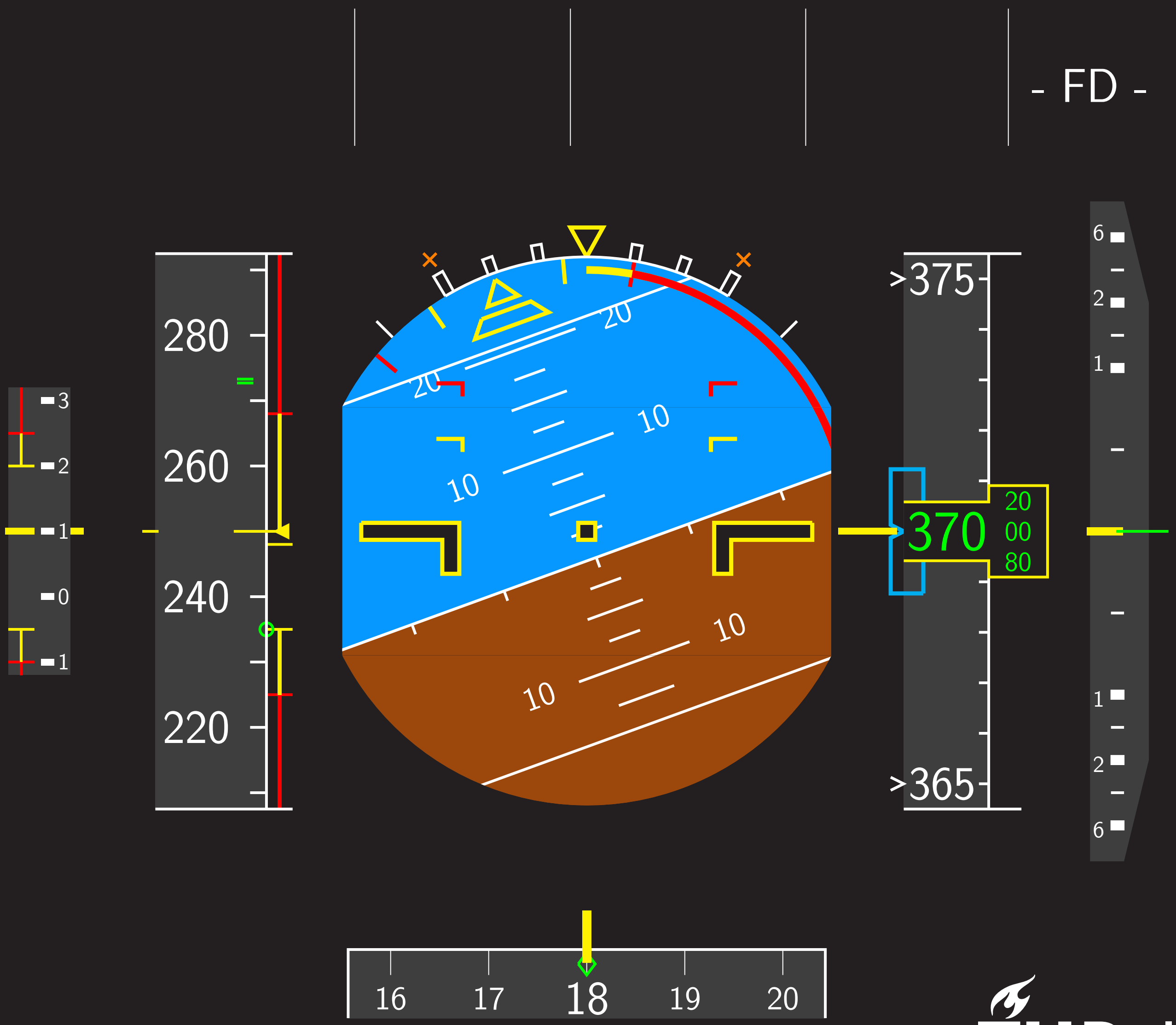
Master thesis

Supplementing haptic feedback through the visual display of flight envelope boundaries

Gijs de Rooij



TU Delft

Master thesis

Supplementing haptic feedback through the visual display of flight envelope boundaries

by

Gijs de Rooij

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Preface

It is with great pride that I present you the result of my masters thesis. The culmination of a flight that started almost eight years ago when I moved to the wonderful city of Delft to study Aerospace Engineering. Despite some turbulence along the way, it has been a gratifying experience shaping me to who I am today. All of this would not have been possible without the support of many people.

First and foremost it is without doubt that Dirk deserves a lot of praise. It has been a pleasure to spent the past year working with you. Without your extensive knowledge about DUECA and haptic feedback, my experiment would never have been as complete as it was. Unfortunately we did not manage to get the motion system up and running for my experiment, but do call me whenever you get that far. I do not mind being your test pilot! Together with Clark, Max and René we had many fruitful meetings. Despite your busy schedules, you encouraged frequent meetings to discuss my progress from which I always returned with a lot of renewed energy and ideas to move forward. I feel privileged to have you all in my graduation committee.

A big thanks also to all the pilots who voluntarily (!) participated in the experiment. While some of their schedules drove me nuts, it has been an amazing experience spending 16 days in their company. Hearing about all the quirks of live as a pilot has been a true inspiration. I would also like to express my gratitude to Olaf and all other SIMONA personal. The simulator performed remarkably well with only a couple of quickly solved hiccups. The fact that nearly all, if not all, pilots joined our database to participate in future experiments must be seen as a big compliment. Speaking of SIMONA, I would like to thank all the volunteers at FlightGear, who have given me such a nice mix of hobby, work and study over the past 12 years. Not entirely by coincident, the visuals of FlightGear were an excellent addition to my experiment and well received by all pilots.

Luckily there was also a life outside university. Mike, thanks for making my time in Delft so much more fun. It's well deserved that you beat me in finishing your masters earlier! We may lose our neighbor status, but I'm sure we'll stay in touch and continue drinking tea for many more years to come. Whenever I needed a break from working on my thesis, I found Joris by my side. Thanks for the many games of Mario Karts – in which you let me win to boost my self-esteem – and thanks for bringing so much joy to my life. Sorry for not being the most enjoyable person during these past months!

Last but not least I would like to thank my mum and dad for supporting me both financially and in any other possible way, allowing me to follow my dreams and shape my future. Together with Aagje you've been an amazing 'ground support' team. Until the very last moment, 'bij-oma' Ankie was another essential member of that team. She showed great interest in my studies and even paid an important role in my first extensive aerospace experiment at high school involving paper airplanes. Ankie, you will be missed.

To finish this preface, let me shortly introduce the structure of this thesis report. It consists of three parts, starting with my thesis article. The preliminary report is included next, containing an extensive literature study and experiment proposal detailing my midterm progress. The report ends with a number of appendices listing additional results and experiment details that were not included in the article itself.

Gijs de Rooij
Delft, May 2019

Nomenclature

AC	Advisory circular
ADIRU	Air data inertial reference unit
AoA	Angle of attack
AI	Attitude indicator
ALTN1	Alternate law with reduced protections
ALTN2	Alternate law without reduced protections
DUECA	Delft University environment for communication and activation
ECAM	Electronic centralised aircraft monitor
EFIS	Electronic flight instrument system
EGLL	London Heathrow Airport
EICAS	Engine indication and crew alerting system
EID	Ecological interface design
FAA	Federal Aviation Administration
FBW	Fly-by-wire
FCOM	Flight crew operation manual
FCTM	Flight crew training manual
FCU	Flight control unit
FE	Flight envelope
FEP	Flight envelope protection
FMA	Flight mode annunciator
FPV	Flight path vector
HMI	Human machine interface
HUD	Head-up display
ILS	Instrument landing system
KATL	Hartsfield-Jackson Atlanta International Airport
KBB	Knowledge-based behaviour
LADS	Labview airplane display system
LOC	Loss of control
MCP	Mode control panel
MHC	Modified Harper-Cooper
ND	Navigation display
NL	Normal law
PFD	Primary flight display
PLI	Pitch limit indicator
RBB	Rule-based behaviour
RMS	Root mean square
RSME	Rating Scale Mental Effort
RTLU	Rudder travel limiter unit
SBB	Skill-based behaviour
SIMONA	Simulation, motion and navigation
SFE	Safe flight envelope
SRS	SIMONA research simulator
TOGA	Takeoff/go-around

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Greek symbols

α	Angle of attack	deg
γ	Flight path angle	deg
δ	Deflection	deg
θ	Pitch angle	deg
ρ	Air density	kg/m^3
ϕ	Roll angle	deg

Latin symbols

C_L	Lift coefficient	-
F	Force	N
k	Spring coefficient	N/rad
L	Lift force	N
n	Load factor	g
g	Gravitational constant	m/s
q	Pitch rate	rad/s
S	Wing area	m^2
V	Air speed	m/s
V_{co}	Crossover speed	m/s
W	Weight	N

Contents

I

Thesis article

Supplementing haptic feedback through the visual display of flight envelope boundaries

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This paper 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 the magnitude and direction of the cues given by the haptic feedback. Fifteen professional Airbus pilots and one Airbus sim instructor participated in an experiment in the SIMONA Research Simulator at Delft University of Technology. In the experiment several approaches in three different scenarios were flown with the old and new PFD while haptic feedback was always enabled. The objective results do not show a clear improvement with the new display, although the time spent outside the flight envelope is slightly reduced. Subjective results indicate a preference, however, for the new display as well as an increased understanding of the haptic feedback. Further research is recommended and should focus on improving the design by removing unused indications and setting up an experiment with a bank scenario that allows the use of the actual bank limits rather than artificially reduced limits.

