when enabling the haptic feedback. When looking in more detail to the individual runs, the cause of this can be found in the order effect: irrespective of which group, i.e., of whether haptic feedback is provided, the first four runs showed such a strong learning effect that this order effect renders the comparison invalid.

The results do show, however, that enabling the haptic feedback appears to *improve the learning rate* over the first runs, and that no after effects are present when removing the feedback. As such, besides the fact that most pilots were positive about the system and indicated that they expect it to improve safety, our experiment suggests a potential training benefit when using haptic feedback. This deserves to be further explored, for instance using a transfer-of-training experiment.

7

Evaluating Stiffness and Position Guidance for Feedback on Flight Envelope Protection

The previous chapter used asymmetric vibrations to cue the pilot on the flight envelope. The evaluation showed no improvement in metrics at the first emergency encounter, yet did show a potential training benefit. Therefore, a new haptic feedback concept was designed with the specific aim to guide the pilot when approaching a limit and provide support from the first time use. This chapter evaluates these haptic feedback designs with 36 active PPL/LAPL pilots who flew a challenging vertical profile and encountered a windshear in a fixed-base simulator. The pilots were divided in three groups who received either cueing, guidance, or no haptic feedback. It was expected that: (i) cueing haptic feedback provides a faster learning rate compared to no-haptics, and (ii) guidance haptic feedback results in best performance from the first run yet worse metrics when no feedback is provided. Comparing the results of the cueing and no-haptic feedback groups confirmed the previous results.Results showed that the guidance haptic feedback resulted in improved metrics at the first run, and the worsening of metrics when no longer provided.

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Authors	D. Van Baelen, M. M. van Paassen, J. Ellerbroek, D. A. Abbink, and M. Mulder

7.1. INTRODUCTION

BOTH international aviation safety boards, such as the European Union Aviation Safety Agency EASA, and airline associations, for example the International Air Transport Association IATA, identify loss of control in flight as one of the key risk areas resulting in most fatalities within aviation. [1, 3] A safety issue contributing to such a loss of control is identified as the inadequate monitoring of the main flight parameters and automation modes. To ensure and improve current safety levels, these loss of control events should be prevented.

Improving the information presented to pilots is expected to help reducing the loss of control occurrences. This can be achieved by augmenting the visual displays on the flight deck with information on the limits of the aircraft, i.e., the flight envelope. Research showed that this can improve safety by reducing the risk of violations of those limits. [51] Once the limits are exceeded, for example in a stall, the information on the PFD can be augmented with recovery guidance which delivers recovery performance improvements as shown in three simulator evaluations. [118]

Apart from the visual channel, pilots can also perceive information through the sense of touch. An example is the haptic interface, which provides force feedback through the control device. This form of information can have a significant positive effect when a pilot is guided along the approach path. [41, 67] Additionally it can be used to show a set of predicted controllability limits, which was shown to be used by pilots in an experiment. [52] Research indicates also that haptic feedback can be used to show pilots information on the FEP. [126]

The latter experiment had two groups where the first group started with haptic feedback which was 'cueing' the pilot on the flight envelope limits, and the second group had no haptic assistance. After a break the groups switched: only the second group received haptic feedback. The initial hypothesis for this experiment was that haptic feedback would support performance, and that performance would reduce after reverting to a condition without haptic support. Contrary to this, however, it was found that haptic feedback mainly contributed to pilot learning, and performance persisted after haptic support was removed. In addition, haptic support did not improve performance during the first run, which indicates that when implemented on an aircraft, it might not provide pilots with support the very first time they encounter a new situation. As the haptic feedback system aimed to support pilots also in new, unforeseen circumstances, a new iteration of the haptic feedback is required.

Actively supporting the pilot has been found to help at the first encounter, yet is subject to reversion to base performance when the support is removed. In a skill acquisition task where a slider had to be moved left and right, four groups of participants received feedback on their performance in a training phase at different times: after each run, or an average score after every five, ten or fifteen runs. [127] Their results showed that increasing the amount of feedback increases performance. Immediately after the training phase, another set of measurements was performed where no feedback was provided. There, the group with the most amount of feedback in the training performed worst, although not significantly different from the other groups. Another measurement was performed two days after the initial training, which showed again a tendency for decreasing performance with increasing feedback during training. This phenomenon is called the “guidance hypothesis”: a dependency on the feedback develops while learning the task; disabling this feedback then results in worse performance, due to required re-adaption. This phenomenon was also reported in a similar, vertical task. [128]

Within the field of haptic feedback, different applications have been recently designed to support the human operator in a task, and to provide support from the first encounter. Examples of this are a support for an abstract control task ([33]), a lane keeping assist in the automotive domain ([129, 130]), and an obstacle-avoidance system for UAV tele-operation. [32] These examples used active haptic feedback, for example an increased stiffness or actively moving control device, to guide the operator to complete the task. Transferring these active haptic feedback principles to the aircraft flight envelope protection system might provide a feedback system which supports pilots from the first run and solve the issue with our previous ‘cueing’ system. [126] Nevertheless, such implementations of haptic support have been found to be also hindered by to the guidance hypothesis described before, and it should be investigated whether this is also true in our particular application.

The aim of this chapter is to present a new haptic feedback for FEP design which is more actively ‘guiding’ the pilot, and to compare the results of this guidance haptic feedback system, as well as the existing ‘cueing’ haptic feedback system, to the results of a group of pilots who did not receive any haptic feedback at all. It is hypothesised that the group without haptic support required more time to learn the task when compared to the results of the ‘cueing’ group, and that the guidance haptic feedback design is able to support pilots from the very first run, however, with possible reversion in performance when the haptic assistance is removed.

This chapter first discusses the different haptic designs used in Section 7.2. Section 7.3 presents the experiment where the participants were required to operate an aircraft at the limits. In Section 7.4 and 7.5, results of the experiment are described and discussed. Finally, the conclusions are shown in Section 7.6.

7.2. FEEDBACK DESIGN

The haptic feedback design is based on a control structure similar to an Airbus A320. Full details are given in our earlier work, see Ref. [131], only the relevant elements for understanding the current experiment will be explained in this section. Two designs are elaborated which use haptic feedback to communicate the flight envelope protection limits by changing the feel on the control device.

Note that the designs shown here do not include a breakout force, i.e., a minimal force required to move the side stick, which is present on an actual A320 aircraft. The two haptic feedback designs to communicate the flight envelope limits are discussed below, respectively a cueing and guidance haptic support system. But first some basic knowledge on the A320 control structure is presented.

7.2.1. AIRBUS A320 CONTROL STRUCTURE

Modern-day Airbus aircraft, like the A320 and the A330, all employ a FBW system. This means that there is no mechanical connection between the control surfaces and the control device. The latter acts as an interface for the pilot to provide inputs to the FCCs which then command the control surfaces with hydraulic actuators. This allows a Flight Envelope Protection (FEP) system to be used, which can check and, if necessary, limit pilot inputs, to ensure that no flight envelope limits are violated.

Longitudinal control in a FBW Airbus, with all sensors functional (a mode designated as the normal law control law), is provided using C^*-control, which is a combination of both pitch rate (q) and load factor (n). [10–13] On top of this control law, a hard envelope limit is employed which protects the pilot from exceeding limits on angle of attack (α), load factor (n), and maximum velocity (V_{MO}). This protection is depicted in Fig. 7.1, where the nominal flight envelope is the extreme limit which can not be exceeded, the safe flight envelope is the point where protections start acting. The envelope is constructed by the maximum (n_{max}) and minimum (n_{min}) load factor, their protection limits ($n_{max_{prot}}$ and $n_{min_{prot}}$, respectively), the maximum operation velocity (V_{MO}, and protection $V_{MO_{prot}}$), and minimum velocity ($V_{\alpha_{max}}$, and protection $V_{\alpha_{prot}}$).

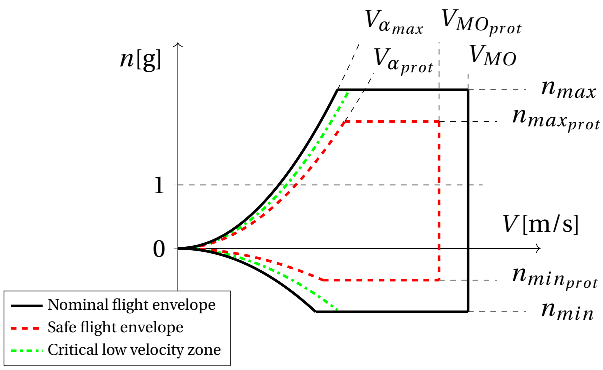


Figure 7.1: Flight envelope, velocity (V) versus load factor (n)

When multiple FCCs fail, or when a sensor failure occurs, the control is reverted to a degraded control law. In this research, we will consider a control law close to the Airbus alternate law without reduced protections, where the same protections apply as before, only the angle of attack protection is lost. Hence, in alternate law the aircraft can be stalled, and it allows the pilot to give more extreme control actions.

Lateral control in normal law is a bank (ϕ) rate command from $-33°$ till $+33°$ of bank. Beyond these limits, positive roll stability is achieved such that the aircraft rolls back to the protection value (ϕ_{prot}) of $\pm33°$. The maximum achievable bank, with full lateral side stick deflection is $\pm66°$ of bank. In alternate law, lateral control reduces to a pure rate command, irrespective of the actual bank angle. More details on the control laws and degraded control laws can be found in Ref. [131].

Given that for both longitudinal and lateral control, a degradation of the control law results in a different effect for a given control input, a clear indication of both the limits and the active protections of the flight envelope is required. Nevertheless, accidents have occurred where pilots were not aware of what control law was active, and what protections were still active. [7] As such, a clear and intuitive way of presenting this information can be found in haptic feedback and a new design is proposed in the following.

7.2.2. CUEING HAPTIC FEEDBACK DESIGN

In the cueing haptic feedback design, the pilot is cued about the flight envelope limits using forcing functions (forces on the control stick) which are asymmetric in both time *and* amplitude. To visualize the feel, the amount of force required to displace the side stick to a certain deflection is combined in the haptic profile as given in Fig. 7.2. This figure shows the nominal feel on an Airbus side stick with a neutral point, the point at which no force on the side stick is required, and a linearly increasing force with a certain spring coefficient with an increased stiffness at 6°. [61] Such a haptic profile provides the pilot with information on the input magnitude: larger inputs require larger forces.

Previous research showed that such an asymmetric vibration can be used to both cue the pilot about an imminent limit, as well as indicate a required control action to move away from that limit. [132] Such a forcing function is vertically shifting the default haptic profile (Fig. 7.2). It is assumed that the forcing functions are short in time and/or amplitude such that the input to the aircraft is minimal. The feedback design uses three cues to communicate the flight envelope limits to the pilot:

1. When the aircraft state leaves the safe flight envelope, i.e., crosses the red line on Fig. 7.1: a sawtooth-shaped forcing function of 1s with an amplitude of 0.282Nm and frequency of 2Hz is activated.

2. As long at the aircraft state remains outside the safe flight envelope: one sawtooth-shaped 'tick' is provided every second, where the intensity of the tick is linearly increasing with the magnitude of the safe flight envelope excursion, up to a maximum of twice the default magnitude.

3. When the velocity drops below $\left(V_{\alpha_{max}} + V_{\alpha_{prot}}\right)/2$, i.e., left of the green line on Fig. 7.1, a stick shaker signal defined by a sinusoid with amplitude of 0.426Nm and frequency of 20Hz is activated.

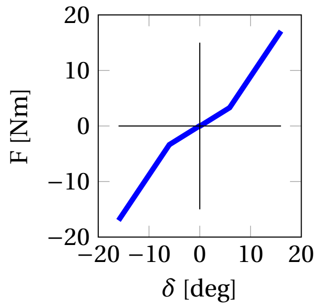


Figure 7.2: Default haptic profile in the cueing design, i.e., force required on the side stick for a given deflection

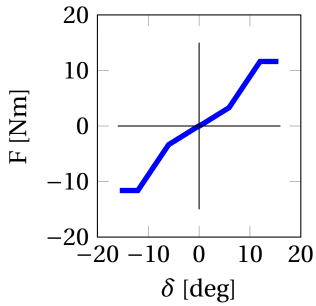
The *direction* of the sawtooth-shaped forcing functions is used to suggest a control direction to move away from the limit. As such, the cue is forward/push for high angles of attack and high load factors, the direction is opposite for other conditions. More details and an example can be found in Chapter 6.

7.2.3. GUIDANCE HAPTIC FEEDBACK DESIGN

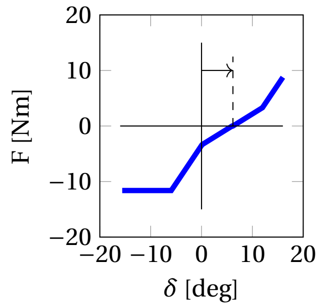
The guidance haptic feedback design informs the pilot on the limits of the flight envelope using two changes to the haptic profile: i) a change in spring coefficient and ii) a displacement of the neutral point position. To guarantee that the pilot has the final authority of the side stick, the maximum amount of force required to displace the stick to the maximum position is limited to 11.6Nm which results in a default haptic profile for the guidance design as shown on Fig. 7.3a. This maximum value is chosen based on the forces exerted by pilots on the stick in the experiment discussed in the previous chapter. A summary of all tuning parameters can be found in Table 7.1. The two cues introduced above are elaborated next.

Table 7.1: Summary of all haptic feedback tuning parameters

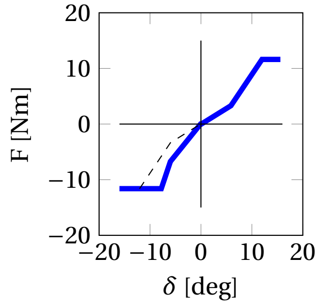
Property	Value
$\delta_{\max}$	16°
$\tau_{\text{overspeed}}$	5s
Δt_α	3s
F_{max}	11.6Nm



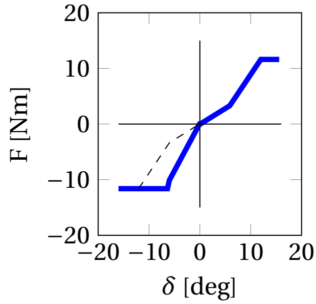
(a) Default feeling in guidance design



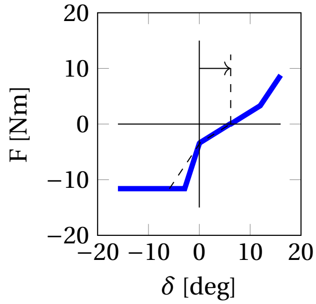
(b) Default guidance design, Fig. 7.3a with shifted neutral point



(c) Guidance design with increased stiffness (severity 0.5)



(d) Guidance design with increased stiffness (severity 1.0)



(e) Guidance design with increased stiffness (severity 0.5), Fig. 7.3c and shifted neutral point

Figure 7.3: Haptic profiles in the guidance design, dashed lines indicate default properties

STIFFNESS FEEDBACK

Increased manipulator stiffness has been investigated in previous research for indicating an undesired control deflection when a pilot-induced oscillation is imminent ([46, 47]), signaling a lagging adaptive controller ([75]), or indicating a limit on the main rotor setting of a helicopter. [74] In our scenario, an undesired control deflection is defined as an input which brings the aircraft closer to the limits of the flight envelope, which can be e.g., a control deflection in one specific direction. As such, our haptic feedback system will increase the spring coefficient in the direction of the unwanted deflection, leaving the other direction unchanged as shown on Fig. 7.3c.

The amount of stiffness change is determined by the magnitude of the safe flight envelope excursion, similarly to the amount of stiffness change in previous research to indicate a criticality. [75] Starting at the edge of the safe flight envelope until the flight envelope limit (respectively, the red-dashed line and black line on Fig. 7.1), the stiffness is gradually increased. Using a generic symbol v for the different limits of the flight envelope (maximum velocity, max/minimum load factor, maximum angle of attack), the default stiffness of the unwanted direction is multiplied with a factor K_k, determined by the gain K_v and the severity of the violation:

$$K_k = \begin{cases} 1 & \text{if } v < v_{prot} \\ 1 + K_v & \text{if } v > v_{nom} \\ 1 + K_v \frac{v - v_{prot}}{v_{nom} - v_{prot}} & \text{else} \end{cases} \tag{7.1}$$

The severity is defined as the ratio of the violation of the safe flight envelope, $v - v_{prot}$, where v_{prot} is the value at the edge of the safe flight envelope, and the distance between the safe and nominal flight envelope, $v_{nom} - v_{prot}$, where v_{nom} is the value at the edge of the nominal flight envelope. To illustrate this, the haptic profile with a stiffness change for a severity of 0.5 is shown on Fig. 7.3c. Increasing the severity to 1 results in a haptic profile shown on Fig. 7.3d which requires even more force for a backwards stick deflection. In this experiment, K_v is set to 2 for all limits.

NEUTRAL POINT FEEDBACK

A shift in the neutral point can be used to indicate a required deflection to follow a certain flight path ([41]) or, in automotive applications, to follow the road ahead. [133] If a positive/push deflection is required, this would result in a haptic profile as shown Fig. 7.3b. In our scenario, the aircraft is nearing its limit and the required deflection to return to the safe flight envelope can be indicated through the side stick. Since the aircraft dynamics at the different edges of the flight envelope are not equal (i.e., high velocity, angle of attack, and load factor), for each of these limits a required side stick deflection is determined as follows:

Velocity protection ($V > V_{\mathbf{prot}}$) When an overspeed occurs, the speed has to be reduced actively by the pilot by either reducing the throttle, or by pitching up such that kinetic energy is rapidly exchanged for potential energy. The Airbus control law will implement a forced nose-up command (see Subsection 7.2.1), which could be translated to a change in neutral point. Nevertheless, the actual implementation of this signal is not known for this research and is approximated as described below. The main reason for this cue is to inform the pilot that maintaining the stick at zero deflection does *not* solve the flight envelope violation, and action needs to be taken. Note that here our research deviates from the A320 FEP: the nose-up command is not activated when crossing V_{MO}, it is already activated when crossing $V_{MO_{prot}}$.

For this research, the nose-up command, and therefore the magnitude of the neutral point shift, is governed by the change in load factor required to bring the positive acceleration to zero. It is determined by starting from the longitudinal equations of motion ([69]), where we assume engine thrust to be parallel to the aircraft longitudinal body axis:

$$T\cos(\alpha) - D - W\sin\left(\gamma\right) = m\frac{dV}{dt} \tag{7.2}$$

The pilot can manipulate the aircraft flight path (γ), through moving the stick. Here, the neutral point is shifted to obtain a flight path angle such that there is no positive acceleration, $\frac{dV}{dt} = 0$. If the aircraft is accelerating before the activation of the neutral point shift, the left part of Equation 7.2 is not zero and can be rewritten to obtain a steady flight path:

$$\gamma_{\text{steady}} = \arcsin\left(\frac{T\cos(\alpha) - D}{W}\right) \tag{7.3}$$

Thrust and drag cannot be measured directly, their effects can be measured through accelerometers, mounted on the aircraft body, which therefore must first be rotated to the velocity reference frame:

$$\begin{aligned} T\cos(\alpha) - D &= m a_{x_a} + W\sin\left(\gamma\right) \\ &= m\left(a_{x_b}\cos\left(\beta\right)\cos(\alpha) + a_{y_b}\sin\left(\beta\right) + a_{z_b}\cos\left(\beta\right)\sin(\alpha)\right) + W\sin\left(\gamma\right) \end{aligned} \tag{7.4}$$

Combining Equation 7.3 with Equation 7.4 then yields the required change in flight path angle for zero acceleration ($\gamma_{\text{steady}} - \gamma$), all expressed in measurable quantities.

As discussed above, the side stick gives load factor commands for high velocities and therefore also a relation between the change in flight path angle and load factor is required. By assuming that the steady state pitch rate is predominantly determined by a change in flight path, the required load factor can be expressed by the required flight path angle and a tuning factor ($\tau_{\text{overspeed}}$) which is an indication of the recovery speed: [73][1]

$$n_{\text{req}} = \frac{V}{g}\cdot q + 1 \approx \frac{V}{g}\cdot\dot{\gamma} + 1 = \frac{V}{g}\cdot\frac{\gamma_{\text{steady}} - \gamma}{\tau_{\text{overspeed}}} + 1 \tag{7.5}$$

Angle of attack protection ($\alpha > \alpha_{\text{prot}}$) When the angle of attack is above the maximum value, the required change to bring it back to the protection value should be translated to the side stick. The required change in load factor can be obtained by starting from the effect of pitch rate on load factor:

$$n = V\cdot q \tag{7.6}$$

[1]The conference publication contained a mistake in the equation derivation and is corrected for this thesis.

7

Furthermore, the required pitch rate can be approximated by a required change in angle of attack over a certain time, assuming that for short periods of time the change in pitch is dominated by a change in angle of attack. As a desired angle of attack is available (α_{prot}), and by choosing a time, the required change in load factor is determined by:

$$n = V \cdot q \approx V \cdot \frac{\alpha - \alpha_{\text{prot}}}{\Delta t_\alpha} \tag{7.7}$$

This results in one tuning parameter (Δt_α) which can be used to indicate how responsive the side stick will move for a given required change in angle of attack. In the current setup, this tuning parameter is set to 3s.

Load factor protection ($n > n_{\text{prot, pos}}$ or $n < n_{\text{prot, neg}}$) When a load factor outside the safe flight envelope occurs, a required change in control inputs can readily be obtained since side stick inputs are proportional to a change in load factor. The required load factor in case of positive load factors is $n_{\text{prot, pos}} = 2.0$g, in case of negative load factors $n_{\text{prot, neg}} = -0.5$g, resulting in a required stick deflection:

$$\delta_n = \begin{cases} \left(n - n_{\text{prot, pos}}\right) \cdot \frac{n_{max,pos}}{\delta_{\max}} & \text{if } n > n_{\text{prot, pos}} \\ \left(n_{\text{prot, neg}} - n\right) \cdot \frac{n_{max,neg}}{\delta_{\max}} & \text{if } n < n_{\text{prot, neg}} \\ 0 & \text{else} \end{cases} \tag{7.8}$$

When this haptic feedback system is implemented, it presents the pilot with continuous feedback which uses the stiffness to indicate an undesired deflection, and a shift in neutral point to show the required deflection to return to the safe flight envelope. The stiffness change and neutral point shift can occur simultaneously, for example in Fig. 7.3e where a positive neutral shift is combined with an increased stiffness for backwards deflections. The combination of these two cues might result in unacceptable high forces required to move the side stick. This is prevented with the implementation of the maximum force, resulting in a flat slope on the haptic profile. The remainder of this chapter discusses the results of an experiment to evaluate both cueing methods.

7

7.3. METHOD

To evaluate the haptic interface designs, an experiment was performed which uses the same setup as used in a previous experiment which investigated the 'cueing haptic feedback', see Chapter 6.

7.3.1. INDEPENDENT VARIABLES

The experiment had a between-participants design, with one independent variable. The participants were divided in three groups: the cueing group, the guidance group, and the manual (no-haptics) group. Each group (12 participants per group) performed two blocks of four runs each, elaborated below, and summarized in Table 7.2.

In the first block, participants were presented with one of the three haptic support conditions. Literature found that an increasing amount of feedback in this initial stage, results in worse performance when that feedback is removed: the "guidance hypothesis". [134] To investigate the consequences of removing the feedback in our application, all participants performed a second block in the manual, no-haptics condition.

The results of the cueing group (12 participants) were obtained from our previous experiment in Chapter 6 which had the exact same experimental setup. Twenty four new participants were invited and numbered in sequence of experiment participation. Even-numbered participants were placed in the guidance group group, all odd-numbered participants are part of the manual group. A total of 36 participants results from combining the previous and present experiment groups.

Table 7.2: Experimental design

Block	1				2			
Run	1	2	3	4	5	6	7	8
Cueing group	Cueing haptics				No haptics			
Guidance group	Guidance haptics				No haptics			
Manual group	No haptics				No haptics			

7.3.2. PARTICIPANTS AND INSTRUCTIONS

For this experiment, data from 36 pilots (1 female, 35 male) with a current PPL or LAPL license were used. As these pilots are not Airbus pilots, they were reminded that the aircraft model used has a mass of 64,000kg and had to be handled with more care than a general aviation aircraft. The experience of the three different groups can be found in Tables 7.3, 7.4 and 7.5. A visual comparison of the flight hours per group is shown Fig. 7.4. A Kruskal-Wallis rank sum test did not show statistical significant differences in experience between groups ($\chi^2 = 3.17$, $p > 0.2$).

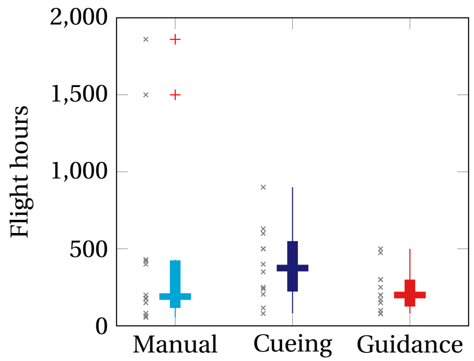


Figure 7.4: Flight hours per group

Table 7.3: Participants in the manual group

Participant	Age	Flight hours	License
M1	65	400	PPL
M2	52	1,500	CPL / IR / FI
M3	66	1,860	PPL / IR
M4	20	150	PPL
M5	62	430	PPL
M6	57	180	LAPL
M7	49	420	CPL
M8	20	82	PPL
M9	62	175	PPL
M10	50	200	PPL
M11	20	55	PPL
M12	23	65	PPL
Mean	45.5	459.8	-
Std.Dev.	19.1	590.4	-

FI Flight Instructor
IR Instrument Rating

Table 7.4: Participants in the cueing group

Participant	Age	Flight hours	License
T1	34	116	PPL
T2	25	80	LAPL
T3	49	205	PPL / E-IR
T4	40	630	PPL
T5	48	350	PPL
T6	24	500	PPL
T7	66	900	PPL
T8	46	250	LAPL
T9	48	500	PPL
T10	50	400	PPL
T11	33	240	PPL
T12	53	600	PPL / E-IR
Mean	43	397.6	-
Std.Dev.	12.3	240.2	-

E-IR Enroute-Instrument Rating

Participants were instructed to always remain within the nominal limits of the flight envelope (black line on Fig. 7.1) which were shown on the PFD using the red indications proposed in Ref. [119]. Additionally, it was mentioned that a simulation run would stop when the aircraft reached an altitude of 50ft above ground level, irrespective of any other event/performance.

Table 7.5: Participants in the guidance group

Participant	Age	Flight hours	License
G1	67	475	PPL
G2	57	300	PPL / IR
G3	26	100	PPL
G4	30	78	PPL
G5	44	170	PPL
G6	50	80	PPL
G7	43	150	PPL
G8	47	500	CPL
G9	71	300	PPL
G10	52	250	PPL
G11	50	200	PPL
G12	60	200	PPL
Mean	49.8	233.6	-
Std.Dev.	13.3	140.5	-

IR Instrument Rating

7.3.3. EXPERIMENTAL SETUP

The experiment was performed in the HMI research simulator of Delft University of Technology. It is a fixed-base simulator, with a near 180° outside field-of-view, used in the first officer position of which an inside-view is shown in Fig. 7.5. Since the pilot was sitting in the first officer position, the display to his front-left was the ND showing a top-down overview of the situation, shown in Fig. 7.6a, combined with a basic engine N1-indication and slats/flaps indication. The display right in front of the pilot was the PFD showing the critical flight states, shown in Fig. 7.6b, which included display indications used to show *why* and *when* the haptic feedback is active. [119] Next to the visual information, auditory warnings were presented when the aircraft angle of attack was above the maximum value, and when the velocity was above the maximum velocity.

A custom-made, hydraulically driven side stick with programmable dynamic properties is located at the right-hand side and was configured to Airbus side stick properties. [61] To the left, a throttle quadrant is present which was used to control the throttle and high lift device settings. Centrally placed, a Boeing 737 Mode Control Panel (Airbus terminology: FCU) enabled the interface with the heading, velocity and altitude references on the displays. Outside visuals were generated using FlightGear[1] and showed the airport infrastructure, terrain and important buildings at the airport. A proprietary A320-like flight dynamics model, including control laws from the German Aerospace Center (DLR), was used as the simulated aircraft. [120]

The nominal, no-haptics control device settings for this experiment, including mass (m), spring coefficient (k), damping coefficient (b) and maximum deflection (δ_{max}), for both longitudinal and lateral side stick axes are given in Table 7.6.

[1]Open source flight simulator available at `http://flightgear.org`

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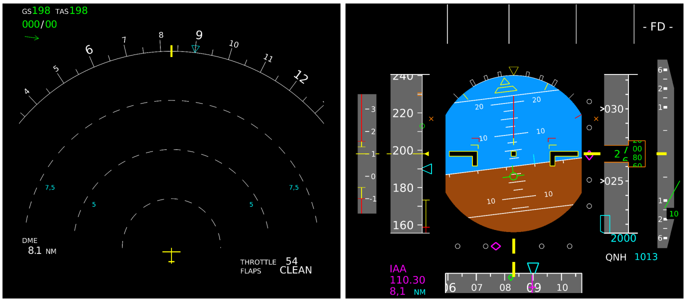
Figure 7.5: Inside view of the HMI flight deck



(a) ND (b) PFD

Figure 7.6: Flight deck display setup used in the experiment

The 'cueing haptic feedback' used: (i) a sawtooth shape of intensity 0.282Nm, duration 1s and frequency 2Hz when exiting the safe flight envelope, (ii) a sawtooth shape with varying intensity proportional to the relative distance of the protection and flight envelope limit, duration 0.5s and frequency 2Hz when remaining outside the safe flight envelope and (iii) a stick shaker for low velocities as a sinusoid with frequency of 20Hz and magnitude 0.426Nm. Further details can be found in Chapter 6.

'Guidance haptic feedback' used an increase in spring coefficient to maximal twice the nominal stiffness, and neutral point shifts to provide recommended side stick deflections as discussed in the design section.

Table 7.6: Control device in the experiment

Property	Value
m	0.2 kg m^2
$k_{lon_{nom}}$	36.3 Nm/rad
b_{lon}	0.4 Nm s/rad
$\delta_{lon_{max}}$	0.279 rad
$k_{lat_{nom}}$	21.8 Nm/rad
b_{lat}	0.4 Nm s/rad
$\delta_{lat_{max}}$	0.314 rad

7.3.4. EXPERIMENT SCENARIOS

The haptic feedback system was designed to communicate the ‘proximity of the flight envelope limits’ to the pilot and therefore required an evaluation at these limits. In analogy to our previous experiment, the scenarios presented a stringent flight path, as discussed below, followed by the emergency scenario encountered during each flight.

FLIGHT PATH

Each run was started when the aircraft was flying 140kts (72.0mps) at 2,500ft (762m) with slats and flaps set for approach (Airbus setting 3), overhead the threshold of runway 23 of Zoersel (Belgium) and aligned with the respective runway. This location was chosen as it has no special terrain features close-by, and the runway was not visible from the starting position as illustrated on Fig. 7.8a. Additionally, the auto-throttle was set to 140kts and activated, reducing the variability of the initial aircraft state when the event was triggered and should provide more consistent results. From this position, pilots were presented with visual markers (squares of 60m by 60m) on the outside visual display to help them fly a flight profile consisting of six ‘hills’, for which an example path is presented in Fig. 7.7 and visualized on the outside visual as shown in Fig. 7.8.

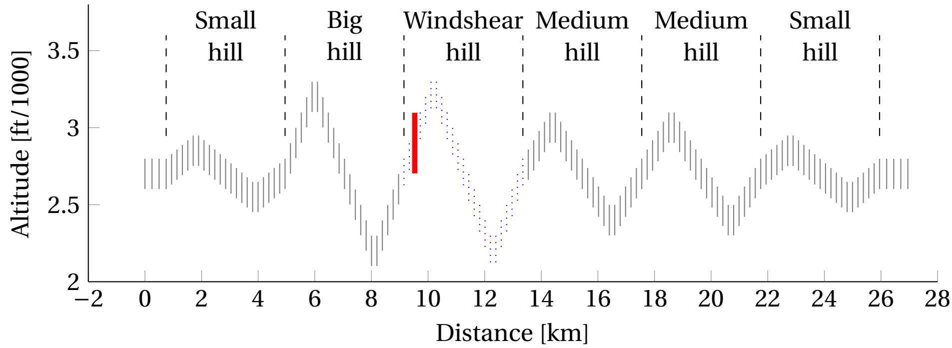
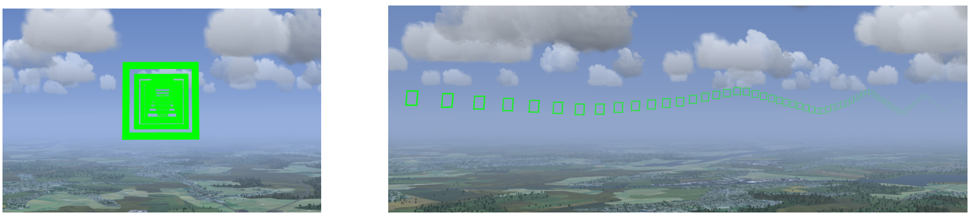


Figure 7.7: Flight path side-view, solid black vertical lines indicate “fly-through gates” shown on the outside visual; the thick red line indicates the trigger point of the windshear (not shown on the outside visual); the dotted blue lines indicate the windshear section used in our evaluation



(a) View at start of run

(b) Perspective view on flight path (viewing angle is for illustrative purpose only, never encountered during flight)

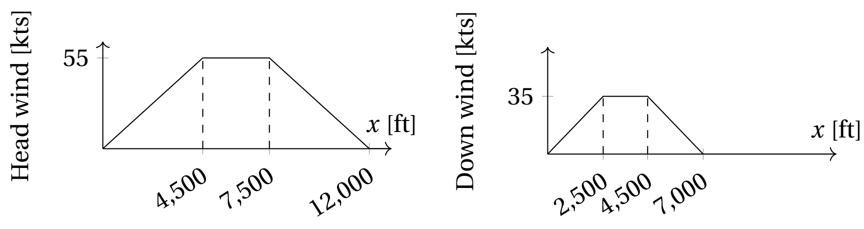
Figure 7.8: Example of the outside visual flight path visualization

A hill was 2.27NM (4,200m) long and had one of three possible amplitudes: 150ft (45.72m), 300ft (91.44m) or 500ft (152.4m). Combining six hills yielded a saw-tooth trajectory. The flight path started with a horizontal segment of 0.41NM (750m) and one hill of the smallest amplitude as run-in. This was followed by a randomized order of hills such that each amplitude of hill occurred twice in the flight path. Each flight ended with a horizontal segment of 0.54NM (1,000m) as run-out. This setup of hills was chosen as it was expected that it allowed the results to be evaluated for each hill separately. Eight different realizations of the randomization were obtained to present pilots with variability in the scenarios. The resulting trajectories are all shown in Section C.2.

EMERGENCY SCENARIO

As the pilots of our initial experiments did express the potential added value of the haptic feedback system in a windshear event, this event is re-used for this research. [110] A wind shear is a meteorological phenomenon where wind velocities are locally rapidly changing, and can be caused by a large cylinder of air suddenly “droping” towards the earth. During such a wind shear event, downdrafts can push the aircraft dangerously close to the ground. [76] To recover from this event, the pilot has to move as close to the stall limit as possible to prevent further height loss and maximise aircraft performance. [13]

The windshear in each run was *always* started when the aircraft moved through the visual marker of the windshear hill at an altitude of 2900ft (883.92m). Each flight path contained two hills with the largest amplitude, only one of them was selected at random to contain the windshear trigger point. The windshear itself was modeled by both a head-on and top-down component as shown in Fig. 7.9. [76] Once the windshear was initiated, the visual and aural warning trigger, and the pilot had to apply the windshear recovery procedure as stipulated in Section B.6, which was based on the Airbus Flight Crew Operating Manual. [13]



(a) Headwind component (b) Downwind component

Figure 7.9: Windshear component distribution

When providing only windshear as the emergency scenario during each run, pilots might anticipate this event, even in the first run. To prevent this, two more checklists for an emergency were presented to the pilots beforehand: the actions required for a single engine stall (Section B.7), and for a sudden center of gravity shift (Section B.8). Therefore, pilots were expecting one of these three emergency scenarios, but were unaware of what scenario was actually triggered. Note that the checklists presented in Fig. B.6 and B.7 are heavily modified from the FCOM, and the checklist for the sudden center of gravity shift is non-existing in the FCOM.

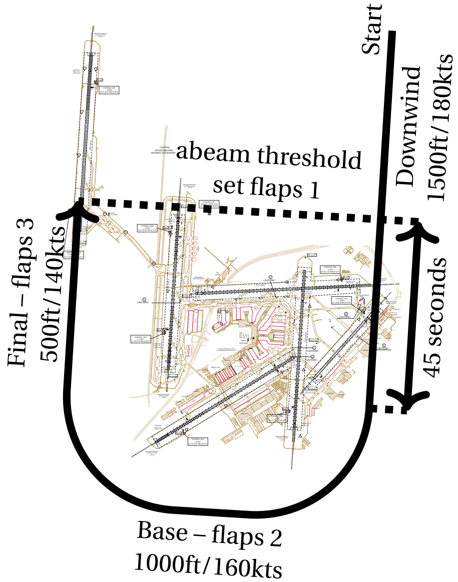


Figure 7.10: Traffic pattern flown to runway 36L at Schiphol (Schiphol layout from AIP [84])

7.3.5. EXPERIMENT DESIGN

To allow pilots to become sufficiently familiar with the simulator and the haptics (if applicable), a familiarization phase was performed, followed by measurement runs.

FAMILIARIZATION

After a briefing on the simulator safety procedures, all pilots were explained the controls and displays by presenting the flight envelope (an image similar to Fig. 7.1), and the PFD (Fig. 7.6b) to the pilot. In this setup, no aircraft model was used, yet the flight envelope state was changed directly (hence changing the velocity and load factor) and all visual and auditory cues were elaborated. After that, pilots in the cueing or guidance groups *felt* the design rationale behind the haptic feedback design using an image similar to Fig. 7.3.

Then the aircraft model was introduced to the pilot by flying a traffic pattern twice to a final approach at Schiphol (EHAM) as shown on Fig. 7.10, without the haptic feedback, hence focusing on familiarization with the model. Pilots were instructed to follow the instructions as indicated. Some pilots encountered a stall and/or an overspeed condition during these first runs. If the pilots did not hit one or both limits, they were asked to deliberately explore those boundaries to ensure that all pilots encountered them before the measurement runs.

MEASUREMENTS

The measurement phase contained eight realizations of the flight path presented above. They were flown in a randomized fashion, distributed over all participants using a Latin-square distribution. Each group performed two blocks of four runs, with a break in between, with haptic feedback as shown in Table 7.2.

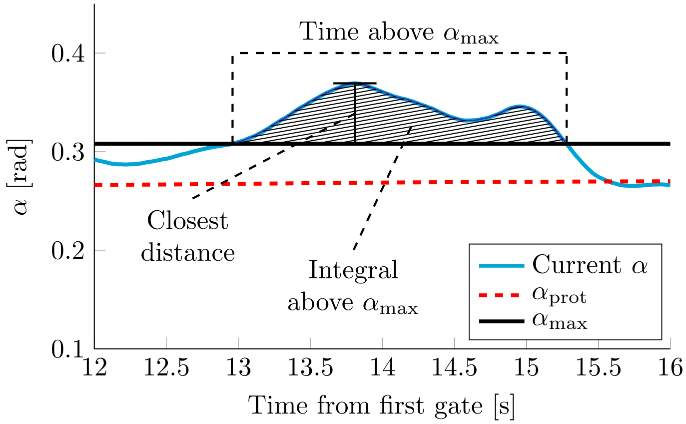


Figure 7.11: Time trace of velocity with safety metrics indicated

After each run, pilots were asked to indicate their workload using a RSME rating [85], and complete a post-run situation awareness questionnaire, to indicate how helpful the visual, auditory and haptic (if supplied) elements are. They also provided a misery scale rating to measure and account for possible effects of motion sickness. [121] Once this was completed, pilots were informed on how much time they spent inside the flight envelope, which they had to maximise.

After each block of four runs, pilots were asked to complete a questionnaire with a modified Cooper-Harper rating scale ([122]), and a Van der Laan-rating scale. [104] After the experiment was completed, pilots were asked to complete a post-experiment questionnaire, which contained a number of questions with Likert-scales on how they experienced the haptic feedback system.

7.3.6. Dependent Measures

The dependent measures are split into objective and subjective measures.

Objective measures

The objective measures are retrieved from the windshear recovery procedure, and focus on performance and safety. To illustrate why these metrics were chosen, a time excerpt of a windshear recovery is shown in Fig. 7.11. Another example is further elaborated in the results section, for now it is sufficient to understand that this shows a participant aiming for the best performance of the aircraft, flying close to the maximum angle of attack.

Looking at the example, one can argue that a safe flight is performed when the aircraft state is within the flight envelope limits, indicated with the solid black line representing α_{max}. Although participants are instructed to stay within the limits at all times, at certain moments in time the pilot could control the airplane beyond these limits. A first performance metric was therefore the *time spent outside the angle of attack limits.*

Participants can push the aircraft by flying very close to its limits, even above the limits, or they can choose to remain well away from the limits. A straightforward metric to determine this safety definition was the *maximum angle of attack obtained relative to the flight envelope limit*: it can indicate how close to the limits the participant dares to control the airplane.

Time by itself only informs about the length of the limit violations, it does not take into account the closest distance: two different limit violations might be of equal time, yet one just slightly over the limit while another one is in a deep stall. As such, a safety metric combining both the time and the magnitude of the violation was the *integral of the angle of attack over the flight envelope limit*.

One additional performance metric on the overall windshear recovery procedure was used: the *total amount of altitude lost during the recovery*. Although not communicated to the participants, the maximum altitude lost from the windshear initiation to the end of the windshear recovery is considered here as an indication of how much of the available aircraft performance is utilized by the participants. Best performance is achieved when this amount of altitude lost is minimum.

Previous research showed that the level of risk humans experience is mostly kept the same when support increases, i.e., risk homeostasis. [86] This was found in an automotive studied where supplying haptic feedback resulted in participants driving at higher velocities. [87] For the current experiment, risk homeostasis was also expected, and can be defined by improved performance, combined with objective safety metrics closer to the maximum value, as pilots obtain a better awareness of the risk involved when supplied with haptic feedback.

SUBJECTIVE MEASURES

Subjective measures are obtained by asking the pilot for an opinion, or experience. The categories and measures are:

- Workload: after each run, the pilot was asked to provide a RSME rating [85]
- Situation awareness questions: after each run, the pilot was asked to answer two questions on a linear scale (0–100) ranging 'Never' left (0), and 'Always' right (100):
    1. Did you have the feeling you were in control of the situation?
    2. Did you have the feeling you missed critical information?
- Usefulness:
    1. Pilots were asked after each run to rate the usefulness of all display and haptic elements on a Likert scale
    2. After each block, pilots were asked to provide a modified Cooper-Harper rating
    3. After each block, pilots were asked to fill a Van Der Laan-questionnaire
- Pilot experience: after the experiment, the pilot was asked to fill in a questionnaire regarding the experience with the haptic feedback system.

The questionnaire presented to the pilots after the experiment used five point Likert-scales where all points are labeled. A different set of questions was presented to the participants in the manual, no-haptics group because they did not experience any haptic feedback at all. Both sets of questions can be found in Section A.8.

7.3.7. HYPOTHESES

In the evaluation of the experiment, the manual group served as a baseline to compare pilot behaviour during the windshear recovery. The expected behaviour of the other two groups is visually summarized in Fig. 7.12 and explained in the following.

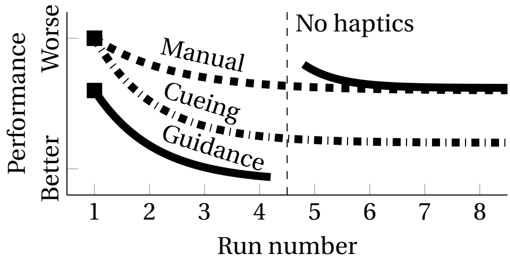


Figure 7.12: Schematic representation of the expected results

We expected the *cueing group* to perform initially at the same performance level, yet have a faster learning rate over the first four runs, have an improved performance level at Run 4, and keep performance equal when no haptic feedback is provided in the final four runs, i.e., no after-effects. In terms of dependent measures, this means no change in performance/safety between the manual and cueing group at Run 1. At Run 4, the cueing group has an improved performance between-groups compared to the manual group, and within-group compared to Run 1. Comparing the metrics of Runs 4 and 8 within the cueing group, should give no differences to indicate no after-effects.

The *guidance group* was expected to have an improved performance from the first run as long as haptic feedback is provided, but when this haptic guidance is not provided, (Run 5), we expected the performance to suddenly worsen following the “guidance hypothesis”. [134] In terms of dependent measures, this would translate to improved performance and safety margins at Run 1 when between-groups comparing the manual and guidance groups. At Run 4, the guidance group has an improved performance between-groups compared to the manual group. After-effects were expected to show up when comparing performance and safety margins of Runs 4 and 5 within the guidance group.

We expected pilots to perceive the *cueing haptic feedback* as a useful source of information, yet the information still needs to be interpreted. Therefore, the subjective workload ratings at Run 1 of the cueing group were expected to not differ from the manual group, yet indicate this group to have an improved situation awareness. At Run 4, the workload of the cueing group is expected to be lower due to familiarization.

The *guidance haptic feedback* was expected to be supporting pilots from the first run, yet it can be less clear in the reason why it provides a cue. It was expected that the subjective workload ratings at Run 1 of the guidance group is lower compared to the manual group, yet deteriorate when no haptic feedback is supplied anymore (at Run 5). Subjective situation awareness ratings of the manual and guidance groups were expected to be similar.

For both haptic designs, we expected the Modified Cooper-Harper ratings and Van Der Laan-ratings to improve. The remainder of this chapter looks into the results of this experiment and discusses whether our hypotheses can be supported.

7.4. RESULTS

Before the metrics are discussed, Subsection 7.4.1 shows one example case where a pilot used the guidance haptic feedback system and two other noteworthy events which happened during the experiment. Next, the objective and subjective measures are presented in, respectively, Subsection 7.4.2 and 7.4.3. Answers to the debriefing questionnaires are presented in Subsection 7.4.4. For reference, all flown trajectories included in the analysis are shown in Section C.2.

When presenting data using box plots, medians are indicated using a horizontal thick line, outliers are indicated using plus-signs; all individual data points are presented next to the boxes using crosses. Furthermore, statistical analyses are performed in R ([123]) and results are only reported if p-values of 0.05 or lower are found. Results are compared both within- and between-groups: within-group the differences of Runs 1, 4 and 8 are examined, the between-group comparison investigates the difference between groups at Runs 1, 4 or 8. Tests are performed using a Kruskal-Wallis rank sum test which indicates whether there is a statistically significant difference. If a difference is found, a post-hoc test is performed using a pairwise Wilcox test where p-values are adjusted using the method proposed by Benjamini and Hochberg. [135]

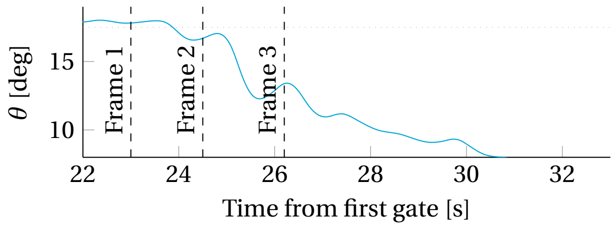
7.4.1. TIME TRACE EXAMPLES

This section discusses three time traces from the experiment: the first shows a participant using the guidance haptic feedback, the second shows the only crash which occurred, and finally a design flaw of the guidance haptic feedback is illustrated.

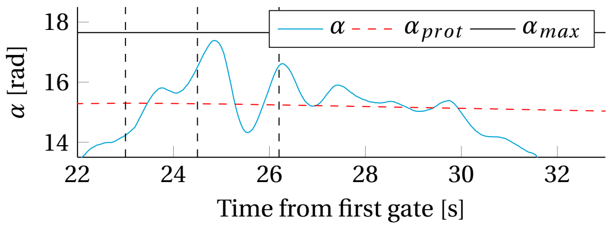
EXAMPLE USE OF GUIDANCE HAPTIC FEEDBACK

This is an example where Guidance Participant 2 during his first run made use of the guidance haptic feedback system proposed in the design section of this chapter. Time traces for pitch angle, angle of attack and control device deflections can be found in, respectively, Fig. 7.13a, 7.13b, and 7.13c. Three frames are indicated for which the haptic profiles are given in Fig. 7.14. The haptic feedback can be seen in the haptic profiles, and on the control device deflection plot: the neutral point (δ_{np}) is the stick shift by the haptic feedback, the actual control device deflection (δ_{cd}) is the sum of haptic feedback and the human operator.

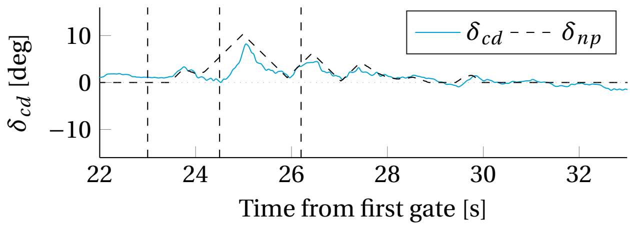
The windshear recovery procedure requires the pilot to use all of the available performance of the aircraft, which can be achieved by operating the aircraft near the maximum angle of attack. Initially, the pilot has to obtain a pitch angle of 17.5°, which is achieved at Frame 1 as can be seen on Fig. 7.13a. Here, the current state is still within the safe flight envelope and the corresponding haptic profile shows the nominal stick feeling on Fig. 7.14a. Next, Frame 2 shows the participant exerting back pressure on the stick to maintain pitch and to avoid the aircraft from descending, despite the haptic feedback indicating that a pitch down input is required to return to the safe flight envelope (shifted neutral point, Fig. 7.13c, and increased stiffness, Fig. 7.14b). Subsequently, the participant notices that a sustained back pressure brings the aircraft too close to the stall and starts following the haptic feedback cues to operate the aircraft near its limits. This can be seen by the matching of the neutral point and the actual control device position on Fig. 7.13c, for which one haptic profile is given in Fig. 7.14c.