Nomenclature and acronyms

C_L = lift coefficient, -
F = stick force, N
L = lift force, N
n = load factor, g
S = wing area, m^2
V = velocity, $m \cdot s^{-1}$
W = weight, N
α = angle of attack, deg
δ = deflection angle, deg
θ = pitch angle, deg
ρ = air density, $kg \cdot m^{-3}$
ϕ = roll angle, deg

AoA = Angle of attack
ATC = Air traffic control
FBW = Fly-by-wire
FE = Flight envelope
FEP = Flight envelope protection
GA = Go-around
ILS = Instrument landing system
LOC-I = Loss of control in-flight
MCH = Modified Cooper-Harper
ND = Navigation display
PFD = Primary flight display
PFD+ = Enhanced primary flight display
RSME = Rating scale mental effort
RW = Runway sidestep
SFE = Safe flight envelope
WS = Windshear

I. Introduction

Although aviation is one of the safest forms of transport, there are still improvements to be made. In the last decade, loss of control in-flight (LOC-I) has been the most common cause of fatal commercial jet airplane accidents [1]. There are multiple slightly different definitions of LOC-I, but a common factor is that it involves flying outside the flight envelope (FE) with the potential of making it impossible for the pilot to control the aircraft [2]. Modern fly-by-wire (FBW) aircraft are protected from such FE 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

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occurrence is Air Asia flight 8501 in 2014 [3]. 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 fault in the RTLU made the aircraft bank to 54°. Startled by this, the crew responded incorrectly, banking the aircraft to even extremer 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 [4] 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.

Previous research on haptic feedback as a way to communicate information to human operators has shown that haptic cues might close this information gap and decrease LOC-I incidents [5]. Nevertheless it was 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 FE is developed to help pilots understand what the haptic feedback is telling them [6]. In combination with haptic feedback, this may assist pilots in recognizing the edges of the FE and act accordingly. Research on an unmanned aerial vehicle collision avoidance system indeed suggests an increase in user acceptance when adding visualizations to a haptic system [7].

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, altough some projects designed stand-alone displays. A common factor in most existing solutions is the separation of input and output space, showing either the limits of the envelope [8–11] or the limits in control inputs that would otherwise bring the aircraft outside that envelope [12]. 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 paper starts with some background information on flight envelopes and haptic feedback in Section II. Section III presents the display design and explains the rationale behind the design choices. The display was tested in a human-in-the-loop simulator experiment involving sixteen professional pilots to asses the added value of said display in terms of performance, safety and pilot appreciation of the haptic cues, as explained in Section IV. Section V lists the results of the experiment, which are then discussed in Section VI together with some recommendations for further research. Finally, Section VII concludes the article.

II. Background

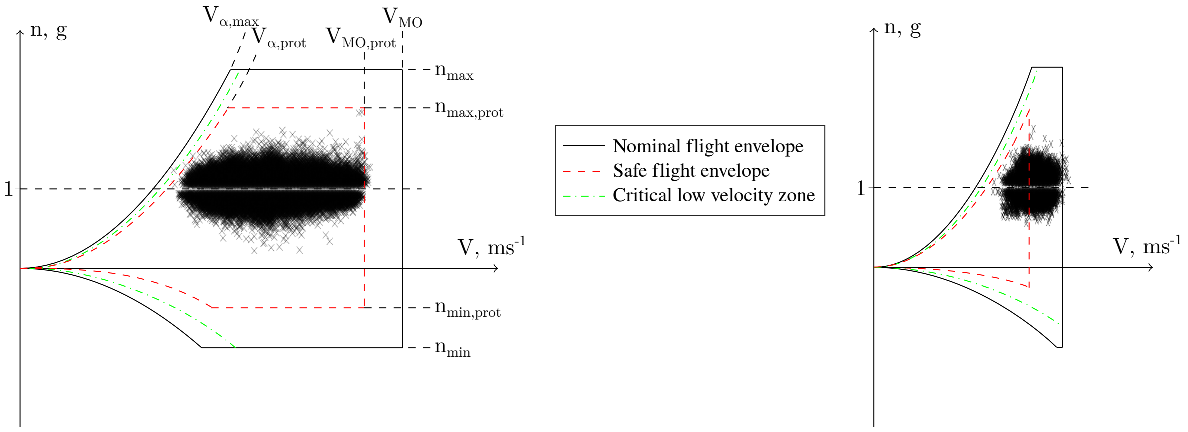
A basic understanding of the flight envelope is required to grasp the working of the haptic feedback and consequential display design choices. This section provides a short introduction to these concepts, together with a couple of implementation details that are specific to this research.

A. Flight envelope

The longitudinal performance limits of an aircraft are often captured in a flight envelope (FE). FEs exist with various relations but the one used here relates velocity (V) to load factor (n). Load factor is an indication for the ratio between lift and weight ($n = \frac{L}{W}$). It not only depends on the magnitude of these two forces, but also on the angle between them. In straight level flight, lift and weight are equal in magnitude and act along the same line (albeit in opposite direction). This corresponds to a load factor of 1. In a level banked turn, the lift vector points away from the neutral and is increased to keep the aircraft leveled. The load factor is now larger than 1. Negative load factors relate to inverted flight.

Aircraft are designed to withstand certain load factors. A common FE shape denoting these limits is depicted by the solid line in Fig. 1. The upper velocity limit is dictated by the maximum velocity or 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 $V_{\alpha,max}$ according to Eq. 1. Flying below the minimum speed at a too high load factor will make the aircraft stall. When extending the flaps, both the minimum and maximum speeds decrease, leading to a much smaller FE (Fig. 1b). Airbus in addition moves the lower and upper load factor limits to 0 and 2 g respectively when the flaps are not up, but the model from this paper keeps the load factor limits fixed at -1 and 2.5 g in order to match the haptic feedback [5].

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



(a) Flaps clean.

(b) Flaps 3.

Fig. 1 Typical flight envelopes with velocity (V) versus load factor (n) [5]. Augmented with load factor data for 10,066 A320 flights [13]. The actual envelopes depend on the aircraft's configuration and loading.

Safety margins are added to the FE to create a so-called safe flight envelope (SFE), indicated by the red dashed line in Fig. 1. The associated *prot* margins are chosen such that pilots have sufficient time to steer the aircraft away from the boundaries after being alerted of leaving the SFE. The load factor margins are 0.5 g and the speed margins vary along the envelope, except for the high-speed margin which is fixed at 20 kts below V_{MO}. Another margin can be distinguished near the lower velocity limit. When this critical low velocity zone (dashed green line) is reached, the aircraft is close to entering a stall.

The envelopes in Fig. 1 are overlaid with maximum and minimum load factors encountered in 10,066 Airbus A320 flights [13]. Note that the envelopes shown here are for illustration purposes only and do not precisely match the actual envelope corresponding to those particular flights. In flaps up, aircraft in general stay well away from the boundaries, nevertheless a number of flights does get close to the limits of the SFE. On the contrary, with the significantly smaller FE corresponding to a flaps 3 configuration, the majority of flights seems to operate outside the SFE and some even outside the FE. This can largely be explained by the fact that the fixed 20 kts overspeed margin of the SFE is not used in real-life operations.