(a) Pitch angle

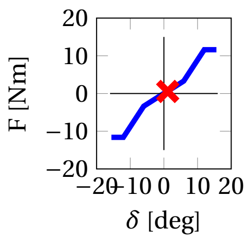


(b) Angle of attack

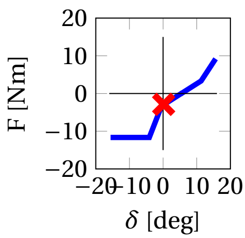


(c) Control device deflection, i.e., input from the side stick to the FCC

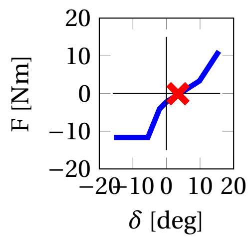
Figure 7.13: Time traces of Guidance Participant 2 using the haptic feedback during the recovery in Run 1



(a) Frame 1



(b) Frame 2



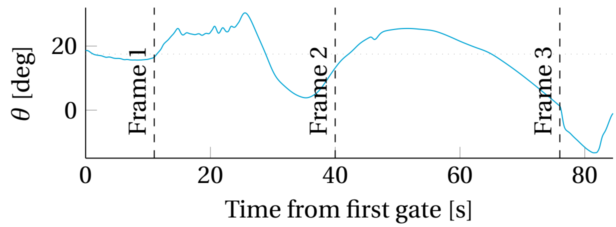
(c) Frame 3

Figure 7.14: Haptic profiles for frames indicated in Fig. 7.13, cross indicates the current state

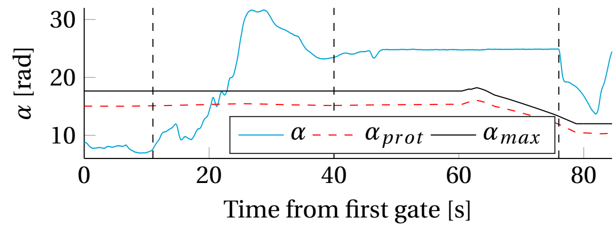
This example shows that this pilot used the haptic feedback, even in the first run where participants were expected not to be fully familiar with the aircraft model, task, or emergencies procedures. The metrics presented next can be used to further investigate whether this is a one-off example, or participants can indeed use the haptic feedback effectively from the first encounter.

ONLY CRASH OF THE EXPERIMENT

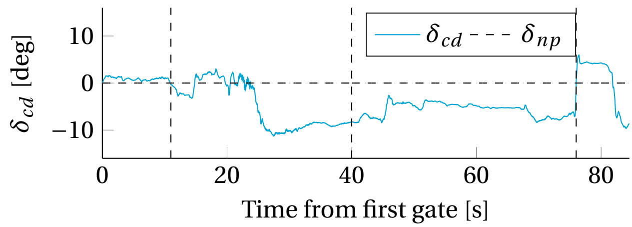
This example shows the first run of Partipant 7 in the manual group, where Fig. 7.16 shows the haptic profiles for the time frames shown on the time traces in Fig. 7.15. As this



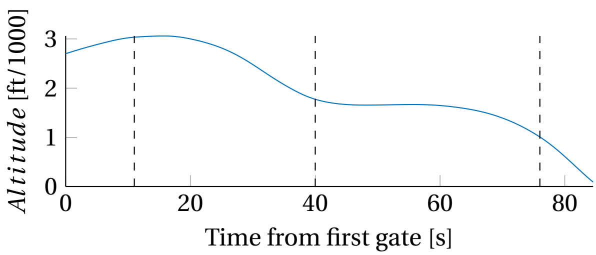
(a) Pitch angle



(b) Angle of attack

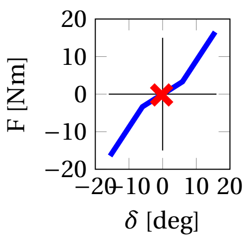


(c) Control device deflection, i.e., input from the side stick to the FCC

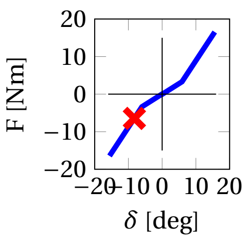


(d) Altitude

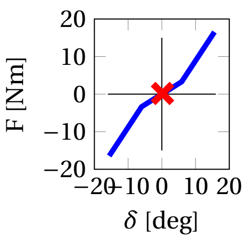
Figure 7.15: Time traces of the crash which occurred during Run 1 of Manual Participant 7



(a) Frame 1



(b) Frame 2



(c) Frame 3

Figure 7.16: Haptic profiles for frames indicated in Fig. 7.15, cross indicates the current state

was the first run, this was also the first time the participant encountered the flight path and windshear. After the windshear warning, the participant aimed for a pitch angle of 17.5°, as can be seen on Fig. 7.15a before Frame 1. At Frame 1, the participant notices that the aircraft is not climbing anymore (Fig. 7.15d), and as indicated in the checklist, increases nose-up input (Frame 1 at Fig. 7.15c, Fig. 7.16a).

After this, the windfield suddenly pushes the angle of attack above the maximum, as shown on Fig. 7.15b, and on the aural stall warning, the particpant starts applying *more* back pressure on the side stick. The input, shown on Fig. 7.15c, one snapshot at Frame 2 in Fig. 7.16b, shows a negative (pull) input of more then 50s during which sustained visual and aural stall warnings are provided, yet no haptic feedback as the participant is part of the manual group. About 60s after the windshear trigger, the participant retracts flaps which reduces in a reduced maximum angle of attack enlarging the problem.

Near the end of the flight, at Frame 3, the participant starts using a positive input and starts to solve the angle of attack excursion. Nevertheless, the action is too late and not sufficient altitude is left for the recovery. The flight is, as indicated in the briefing, stopped 50ft above ground level.

After this run, the participant filled the required questionnaires and he was told that he had a sustained stall, reducing his time inside the flight envelope. Additionally, he was reminded that one of the windshear recovery items indicates *not to change configuration*, i.e., do not change flaps. During the next run, the participant was able to recover from the windshear and complete the next flights. Although this crash is a one-off example, the only crash throughout the entire experiment campaign did occur when no haptic feedback of any form was present.

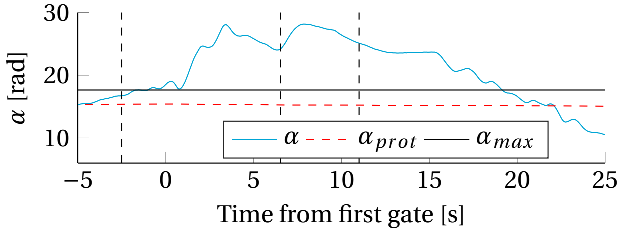
7

GUIDANCE HAPTIC FEEDBACK DESIGN ISSUE

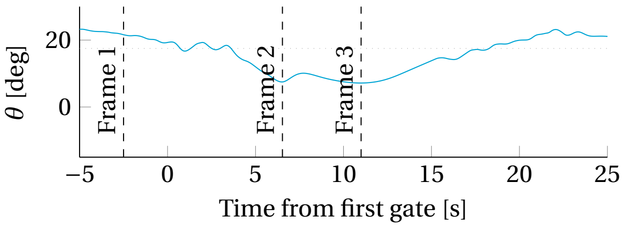
The third example shown is the first run of Guidance Participant 5 with time traces in Fig. 7.17 and corresponding haptic profiles in Fig. 7.18. It is a show-case of a flaw in the current design of the guidance haptic feedback: a possible haptic 'lock-in' where eventually all haptic feedback is lost. The origin of the flaw can be traced back to the method used to guarantee that the pilot always has final authority over the automation on the side stick: with a changing neutral point and an increasing stiffness, a certain deflection of the side stick might require a force level which is not reasonable anymore to be achieved. Therefore, as mentioned in the design section, the maximum amount of force required to move the side stick is limited to 11.6Nm.

Looking at the angle of attack before the windshear trigger, indicated as negative times on Fig. 7.17a, at Frame 1 the state of the aircraft was already near the limits and the participant was informed as such using a shift in neutral point and increased stiffness for negative inputs as shown on Fig. 7.18a. At that moment, the participant was trying to follow the tunnel-in-the-sky presented on the outside visual and needed all available performance to do so as he was slightly below the tunnel. On the windshear trigger, the condition worsened and the haptic feedback provided a full stick forward input which is maintained throughout the time trace as can be seen on Fig. 7.17c.

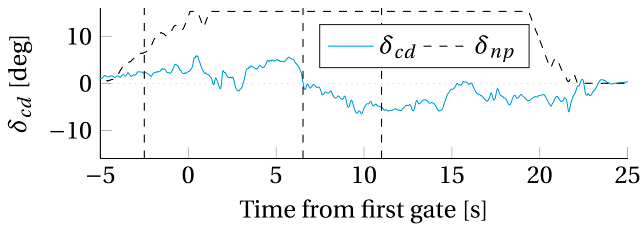
Starting from Frame 2, the participant reached a backwards pressure of the limiting 11.6Nm, resulting in a flat haptic profile as in Fig. 7.18b. The participant maintained the backwards input, nevertheless, one level of force on the side stick is required for all negative deflections. As a result, the participant was inputting significant pitch-up



(a) Angle of attack

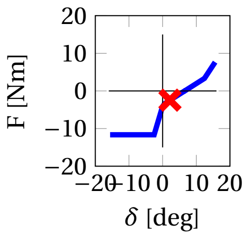


(b) Pitch angle

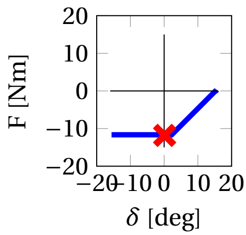


(c) Control device deflection, i.e., input from the side stick to the FCC

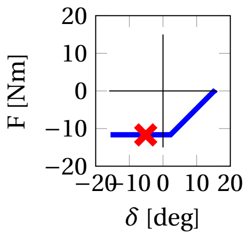
Figure 7.17: Time traces of the design flaw which occurred during Run 1 of Guidance Participant 5



(a) Frame 1



(b) Frame 2



(c) Frame 3

Figure 7.18: Haptic profiles for frames indicated in Fig. 7.17, cross indicates the current state

commands for a significant time, with one snapshot in Frame 3 (Fig. 7.18c), possibly without noticing the magnitude of the input due to the lack of a force gradient: the participant was 'locked-in'. Additionally, in this situation, whatever the neutral point shift or stiffness changes, the participant is not able to perceive this feedback.

One possible solution to avoid such a haptic 'lock-in' is to not use a flat haptic profile, yet implement a very shallow slope. By using a minimal slope, the participant is able to distinguish between different magnitudes of input, and the neutral point shift by the haptic feedback can still be observed. In the runs after this, the participant was able to apply the recovery procedure without entering a haptical lock-in.

7.4.2. OBJECTIVE MEASURES

Objective measures are directly retrieved from the simulation data and are discussed in the following.

ALTITUDE LOST DURING RECOVERY

The amount of altitude lost during the windshear recovery is shown in Fig. 7.19.For the manual and cueing groups, a learning process is present: from Run 1 onward, performance increases and less altitude is lost during the recovery. Comparing Runs 1, 4 and 8 within one group shows a statistical significant difference for the manual group ($p < 0.05$, $\chi^2 = 6.87$) where the post-hoc indicates that only Run 1 and Run 8 contain a difference ($p < 0.05$). This indicates that the group improved performance from the start till end, yet at Run 4, the participants were not fully learned yet. For the cueing group, differences are present ($p < 0.005$, $\chi^2 = 12.87$) between Run 1 and Run 4 ($p < 0.005$), and between Run 1 and Run 8 ($p < 0.005$). This confirms that after Run 1, the participants quickly learned how to handle the windshear recovery, yet were not able to reach the final performance at the first run. Within the guidance group, no large differences are observed, which is confirmed by no significant differences between Runs 1, 4 and 5.

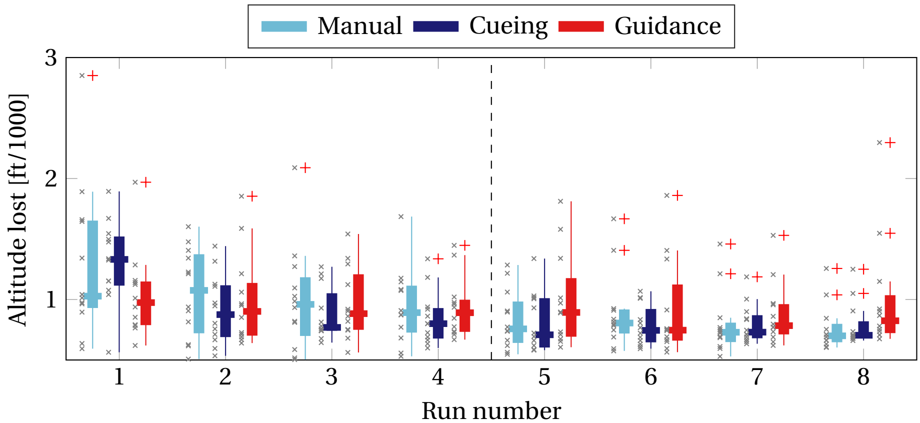


Figure 7.19: Altitude lost during windshear recovery

At first glance, the guidance group seems to have a lower median and lower spread compared to the other groups. At Run 4, the differences do not seem large. Nonetheless, no statistical significant results are found by the Kruskal-Wallis test. When no haptic feedback is supplied, performance of the guidance group seems to have a larger spread for worse performance. For Run 8, there is a 'near statistical significant' result of the Kruskal-Wallis test ($p = 0.06$, $\chi^2 = 5.64$), and the post-hoc test points to a difference between the guidance and cueing group ($p = 0.09$), as well as between the guidance and manual group ($p = 0.09$), indicating that the observation can be right, yet not supported by clear statistical significance.

TIME ABOVE MAXIMUM ANGLE OF ATTACK

The duration of the flight spent above the maximum angle of attack, Fig. 7.20 – a metric that was also communicated to the participants received after each run which they had to optimize – clearly shows the learning effect: starting from Run 1, this metric reduces, and thus participants also spent less time with the stall warning active. Within each group, this learning effect is confirmed with statistical tests: the manual group ($p < 0.005$, $\chi^2 = 12.60$) has significant differences between all runs (Run 1 and 4 $p < 0.05$, Run 1 and 8 $p < 0.005$, Run 4 and 8 $p < 0.05$) indicating that they improved over the course of the entire experiment. The cueing group has significant differences ($p < 0.001$, $\chi^2 = 23.50$) between Run 1 and 4 ($p < 0.001$), as well as between Run 1 and 8 ($p < 0.001$), indicating that they improved performance from Run 1 to 4, yet kept there performance level afterwards. The guidance group has only statistical differences ($p < 0.05$, $\chi^2 = 7.11$) between Runs 1 and 4 ($p < 0.05$) indicating an improvement over the first block of four runs, yet the lack of significant differences between Runs 1 and 5 might indicate the slight deterioration of the metric which is also visible on Fig. 7.20.

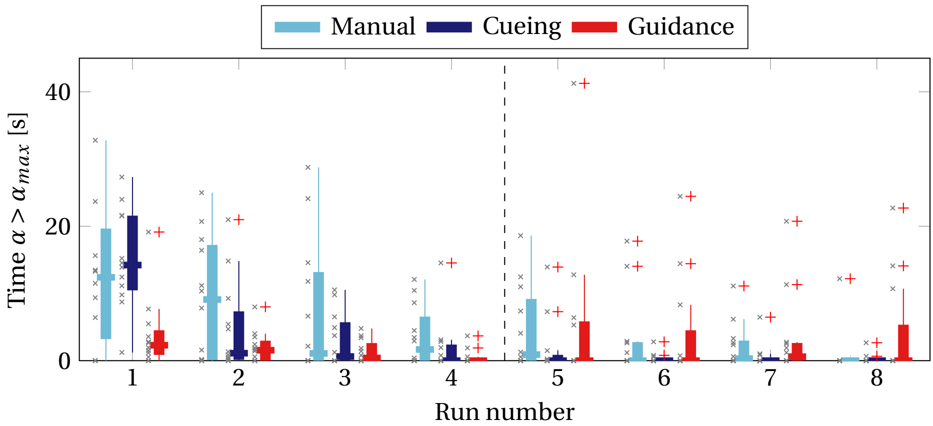


Figure 7.20: Time with angle of attack above limit during windshear (Manual Participant 7, 61.7s, not shown)

The time above the maximum angle of attack shows that at Run 1 the guidance group has a better performance compared to the two other groups. This is confirmed by a significant result of the Kruskal-Wallis test ($p < 0.01$, $\chi^2 = 9.92$), and post-hoc analysis indicates differences between the guidance and cueing group ($p < 0.005$), and 'near significant' difference between the guidance and manual group ($p = 0.10$). At Run 4, the boxplot of the manual group shows more participants still encounter a stall warning, yet this is not supported by statistical evidence. At Run 8, the guidance group appears to have three participants encountering a stall warning, compared to one in each of the other groups, but without statistical significance.

Another between-groups observations can be made regarding the spread of the data on the first block of four runs: each run of the manual group has the largest spread, and each of the guidance group has consistently the lowest spread. This might indicate that the guidance feedback is more stringent in its communication of the flight envelope limits, compared to the cueing feedback, and especially compared to the manual group.

HIGHEST ANGLE OF ATTACK

Fig. 7.21 shows how the largest angle of attack obtained throughout the recovery relates to the maximum angle of attack, i.e., it indicates how close pilots operate the aircraft near the limits, and if a maximum angle of attack violation is made, its magnitude. Again, a learning effect is present: the metric improves over the runs. Within the manual group, the plot shows that the learning effect seems to be rather slow, and this is confirmed by the statistical analysis: there are statistically significant difference ($p < 0.01$, $\chi^2 = 9.28$), more specifically, the post-hoc test reveals significant differences between Runs 1 and 8 ($p < 0.05$), and Runs 4 and 8 ($p < 0.05$), not between Runs 1 and 4.

Combining the lack of statistical difference between Run 1 and 4, and the large spread of the data indicates that participants in the manual group need more time to learn how to properly control the angle of attack. The values obtained for the cueing group show the worst results on the plot but improves over the four runs: the results have significant differences between runs ($p < 0.001$, $\chi^2 = 19.18$) and post-hoc indicates differences between Runs 1 and 4 ($p < 0.001$) and Runs 1 and 8 ($p < 0.001$), indicating that indeed participants made a significant difference in the first four runs and maintained this control strategy during the subsequent runs. For the guidance group, the Kruskal-Wallis test indicates 'near statistical' differences ($p = 0.076$, $\chi^2 = 5.15$) between runs, yet the post-hoc test only indicates 'near statistical' differences between Runs 1 and 4 ($p = 0.06$) and Runs 1 and 8 ($p = 0.07$). The plot does show a decrease in median during the first four runs, and an increase in spread when no haptic feedback is provided anymore.

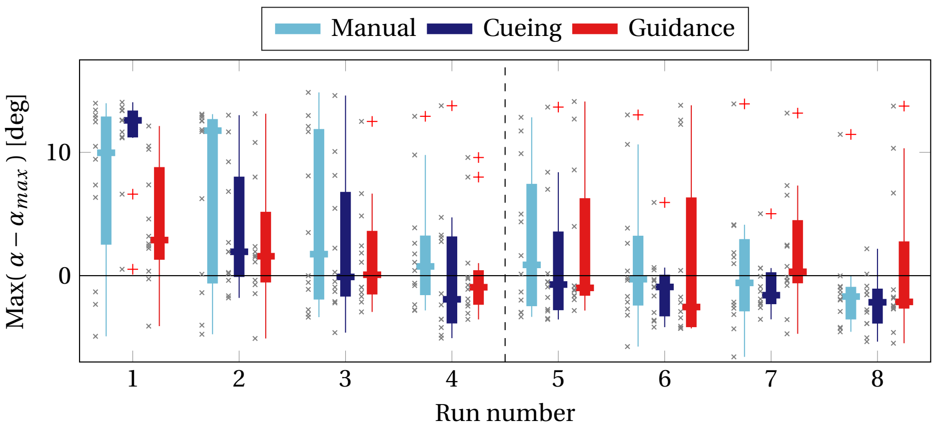


Figure 7.21: Highest angle of attack obtained during the windshear, relative to the maximum angle of attack (positive values result in a stall warning)

At Run 1, the guidance group seems to have the lowest, yet still positive, safety margin compared to both other groups. This is confirmed partly as significant differences between groups ($p < 0.01$, $\chi^2 = 9.61$) are present, yet only between the cueing and guidance groups ($p < 0.005$) indicating that the participants in the guidance group have consistently lower maximum angle of attack violations compared to the cueing group. No significant difference is found between the manual and guidance groups probably due to the spread of the data. One key difference between groups which is not captured by the statistical test is where the median is located with respect to zero, in other words, whether a median angle of attack above the maximum is achieved. At Run 1, the guidance group clearly has the median closest to zero. Furthermore, it takes the manual group until Run 6 to achieve a median below the maximum value, whereas both the cueing and guidance group achieve this at Run 3.

INTEGRAL ABOVE MAXIMUM ANGLE OF ATTACK

Combining time and distance above the maximum angle of attack results in the integral as shown in Fig. 7.22. The figure shows that from Run 1, the guidance group has the least amount of angle of attack above the maximum value. Additionally, the learning effect of both other groups is clearly visible, and the cueing group appears to have a smaller spread compare to the manual group. All groups though, seem to be able to reduce the amount of angle of attack above the maximum to an reduced level by Run 4.

Within the manual group, the learning effect is confirmed by statistical test: a significant difference is found ($p < 0.005$, $\chi^2 = 12.14$) and the post-hoc test indicates statistical significant differences between all runs (Runs 1 and 4 $p < 0.5$, Runs 1 and 8 $p < 0.01$, Runs 4 and 8 $p < 0.05$). The cueing group has differences ($p < 0.001$, $\chi^2 = 22.86$) between Runs 1 and 4 ($p < 0.001$), and between Runs 1 and 8 ($p < 0.001$), again indicating the initial learning effect and no after-effects in this metric. Statistical difference are present in the guidance group group ($p < 0.05$, $\chi^2 = 6.26$), with the post-hoc pointing to a difference between Runs 1 and 4 ($p < 0.05$), no difference between Run 4 and 5. This again indicates that participants perform better over the first four runs, but the next run has no statistical evidence. The figure does show that in the second block of four runs, without haptic feedback, the spread of the guidance group is slightly higher.

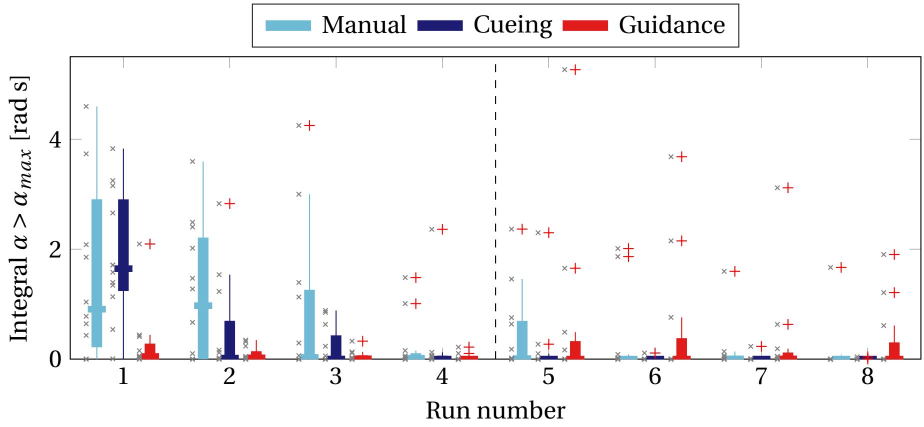


Figure 7.22: Integral above angle of attack limit during windshear (Manual Participant 7, 8.45rad s, not shown)

At the first run, we saw that the guidance group has the lowest median. The statistical test indeed confirms differences ($p < 0.01$, $\chi^2 = 9.76$), yet the post-hoc only confirms differences between cueing and guidance groups ($p < 0.005$). Differences between manual and guidance groups are almost significant ($p = 0.10$). At Run 4 and 8, no statistical significant differences are found.

7.4.3. SUBJECTIVE MEASURES

The first subjective measures are obtained after each run: a measure for situation awareness by asking the pilot whether (s)he was in control and whether (s)he was missing information, and a measure of workload. After each block of four runs, another questionnaire asked the participants to provide a Van Der Laan and MCH rating.

WAS THE PILOT IN CONTROL?

The results of the first measure can be found in Figs. 7.23 and 7.24, where no clear differences between groups can be observed. All groups seem to show an improving trend from Run 1 to Run 8.

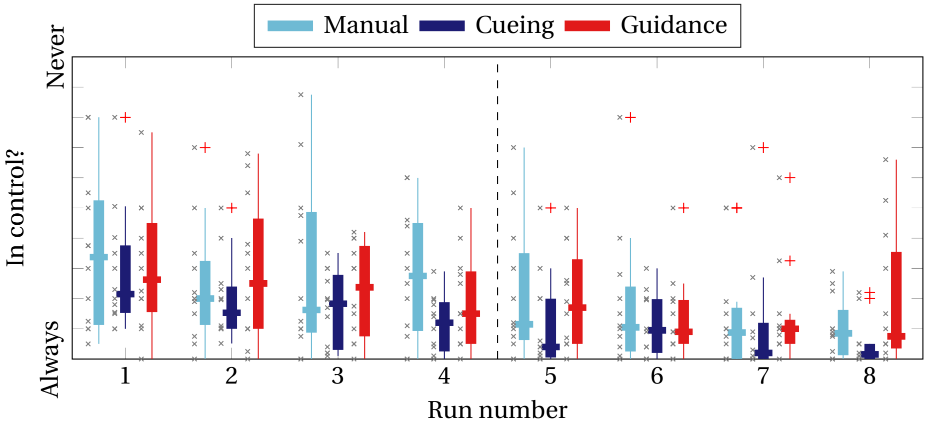


Figure 7.23: Was the pilot feeling in control?