B. Haptic feedback

The various limits of the flight envelope can be communicated to pilots by means of haptic feedback [11]. In current Airbus aircraft, the side stick does not provide any feedback, other than a force delivered by a spring that is proportional to the displacement of the stick and therefore identical at all speeds, aircraft configurations and attitudes [14]. With the haptic feedback system, the forces in the stick can be adjusted in real-time [5]. While only longitudinal haptic feedback was considered in the original research, lateral feedback based on the same principles, has since been implemented and both were used in this research.

Figure 2 shows the haptic system at work. The haptic profiles visualize the relation between the stick deflection angle δ and the force F that is required to maintain that angle. When the pilot releases the stick it returns to its neutral point δ_{np}. Break-out zone δ_{br} and associated spring coefficient k_{br} give the pilot a haptic feeling of the neutral point. Outside this break-out zone the spring coefficients are related to the negative (k^{-}) or positive (k^{+}) deflection of the stick.

As long as the aircraft is within the SFE, the profile is unaltered from the current symmetric[*] Airbus profile shown in Fig. 2a. When the aircraft leaves the SFE however, a discrete force cue warns the pilot that he is leaving the SFE, depicted by the in-set graph in Fig. 2b. This pulse is felt as a 'tick' in the stick towards the control direction that would bring the aircraft back into the SFE. At this point the profile itself is still unaltered. When the pilot continues to steer the aircraft out of the SFE, however, the stiffness of the stick is progressively increased as the aircraft gets closer to the boundaries of the flight envelope (Fig. 2c). As shown by the asymmetric profile, it is now harder to apply a control input in the 'wrong' direction. The pilot can however still ignore this by applying sufficient force.

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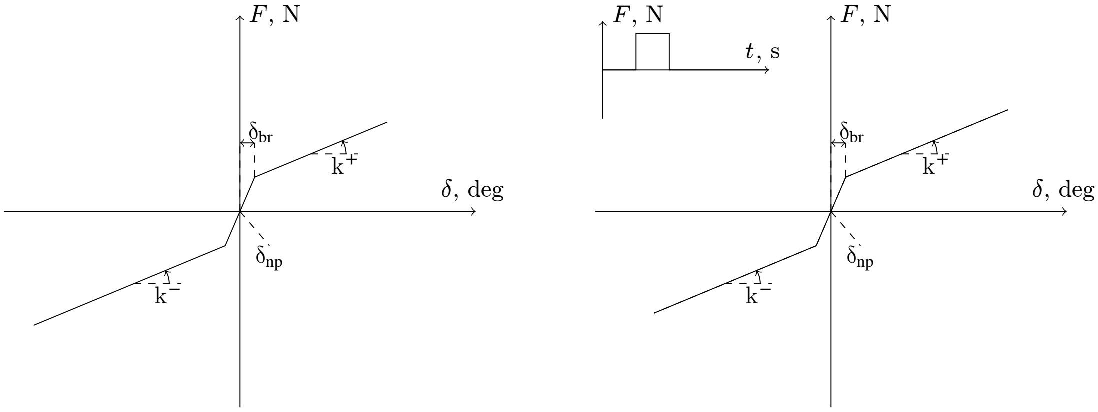
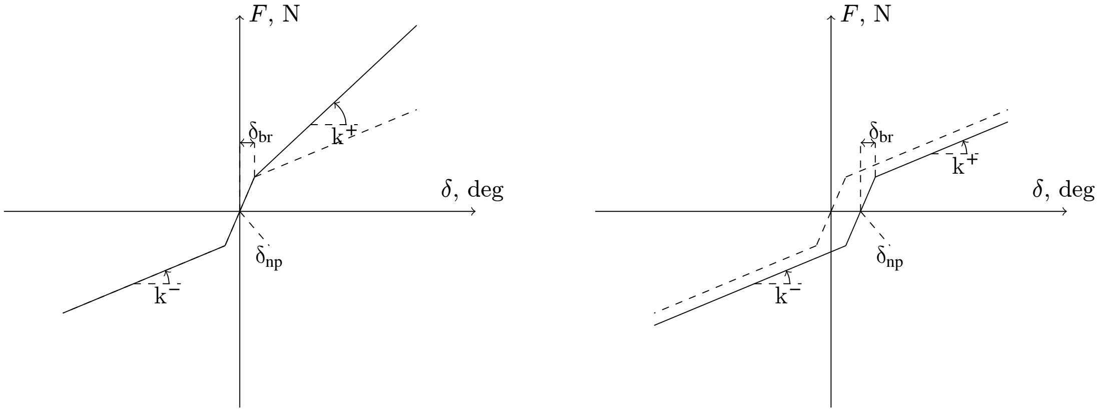
[*] In roll the profile is slightly asymmetric [14].

Apart from changing the stick's stiffness the system can suggest a corrective control input by shifting the neutral point of the stick (Fig. 2d). In an overspeed situation the stick is shifted such that it mimics the automatic pitch up command from Airbus, as long as the aircraft is accelerating. In the low speed regime, whenever a return to 1 g is insufficient to get back to the SFE, the neutral point moves to a nose down position to initiate an acceleration. Finally a stick shaker following a sinusoidal forcing function is enabled as additional warning when the aircraft approaches the stall speed. Unlike Boeing, Airbus does not utilize a stick shaker in its FBW airliners because they are protected from stalling in normal law [15].



(a) Unaltered profile.

(b) Added positive (push) pulse.



(c) Increased spring coefficient for positive deflections.

(d) Positive shift in position of the neutral point.

Fig. 2 Haptic control device profiles [5].

III. Display design

The haptic feedback system from Section II.B was tested with professional pilots in previous research, resulting in a recommendation to investigate the addition of a display to visualize the haptic cues [6]. Combining haptic feedback with a visual display could fulfill the principle of multiple resources, important when presenting information [16]. 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 (S)FE 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.

A. 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. The haptic system provides four different cues, as discussed in Section II.B:

- Change in spring coefficient
- Discrete tick
- Stick shaker
- Shift of neutral position

The first two cues can be visualized by an ordinary spring (upper part of Fig. 3) that is positioned next to the side stick. When the aircraft approaches the edge of the SFE as discussed in Section II.A the spring moves towards the stick. Upon leaving the SFE 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.

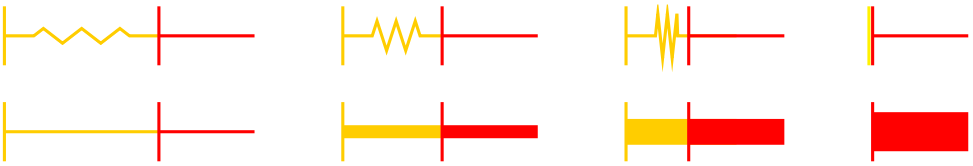


Fig. 3 Spring (top) and piston (bottom) symbols with increasing levels of compression.

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. 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 SFE. All of this is known to help pilots understand and consequently appreciated haptic feedback better [7].

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

The piston analogy is used throughout the enhanced display. The symbols and colors that are used are kept uniform over the various indications to adhere to Wicken's 13th design principle of consistency [16]. In line with industry recommended color coding [17], yellow is used to indicate the protection limit, beyond which the aircraft is outside the SFE but still within the flight envelope. 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. Figure 4 shows the PFD with all of the flight envelope indications in place. The various elements are discussed in greater detail below.

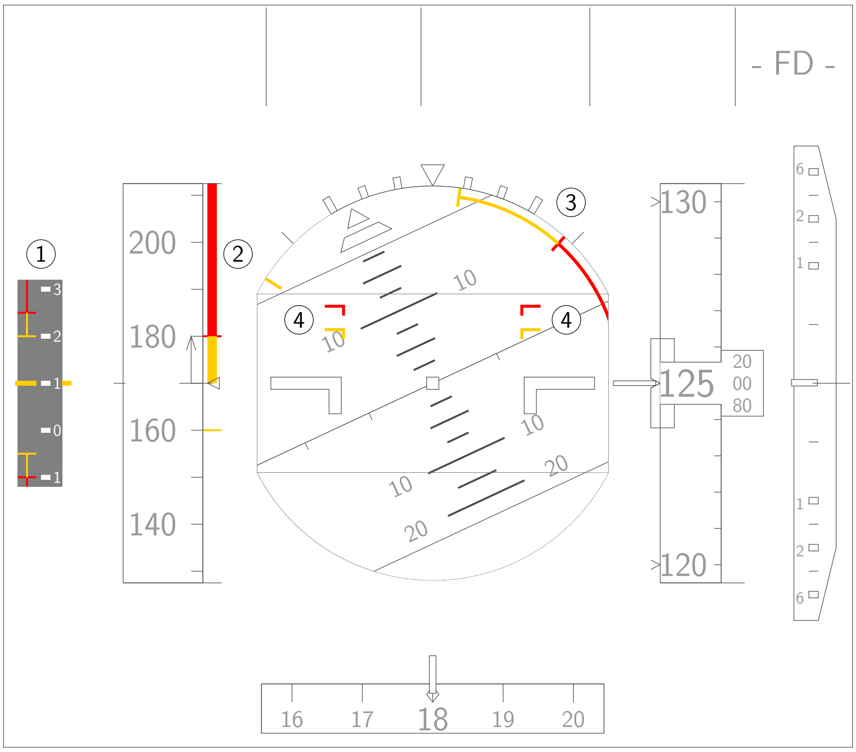


Fig. 4 Wireframe view of the Airbus A320 PFD with additional load factor indicator ① and flight envelope limits for overspeed ②, bank ③ and angle of attack ④.

B. Load factor

The first addition is a load factor indicator, added to the left of the airspeed tape (Fig. 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 1 g and minor tick marks every 0.5 g. The flight envelope limits are indicated by horizontal lines that attach to vertical lines running away from the fixed reference line. The hard limit is indicated in red, while the soft limit is shown in yellow. When the aircraft enters the soft limit region, the thickness of the vertical lines 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. 5. The big red line at the top of the scale on the rightmost figure gives a clear cue to the pilot that he should pitch down. Approaching and crossing the lower load factor limit exhibits a similar but mirrored sequence on the lower part of the scale.

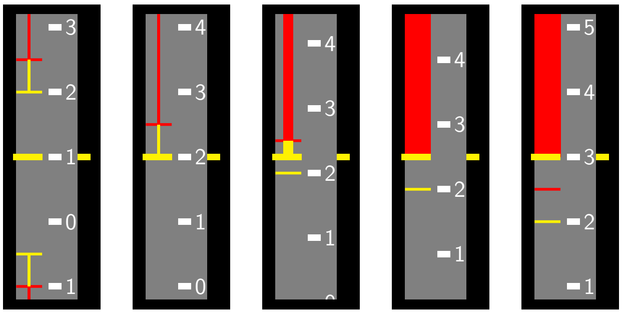


Fig. 5 Load factor indicator progressively reaching and eventually exceeding the upper limit.

C. Angle of attack

An indication for margin to stall AoA is added to the PFD as shown in Fig. 6. The distance from the ‘whisker’ indications to the fixed aircraft symbol equals the margin of the current angle of attack to the stall AoA, similar to Boeing’s pitch limit indication (PLI) [18]. 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, and are placed besides the pitch ladder to not obstruct the ladder.

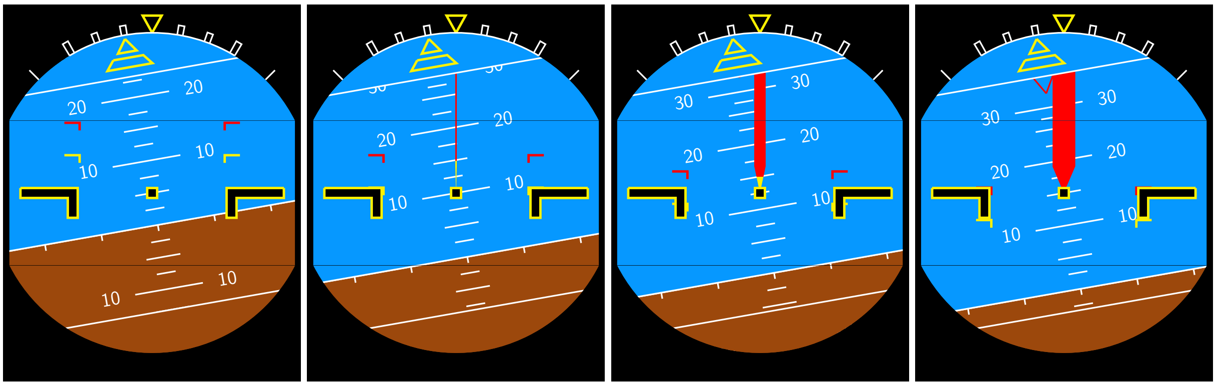


Fig. 6 AoA indicators relative to the fixed aircraft symbol progressively reaching the AoA limit.

D. Bank angle

For the bank angle protection, yellow and red regions are indicated below the bank indicator scale (Fig. 7). Note that the angle of attack indications are removed from the figure for clarity but are visible on the actual instrument. The yellow line perpendicular to the scale corresponds to the protection limit of the haptic system, at which a discrete force cue is generated to alert the pilot of the excessive bank angle. When the aircraft banks further, the stick force is progressively increased to suggest the pilot to decrease the bank angle. Synchronous to this increase in required stick force, the curved line’s thickness increases as the yellow region is compressed. An example of an extreme bank is shown in Fig. 7. In this particular example, the pilot should roll left to lower the bank angle.

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 [16].

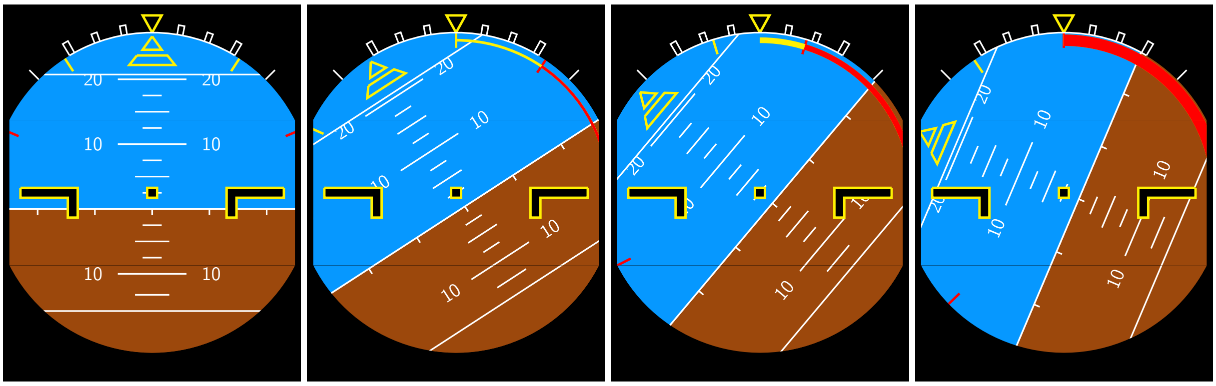


Fig. 7 Bank angle indicator progressively reaching the limit.

E. 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. 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 20 knots below the maximum speed. An evolving overspeed situation is shown in Fig. 8. Once the aircraft crosses the protection limit, a gentle nose up command is encouraged by the haptics and the vertical line increases in thickness. At the maximum speed limit, the vertical line has reached its maximum thickness, giving a strong alert to the pilot that the aircraft's speed is too high.

A similar indication on the lower side of the speed tape corresponds to the low speed part of the flight envelope. When the aircraft decelerates into the yellow region of this indication, the haptics will 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.

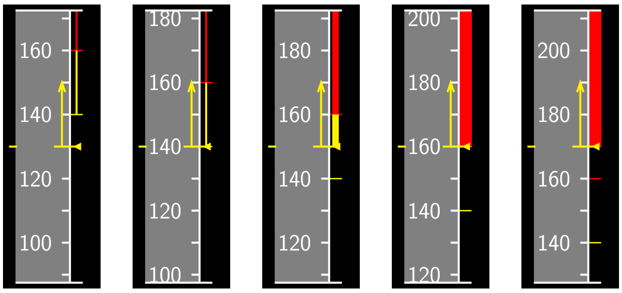


Fig. 8 Overspeed indicator progressively reaching and eventually exceeding the limit.

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 [16]. 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. Since the speed tape on the A320's PFD already has an indication for overspeed that is similar in direction to this new piston-symbol, it can be considered an acceptable design.