Statistical tests show significant differences between the runs for the manual group ($p < 0.05$, $\chi^2 = 8.86$), post-hoc indicates a significant difference between Runs 1 and 8 ($p < 0.05$), and 'near significance' between Runs 4 and 8 ($p = 0.06$). This confirms the observation of improving over all runs and indicates a gradual change of the runs. The differences within the cueing group are also significant ($p < 0.001$, $\chi^2 = 14.34$), and post-hoc indicates differences between Runs 1 and 4 ($p < 0.05$), between Runs 1 and 8 ($p < 0.005$), and not between Runs 4 and 8. As with the objective metrics, this can indicate that the metric improved over the first block, yet did not significantly improve after that.

WAS THE PILOT MISSING INFORMATION?

Results for the amount of information missed by the pilots did not result in any statistical significant results. Fig. 7.24 shows that the cueing group has an increased spread from Run 4 to Run 5. At the latter run, no haptic feedback was provided, possibly pointing out that the haptic feedback was providing the pilot with extra information. Additionally, the spread of the guidance group seems to be larger over most runs compared to the other groups, especially for the last three runs, where the spread is larger compared to the other groups.

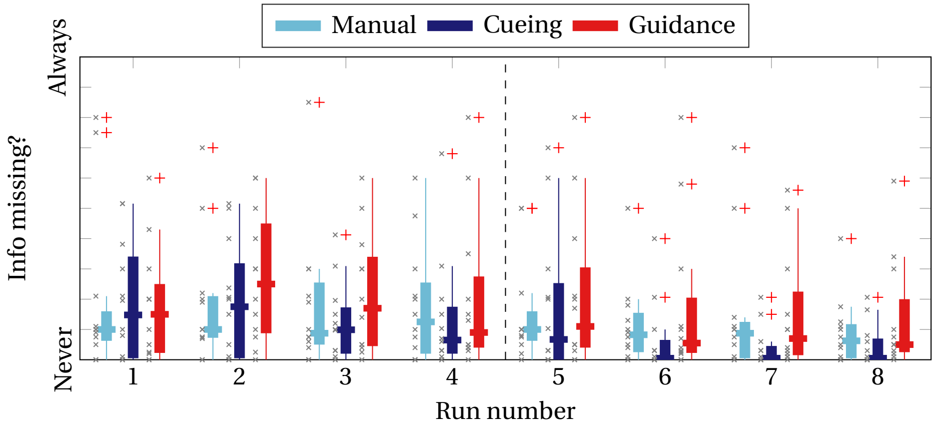


Figure 7.24: Was the pilot missing information?

RSME

The mental load required for each of the runs was measured using the RSME and is shown in Fig. 7.25. Within groups, a general decreasing trend, can be observed. Statistical analysis for the cueing group shows differences ($p < 0.05$, $\chi^2 = 7.48$) and the post-hoc indicates significant differences between Run 1 and 8 ($p < 0.05$), confirming the general decreasing trend. Two between-group observations can be made: the median of the manual group for each run, except Run 7, is the highest, and the median of the cueing group, except Run 1, is the lowest. These last observations are not statistically significant.

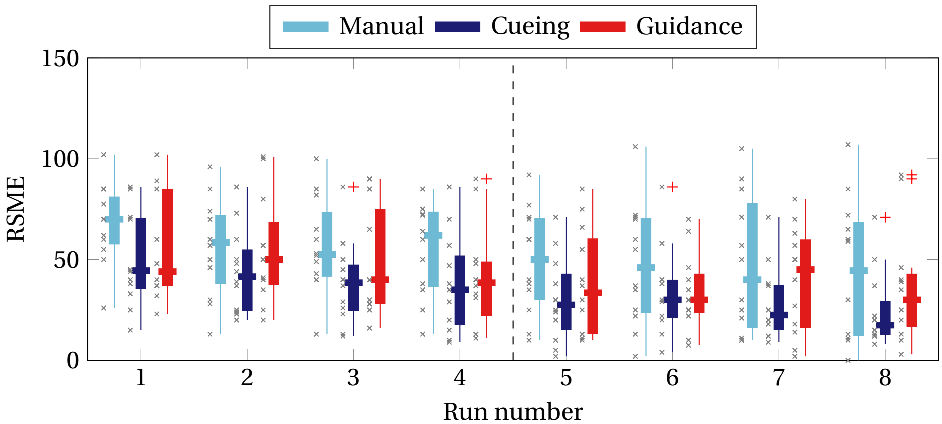
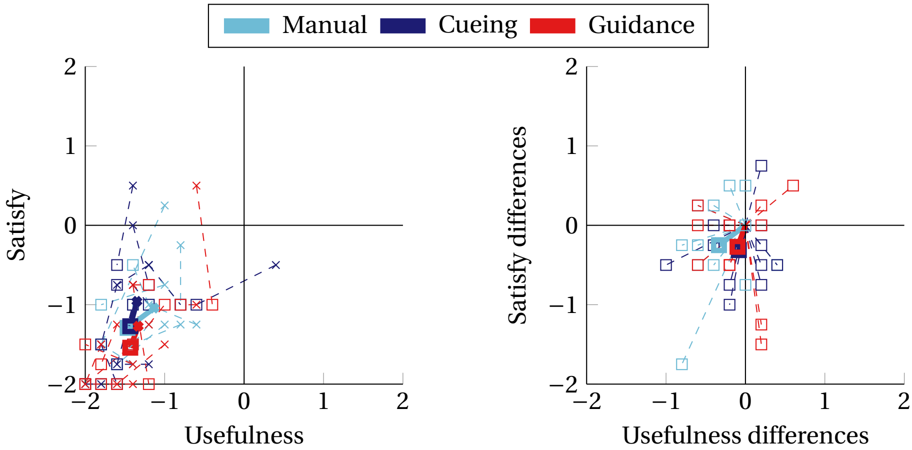


Figure 7.25: Rating Scale Mental Effort (RSME)

VAN DER LAAN RATINGS

The Van Der Laan uses nine questions to score the system on usefulness and satisfaction, a perfectly useful and satisfying system would score minus two on both scales. As suggested by Van der Laan, both the absolute values and the difference from Block 1 to Block 2 are shown in respectively Fig. 7.26a and Fig. 7.26b. The absolute values show that the systems are in general well received and that the averaged-per-group results, indicated by thick indications, are situated close together, i.e., there is little effect of the haptic feedback support on the initial rating. No statistical significant difference is found between blocks, or between groups within one block.



(a) Raw data

(b) Change in rating from Block 1 to Block 2

Figure 7.26: Van Der Laan-ratings; crosses represent the score after Block 1, squares after Block 2, bold indicate group means

Looking at the change in rating after Block 2, the manual group seems to have an improvement in both usefulness *and* satisfaction, both other groups change mainly in satisfaction, to a lesser extent in usefulness. This corresponds to the verbal comments pilots gave after the second block: *“The visuals need time to learn to understand and use them.”*, implying that the system becomes more useful after more training. The groups provided with haptic feedback made such comments less frequently. Nevertheless, this difference is again not statistically significant.

MCH RATINGS

Results for the MCH rating, shown in Fig. 7.27, are obtained using a decision-tree format and the main decision points are indicated with horizontal dashed lines. Note that lower scores are better, and going from score three to two requires that ‘The information facilitates efficient decision making.’ Two ratings do stand out: one participant rated the system twice as ten, where he indicated that all the information was too cluttered (especially the visual display), and warnings should only be provided when close to the limits. Other ratings provided by the participants in the guidance group did not change between blocks. Ratings for the two other groups have reduced spread and shift towards an improved rating: more participants rated the system one or two after Block 2. This indicates that the systems can provide efficient decision making, yet after training. Nonetheless, no statistical differences are found between blocks, nor between groups within a block.

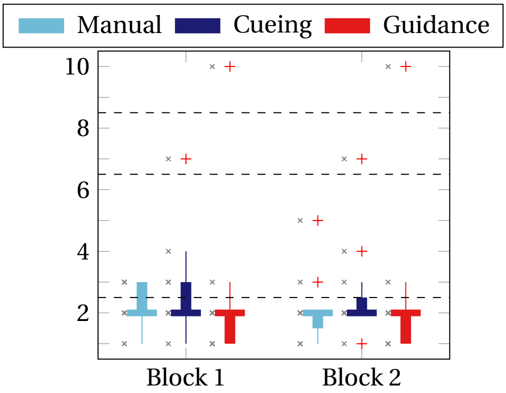


Figure 7.27: Modified Cooper-Harper rating

7.4.4. DEBRIEFING QUESTIONNAIRE

A final questionnaire is used to structure the debriefing session and involved 19 questions when participants were in either the cueing or guidance group, 14 when in the manual group, as shown in Section A.8. The first question simply queried the pilots of the cueing and guidance groups whether they prefer flying the aircraft with, or without haptic feedback. The results in Fig. 7.28 show that in the guidance group all but one pilot prefered to fly with the haptic feedback, in the cueing group opinions are divided evenly. The difference between groups is confirmed with statistical significance ($p < 0.05$, $\chi^2 = 42$).

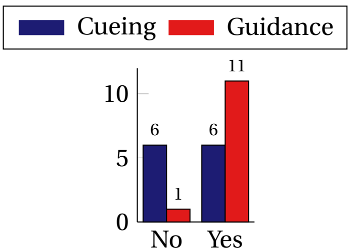
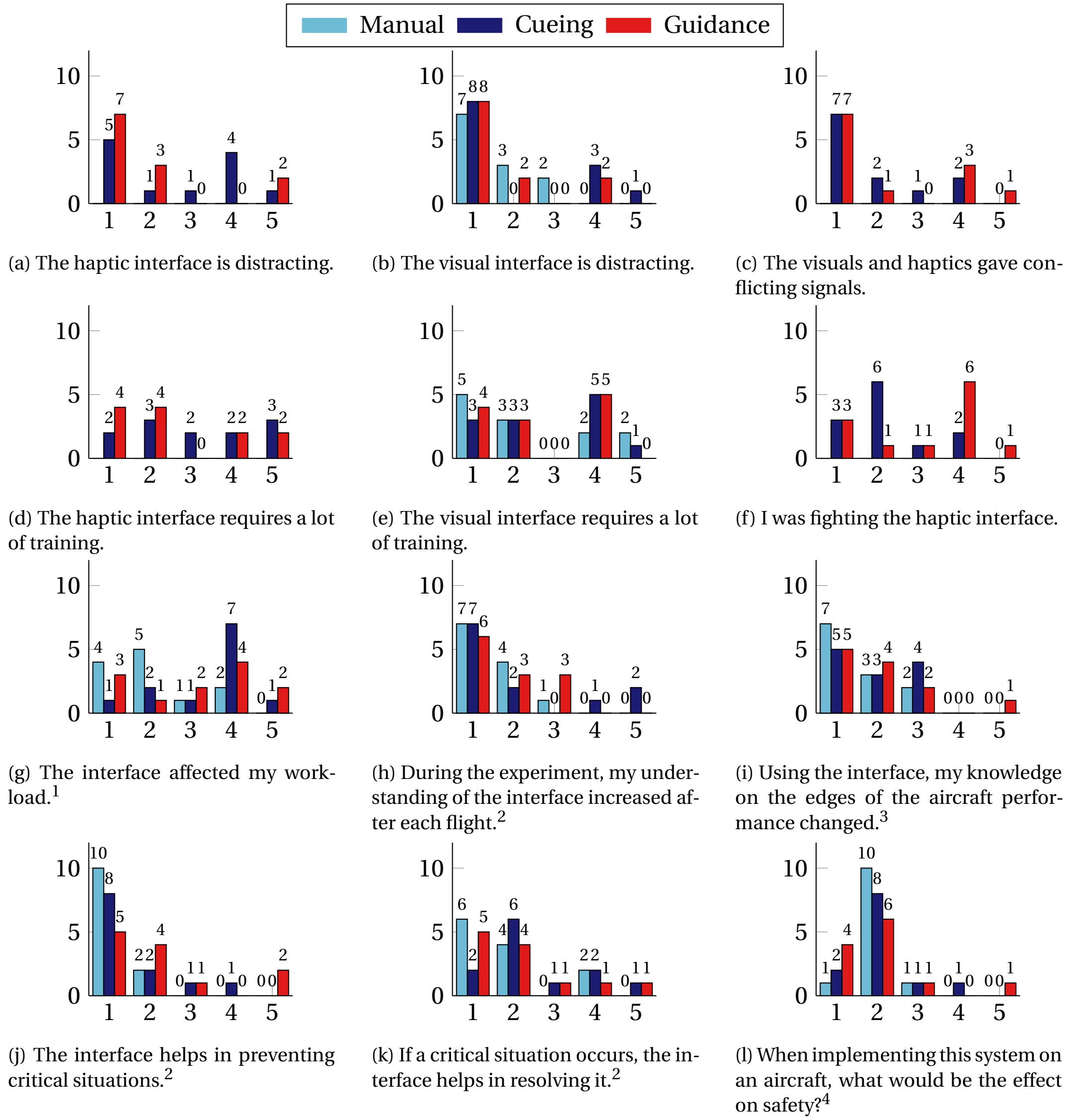


Figure 7.28: Do you prefer to fly with the haptic feedback system?

Unless mentioned otherwise, debriefing questions presented in this chapter used a five-point Likert scale, the results are shown in Fig. 7.29. Fig. 7.29a shows that about half of the participants in the cueing group agrees that the supplied haptic feedback is distracting, whereas the guidance group was more inclined to disagree with this statement.

Concerning the visual system, Fig. 7.29b, pilots in general disagree, i.e., the visual system is not distracting. For both the haptic and visual interface, all groups are unde-



(a) The haptic interface is distracting.

(b) The visual interface is distracting.

(c) The visuals and haptics gave conflicting signals.

(d) The haptic interface requires a lot of training.

(e) The visual interface requires a lot of training.

(f) I was fighting the haptic interface.

(g) The interface affected my workload.[1]

(h) During the experiment, my understanding of the interface increased after each flight.[2]

(i) Using the interface, my knowledge on the edges of the aircraft performance changed.[3]

(j) The interface helps in preventing critical situations.[2]

(k) If a critical situation occurs, the interface helps in resolving it.[2]

(l) When implementing this system on an aircraft, what would be the effect on safety?[4]

Figure 7.29: Debriefing Likert-scale questions. Possible answers (unless specified otherwise) were: 1) Disagree 2) Slightly disagree 3) Disagree nor agree 4) Slightly agree 5) Agree

[1] Possible answers: 1) Decreased 2) Marginal decrease 3) Did not change 4) Marginal increase 5) Increased
[2] Possible answers: 1) Agree 2) Slightly agree 3) Disagree nor agree 4) Slightly disagree 5) Disagree
[3] Possible answers: 1) Increased 2) Marginal increase 3) Did not change 4) Marginal decrease 5) Decreased
[4] Possible answers: 1) Much safer 2) Safer 3) Safer nor unsafer 4) Unsafer 5) Much unsafer

7

cided on whether much training is required (Fig. 7.29d and 7.29e). The majority of the pilots who received haptic feedback did agree that the visual and haptic feedback did not give conflicting signals, attesting to the design work reported in Ref. [119]. Nevertheless, a difference in groups might be present on whether the pilots were fighting the haptic system: Fig. 7.29f shows that for the majority of the cueing group this was not an issue, whereas the majority of the guidance group reported to be 'fighting' the haptic system.

Looking at the subjective effect on workload, Fig. 7.29g, the manual group indicates a decrease, the cueing group indicates an increase, and the guidance group is undecided. This is the second question where a statistical difference is found between groups ($p < 0.05$, $\chi^2 = 6.15$), and the post-hoc test indicates that there is a significant difference between manual and cueing groups, confirming the difference between these two groups.

Participants are almost unanimous on the possible learning effect: Fig. 7.29h indicates that their understanding of the interface increased throughout the experiment. Finally, when one of the systems (visual, cueing haptics, of guidance haptics) is implemented, participants expect the knowledge on the aircraft performance boundaries to increase (Fig. 7.29i), it prevents critical situations to occur (Fig. 7.29j), and if a critical situation occurs, it can help in resolving it (Fig. 7.29k). In conclusion, pilots expect the visual and haptic systems to increase safety (Fig. 7.29l).

The questions at the end of the debriefing questionnaire allowed participants to elaborate on any of the above questions, comment on the reality of the simulator, and possible other comments. The manual group indicated that the display increased awareness, yet might could lead to pilots focussing on the instruments, not looking outside. Participants in the cueing group used the haptics as an alerting cue, and the visual display as a measure of criticality. The guidance haptic feedback made flying at the limits harder, yet provided intuitive feedback.

Both groups who received haptic feedback indicated that more training might be required. All groups indicated that their performance might have improved solely due to familiarity with the simulator. Verbatim comments can be found in Section C.3.

7.5. DISCUSSION

With the results of the experiment presented before, two designs of haptic feedback were evaluated for their effect on training and their general acceptance by pilots. First of all, the debriefing questionnaires showed that pilots appreciated the haptic feedback and expect the system to support in knowledge of the flight envelope limits, prevent critical situations, and even help in resolving them. However, in each group they do voice a concern for over-reliance on the haptic and/or visual system.

The design principle with haptic feedback is to keep the pilot in the loop, thereby making the pilot more aware of the situation and possibly less likely to be surprised to an automation failure compared to supervising an autopilot. Nonetheless, a next step to investigate this can be the inclusion of haptic feedback failures in the experiment design. In the following paragraphs, both the cueing and guidance haptic feedback design is discussed separately to evaluate the hypotheses presented before.

7.5.1. CUEING HAPTIC FEEDBACK

Using the results of the manual group as a baseline, the cueing group was expected to obtain similar performance levels and safety margins at the first run. All metrics showed the expected result at Run 1, both as observed from the graph, and confirmed by lack of significant differences between the results of the manual and cueing groups.

Next, the cueing group was expected to learn faster, which would result in differences between both groups at Run 4. Although not directly visible in the altitude lost or integral of angle of attack over the maximum, looking at the time where the maximum angle of attack is exceeded, the cueing group is indeed closer to zero compared to the manual group (although not statistically significant). Additionally, the median of the highest angle of attack achieved during the recovery for the cueing group is below the maximum, whereas this is not the case for the manual group.

Furthermore, the cueing group shows a quicker improvement of the safety margins over Runs 2, 3, and 4. When removing the haptic feedback from the cueing group, no after-effects are expected, i.e., no changes in metrics from Run 4 to Run 8. This latter is present in all objective metrics used, hence the pilots used the haptic feedback to learn quicker how to stay within the angle of attack limits, and they are still able to do so when no haptic feedback is provided anymore.

These observations are in line with the results found in our previous experiment, see Chapter 6. That experiment contained a group which did not receive haptic feedback in Block 1, followed by the cueing haptic feedback in Block 2. Since the second block contained haptic feedback, the data from that group can not be used as a comparison for training effects. The first block did, however, show also that participants who did not receive haptic feedback had a much harder time keeping the aircraft within its limits. Participants in the earlier experiment had even more difficulty compared to the current manual group in this experiment.

The cueing haptic feedback was expected to provide pilots with an increased situation awareness at the cost of an increased workload and without the benefit of immediate improvements at the first run. Both the information missing as the feeling of being in control for the manual and cueing group did not differ, providing no evidence that an increased situation awareness is present at Run 1.

The RSME, however, did show a (non statistical significant) difference: the median of the cueing group is lower compared to the manual group, actually indicating less workload in contradiction to what was expected. The workload for cueing group was expected to decrease to Run 4 due to familiarization, which is partly confirmed by the RSME data: the statistical analysis only showed a difference between Runs 1 and 8, nonetheless, a decreasing trend in median RSME is visible supporting the expected decrease in workload due to familiarization.

The subjective situation awareness scales did not provide any evidence that a difference between groups is present at Run 1, 4, or 8. It did show an improving trend over the runs for all groups. This is to be expected due to familiarization with the task and model. Interestingly, going from Run 4 to Run 5, i.e., disabling the cueing haptic feedback, increased the spread for information missing. This can indicate that the haptic feedback is providing pilots information which they are consciously integrating in their control loop.

Modified Cooper-Harper ratings did not indicate any differences compared to the manual group. The change in Van Der Laan ratings between blocks showed that the cueing group did not have an improvement in usefulness, whereas the manual group did. This might indicate that the haptic feedback made the pilots understand the visuals more easily, yet differences are very small. For these two system evaluation ratings, differences are considered too small to draw any conclusions from them.

In contrast to the observations on workload before, the debriefing questionnaire showed that participants who received the cueing feedback indicated a marginal increase in workload. This might be attributed to the fact that the haptic feedback is slightly distracting, as the pilots indicated as well. Because of the contradicting answers in the RSME and the debriefing no clear conclusions can be draw for a change in workload when using the cueing haptic feedback.

In conclusion, the cueing haptic feedback system is able to provide the pilots with support in the learning process without after-effects, and without having large effects on workload or situation awareness. It does lack the ability to support the pilot at the very first encounter with a certain limit. Therefore, it might be well-suited to provide such feedback to pilots in simulators to support the learning process, without the disadvantage of dependency on such a system when transferring to the real aircraft.

7.5.2. GUIDANCE HAPTIC FEEDBACK

The guidance group was expected to have an improved performance and safety margin compared to the other groups already at Run 1. For all metrics, there is a significant improvement in relation to the cueing group, and only 'near statistical significance' differences compared to the manual group. Nevertheless, the plots of all metrics show that the guidance group obtained a lower median *and* a lower spread. This means that the participants in the guidance group did not only do better, they were also more consistent across all participants. In other words, when using this haptic feedback system, a safer operation from the first time can be expected.

At Run 4, performance and safety margins are not statistically different from the manual group, yet the time of angle of attack above the maximum only shows two outliers above zero, and the highest angle of attack is clearly below the maximum value. This indicates that better metrics are achieved compared to the manual group. They are, however, of similar value as the cueing group. An improvement for the guidance group in time and integral of angle of attack above the maximum is found from Run 1 to Run 4, indicating that a minor learning process is still present.

When the haptic feedback is disabled, we expected the performance and safety margins to deteriorate. This did not largely happen in the amount of altitude lost, yet in the other safety margin metrics an increase in spread of the data can be seen. In other words, when no haptic feedback is supplied, three participants (or 25%) did exceed the angle of attack limits, giving some evidence for the "guidance hypothesis". This improved spread also contributes to the lack of significant changes between Run 1 and Run 5 for the guidance group.

The guidance haptic feedback was expected to actively support the pilot from the first run and thereby reducing the workload, at a cost of decreased situation awareness. The lack of changes in information missing and feeling of being in control at Run 1 gives no evidence that a decrease in situation awareness is present. The workload ratings at Run 1 show a (non-statistical significant) lower median rating compared to the manual group, indicating a reduced workload. This is a similar observation as with the cueing group which can indicate that for this setup/model/task, a multi-modal system, including haptic and visual feedback, is preferred over visual only.

Looking at all runs, the workload rating of the guidance group is consistently between the ratings of the cueing and the manual group, indicating that the guidance haptic feedback provides a reduced workload compared to no haptic. Nevertheless, in the debriefing questionnaire, not all pilots were convinced that a lower workload is achieved, and it shows that a number of them reported fighting the haptic feedback system at times. As the RSME and questionnaire are again contradicting, no clear conclusions can be draw with respect to workload.

Although the subjective situation awareness did not differ at Run 1, the larger spread on the amount of information missing for the guidance group can indicate that the haptic feedback is supporting the pilots, yet it is not transparent in why it is doing so. Additionally, during the final four runs, the spread of the data is much higher compare to the manual group, indicating that the pilots who do not receive guidance feedback anymore have difficulty adjusting to the new situation.

As before, modified Cooper-Harper ratings did not change, and no change in usefulness was present for the Van Der Laan ratings of the guidance group. The latter might indicate that the visuals were better understood because of the presence of haptics, i.e., multi-modal information. Nonetheless, differences for both ratings are considered too small to have any meaningful indication.

Compared to no haptic feedback, the guidance haptic feedback system is able to provide pilots with support during operation of the aircraft, without having large effects on workload or situation awareness. It is subjected to after-effect, as the spread of both the objective metrics and the amount of information missing increases when haptic feedback is no longer supplied. As such, it might be well-suited to provide such feedback to pilots during continuous operation of the aircraft. The after-effects have to be mitigated, for which more research is needed. Possibly a visual/aural indication can be added such that pilots are aware when the system is disabled and do not rely on it.

The design of the guidance haptic feedback was setup to make sure the pilot is in final control and can always over-ride the haptic inputs. To guarantee this with an increasing stiffness, a maximum force required to move the side stick was implemented after which a zero-slope force was present. The last example presented in the results showed one design flaw: when the participant exerts a force on the side stick of this maximum value, the feeling can be 'lock-in' on the flat slope. In this situation, the stiffness and neutral point can still change, yet the participant will not notice this as (s)he is already pulling at the maximum force level. Future designs are recommended to avoid such a condition by, for example, implementing a shallow force gradient beyond the maximum force such that at least the effect of the neutral point shift can be felt.