F. Typical windshear recovery

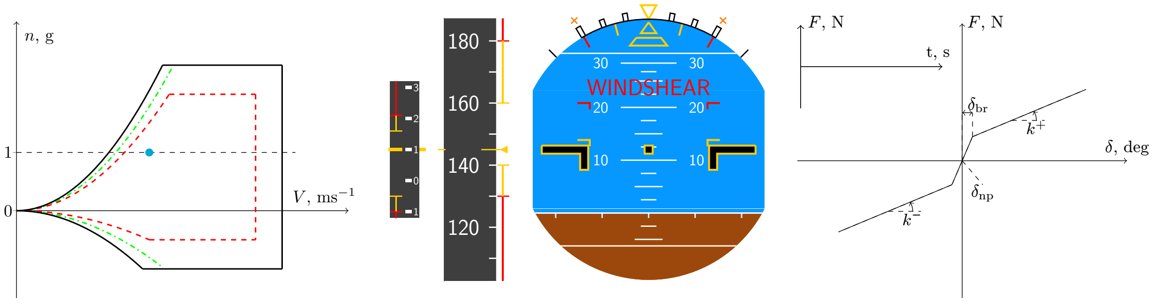
To illustrate the synergy between the flight envelope, display and haptic feedback, Fig. 9 shows the display indications during a typical windshear escape procedure side-by-side to the flight envelope and haptic profiles. The series of four frames follows the actions a pilot would typically perform.

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 standard windshear procedure by applying full thrust and pitching the aircraft to 17.5° of pitch [15].

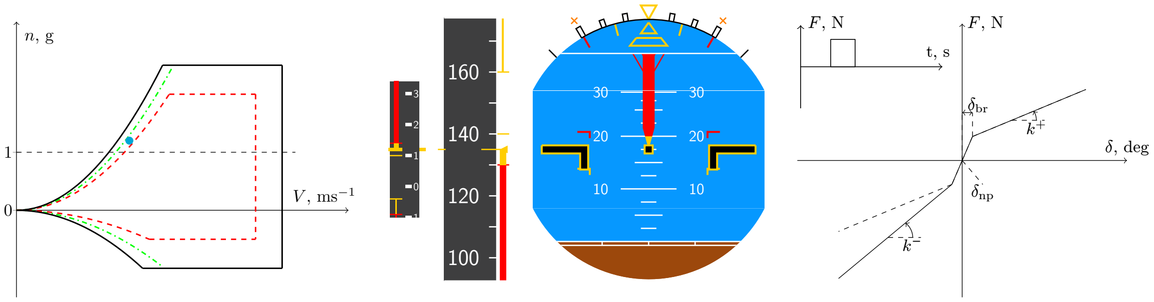
Frame 2: The pilot receives a tick on the stick's pitch axis to alert him that the speed is decreasing outside the SFE. On the speed tape this is shown by the current speed protruding into the yellow part of the low-speed piston. At the same time, the load factor indication shows that the aircraft is above the safe load factor limit for the current airspeed. And finally the angle of attack indication on the pitch scales 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 also felt in the stick by an increase in stiffness on the nose-up side. Additionally the neutral point of the stick is shifted forwards at this point to help the pilot lower the nose.

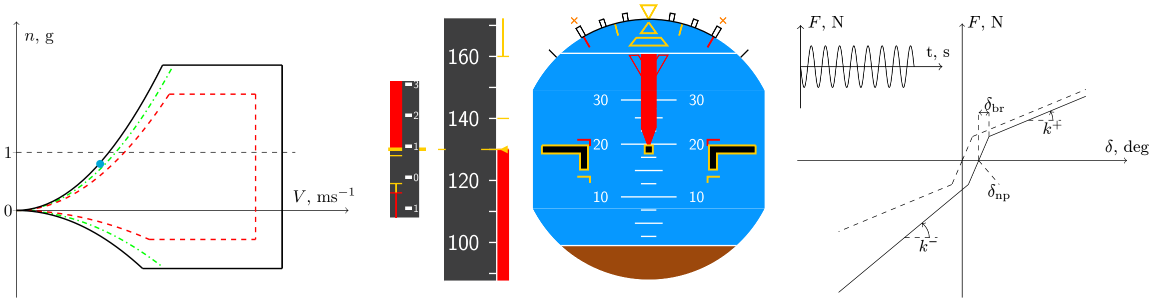
Frame 4: After the initial recovery from the windshear, the aircraft is now accelerating. When approaching the maximum velocity limit as shown here, a tick warns the pilot of an imminent excursion and the stick moves backwards to help the pilot bleed of airspeed. The spring stiffness of the stick is 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.



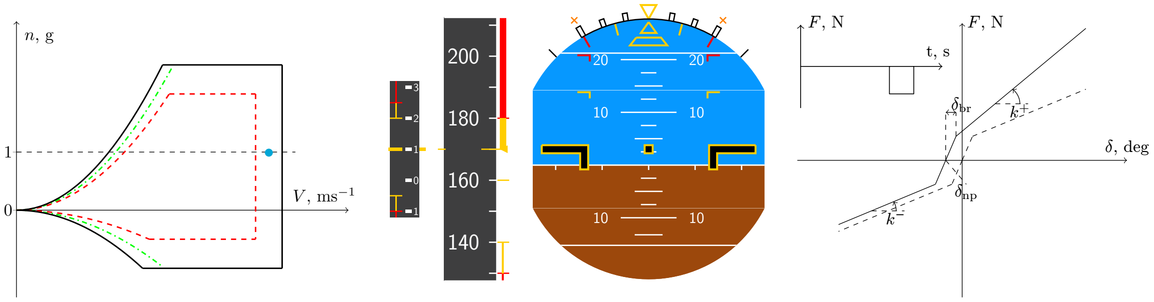
(a) Frame 1.



(b) Frame 2.



(c) Frame 3.



(d) Frame 4.

Fig. 9 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.

IV. 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 is 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.

A. 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 16 participants is shown in Table 1. The pilots were divided over two groups (A and B) that experienced a different display order. Four pilots had previously participated in research on the examined haptic feedback system, namely A5, A6, B1 and B6. It is worth noting that the second officers – while not certified to operate the aircraft below 20,000 ft – 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 1 Participants in the experiment.

Pilot	Age	Flight hours	Airbus flight hours	Position	Main aircraft type
A1	52	13,500	2000[2]	SFI	A320
A2	48	13,500	700	First officer	A330
A3	27	2800	2300	First officer	A320
A4	56	10,000	6000	Captain	A330
A5[1]	57	9500	9000	Captain	A320
A6[1]	47	15,000	1500	Captain	A330
A7	28	1200	600	Second officer	A330
A8	25	2300	200	Second officer	A330
B1[1]	48	16,000	5000	Captain	A330
B2	50	16,000	5000	Captain	A330
B3	43	12,500	7500	Captain	A320
B4	30	3000	400	Second officer	A330
B5	49	13,000	2000	Captain	A330
B6[1]	31	5500	5300	Captain	A320
B7	47	13,950	3300	Captain	A330
B8	39	8787	6178	Captain	A320
Mean	42	9784	3561		
Std. dev.	11	5235	2758		

[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.

B. Apparatus

The experiment took place in the Simulation, Motion, and Navigation (SIMONA) Research Simulator (SRS) at Delft University of Technology. The simulator's exterior and interior are shown in Fig. 10 and 11 respectively. SIMONA is a six degrees of freedom motion simulator with a full fledged cockpit shell. The interior can be configured to resemble any modern glass cockpit transport aircraft. For this particular experiment the motion system was not used.

An electrically controlled Moog FCS Ecol-8000 side stick with force feedback capabilities as described in [5] was located on the right hand side of the pilot who is 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

Fig. 10 Exterior of SIMONA at TU Delft.

Fig. 11 Interior of SIMONA at TU Delft.

terminology) complemented the interior. The outside visuals were provided by FlightGear[†] and showed the runway(s), airport infrastructure, surrounding 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 50 ft 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 [19]. The PFD and ND were drawn using OpenGL (see Fig. 18 and 19) and very closely resembled the real Airbus displays.

C. Procedure

All participants engaged in the procedure outlined in Table 2. The pilots were divided over two groups that experienced a different display order. Group A first used the original PFD and then the new PFD, denoted as PFD+, while the order was reversed for group B. All in all the experiment took circa five hours per pilot.

Table 2 Experiment procedure.