7.6. CONCLUSION

This chapter compared two designs of a haptic feedback system, using force feedback on the control device, to a situation without haptic feedback. These systems are expected to inform pilots on the flight envelope limits and protections in a modern fly-by-wire aircraft. One design used forcing functions which are asymmetric in time and amplitude, and warn the pilots of an approaching limit, as well as of the direction of the corrective action. In other words, this design is haptically *cueing* the pilot on the limits.

The second design actively changed the side stick mechanical properties to indicate a required direction to remain clear of the limits, as well as increased the stiffness for an input which brings the aircraft closer its limits. Therefore, this second design is haptically *guiding* the pilot near the limits.

Three groups – one with the cueing, one with the guiding, and one without haptic feedback – of each 12 PPL/LAPL pilots were used to evaluate the systems by flying 8 runs. Each run contained a trajectory shown on the outside visual and during the run a windshear was encountered. The first 4 runs were flown with haptic feedback for two out of three groups, the last four runs were flown without haptic feedback.

The results of the pilots flying with the cueing haptic feedback, compare to those who flew without haptic feedback, showed that the cueing feedback is able to provide support in the learning process. It can do so without suffering after-effects, i.e., when transitioning to a condition without haptic assistance. Additionally, it does not have large effects on workload or situation awareness. This system does not support the pilot at the first encounter with a certain limit.

Results showed that the guidance haptic feedback system is able to provide the pilots with support during operation of the aircraft, also without having large effects on workload or situation awareness. It is sensitive to an after-effect, and creates a reliance on the system, as the spread of both the objective metrics and the amount of information missing increases when no haptic feedback is supplied.

8

Discussion, Recommendations, Conclusion

Each chapter in this thesis looks at an individual aspect or iteration of the haptic feedback system for flight envelope protection. This last chapter revisits the conclusions presented in those previous chapters and indicates how these provide answers to the main research questions. This information is used to form recommendations for future haptic feedback implementations and evaluations. Finally, the conclusion of this thesis is presented.

Parts of this chapter are currently under review to be published as:

Title	Flying by Feeling: Communicating Flight Envelope Protection through Haptic Feedback
Journal	International Journal of Human-Computer Interaction
Authors	D. Van Baelen, M. M. van Paassen, J. Ellerbroek, D. A. Abbink, and M. Mulder

8.1. DISCUSSION

WITH the advent of fly-by-wire, the mechanical connection between the pilot and the control surfaces disappeared. This resulted in the loss of haptic information, i.e., through the sense of touch on the controls, on the aircraft near the limits of the flight envelope. For example, a change in velocity did not result in a different force required on the controls, nor did the controls show the stall buffet. Missing this information might contribute to a reduced situation awareness near the limits of the aircraft. Additionally, the fly-by-wire systems enabled designers to include a flight envelope protection system: when approaching a limit of the aircraft flight envelope, the computer over-rides the inputs of the pilot to make sure no limit excursion will occur. Nevertheless, the state of such a system is not always clearly communicated to the pilots.

New control devices have the possibility to re-introduce haptic feedback on the flight deck, and are not limited to the feel of flight controls physically connected to the control surfaces. This presents a new design opportunity: using the haptic feedback to provide the pilot with information on the flight envelope protection system. In order to see how such feedback system can be designed, this thesis investigated several concepts.

In the following sections, each of the research questions presented in Chapter 1 are revisited and discussed. Those answers are used in the recommendations which follow in the next section. Finally, the conclusion of this thesis is presented.

8.1.1. FIRST DESIGN ITERATION

Previous exploratory research showed that a haptic feedback system could be useful, yet pilots noted that they missed a clear cue on the flight envelope protection activation. This thesis started with an investigation into the addition of such a cue to the haptic feedback system and results in the first research question:

Research Question 1: Combining vibrations and guidance design

Does a haptic feedback design combining stiffness changes, neutral point shifts, stick shaker, and discrete cues improve pilot situation awareness?

8

Chapter 2 described a haptic feedback system involving all those cues to inform pilots on the flight envelope protection system. To evaluate this design, an experiment involving eleven Airbus pilots was conducted as presented in Chapter 3. Pilots were asked to fly approaches during which they encountered either a windshear, or ice building up on the wings. The first scenario required the pilots to move close to the aircraft limit, while in the second scenario the limits approach the current aircraft state.

Results showed no significant changes in performance and safety margins for any of the conditions or control laws used. Nevertheless, the haptic feedback did not hinder pilots in performing their tasks either. The debriefing indicated that some pilots experienced an increased situation awareness, and most pilots see a potential benefit of implementing the haptic feedback system on a modern fly-by-wire flight deck. In conclusion, although most trends were positive, the experiment did not provide conclusive evidence of improved pilot situation awareness. Research Question 1 could not be answered due to the lack of evidence.

This conclusion corroborates with the systems evaluated in literature: multiple haptic concepts show great potential, yet lack clear conclusive evidence. This was found for the evaluation of system which changes the reference point of the control input, and limits the deflection based on the remaining control space ([52]), as well as the starting point of this thesis. [53, 54] The evaluation of an increased resistance near the flight envelope edges did show more conclusive results, although it used several non-pilots in the evaluation which renders the results less convincing. [50]

A probable reason for the lack of conclusive evidence for the results presented in Chapter 3, and possibly for the evaluation in literature, is the low number of experiment participants, the natural tendency of pilots to stay away from the limits, and the difference in behavior of multiple pilots.

8.1.2. COMPLEMENTING VISUALS

Pilots in the first design evaluation indicated that the trigger of a haptic cue was not always clear. A solution was expected to be found in providing the information using multiple modalities, i.e., multiple senses. Therefore, a visual addition was proposed in the next research question:

> **Research Question 2: Complementing visuals**
>
> What kind of visual display can be used to complement the haptic information?

Chapter 4 looked into the design and evaluation of such a visual addition to the primary flight display to complement the haptic feedback in the communication of the flight envelope protections. The primary goal was to visualize the direction and force of the haptic feedback so as to make the cause of the haptic feedback cues more transparent with multi-modal signals.

8

The combination of haptic and visual feedback was evaluated by 16 professional Airbus pilots. These pilots flew twelve approaches for the measurement phase in which one of three scenarios occurred. Either a windshear occurred, a sidestep to an adjacent runway was required, or ATC required the pilot to discontinue the approach and go-around. The windshear scenario was, as in the previous evaluation, intended to force pilots to fly at the longitudinal aircraft limits, the sidestep scenario was intended to force pilots to the lateral aircraft limits.

Results did not show significant differences in performance, or safety metrics. The debriefing of this experiment revealed that pilot appreciation of the haptic feedback marginally increased, and that their understanding of the haptic feedback was increased. It is therefore recommended to show the flight envelope protection information using multiple modalities, in other words, we advice to use the visual display proposed in Chapter 4 when providing haptic feedback, answering Research Question 2.

Literature corroborates this conclusion since multi-modal information is generally assumed to improve acceptance. [58] Such improved acceptance with visual and haptic information was found in a remote-pilot task ([92]), and in an automotive context. [136] As such, independent of the application, any haptic feedback should be complemented with a visual indication.

8.1.3. VIBRATIONS DESIGN

The debriefing of the first design iteration showed that the vibro-tactile cue, the 'tick-on-the-stick', was particularly well received by the participating pilots. Nevertheless, the direction of that cue was not always clear. The next research question focused on further investigation of those vibro-tactile cues, or vibrations, to inform the pilot of an active flight envelope protection:

> **Research Question 3: Vibrations design**
>
> Does a haptic feedback design using only vibrations improve pilot situation awareness?

First, an experiment was performed in the perceivability of direction and activation of such vibrations in Chapter 5. Results showed that a sawtooth-shaped vibration had a lower threshold compared to a triangular shape. At the threshold, participants are just able to tell that a cue was provided *and* indicate the correct direction of the cue. Therefore, the sawtooth-shaped vibration was recommended for implementation as a cue to alert pilots.

This sawtooth-shaped vibration was included in the haptic feedback system in Chapter 6. It is used to inform pilots on an approaching flight envelope limit as well as on the direction of the corrective action. It was evaluated by 24 PPL/LAPL pilots who flew two sets of four runs. One set included haptic feedback, one did not. Each run consisted of a flight trajectory shown on the outside visual and included a windshear encounter.

Results did not show the expected changes: most metrics were unchanged when switching the haptic feedback, only the acceptance scale (Van Der Laan-questionnaire) improved slightly when enabling the haptic feedback. This could be contributed to an order effect: the first four runs caused such a strong learning effect that this order effect rendered the comparison invalid.

The results also indicated, however, that enabling the haptic feedback appeared to improve the learning rate after the first run, and that no after-effects were present when the feedback is removed. As such, besides the fact that most pilots were positive about the system and indicated that they expect it to improve safety, the results suggest a potential training benefit. Such an effect could only be possible if some useful information is provided by the haptic feedback system, and therefore it should improve situation awareness, answering Research Question 3.

The training benefit makes the cueing design a possible addition to a flight simulator training device in order to enhance learning. It could, for example, be used to improve the cues during the training of the flare manoeuvre to indicate off-nominal states. [125]

Vibro-tactile cues in the form of asymmetric vibrations are used in domains other then aerospace, for example, in automotive to indicate an imminent lane departure. [36, 71] The sawtooth-shaped asymmetric vibration used in our application proved to be more powerful in communicating the direction of the cue. It is therefore recommended to use this cue in other applications, like automotive, to improve haptic communication.

8.1.4. GUIDANCE DESIGN

The haptic design based on vibrations alone did not help on the first encounter, and a different haptic feedback design approach was required. Literature showed that a design involving force feedback is often better able to guide pilots near the limits, which is the topic of the final research question:

> Research Question 4: Guidance design
>
> Does a haptic feedback design combining stiffness changes and neutral point shifts improve pilot situation awareness?

Chapter 7 presented a design that actively changed the side stick mechanical properties to indicate a required direction to remain clear of the limits, as well as increased the stiffness of the stick for inputs which would bring the aircraft closer its limits. Therefore, it is haptically guiding the pilot near the limits.

It was evaluated in a similar setup as the previous design using runs where pilots followed a trajectory shown on the outside visual during which a windshear was encountered. In the first set of four runs, one group (of twelve pilots) received the guidance haptic feedback, one group did not receive any haptic feedback at all. Next, a second set of four runs was flown where all groups performed the task without haptic feedback.

Results show that the guidance haptic feedback system is able to provide the pilots with support during operation of the aircraft, without having large effects on workload or subjective situation awareness. Since it supports from the very first use, it *has* to transfer information to the pilot and therefore, implicitly, improve pilot situation awareness, answering Research Question 4. The concept is, however, sensitive to an after-effect: it creates a reliance of the pilot on the system as indicated by the spread of both the objective metrics, and pilots commenting that information is missing when the haptic feedback is no longer supplied. This indicates that this last design can be useful to be implemented on the control device of an aircraft, as long as the support is always provided.

This conclusion is corroborated by literature on concepts which use force feedback to provide support from the first use, and is typically denoted as the "guidance hypothesis". [127] It was found in, for example, an abstract control task ([33]), and automotive examples. [38] Therefore, any application using force feedback should always provide the feedback, and should consider the implications when such feedback can no longer be supplied.

8.2. RECOMMENDATIONS

Based on the findings of the concept evaluations a number of general design recommendations can be given. In addition, some avenues for future research in haptic feedback support for envelope protection systems are stated as well.

8.2.1. DESIGN GUIDELINES

Chapter 1 introduced the two main types of haptic feedback discussed in this thesis: vibro-tactile and force feedback. The first concept, presented in Chapter 2, mixes both type of feedback: it uses both a 'tick-on-the-stick' to warn the pilot of the approaching limit, i.e., vibro-tactile feedback, and adjusted the stiffness to indicate the proximity, i.e., force feedback. The second design, presented in Chapter 6, involved only vibro-tactile cues in the form of asymmetric vibrations, and the last design, in Chapter 7, used pure force feedback by changing the stiffness and changing the neutral point.

Combining the division of the concepts based on the type of haptic feedback, together with the discussion of the research question presented above, results in the three main design guidelines from this thesis:

1. A haptic feedback system for flight envelope protection should be complemented with visual indications.

   It shows pilots why a haptic cue is provided and improves pilot acceptance.

2. Vibro-tactile cues should be used during training to inform the pilot of the flight envelope protection system.

   It increases learning rate, and it appears that such systems do not shown after-effects when support is removed.

3. Force feedback should be provided throughout the operation of the aircraft to inform the pilot of the flight envelope protection system.

   It supports the pilot in staying within the flight envelope limits, yet is susceptible to performance degradation when removed.

8

8.2.2. FUTURE RESEARCH

To further investigate the application of haptic feedback on the modern flight deck, more research is required on several aspects.

Flight envelope protection system One common denominator across all concepts and evaluations is the data used to trigger the haptic feedback: each concept used an Airbus A320 model and the associated flight envelope protection system. Other aircraft manufacturers can have different approaches on how to provide flight envelope protection, for example, where Airbus typically has a 'hard' flight envelope protection in normal law, i.e., the aircraft can not be controlled outside the nominal flight envelope limits, Boeing aircraft have a 'soft' flight envelope protection, i.e., the flight control computers allow states outside the nominal flight envelope when the pilot exerts extreme control inputs. In the latter, pilots are informed about the flight envelope limits by aural, visual cues, and an increased stiffness, which resembles the stiffness used on our haptic shared designs. [137]

Although the concepts have been evaluated on a single flight envelope protection system, the concepts have not only been tested on a hard flight envelope protection system. The first evaluation was performed with both Airbus normal and alternate control law, respectively a hard and a soft flight envelope protection system. [13] The other haptic feedback concepts were only evaluated in alternate law, to provide the participants with a more challenging environment.

It was argued in Chapter 2 that the haptic feedback concepts are intended to provide the same haptic cues in both normal and alternate law, i.e., in both hard and soft flight envelope protection systems. Since pilots should always be able to over-rule the haptic feedback, it provides a layer of soft flight envelope protection in all situations. As such, the concepts presented in this thesis can be used in conjunction with either a hard or soft flight envelope protection system.

A possible difference in the flight envelope protection system between aircraft manufacturer can be the variables which define the flight envelope. [138] For all concepts in this thesis, the flight envelope was defined by angle of attack, load factor, velocity and bank limits, which are commonly used throughout the aviation domain. We expect that the haptic cues used in this thesis can be extrapolated to other flight envelope definitions, yet this needs to be further investigated.

Startle by haptic feedback As mentioned in the previous paragraphs, the haptic feedback was designed to be used in both normal and alternate control law and provide intuitive support. This strategy results in pilots being more accustomed to the haptic feedback. Familiarity with the system is required as the haptic feedback system for flight envelope protection is activated only when the aircraft state approaches the flight envelope limits, which occurs very rarely. [98] If a pilot is not accustomed to the haptic feedback system, there is a risk for pilot startle. [139]

In the evaluations performed in this thesis, the haptic feedback system was explained in detail to each participant, and practised with, prior to starting the measurement phase. This procedure made sure that all participants were familiar with the simulator and the interfaces, including the haptic feedback, to reduce startle to a minimum. Next, the aircraft in each measurement run was operated at the edge of the flight envelope, making the participant accustomed to the warnings.

Although startle should not have been present in the evaluations, warnings are known to be a possible source of startle. [140, 141] Future research should therefore investigate whether the haptic feedback concepts in this thesis are prone to startle. Such experiment could, for example, simulate a departure and cruise phase, followed by an emergency situation, comparable to what happened to Air France 447.

Implementing asymmetric vibrations Asymmetric vibrations were found to provide an alerting and directional cue in Chapter 5, and were evaluated as a flight envelope protection cue in Chapter 6. The effects of those cues on the aircraft dynamics were investigated in Section 5.6, and considered to be minor. Similar vibrations were implemented in an automotive study and found that most of the motion is dampened by the driver holding the steering wheel. [36] Chapter 6, however, assumed that these cues could be implemented such that they have no effect on the aircraft dynamics.

Such an implementation was not designed and should be done in a next step. Possible solution could be at hardware level, for example, by providing the vibration internally in the side stick, or at software level by subtracting the vibration force from the measured force on the side stick.

After-effects The analysis of the haptic feedback systems presented in Chapter 6 and Chapter 7, looked into a possible effect of the haptic feedback system on the learning rate. It included a block of runs in which no haptic feedback was provided anymore to investigate any after-effects, i.e., a possible change in metrics when the feedback is not provided. Those experiment were confined to one scenario, windshear, which was repeated several times. Although two other checklists for other scenarios were presented, some participants indicated that they started to expect the windshear.

Using one scenario for training and evaluation is an approach similar to those found in evaluations of other haptic support systems with force feedback. [33, 127, 128] This approach was useful to compare results found in this thesis to those found in literature. Nevertheless, pilots are expected to encounter a large variety in scenarios during operation.

To further investigate the effect of the repeated scenario on the results and possible after-effects, an experiment which presents different scenarios to the pilots should be performed. If the repeated scenario of the experiments in Chapter 6 and Chapter 7 was not a confound, this new experiment should provide similar results.

Additionally, the guidance design presented in Chapter 7 was showing evidence of the guidance hypothesis: when the haptic feedback is no longer provided, a degradation in pilot situation awareness was present. The impact of this degradation should be further investigated and has to be mitigated. Such mitigation could involve a visual and/or aural indication to inform the pilot on the loss of haptic feedback.

Transfer-of-training Another element in training is the transfer-of-training which is an combination of how much knowledge obtained in the training is transferred to the targeted task, and whether that knowledge can be generalized. [142] The former was evaluated, for the experiments in Chapter 6 and Chapter 7, when the haptic feedback was no longer provided in the second phase of the experiment. The latter, whether the knowledge is generalized, is not evaluated in this thesis.

To evaluate whether the skill obtained during training can be used in different scenarios, a new generalization scenario should be presented to the participants. For example, in a flare training, an different approach was presented to the participants. [125] The generalization scenario in the context of this thesis should provide a new situation to the participants in which the flight envelope protection system is activated, but due to a different emergency. Evaluating the possible changes in metrics can indicate whether the participants can apply the skill to different applications, i.e., whether they can generalize the knowledge obtained during training.

Single-pilot operations Economic advantages of having fewer pilots are transitioning future flight decks of commercial passenger aircraft from multi-pilot to single-pilot operations. [143] Although this transition is already present for smaller aircraft, such as business jets like the Cessna CJ series, larger aircraft did not make the transition yet. A major hurdle for this transition is maintaining situation awareness of the pilot on all systems, and the increase in workload when operating large aircraft in the highly congested airspace with fast communication and without room for deviations. [144]

In order to cope with the challenges of those single-pilot operation flight decks, disruptive changes are required to current flight decks of which several are investigated with grants from the National Aerospace Technology Exploitation Program, for example, see Ref. [145] and in the 'Disruptive Cockpit for Large Passenger Aircraft'-project of the Clean Sky program. [146] Their publications indicate that those technologies focus on improving automation, for example using vision-augmented approaches and autonomous instrument monitoring, and interfaces for pilots, for example using touch screens. However, the latter does not seem to include haptic feedback through the control device.

Haptic feedback has been shown in this thesis to have a potential to improve pilot awareness of the flight envelope protection system. Therefore, it should be used in those single-pilot flight decks to support the pilot. Additionally, haptic feedback has been used to support pilots in a path-following task ([41]), which could be used to inform the pilot on the nominal autopilot control action.

To mitigate high workload during an emergency, a remote pilot can assist the on-board pilot. [143] Proper crew resource management is a vital component for a successful cooperation. Haptic feedback can be used to communicate control actions between pilots, for example, by linking the movements of the control devices such that each pilot can feel the control actions of the other.

This thesis has investigated the use of haptic feedback for flight envelope protection system awareness. A haptic feedback design for the other uses might include similar cues, resulting in possible mixed messages. Following the research on the visual display complementing haptic feedback, any design should be supported by a matching visual indication. Nevertheless, more research is required to evaluate whether some or all types of haptic feedback can be mixed to support pilots in future single-pilot flight decks.

8.3. CONCLUSION

This thesis started with a concept which involved both types of haptic feedback considered: vibro-tactile *and* force guidance. It was important to make the distinction between both types as the evaluation of the combined system showed no conclusive results. To further investigate the two types of haptic feedback, both were separately developed further and tested. The evaluations of these concepts did not result in large differences in metrics, but each concept was found to have its strengths: vibro-tactile feedback proved to be valuable during training, force guidance valuable during continuous operation. Results indicated that pilots did not perform any worse when provided with haptic feedback. Overall, pilots agree with the potential added benefit of the haptic feedback. With this information, we can look back at the main research goal of this thesis:

Research goal

Within the current fly-by-wire flight deck, improve pilot situation awareness of the aircraft flight envelope protection system using haptic feedback.

The concepts considered in this thesis used haptic feedback to communicate the flight envelope limits, and therefore the flight envelope protection activation. Each concept was shown to provide this information for a specific use-case.

Therefore, this thesis proposes that pilot situation awareness of the aircraft flight envelope protection system can be improved using haptic feedback and should be implemented on the fly-by-wire flight deck.

Appendices

A

EXPERIMENT QUESTIONNAIRES

THIS appendix shows the documents used during an experiment, specifically the experiment performed to investigate the asymmetric vibrations for flight envelope protection. The briefing provided to the pilots approximately two days before the experiment is shown in Section A.1. Before the actual experiment starts, all pilots are asked to provide information concerning their experience, Section A.3, as well as sign an 'informed consent form' shown in Section A.2.

During the measurement phase of the experiment, participants are asked to fill in a short questionnaire after each run which is slightly different when the run was provided with or without haptic feedback, as exemplified in respectively Section A.4 and Section A.5. After a block, i.e. after four runs, the participants are asked to fill another questionnaire concerning their experience with the system provided covering all four runs, again slightly different when haptics is or is not provided as shown in Section A.6 and Section A.7. Finally, to streamline the debriefing after the experiment, a final questionnaire is provided to the participants for which an example is shown in Section A.8.

Three sets of debriefing questionnaires are used throughout this thesis: i) the set used in the first experiment, Table A.1, ii) one set for the groups who received haptic feedback in the later experiments, Table A.2, and iii) one for the group who did not receive haptic feedback in the last experiment where the questions are altered to reflect the visual interface, Table A.3. Note that the questions of the latter are numbered one to 14 when presented to the pilots, the numbering is changed here to match the question numbering of the other groups.

A.1. EXPERIMENT BRIEFING

Interface experiment briefing

Dear pilot

First of all, thank you for participating in our research experiment! Without your valuable contribution, our analysis cannot achieve a practical implication. Throughout this experiment, we will investigate the possibility of combining visual, aural and haptic feedback (also known as force feedback through the control device) in different sections of the flight envelope. To prepare you for the experiment, this document provides you with the most essential information.
If you have any remaining questions, feel free to contact me!

Kind regards

Dirk Van Baelen

1 Logistical information

Time:	13:00 - approximately 16:00
Location:	Human-Machine-Interdace Simulator, Kluyverweg 1, 2629HS Delft
	Route description can be found on https://iamap.tudelft.nl/poi/gebouw-62/
Meeting place:	Service desk in the main entrance, you can ask at the desk for me (Dirk Van Baelen)
Telephone:	(0031) 15 278 9108
Email:	d.vanbaelen@tudelft.nl

2 Apparatus

The experiment is conducted in the Human Machine Interaction (HMI) simulator at the faculty of Aerospace Engineering, University of Technology Delft. It contains a glass cockpit setup resembling the displays of an Airbus. Furthermore, a projection system generates the outside world. You will be seated in the first officer position where you have access to the side stick, pedals, throttles and FCU which resemble an Airbus as close as possible in the simulator. An impression of the flight deck can be seen in Figure 1.

You will fly an Airbus A320-alike model. We are aware that you might not be accustomed to the size of such an aircraft, so we will provide you time to get accustomed to the model, its behavior and controls.

Figure 1: Human Machine Interaction Simulator

A

A.2. INFORMED CONSENT

3 Experiment procedure

The experiment starts around 13:00 and ends at approximately 16:00. We have allocated time for a break, if you do need an extra break, please inform me.

Before we start flying, I will explain the visual, aural and haptic interfaces, as well as the emergency procedures for three scenarios. A small training flight is used to get you accustomed with the setup and model. If you have any questions during this part, or anywhere in the following, give a shout.

During the majority of the time, you are asked to fly through a series of climbing/descending gates which are shown on the outside visuals. Each run is ended with a small questionnaire concerning the visual/aural/haptic interfaces. Several runs are combined in a block, which is again ended with a small questionnaire. At the end of the experiment, one final questionnaire inquires you on the overall experience in the experiment. If any questions remain, I will make sure they are answered at that time!

Throughout the experiment, in each of the runs performed, we ask you to fly as you would in a real aircraft in the given circumstances. Note that due to limitations of the simulation, each flight is stopped when the limit of 50 ft AMSL is reached, regardless of any other event.

4 Your rights

Participation in the experiment is entirely voluntary. This also means that you can withdraw for any reason, even during or after the experiment. Collected data (log of the simulation states and paper forms) is saved anonymously. By participating you also agree that your (anonymous) data can be used in publishing this study. There will be no sound or image recordings. On the day of the experiment, I will ask you to sign a form indicating that you understand and agree with the above.

I am looking forward to welcoming you on the day of the experiment.

A

A.3. BEFORE THE EXPERIMENT

☐
pilot

Personal and professional information

To be able to put the results in relation to experience, you are asked to fill in this questionnaire.

1	**PERSONAL**		
1.1	Age ______________		
1.2	Gender ☐ Male ☐ Female ☐ Other		

2	**FLIGHT EXPERIENCE**		
2.1	License type(s)	☐ PPL ☐ CPL ☐ GPL	☐ LAPL ☐ ATPL ☐ ______________
2.2	Flight hours	Total: __________ Airbus: __________	
2.3	Class-rating(s)	Current: __________________________ Previous: ________________________	
2.4	Type-rating(s) (if applicable)	Current: __________________________ Previous: ________________________	
2.5	Current professional pilot function (if applicable)	☐ Captain ☐ N/A	☐ First officer ☐ ______________
2.6	Do you have experience with glass cockpits?	☐ Yes, in flight ☐ Yes, simulator	☐ No
2.7	Have you ever experienced windshear while airborne?	☐ Yes	☐ No
	During which flight phase did the windshear occur?	☐ Take-off ☐ Climb ☐ Cruise	☐ Approach ☐ Landing ☐ ______________
2.8	Have you ever experienced one engine out while airborne?	☐ Yes ☐ N/A, no ME	☐ No
	During which flight phase did this occur?	☐ Take-off ☐ Climb ☐ Cruise	☐ Approach ☐ Landing ☐ ______________
2.9	Have you ever experienced a sudden change in CG? (for example a sudden load change, ...)	☐ Yes	☐ No
	During which flight phase did this occur?	☐ Take-off ☐ Climb ☐ Cruise	☐ Approach ☐ Landing ☐ ______________
2.10	Did you receive an upset prevention and recovery training (UPRT)?	☐ Yes	☐ No

3	**RESEARCH EXPERIENCE**		
3.1	Have you ever participated in a research experiment?	☐ Yes	☐ No
	If yes, please elaborate on the type of experiment. (handling qualities research, motion cueing research, ...) ______________________________ ______________________________ ______________________________ ______________________________		

Page 3 / 4

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Information beyond this point is treated separately from the above to ensure anonymity.

INFORMED CONSENT

DECLARATION OF PARTICIPATION

Recorded data will be separated from your identity; at no time, neither now, nor in the future, will any information you provide be published that allows you as an individual to be identified. We certify to treat collected data according to good practice and follow sound ethical rules.

Note that we do record simulation states, and we do NOT record images or sounds throughout the experiment.

I hereby confirm that I have read the experiment briefing. I affirm that I understand the experiment instructions, and I declare that I voluntarily participate in this experiment. Also, I am aware that the collected data can be published in relation to this work on asymmetric vibrations. Finally, I have been clearly informed that I can opt-out of my participation in the experiment at any moment before, during, or after the experiment.

Please provide your signature below to indicate that you agree to participate in this experiment and accept the above. Signing this form does not annul the responsibilities of the researcher and Delft University of Technology towards you as a participant.

Name ______________________ Age ______ Date ___________ Signature ______________________

Page 4 / 4

A.4. After each run with haptics

pilot	run
	1

Questionnaire after run with haptics

1 MENTAL LOAD

1.1 How demanding was this run?

150	
140	
130	
120	
110	EXTREME EFFORT
100	VERY GREAT EFFORT
90	
	GREAT EFFORT
80	
70	CONSIDEREABLE EFFORT
60	
	RATHER MUCH EFFORT
50	
40	SOME EFFORT
30	
	A LITTLE EFFORT
20	
	ALMOST NO EFFORT
10	
	ABSOLUTELY NO EFFORT
0	

2 SITUATION

2.1 Did you have the feeling that you were in control?

Never — Always

Why (not)? ____

2.2 Did you have the feeling that you were missing information?

Never — Always

If yes, which? ____

3 INTERFACE

3.1 Indicate how helpful the elements are to stay within the limits during the emergency (if encountered).

	Not at all	Slightly	Moderately	Very	Extremely
Display: Yellow bar	☐	☐	☐	☐	☐
Display: Red bar	☐	☐	☐	☐	☐
Display: Bar thickening	☐	☐	☐	☐	☐
Haptics: Initial tick	☐	☐	☐	☐	☐
Haptics: Repeated tick	☐	☐	☐	☐	☐
Haptics: Stick shaker	☐	☐	☐	☐	☐

4 MISC SCALE

4.1 Did you experience any motion sickness symptoms?

		Typical symptoms				Nausea				
☐ 0 No problems	☐ 1 Uneasiness	☐ 2 vague	☐ 3 slight	☐ 4 fairly	☐ 5 severe	☐ 6 slight	☐ 7 fairly	☐ 8 severe	☐ 9 (near) retching	☐ 10 Vomiting

Typical symptoms include dizziness, warmth, headache, stomach, awareness, sweating, ...

A

A.5. AFTER EACH RUN WITHOUT HAPTICS

pilot	run
	1

Questionnaire after run with visuals

1 MENTAL LOAD

1.1 How demanding was this run?

150	
140	
130	
120	
	EXTREME EFFORT
110	
	VERY GREAT EFFORT
100	
90	
	GREAT EFFORT
80	
70	CONSIDEREABLE EFFORT
60	
	RATHER MUCH EFFORT
50	
40	
	SOME EFFORT
30	
	A LITTLE EFFORT
20	
	ALMOST NO EFFORT
10	
0	ABSOLUTELY NO EFFORT

2 SITUATION

2.1 Did you have the feeling that you were in control?

Never .... Always

Why (not)? ____________________

2.2 Did you have the feeling that you were missing information?

Never .... Always

If yes, which? ____________________

3 INTERFACE

3.1 Indicate how helpful the elements are to stay within the limits during the emergency (if encountered).

	Not at all	Slightly	Moderately	Very	Extremely
Display: Yellow bar	☐	☐	☐	☐	☐
Display: Red bar	☐	☐	☐	☐	☐
Display: Bar thickening	☐	☐	☐	☐	☐

4 MISC SCALE

4.1 Did you experience any motion sickness symptoms?

		Typical symptoms				Nausea				
No problems	Uneasiness	vague	slight	fairly	severe	slight	fairly	severe	(near) retching	Vomiting
0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Typical symptoms include dizziness, warmth, headache, stomach, awareness, sweating, ...

A.6. AFTER EACH BLOCK WITH HAPTICS

A

pilot

☐

Questionnaire after runs with haptics

1	GENERAL
1.1	How would you rate the interface? Tick one mark on each line.

useful	☐ ☐ ☐ ☐ ☐	useless
pleasant	☐ ☐ ☐ ☐ ☐	unpleasent
bad	☐ ☐ ☐ ☐ ☐	good
nice	☐ ☐ ☐ ☐ ☐	annoying
effective	☐ ☐ ☐ ☐ ☐	superfluous
irritating	☐ ☐ ☐ ☐ ☐	likeable
assisting	☐ ☐ ☐ ☐ ☐	worthless
undesirable	☐ ☐ ☐ ☐ ☐	desirable
raising alertness	☐ ☐ ☐ ☐ ☐	sleep-inducing

2	DISPLAY
2.1	Indicate how helpful the visual indications are to stay within the limits.

	Not at all	Slightly	Moderately	Very	Extremely
Yellow bar	☐	☐	☐	☐	☐
Red bar	☐	☐	☐	☐	☐
Bar thickening	☐	☐	☐	☐	☐

2.2 Do you want to remove an indication from the display?

☐ None ☐ Red bar

☐ Yellow bar ☐ Bar thickening

If you want to remove an item, please elaborate why:

____

____

2.3 Do you want to add an indication to the display?

☐ No

☐ Yes

If yes, please elaborate what and why:

____

____

Page 1 / 3

A

pilot

☐

3	HAPTICS
3.1	Indicate how helpful the haptic indications are to stay within the limits.

	Not at all	Slightly	Moderately	Very	Extremely
Initial tick	☐	☐	☐	☐	☐
Repeated tick	☐	☐	☐	☐	☐
Stick shaker	☐	☐	☐	☐	☐

3.2 Do you want to remove a cue from the haptics?

☐ None ☐ Repeated tick

☐ Initial tick ☐ Stick shaker

If you want to remove a cue, please elaborate why:

____

____

3.3 Do you want to add an indication to the haptics?

☐ No

☐ Yes

If yes, please elaborate what and why:

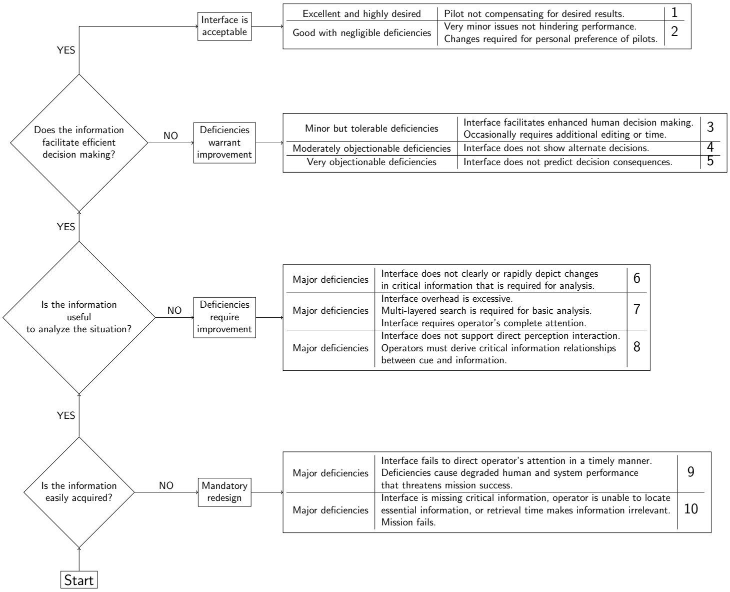
____

____

pilot

4	**STATEMENTS**
4.1	Following the scheme below, which mark would you give to the system concerning the communcation of the limits of the airplane?

1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐



End of questionnaire

A

A.7. After each block without haptics

pilot

☐

Questionnaire after runs with display

1 GENERAL

1.1 How would you rate the interface? Tick one mark on each line.

useful	☐ ☐ ☐ ☐ ☐	useless
pleasant	☐ ☐ ☐ ☐ ☐	unpleasent
bad	☐ ☐ ☐ ☐ ☐	good
nice	☐ ☐ ☐ ☐ ☐	annoying
effective	☐ ☐ ☐ ☐ ☐	superfluous
irritating	☐ ☐ ☐ ☐ ☐	likeable
assisting	☐ ☐ ☐ ☐ ☐	worthless
undesirable	☐ ☐ ☐ ☐ ☐	desirable
raising alertness	☐ ☐ ☐ ☐ ☐	sleep-inducing

2 DISPLAY

2.1 Indicate how helpful the visual indications are to stay within the limits.

	Not at all	Slightly	Moderately	Very	Extremely
Yellow bar	☐	☐	☐	☐	☐
Red bar	☐	☐	☐	☐	☐
Bar thickening	☐	☐	☐	☐	☐

2.2 Do you want to remove an indication from the display?

☐ None ☐ Red bar

☐ Yellow bar ☐ Bar thickening

If you want to remove an item, please elaborate why:

____

____

2.3 Do you want to add an indication to the display?

☐ No

☐ Yes

If yes, please elaborate what and why:

____

____

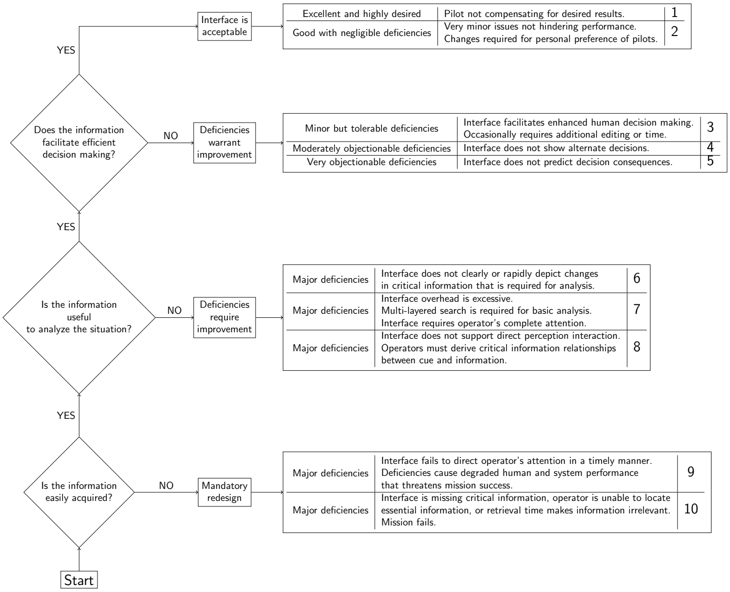
Page 1 / 2

A

pilot

3	**STATEMENTS**
3.1	Following the scheme below, which mark would you give to the system concerning the communcation of the limits of the airplane?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10 ☐



End of questionnaire

A

A.8. AFTER THE EXPERIMENT

pilot

Questionnaire after the experiment

Just one final set of questions left. Please complete the following questionnaire, it consists of 19 questions.

1 HAPTICS AND DISPLAY

1.1 Which interface has your preference?

- ☐ Only visual
- ☐ Visual and haptics

		Disagree	Slightly disagree	Disagree nor agree	Slightly Agree	Agree
1.2	The visuals and haptics gave conflicting signals.	☐	☐	☐	☐	☐
		Disagree	Slightly disagree	Disagree nor agree	Slightly Agree	Agree
1.3	I was fighting the haptic interface.	☐	☐	☐	☐	☐
		Decreased	Marginal decrease	Did not change	Marginal increase	Increased
1.4	Using the haptic system, my knowledge on the edges of the aircraft performance changed.	☐	☐	☐	☐	☐
		Disagree	Slightly disagree	Disagree nor agree	Slightly Agree	Agree
1.5	During the experiment (after the training), my understanding of the haptic interface increased after each flight.	☐	☐	☐	☐	☐
		Disagree	Slightly disagree	Disagree nor agree	Slightly Agree	Agree
1.6	The haptic interface requires a lot of training.	☐	☐	☐	☐	☐
		Disagree	Slightly disagree	Disagree nor agree	Slightly Agree	Agree
1.7	The visual interface requires a lot of training.	☐	☐	☐	☐	☐
		Disagree	Slightly disagree	Disagree nor agree	Slightly Agree	Agree
1.8	The haptic interface is distracting.	☐	☐	☐	☐	☐
		Disagree	Slightly disagree	Disagree nor agree	Slightly Agree	Agree
1.9	The visual interface is distracting.	☐	☐	☐	☐	☐
		Decreased	Marginal decrease	Did not change	Marginal increase	Increased
1.10	The haptic interface affected my workload.	☐	☐	☐	☐	☐

Page 1 / 2

pilot

		Disagree	Slightly disagree	Disagree nor agree	Slightly Agree	Agree
1.11	The haptic interface helps in preventing critical situations.	☐	☐	☐	☐	☐
1.12	If a critical situation occurs, the haptics helps in resolving it.	☐	☐	☐	☐	☐
1.13	The haptics influenced my behavior.	☐	☐	☐	☐	☐
1.14	If you changed your behavior, can you indicate the change? ____________					

		Much unsafer	Unsafer	Safer nor unsafer	Safer	Much safer
1.15	When implementing this system on an aircraft, what would be the effect on safety?	☐	☐	☐	☐	☐

1.16	Do you expect any negative consequences of the haptic interface? ☐ No ☐ Yes If you expect any negative outcome, please elaborate which: ____________ ____________
1.17	Do you have further comments concerning the above statements, or do you want to elaborate an answer? ____________ ____________

2	**SIMULATION**
2.1	Do you have any comments regarding the level of reality of the simulation? ____________ ____________

3	**OTHER**
3.1	Is there anything else you think we should know? Events that you think we should know about or comments you would like to make? ____________ ____________

End of questionnaire

Thank you for filling out all the questionnaires and for participating!
I you do have any further comments after this experiment, feel free to contect me (d.vanbaelen@tudelft.nl).

Page 2 / 2

Table A.1: Debriefing questionnaire elements

Question	Left label	Center label	Right label
What is your general feeling on the haptic feedback as an information cue about the flight envelope?	Negative	Neutral	Positive
The haptic interface affected my workload.	Less	Neutral	More
Using the haptic system, my knowledge on the edges of the aircraft performance changed.	Less	Neutral	More
If a critical event occurs, the haptic interface helps to mitigate the consequences.	Disagree	Neutral	Agree
The haptic interface changes the likelihood of human error.	Decreased	Neutral	Higher possibility
The haptic interface changed my behavior.	Disagree	Neutral	Agree
The haptic interface distracts me.	Disagree	Neutral	Agree
I was fighting the haptic interface.	Never	Sometimes	Always
Do you expect any adverse impact on outcomes when using this technology? (on a two point scale)	No		Yes
How would you grade the A320-alike dynamics?	Unrealistic	Acceptable	Perfect
How would you grade the controls? (side stick with nominal feeling)	Unrealistic	Acceptable	Perfect
How would you grade the displays?	Unrealistic	Acceptable	Perfect
How would you grade the weather?	Unrealistic	Acceptable	Perfect

Table A.2: Questions presented to the pilots in CHG and GHG after the experiment

	Question	Left label		Center label		Right label
1	*Which interface has your preference?* (on a two-point scale)		Only visual		Visual and haptics	
2	*The visuals and haptics gave conflicting signals.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
3	*I was fighting the haptic interface.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
4	*Using the haptic system, my knowledge on the edges of the aircraft performance changed.*	Decreased	Marginal decrease	Did not change	Marginal increase	Increased
5	*During the experiment (after the training), my understanding of the haptic interface increased after each flight.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
6	*The haptic interface requires a lot of training.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
7	*The visual interface requires a lot of training.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
8	*The haptic interface is distracting.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
9	*The visual interface is distracting.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
10	*The haptic interface affected my workload.*	Decreased	Marginal decrease	Did not change	Marginal increase	Increased
11	*The haptic interface helps in preventing critical situations.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
12	*If a critical situation occurs, the haptics helps in resolving it.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
13	*The haptics influenced my behavior.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
14	*If you changed your behavior, can you indicate the change?*			open question		
15	*When implementing this system on an aircraft, what would be the effect on safety?*	Much unsafer	Unsafer	Safer nor unsafer	Safer	Much safer
16	*Do you expect any negative consequences of the haptic interface? If yes, please elaborate.* (on a two-point scale)	No	Yes	space to indicate change		
17	*Do you have further comments concerning the above statements, or do you want to elaborate an answer?*	open question				
18	*Do you have any comments regarding the level of reality of the simulation?*	open question				
19	*Is there anything else you think we should know? Events that you think we should know about or comments you would like to make?*	open question				

A

Table A.3: Questions presented to the pilots in NHG after the experiment

	Question	Left label		Center label		Right label
4	*Using the support system, my knowledge on the edges of the aircraft performance changed.*	Decreased	Marginal decrease	Did not change	Marginal increase	Increased
5	*During the experiment (after the training), my understanding of the visual interface increased after each flight.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
7	*The visual interface requires a lot of training.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
9	*The visual interface is distracting.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
10	*The visual interface affected my workload.*	Decreased	Marginal decrease	Did not change	Marginal increase	Increased
11	*The visual interface helps in preventing critical situations.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
12	*If a critical situation occurs, the visuals help in resolving it.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
13	*The visual influenced my behavior.*	Disagree	Slightly disagree	Disagree nor agree	Slightly agree	Agree
14	*If you changed your behavior, can you indicate the change?*			open question		
15	*When implementing this system on an aircraft, what would be the effect on safety?*	Much unsafer	Unsafer	Safer nor unsafer	Safer	Much safer
16	*Do you expect any negative consequences of the visual interface? If yes, please elaborate.* (on a two-point scale)	No	Yes	space to indicate change		
17	*Do you have further comments concerning the above statements, or do you want to elaborate an answer?*	open question				
18	*Do you have any comments regarding the level of reality of the simulation?*	open question				
19	*Is there anything else you think we should know? Events that you think we should know about or comments you would like to make?*	open question				

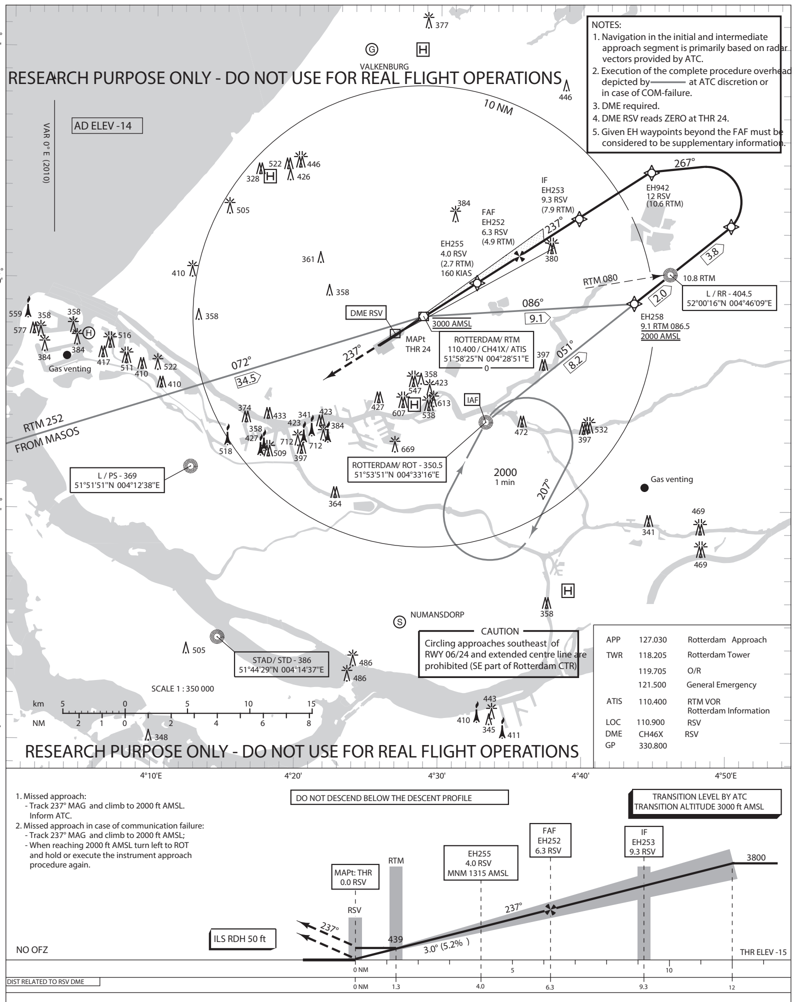
B

APPROACH CHARTS AND CHECKLISTS

THIS appendix shows the documents required to provide context to the scenarios for the pilots. In the first experiment, Chapter 3, professional pilots were invited to fly different approaches for which the required information is shown on an approach chart. The icing scenario involved an instrument landing in both the training and measurement phase, respectively to Rotterdam (EHRD) and Amsterdam/Schiphol (EHAM). Corresponding approach charts are shown in Section B.1 and B.2. Training and measurement of the windshear scenarios was performed during an approach to respectively Nice (LFMN, Section B.3) and Montpellier (LFMT, Section B.4). The checklist for the windshear recovery procedure as presented to the pilots is provided in Section B.5, which is retrieved fro mthe FCOM.

The later experiments did not use an approach chart as the flight path was shown on the outside visual. Pilots were provided with checklists for three emergency scenarios: i) a windshear recovery procedure, Section B.6, ii) a single engine stall, Section B.7, and iii) a sudden center of gravity shift, Section B.8. This second windshear recovery procedure is a modified version of the one used in the first experiment. The alterations are added to make pilots fly manually, and by stressing that loss of altitude had to be prevented, force pilots more towards the edge of the flight envelope. The single engine stall procedure is also heavily modified from the FCOM, and the checklist for the sudden center of gravity shift does not exist.

B.1. EHRD APPROACH CHART



GS IN KT	60	80	100	120	140	160	180
VERTICAL SPEED	320 ft/min	425 ft/min	530 ft/min	635 ft/min	745 ft/min	850 ft/min	955 ft/min

OCA (OCH) ELEV THR 24: -14.6 ft

ACFT CAT	CAT I	LOC MAPt: THR	CIRCLING*
A	133 (147)	430 (450)	440 (460)
B	144 (158)		520 (530)
C	154 (168)		730 (740)
D	166 (180)		760 (770)

* Circling SE of RWY 06/24 is prohibited (see CAUTION).