	45 min	40 min	30 min	30 min	60 min	60 min	20 min
Group A	Briefing	Familiarization	Training flights	Lunch	PFD flights	PFD+ flights	Debriefing
Group B					PFD+ flights	PFD flights	

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 to the pilot as some of them were not completely resembling their Airbus counterparts. For instructional purposes, the PFD was temporarily moved to the left screen – the normal location of the ND – while the right screen was occupied with a special display showing the flight envelope and haptic profiles (Fig. 12). The flight envelope is shown in black in Fig. 12a, while the red lines indicate the SFE beyond which the protections become active. The green lines indicate the speed below which the stick shaker is activated. A red dot shows the current state of the aircraft. Adjacent to the envelope, the haptic profiles show the stick deflection versus the force in the stick (Fig. 12b and 12c). Both the flight envelope and the haptic profiles are adjusted in real-time while the simulation is running.
The simulator was put in a static state, allowing the operator to adjust the state of the aircraft with respect to the flight envelope and show the corresponding indications on the displays without actually flying the aircraft. With the pilots holding the stick, the aircraft was brought to various locations inside and outside the flight envelope to

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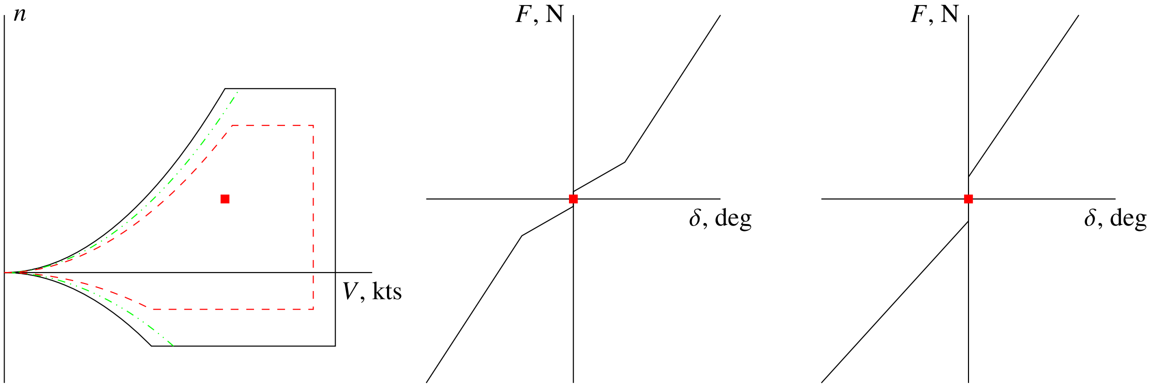
[†] Open source flight simulator available at `http://flightgear.org`

demonstrate the associated haptic cues. 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. At first the original PFD was shown alongside the haptic display, followed by the PFD+ and all cues were thoroughly presented and experienced once again.



(a) Flight envelope ($V - n$). **(b) Stick force vs pitch deflection.** **(c) Stick force vs roll deflection.**

Fig. 12 Haptic displays as shown to the pilot during the briefing.

2) **Familiarization** – In order to familiarize the participants with the flight model and controls, a simple right-hand circuit was flown at Amsterdam Airport Schiphol (EHAM). The circuit ended with a manual landing at runway 36L. This end of the runway is never used for landing in real life, so the pilots had to land without instrument landing system (ILS) or precision approach path indicator (PAPI) guidance. The circuit was flown twice with the baseline PFD.
   Once the pilots had a basic feeling of the aircraft model, they were brought to an area over the North Sea. There the pilots were asked to perform the following series of exercises that brought them towards and over the edges of the flight envelope so they could experience the associated haptic cues:
   1) Pilot induced stall by maintaining altitude with idle throttle.
   2) Overspeed by full throttle and pitching down.
   3) Nose-dive followed by a strong back stick input to reach the high-g region.
   4) Rolling to the left and right.
   5) 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 be more like 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. 13. The baseline PFD was used on the first two approaches, while the novel indications were present on the latter two approaches. The conditions per flight are shown in Table 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 in two groups. Group A first flew a series of flights with the old PFD before doing a similar series of flights with the new PFD. For Group B the display order was exactly the other way around.
   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 flight model, haptic feedback and when applicable PFD+ after a (lunch) break. This run was not concluded with a questionnaire, so the score was given right away.
   Next the six measurement runs were flown. Each ended with a questionnaire, followed by the presentation of the score for that particular flight. The questionnaire contained a rating scale mental effort, two scales on the feeling of being in control and lacking information and a couple of Likert scales on the use of haptic and visual cues. The questions about the visual cues were only present on runs with the new PFD. The airports and scenarios for

Table 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+

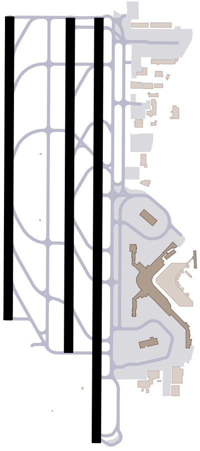


Fig. 13 Airport diagram of KSEA [20].

these flights were assigned according to a balanced Latin square distribution.

At the end of the six flights, the pilots were asked to fill in another questionnaire about the complete set of six flights. This questionnaire included a Van der Laan rating scale, a Modified Cooper-Harper rating scale, several Likert scale questions and some open questions [21, 22].

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.

D. 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 ($\mu = 20$ and $\sigma = 2.5$ seconds). The texts were read out loud by a female American-English accent from the Festival[‡] text-to-speech generation library, developed by the University of Edinburgh.

E. 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 balanced Latin square was used. The airport and scenario were varied constantly, while the display variant was fixed during a series of six flights in order to prevent pilots from having to re-adapt to the available cues all the time.

1. 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 terminal buildings with comparable runway spacing (KATL: 1340 m, EGLL: 1420 m) and more or less adjacent thresholds. The airport layouts can be found in Fig. 14 and 15. An instrument landing system (ILS) was available on the approach runway, with corresponding ILS guidance indications visible on the PFD. The pilots were provided with approach charts for both airports, including a schematic of the runway layouts.

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

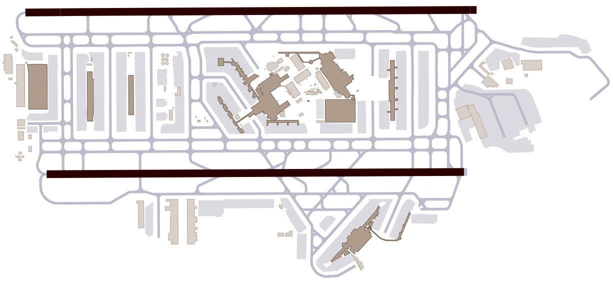


Fig. 14 Airport diagram of EGLL [20].

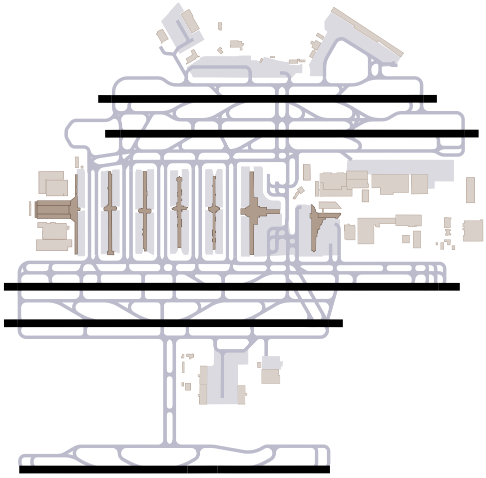


Fig. 15 Airport diagram of KATL [20].

Each flight started circa 12 NM away from the airport in trimmed flaps up condition at an intercept heading of circa 45°, straight 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. Figure 16 shows a typical trajectory towards EGLL.

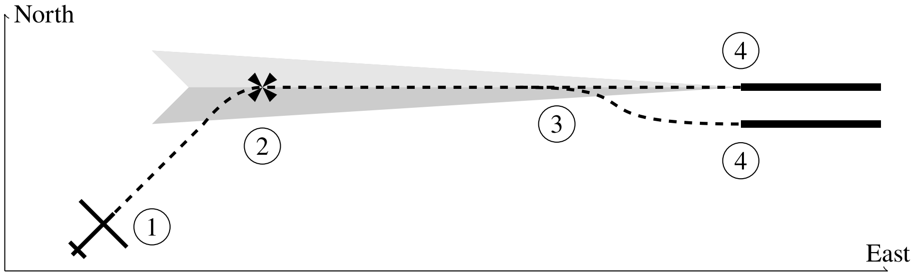
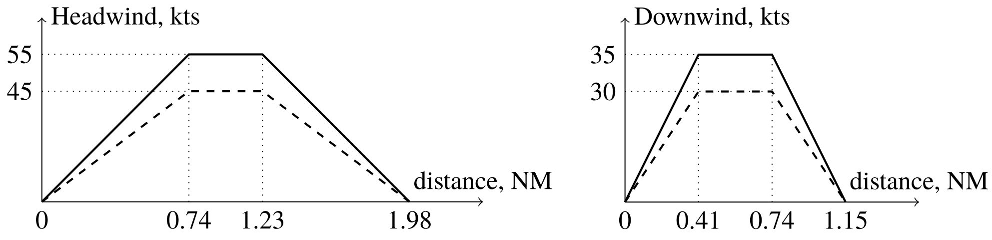


Fig. 16 Flight plan for EGLL (not to scale). Start ①, localizer interception at FAF ②, scenario triggering point ③ and end of flight ④.