THR 24	51°57'43"N	004°27'10"E
EH252	52°01'03"N	004°35'33"E
EH253	52°02'40"N	004°39'38"E
EH255	51°59'53"N	004°32'36"E
EH258	51°59'01"N	004°43'37"E

CEILING AND VISIBILITY MINIMA

TAKE-OFF	DAY:	NA	NIGHT:	NA
LANDING	DAY:		NIGHT:	

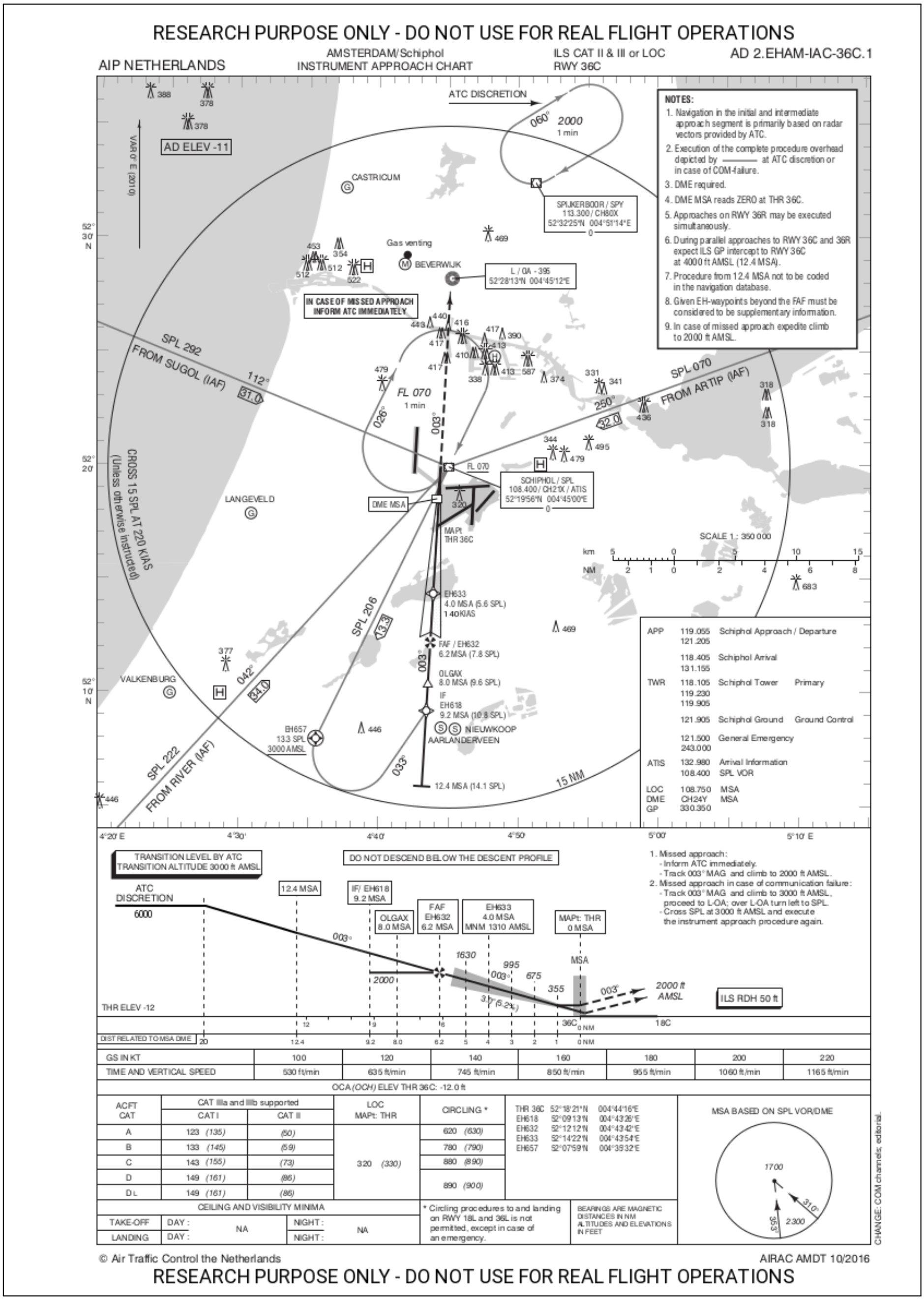
BEARINGS ARE MAGNETIC DISTANCES IN NM ALTITUDES AND ELEVATIONS IN FEET

MSA BASED ON RTM VOR/DME

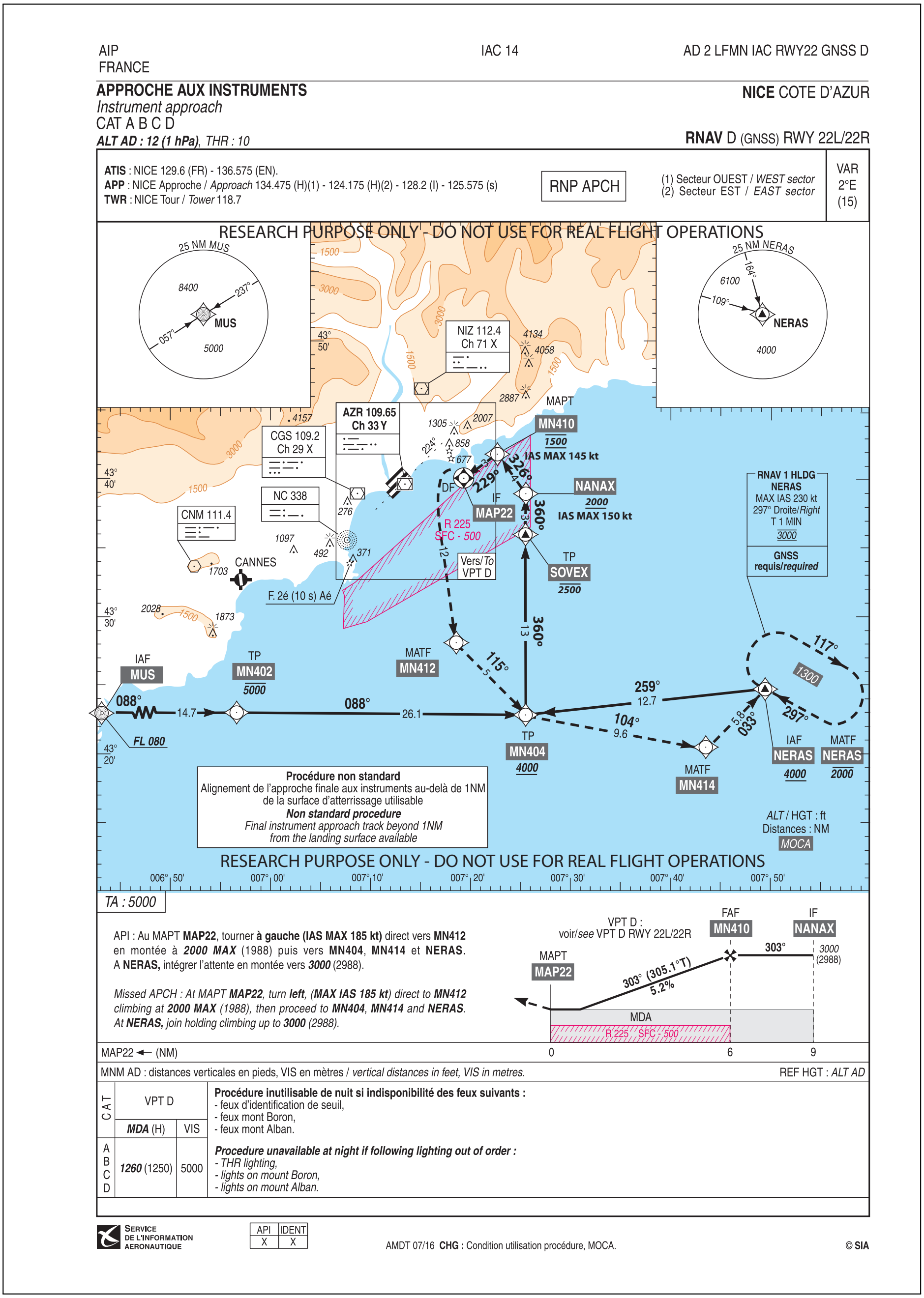
CHANGE: COM channels; editorial.

AIRAC AMDT 10/2016

B.2. EHAM APPROACH CHART



B.3. LFMN Approach Charts


AIP
FRANCE

IAC 14

AD 2 LFMN IAC RWY22 GNSS D

APPROCHE AUX INSTRUMENTS
Instrument approach
CAT A B C D
ALT AD : 12 (1 hPa), *THR : 10*

NICE COTE D'AZUR

RNAV D (GNSS) RWY 22L/22R

ATIS : NICE 129.6 (FR) - 136.575 (EN).
APP : NICE Approche / *Approach* 134.475 (H)(1) - 124.175 (H)(2) - 128.2 (I) - 125.575 (s)
TWR : NICE Tour / *Tower* 118.7

RNP APCH

(1) Secteur OUEST / *WEST sector*
(2) Secteur EST / *EAST sector*

VAR 2°E (15)

TA : 5000

API : Au MAPT **MAP22**, tourner **à gauche (IAS MAX 185 kt)** direct vers **MN412** en montée à ***2000 MAX*** (1988) puis vers **MN404**, **MN414** et **NERAS.** A **NERAS,** intégrer l'attente en montée vers ***3000*** (2988).

*Missed APCH : At MAPT **MAP22**, turn **left**, (**MAX IAS 185 kt**) direct to **MN412** climbing at **2000 MAX** (1988), then proceed to **MN404**, **MN414** and **NERAS**. At **NERAS**, join holding climbing up to **3000** (2988).*

MNM AD : distances verticales en pieds, VIS en mètres / *vertical distances in feet, VIS in metres.*

REF HGT : *ALT AD*

CAT	VPT D		Procédure inutilisable de nuit si indisponibilité des feux suivants :
	MDA (H)	VIS	
A B C D	***1260*** (1250)	5000	**Procédure inutilisable de nuit si indisponibilité des feux suivants :** - feux d'identification de seuil, - feux mont Boron, - feux mont Alban. ***Procedure unavailable at night if following lighting out of order :*** *- THR lighting, - lights on mount Boron, - lights on mount Alban.*

SERVICE DE L'INFORMATION AERONAUTIQUE

API	IDENT
X	X

AMDT 07/16 **CHG :** Condition utilisation procédure, MOCA.

B

AIP
FRANCE

IAC 11

AD 2 LFMN IAC RWY22 VPT D

APPROCHE AUX INSTRUMENTS
Instrument approach
CAT A B C D (1)
***ALT AD : 12 (1 hPa)**, THR : 10*

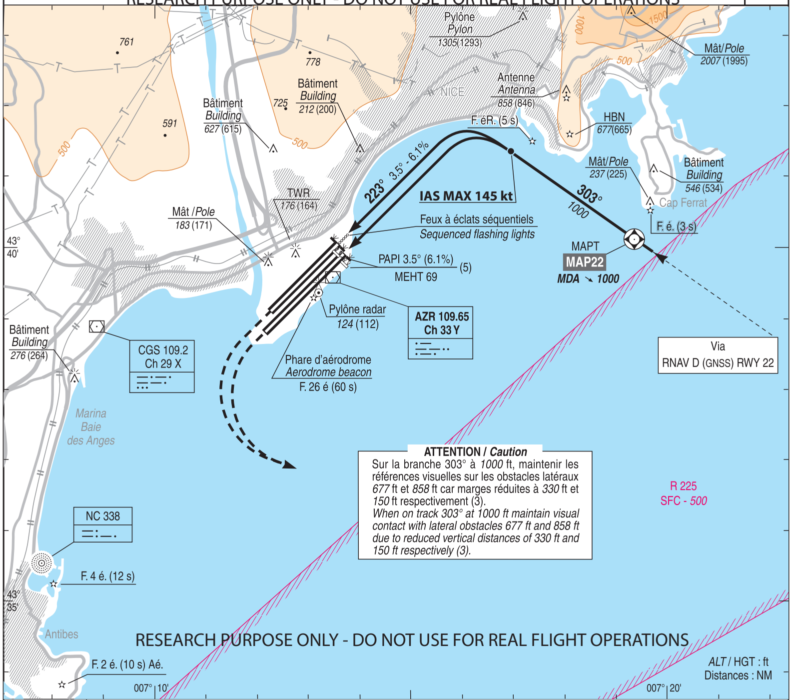
NICE COTE D'AZUR

VPT D RWY 22L/22R

ATIS : NICE 129.6 (FR) - 136.575 (EN)
APP : NICE Approche / *Approach* 134.475 (H)(1) - 124.175 (H)(2) - 128.2 (I) - 125.575 (s)
TWR : NICE Tour / *Tower* 118.7

(1) Secteur OUEST / *WEST sector*
(2) Secteur EST / *EAST sector*

VAR
2°E
(15)



TA : 5000

Trajectoire de remise des gaz : Tourner à **gauche** en bout de piste, en montée vers ***2000*** (1988) et procéder conformément à l'API.

*Go around track : Turn **left** when overflying extremity of RWY, climbing up to **2000** (1988) and proceed according to missed APCH.*

MNM AD : distances verticales en pieds, VIS en mètres / *vertical distances in feet, VIS in metres.* REF HGT : *ALT AD*

CAT	VPT D		
	MDA (H)	VIS	
A B C D	***1260*** (1250)	5000	**(3) Procédure inutilisable de nuit si indisponibilité des feux suivants :** - feux d'identification de seuil, - feux mont Boron, - feux mont Alban. ***(3) Procedure unavailable at night if following lighting out of order :*** *- THR lighting,* *- lights on mount Boron,* *- lights on mount Alban.*

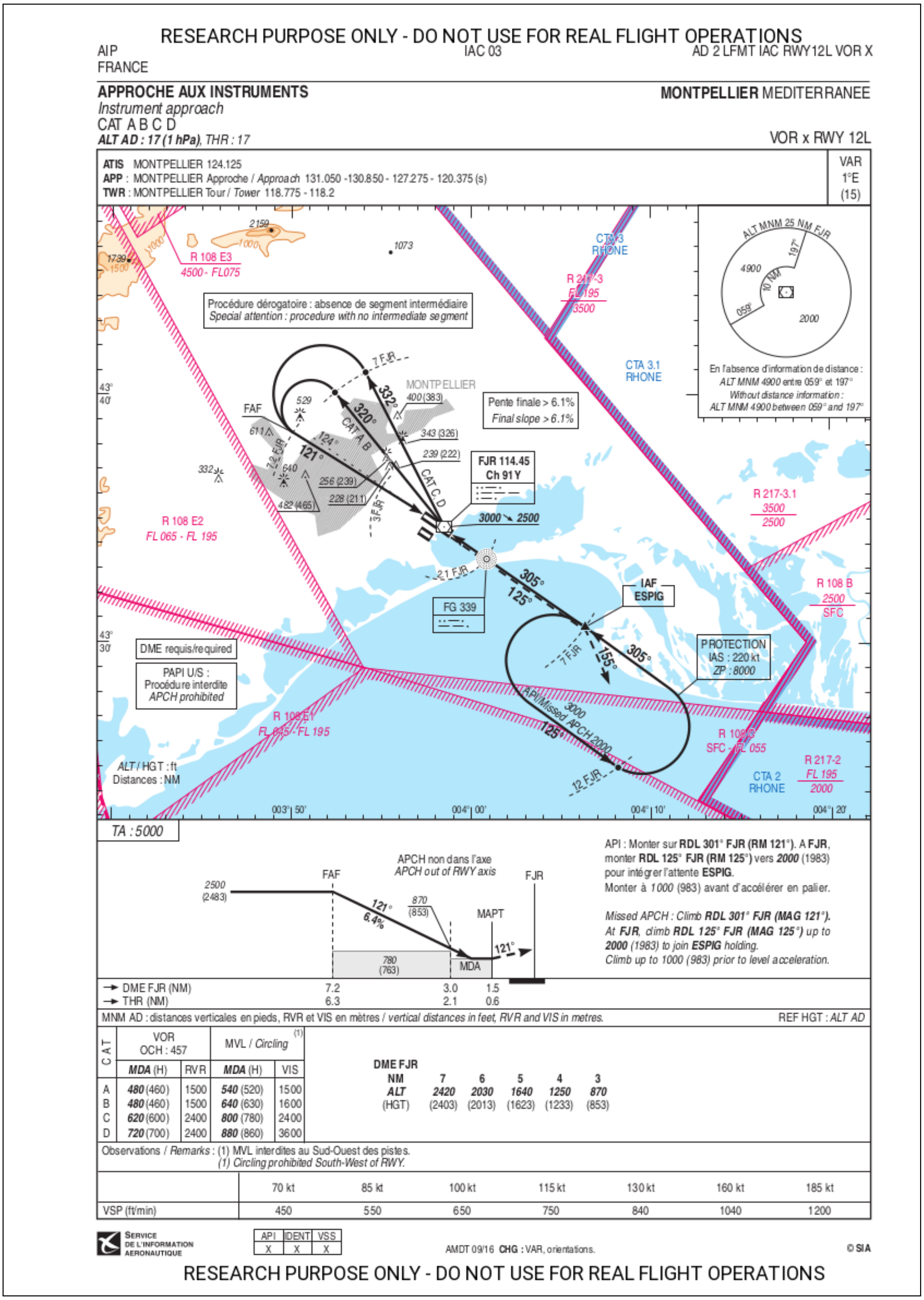
Observations / *Remarks* : (5) PAPI RWY 22L/R : Obligatoire. Divergence axe de piste 5° et surface de protection obstacles limitée à 7 km.
Mandatory. Offset 5° from RWY centreline and obstacle clearance guaranteed up to 7 km.

SERVICE DE L'INFORMATION AERONAUTIQUE

API	IDENT
X	X

AMDT 07/15 **CHG :** VAR, orientations, consignes.

B.4. LFMT Approach Chart



B

B.5. WINDSHEAR PROCEDURE (1)

A319 A320 A321 FLIGHT CREW OPERATING MANUAL	ABNORMAL AND EMERGENCY	3.02.80	P 19
	MISCELLANEOUS	SEQ 100	REV 35

WINDSHEAR

A red flag "WINDSHEAR" is displayed on each PFD associated with an aural synthetic voice "WINDSHEAR" repeated three times.

If windshear is detected either by the system or by pilot observation, apply the following recovery technique:

■ **At takeoff**

● **If before V1**

The takeoff should be rejected only if significant airspeed variations occur below indicated V1 and the pilot decides that there is sufficient runway remaining to stop the airplane.

● **If after V1**

– THR LEVERS . . . . TOGA
– REACHING VR . . . . ROTATE
– SRS ORDERS . . . . FOLLOW

■ **Airborne, initial climb or landing**

– THR LEVERS AT TOGA . . . . SET OR CONFIRM
– AP (if engaged) . . . . KEEP
– SRS ORDERS . . . . FOLLOW

This includes the use of full back stick, if demanded.

Note : 1. If engaged, the autopilot disengages when α is greater than α prot.
2. If the FD is not available, use an initial pitch attitude up to 17.5°. If necessary to minimize the loss of height, increase this pitch attitude.

– DO NOT CHANGE CONFIGURATION (SLATS/FLAPS, GEAR) UNTIL OUT OF SHEAR.
– CLOSELY MONITOR FLIGHT PATH AND SPEED.
– RECOVER SMOOTHLY TO NORMAL CLIMB OUT OF SHEAR.

B.6. WINDSHEAR PROCEDURE (2)

WINDSHEAR

A red flag "WINDSHEAR" is displayed on each PFD associated with an aural synthetic voice "WINDSHEAR" repeated three times.
If windshear is detected either by the system or by pilot observation, apply the following recovery technique:

- At takeoff:
  - If before V1:

    The takeoff should be rejected only if significant airspeed variations occur below indicated V1 and pilot decides that there is sufficient runway remaining to stop.

  - If after V1:

    THR LEVERS .... TOGA
    REACHING VR .... ROTATE
    SRS ORDERS .... FOLLOW

    If necessary the flight crew may pull the sidestick full back.

    Note: If FD bars are not displayed, move toward an initial pitch attitude of 17.5 °
    Then, if necessary, to prevent loss in altitude, increase pitch attitude.

- Airborne, initial climb or landing:

  AP and A/THR .... DISENGAGE
  THR LEVERS AT TOGA .... SET OR CONFIRM
  CONFIGURATION .... DO NOT CHANGE
  PITCH 17.5
  FLIGHT PATH AND SPEED .... MONITOR
  PREVENT LOSS OF ALTITUDE .... INCREASE PITCH AS REQ

- Out of shear:

  AP and/or A/THR .... ENGAGE AS REQ
  FLIGHT PATH .... RESUME FPL

B

B.7. SINGLE ENGINE STALL

TUDelft A32X QUICK REFERENCE HANDBOOK	ABNORMAL AND EMERGENCY PROCEDURES	70.07A AUG 19

ENG 1(2) STALL

- N2 between 50% and IDLE

  THR LEVER (AFFECTED ENGINE) .... IDLE
  ENG MASTER (AFFECTED ENGINE) .... OFF

  <u>ENG 1(2)</u> SHUT DOWN

- N2 above IDLE (title and procedure not displayed on ECAM):
  - On ground :

    THR LEVER (AFFECTED ENGINE) .... IDLE
    ENG MASTER (AFFECTED ENGINE) .... OFF

  - In flight :

    THR LEVER (AFFECTED ENGINE) .... IDLE
    ENG PARAMETERS (AFFECTED ENGINE) .... MONITOR

    - If abnormal :

      ENG MASTER (AFFECTED ENGINE) .... OFF

      <u>ENG 1(2)</u> SHUT DOWN

    - If normal :

      THR LEVER (AFFECTED ENGINE) .... SLOWLY ADVANCE

      - If a stall recurs :

        THR LEVER (AFFECTED ENGINE) .... REDUCE

      - If a stall does not recur :

        Continue engine operation.

B.8. SUDDEN CENTER OF GRAVITY SHIFT

TU Delft A32X QUICK REFERENCE HANDBOOK	ABNORMAL AND EMERGENCY PROCEDURES	25.03A AUG 19

SUDDEN CG SHIFT

A sudden CG shift can be caused by a shift in payload during a steep climb or descent. It is observed by an immediate change in pitch rate with AP disconnect, without other immediate causes, typically accompanied by a loud bang or other noises. This event should be prevented by evenly distributing the payload and using cargo nets.

In case this does happen, the AP and AUTO TRIM will disable.

The following actions are required:

- On ground:

  Return to gate

- In flight:

  AP .... CONFIRM OFF
  PITCH .... STABILIZE
  PITCH TRIM .... MANUALLY ADJUST
  SPEED .... MONITOR
  FLIGHT PATH .... MONITOR

  Note: Stabilizing pitch might require full sidestick deflection.

  Once control is fully regained, a choice has to be made, depending on the situation:
  - Land at closest airport
  - Continue FLP

C

EXPERIMENT DATA

THIS appendix contains more details on the results of the the final two experiments presented in Chapter 6 and 7. Section C.1 shows the flight paths of all trajectories for the vibrations design, as well as the flight paths of an experienced pilot. The latter is used to verify the results of the participants. Flight paths for the evaluation of the guidance design are shown Section C.2. Finally, responses to the open questions of the debriefing questionnaire of those experiments are shown in Section C.3.

Data for the flights are grouped per realization of the flight path. Plots show the entire flight of each pilot and indicate the flight phase where the windshear recovery had to be performed. The metrics used in the corresponding chapters are calculated on this specific part of the flights.

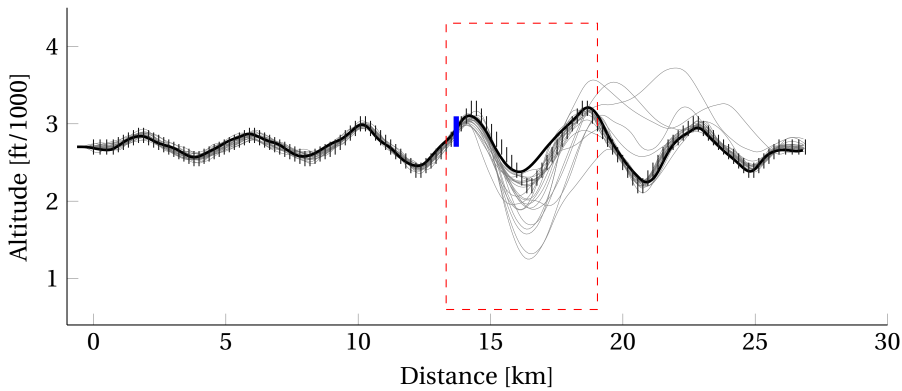
C.1. VIBRATIONS DESIGN FLIGHT PATHS

The plots in this section show the flights of the experiment presented in Chapter 6. Each plot includes a thicker black line which represents the flights of one extra participant (male) who was not included in the results. This participant was an outlier in terms of experience: although the participant had a valid current PPL, he was a retired professional pilot with 18,000 flight hours logged in jet fighters and large commercial aircraft (Boeing 747/767/777). Nevertheless, this participants was still invited to verify the results of the (in terms of large aircraft) inexperienced PPL/LAPL pilots.

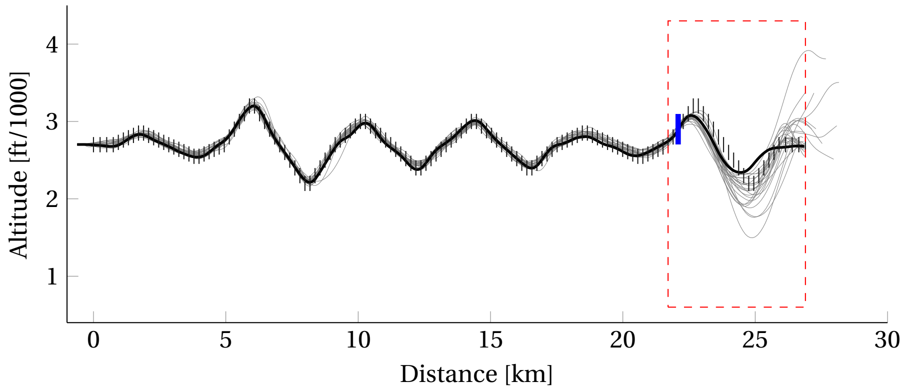
For now, the verification of the results is limited to comparing the flight paths of the experienced pilot with the other pilots. This shows that in nominal conditions, the behavior of all pilots is comparable: they all follow the flight path presented on the outside visual. As discussed in Chapter 6, the flight path itself is rather challenging which is confirmed by the comments of the experienced pilot.