2. Scenario

The pilots were subjected to three scenarios. These were automatically triggered upon descending through a pre-determined altitude.

1) **Windshear** – The windshear was implemented using the standard take-off wind model from the FAA [23] with wind components as shown in Fig. 17. Even though the pilots in this experiment only flew approaches, the 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. 17.
   In accordance with the accompanying procedure in the FCOM, 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 [15]. 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.



(a) Headwind component. **(b) Downwind component.**

Fig. 17 Windshear model, based on [23]. The dashed profile was used in the training runs.

3) **Go-around** – When ATC would make the following call '{Company} 107, go-around', pilots were supposed to climb to the missed approach altitude with 2000 ft/min.

Table 4 lists the triggering altitudes of the various scenarios. The windshear started as soon as the triggering altitude was reached, for the other two scenarios the ATC commands were sent to the text-to-speech engine upon descending through the specified altitude above sea level (ASL) and played after a short delay.

Table 4 Scenario triggering altitudes.

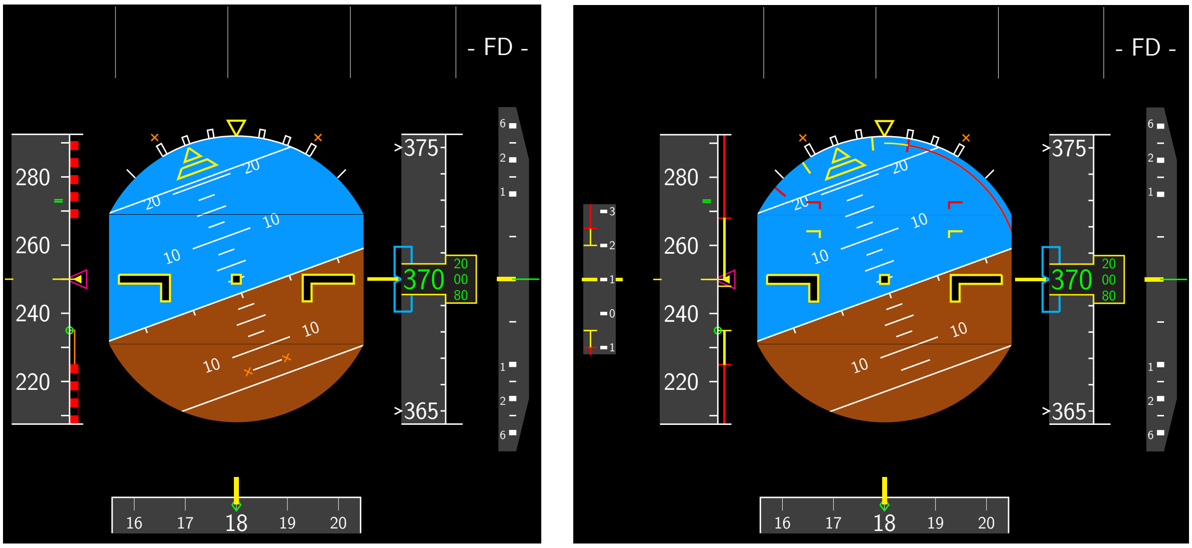
Scenario	Airport	Triggering altitude			
		ASL, ft		AGL, ft	
		PFD	PFD+	PFD	PFD+
Windshear	EGLL	1500	1500	1420	1420
	KATL	2500	2500	1475	1475
	KSEA	1700	1650	1270	1220
Sidestep	EGLL	1200	1200	1120	1120
	KATL	2100	2100	1075	1075
	KSEA	1500	1500	1070	1070
Go-around	EGLL	800	1000	720	920
	KATL	1700	1900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

3. Display

Two variants of the PFD were used in the experiment. The original PFD was a replica of the PFD on the real A320. The new PFD+ was similar to the original PFD with the addition of several new indications as discussed in Section III. Figure 18 shows the two variants of the PFD. The A320-like ND was the same throughout the experiment and always showed the final approach fix and runway threshold as waypoints (Fig. 19).

F. 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. 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 [15] 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.



(a) PFD **(b) PFD+**

Fig. 18 Two variants of the PFD as used in the experiment showing the same situation.

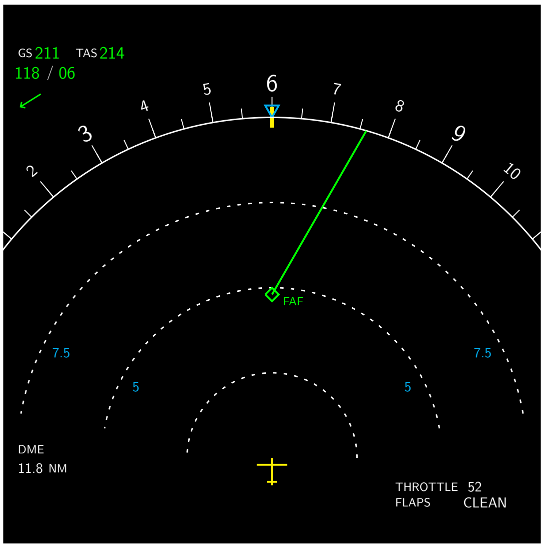


Fig. 19 Navigation display as used in the experiment.

G. Dependent measures

Both objective and subjective measures were defined to be able to assess the display in terms of performance, safety and pilot appreciation.

1. Objective measures

Objective data from the simulator were automatically logged at a rate of 100 Hz. Some of the objective measures were afterwards computed from this data or handwritten notes on the secondary task.

- 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. A corresponding 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 300 ft offset to either side of the localizer of that runway.
  - Go-around – Percentage of time during climb at which vertical speed was between 1500 and 2500 ft/min. The climb section was defined from 100 ft above the triggering altitude till 100 ft below the missed approach altitude.
- Workload through a secondary task: ratio of correct responses to ATC requests.

2. *Subjective measures*

Subjective measures were collected from the pilots through a number of paper questionnaires at various times throughout the experiment day.

- After each flight:
  - Workload through a RSME questionnaire [24].
  - Situation awareness through two questions on a linear 0 - 100 scale ranging from 'Never' on the left (0) to 'Always' on the right (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 [21].
    - ∗ Modified Cooper-Harper rating [22].
  - Five-point Likert scale questions on the following statements, with labels at the minimum (*disagree*), middle (*neutral*) and maximum (*agree*):
    - ∗ *The haptics influenced my behavior.*
    - ∗ *The haptics and PFD provided conflicting signals.*
    - ∗ *The new display elements influenced my behavior* (only with PFD+).
  - Questions on the usefulness of the following haptic and display properties in helping the pilot to stay within the limits of the flight envelope. Five-point Likert scale labeled as *not at all, slightly, moderately, very* and *extremely*.
    - ∗ *Increasing stiffness towards the edge of the flight envelope.*
    - ∗ *Stick shaker in the stall region.*
    - ∗ *Tick upon leaving the protected zone.*
    - ∗ *Change in neutral position at high speed.*
    - ∗ *Change in neutral position at low speed.*
    - ∗ *Indication of the protected zone* (only with PFD+).
    - ∗ *Indication of the maximum limit* (only with PFD+).
    - ∗ *Increasing thickness of the indication* (only with PFD+).
  - 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:
    - ∗ *The combination of haptics with new display indications made me understand the haptics better than with just the traditional display.*
    - ∗ *The system requires a lot of training.*
    - ∗ *With the display indications I knew faster how to return to the SFE than with only haptics.*

        - *Throughout the experiment (after the training) my understanding of the haptics and display increased with every flight.*
        - *The system helps prevent critical situations.*
        - *If a critical situation does occur, the system helps solving it.*
        - *I think additions to the display like in this experiment are too distracting to be useful.*
    - Five-point Likert scale question on safety with a minimum (*unsafer*), middle (*unchanged*) and maximum (*safer*) label:
        - *What would be the effect of implementing this system on safety?*
    - Five-point Likert scale questions on the realism of various simulation aspects with a minimum (*unrealistic*), middle (*acceptable*) and maximum (*perfect*) label:
        - *How would you describe the A320-like flight dynamics?*
        - *How would you describe the sidestick while not flying in the limits?*
        - *How would you describe the PFD (apart from the new elements) for the flown tasks?*
        - *How would you describe the ND for the flown tasks?*
        - *How would you describe the weather?*
        - *How would you describe the projected environment (landscape, airport, sky)?*

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.