His first four flights (first block) were flown without haptic feedback, the final four flights (second block) are flown with haptic feedback. Flight paths are presented to the experienced pilot in the following order: five (Fig. C.1e), four (Fig. C.1d), eight (Fig. C.1h), six (Fig. C.1f), two (Fig. C.1b), one (Fig. C.1a), seven (Fig. C.1g), and three (Fig. C.1c). The figures show that the windshear performance (maximum altitude loss during recovery) is improving in that order. Furthermore, the initial performance on Fig. C.1e is similar to all other pilots. Starting from his fourth flight (flight path realization 6, Fig. C.1f), the experienced pilot is outperforming the other participants, even without haptic feedback.

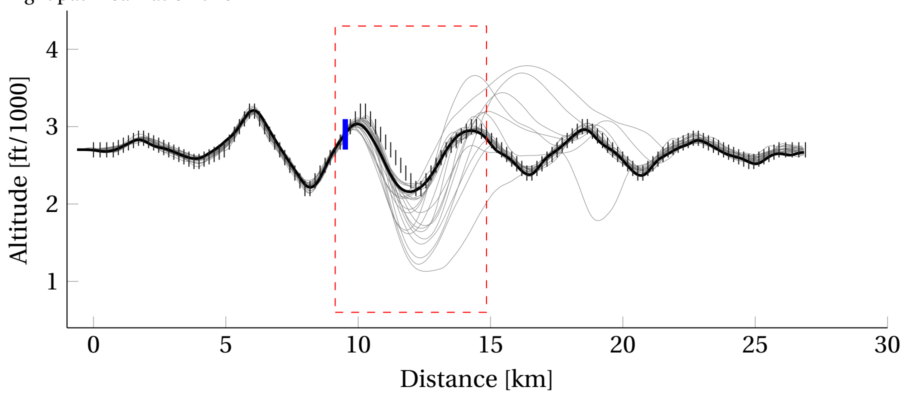
As there is similar behavior during nominal and emergency situations and although this is based on one comparison, we believe that the results obtained with the 24 pilots can be extrapolated to results obtained with professional pilots.



(a) Flight path realization one

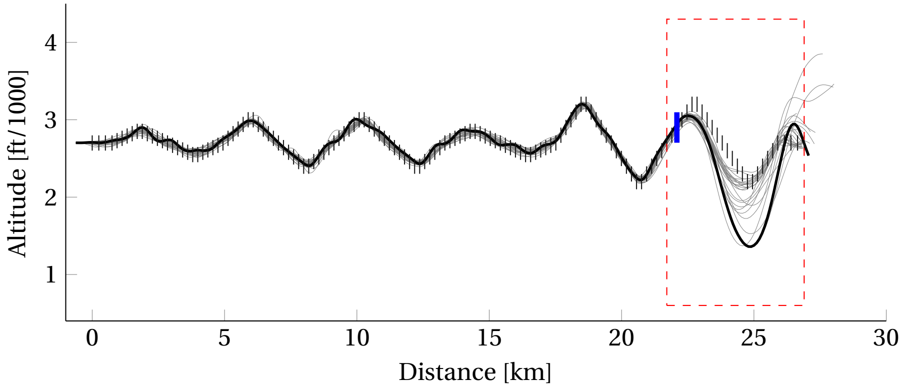


(b) Flight path realization two

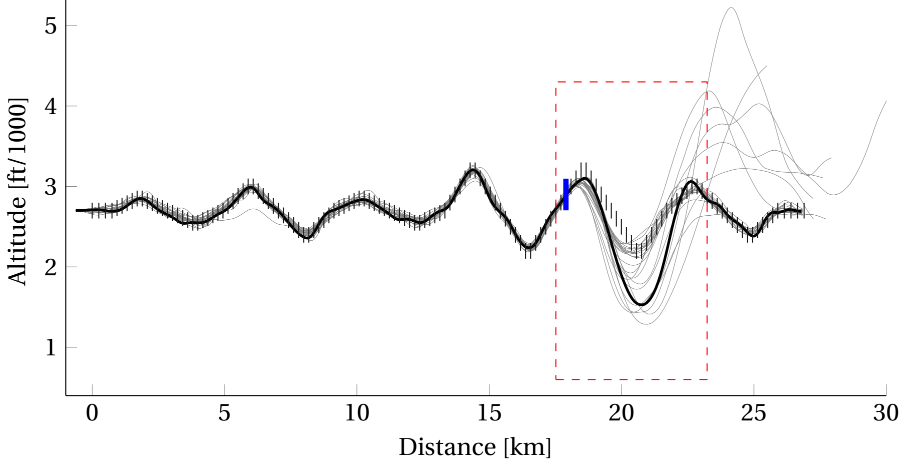


(c) Flight path realization three

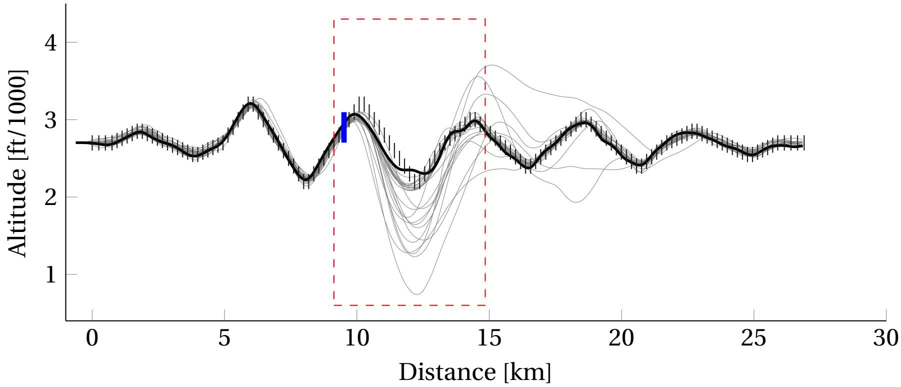
Figure C.1: All flown flight paths by all pilots, vertical lines indicate the gates on the outside visual, vertical thick blue line indicates windshear trigger, thick blue line represents flight path of experienced participant, dashed box indicates data used in the evaluation



(d) Flight path realization four



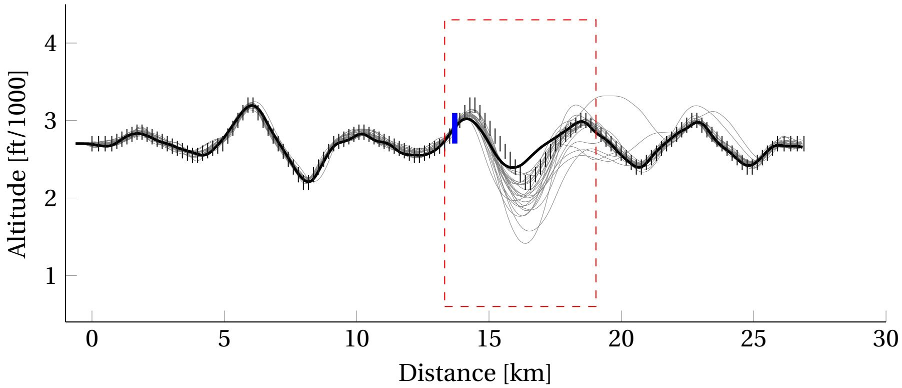
(e) Flight path realization five



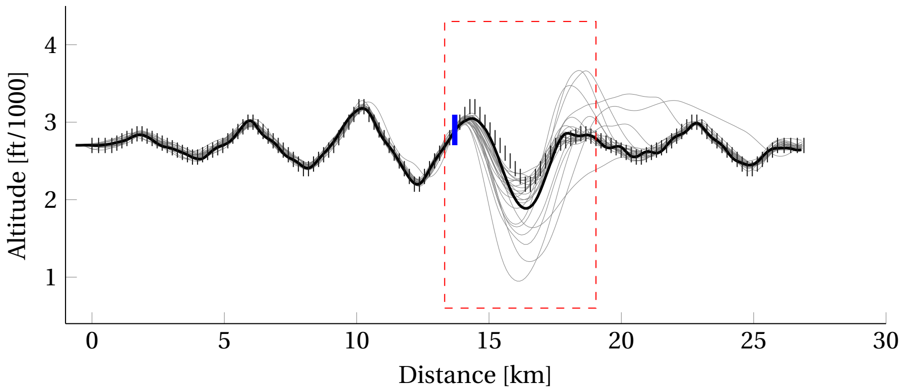
(f) Flight path realization six

Figure C.1: (continued)

C



(g) Flight path realization seven

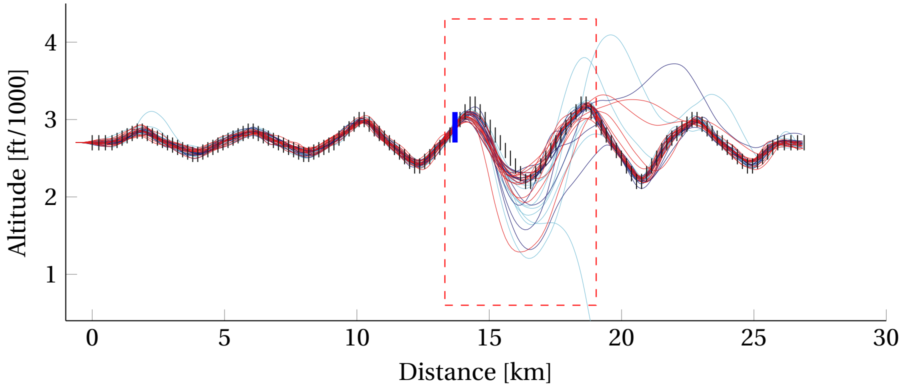


(h) Flight path realization eight

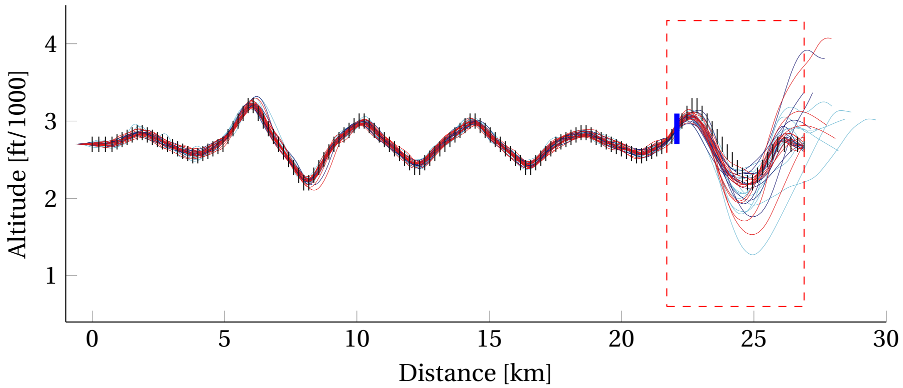
Figure C.1: (continued)

C.2. GUIDANCE DESIGN FLIGHT PATHS

The plots in this section show the flights of the experiment presented in Chapter 7. Light blue lines represent the group without haptic feedback, dark blue lines represent the group with cueing haptic feedback, and red lines represent the group with guidance haptic feedback.



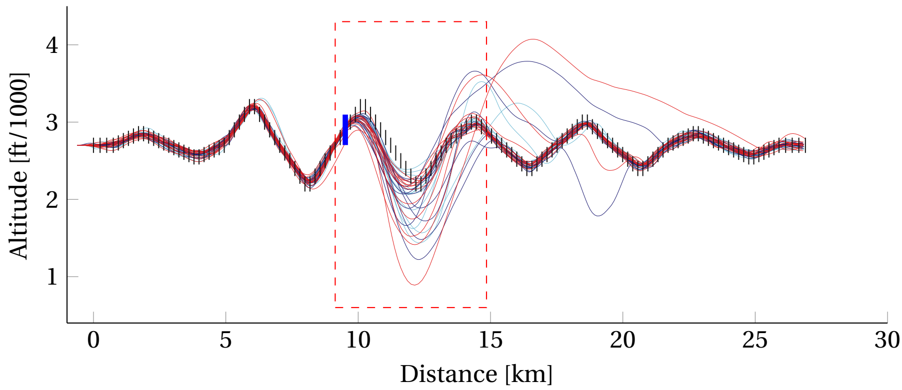
(a) Flight path realization one



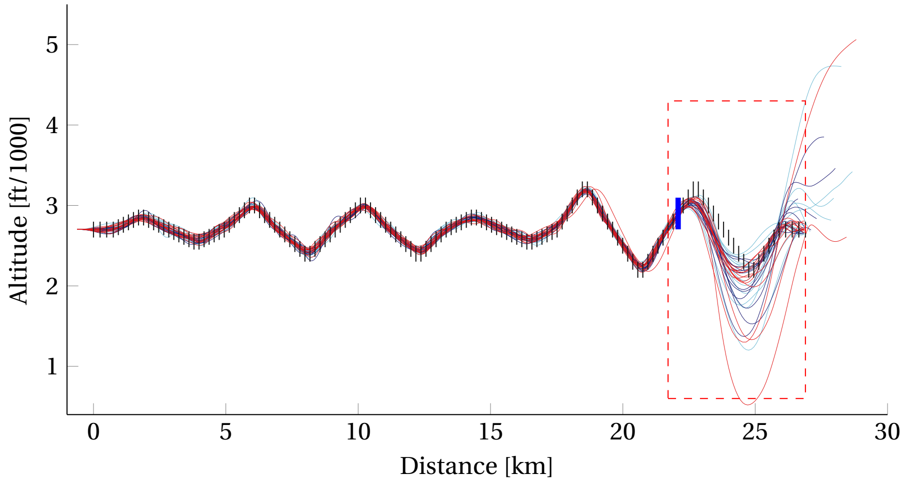
(b) Flight path realization two

Figure C.2: All flown flight paths by all pilots, vertical lines indicate the gates on the outside visual, vertical thick blue line indicates windshear trigger, dashed box indicates data used in the evaluation

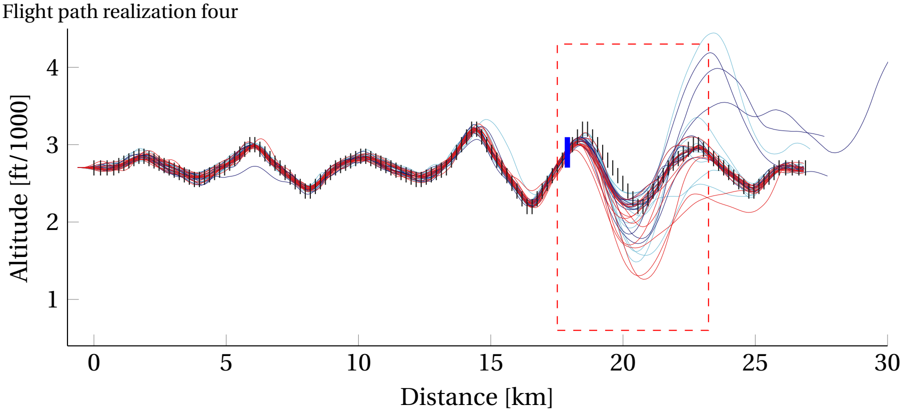
C



(c) Flight path realization three



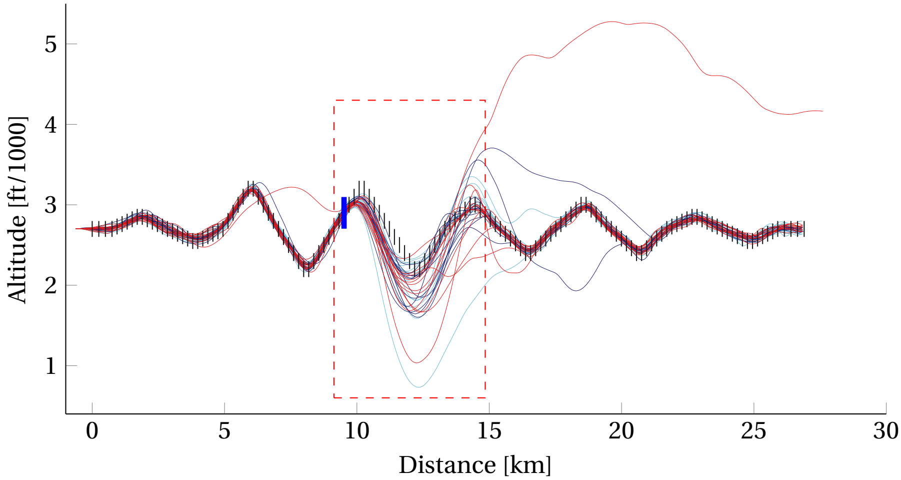
(d) Flight path realization four



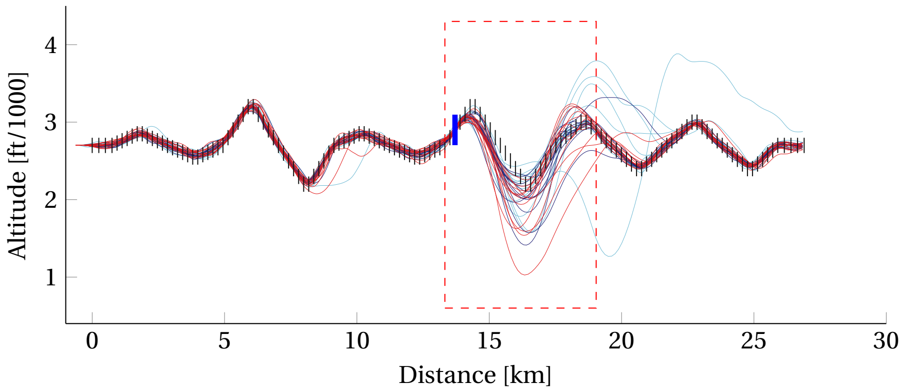
(e) Flight path realization five

Figure C.2: (continued)

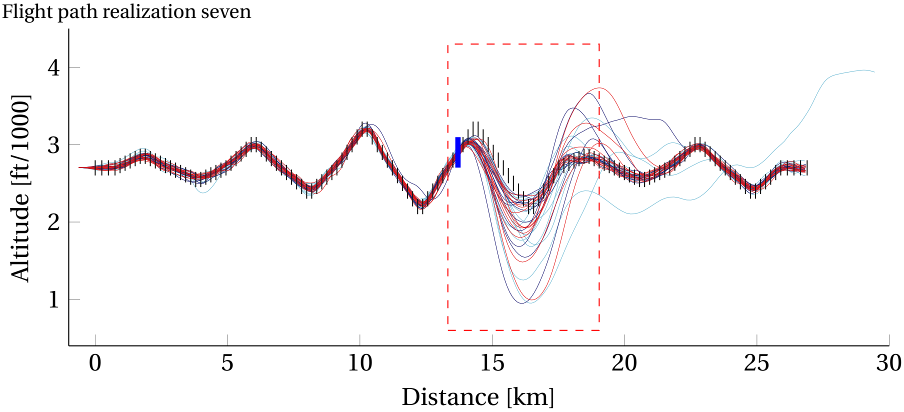
C



(f) Flight path realization six



(g) Flight path realization seven



(h) Flight path realization eight

Figure C.2: (continued)

C.3. EXPERIMENT DEBRIEFING STATEMENTS

The questions at the end of the debriefing questionnaire provided the participants to elaborate on any of the above questions, comment on the reality of the simulator, and possible other comments. Additionally, expected negative effects and reported changes in behavior are reported below. Not every individual comments is shown, we tried to make sure that all comments made within one group are captured by one of the comments below.

Comments from the manual group include:

- *Better anticipation of required aircraft control input based on visuals.*
- *More general awareness.*
- *More relaxed and more time to see ahead.*
- *A negative consequence could be that one starts flying by following only the visual signals.*
- *Display can distract from the actual flying.*
- *Resolving a critical situation could be further assisted with audible commands like "climb", "descend", etc.*
- *Besides this info, throttle awareness is the next most important item needing assistance.*
- *Beginning was quite a start-up, but I got used to the flying of the airplane.*

Participants in the cueing group provided the following comments:

- *I was not looking at instruments anymore, I reacted naturally to the haptics, and looked outside to monitor the behavior of the airplane.*
- *I made slightly stronger inputs.*
- *The haptic feedback could lead to too much stimulus together with sound/visual.*
- *I used the haptics to double check whether my input was correct, if so I made a stronger input.*
- *The haptic feedback indicates a problem, the visuals gives the possible space left (criticality).*
- *I followed the indicated direction for the suggested correction.*
- *Increased awareness of critical situation in angle of attack and speed.*
- *I made more subtle movements and anticipated more with the haptic feedback.*
- *When using all warning systems, extra training is recommended to process everything correctly.*
- *I think my performance improved solely due to experience with the sim.*
- *Audio warnings are best for VFR, with minimal visual information, and only shaker for stall.*
- *Sound can be added to support the protections.*

Finally, the comments made in the guidance group included the following:

- *You need to work harder to fly intentionally on the limit.*
- *Steers you easily towards the correct actions.*
- *Haptics makes you do a faster response, and you than check visuals for clues.*
- *I was struggling with conflicting visual and haptic inputs.*
- *More attention to critical situation, where you can follow your feeling.*
- *The haptic feedback might give a false sense of safety.*
- *I was distracted to what the reason was of the force? What is going on?*
- *Angle of attack should appear more prominently on the visuals.*
- *Training effect of each session has effect on my relation with haptic feedback.*
- *If possible, make the haptic settings adjustable to personal preferences.*

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Dirk Van Baelen, November 2020

Curriculum Vitæ

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2019	AIAA Guidance Navigation and Control Student Paper Finalist
2018	Excellent Student Prize of the International Graduate Summer School in Aeronatics and Astronautics, Beihang University
2017	Winner of the 'Extreme environments'-session at the PhD symposium organized by the Aerospace Faculty PhD Council/Graduate School
2013	Bachelor acquired Cum Laude

List of Publications

10. **D. Van Baelen**, M. M. van Paassen, J. Ellerbroek, D. A. Abbink, and M. Mulder, *Evaluating Stick Stiffness and Position Guidance for Feedback on Flight Envelope Protection*, Accepted for publication in the proceedings of the 2021 AIAA Modeling and Simulation Technologies Conference, Nashville (TN).

9. A. van den Hoed, H. M. Landman, **D. Van Baelen**, O. Stroosma, M. M. van Paassen, E. L. Groen, M. Mulder, *A Scenario for Inducing the Leans Illusion in a Hexapod Motion Simulator*, Accepted for publication in the proceedings of the 2021 AIAA Modeling and Simulation Technologies Conference, Nashville (TN)

8. **D. Van Baelen**, J. Ellerbroek, M. M. van Paassen, D. A. Abbink, M. Mulder, *Just Feeling the Force: Just Noticeable Difference for Asymmetric Vibrations*, Proceedings of the 2020 IEEE International Conference on Human-Machine Systems, Rome (Italy).

7. **D. Van Baelen**, J. Ellerbroek, M. M. van Paassen, M. Mulder, *Design of a Haptic Feedback System for Flight Envelope Protection*, Journal of Guidance, Control, and Dynamics **43**, pp. 700 – 714 (2020)

6. **D. Van Baelen**, J. Ellerbroek, M. M. van Paassen, D. A. Abbink, M. Mulder, *Using Asymmetric Vibrations for Feedback on Flight Envelope Protection*, Proceedings of the 2020 AIAA Modeling and Simulation Technologies Conference, Orlando (FL).

5. G. de Rooij, **D. Van Baelen**, C. Borst, M. M. van Paassen, M. Mulder, *Supplementing Haptic Feedback Through the Visual Display of Flight Envelope Boundaries*, Proceedings of the 2020 AIAA Guidance, Navigation and Control Conference, Orlando (FL).

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3. D. G. Beeftinkg, C. Borst, **D. Van Baelen**, M. M. van Paassen, M. Mulder, *Haptic Support for Aircraft Approaches with a Perspective Flight-Path Display*, Proceedings of the 2018 IEEE International Conference on Systems, Man, and Cybernetics, Miyazaki (Japan).

2. P.-J. Deldycke, **D. Van Baelen**, D. M. Pool, M. M. van Paassen, M. Mulder, *Design and Evaluation of a Haptic Aid for Training of the Manual Flare Manoeuvre*, Proceedings of the 2018 AIAA Modeling and Simulation Technologies Conference, Kissimmee (FL).

1. **D. Van Baelen**, J. Ellerbroek, M. M. van Paassen, M. Mulder, *Design of a Haptic Feedback System for Flight Envelope Protection*, Proceedings of the 2018 AIAA Modeling and Simulation Technologies Conference, Kissimmee (FL).

How do you do it, Mike? How come you're never stressed?

It's easy in research to get tunnel vision.
You feel isolated, like you're the only person with your problem.
But the truth is, you're not alone.
And whenever I get stressed,
I just ask myself the question:
Do I really care?
Would I rather be doing anything else?

— The PHD Movie


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