H. 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. The PFD+ shows the pilot in advance where the limits are, so he knows what to expect and can intervene timely without overshoot. This is favorable, since less control activity generally means less workload for the pilot and a smoother ride for the passengers. 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. For example requiring less altitude loss to recover from a windshear.

H3 **Safety** – Previous research on increasing the available information to pilots stated a relation between perceived risk and risky behavior called risk homeostasis [25]. When presented with more information, pilots may fly closer to the limits. Effectively returning to the higher level of risk equal to that flying without PFD+. However, since the SFE utilized here is smaller than the actual flight envelope, pilots are expected to consider the edge of the SFE as the maximum allowable risk. With respect to safety it is therefore hypothesized that the margins to the ultimate flight envelope limits will be larger when flying with the PFD+. This is also funded by the fact that, with the PFD+, pilots do not have to move all the way to the protection limits before recognizing these limits through haptic cues. Additionally, pilots will probably be made more aware of being outside the SFE, as previous research showed that haptic cues were sometimes missed or not understood due to a lack of visualization[6].

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. The PFD+ should not only support the corrective action needed to recover but also help them identify the envelope boundary that triggered the feedback. These features are hypothesized to tackle the main acceptance issues raised by pilots on previous haptic feedback projects [6].

H5 **Indicator usefulness** – It is furthermore expected that the load factor display brings the least improvement compared to the old display. The load factor limits are almost only encountered in combination with other limits, so those limits already provide sufficient indication of what to do to unload (e.g., lower the nose). The angle of attack indication is expected to be most useful, especially in the windshear scenario, as it provides critical information that is currently not directly communicated to the pilot.

V. Results

Several events warranted the selection of data, as some flights could not be used for the main analysis. Section V.A elaborates on this selection. The results are then split in objective results as shown in Section V.B and subjective results in Section V.C 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.

A. Data selection

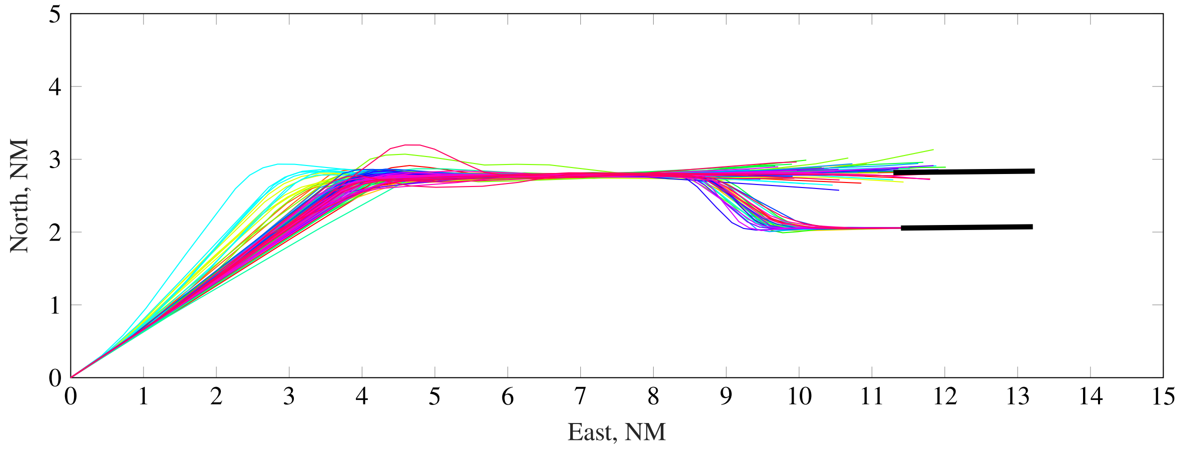
Sixteen pilots participated in the experiment, each flying 12 measurement conditions. Some flights in which a simulator hiccup prevented proper execution were restarted. Fortunately all of these hiccups occurred before reaching the scenario trigger point. Two pilots crashed their aircraft during the 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.

B. Objective results

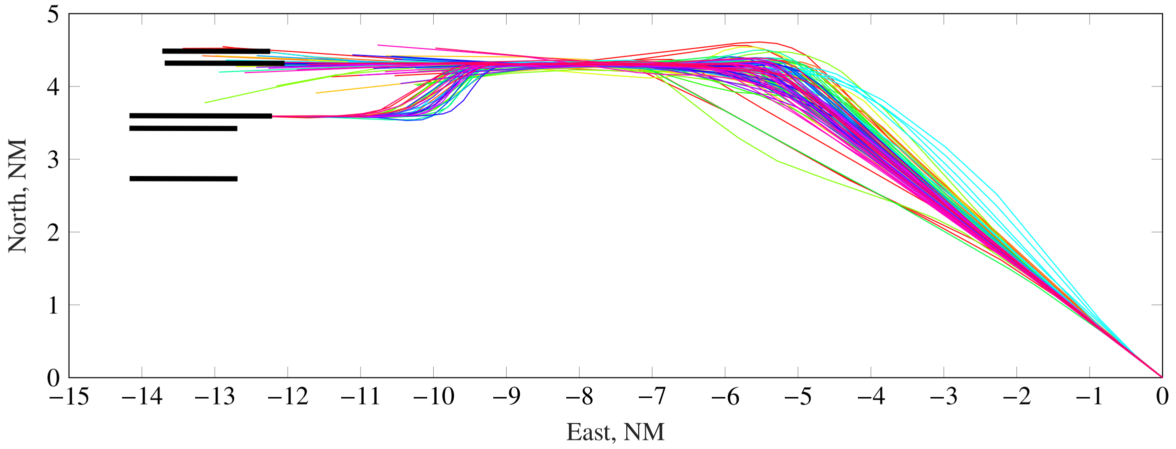
All flown tracks for both airports are shown in Fig. 20. The freedom of the pilots to choose their flight path is clearly visible. Some pilots steered away from the localizer to give themselves a smaller intercept angle, while other pilots steered towards the localizer to be able to fly over the FAF while already lined up with the runway. Figure 21 however shows that this intercept angle – when taken as the angle between the runway and a least squares fit of the approach path until the heading is within 25° of the runway – is not dependent on the display and thus has no significant influence on the results. 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, the flights are therefore cut into several sections based on the following criteria:

- **Approach** – From the start of the flight until the triggering of the scenario. Shortly before reaching the FAF, most pilots started turning towards the runway heading to anticipate the localizer. On many flights the localizer was initially overshot. The approach – including the localizer interception – is performed in every flight.
- **Windshear** – For the windshear scenarios, everything is included from the onset of the windshear until the aircraft is stable at the missed approach altitude.
- **Runway sidestep** – The sidestep section starts the moment the sidestep command is sent to the text-to-speech generator and ends with the ‘landing’ of the aircraft upon reaching 50 ft AGL.
- **Go-around** – The go-around section starts the moment the go-around message is sent to the text-to-speech generator and ends when the aircraft is stable at the missed approach altitude.



(a) EGLL.



(b) KATL.

Fig. 20 Flight tracks of all flights combined, colored per pilot.

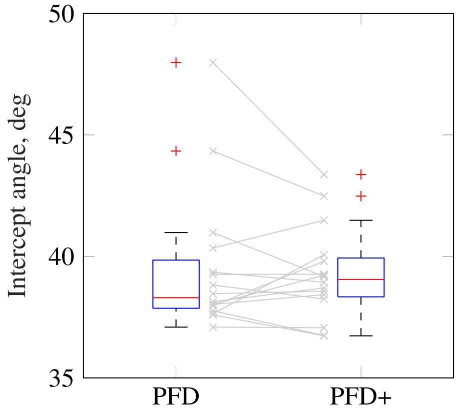


Fig. 21 Mean localizer intercept angles per subject.

1. Typical data

Figure 22 shows all of the protection limits on a typical flight with windshear scenario. The flight is split in an 'approach' and a 'windshear' section, as discussed before. The flap adjustments are clearly reflected in the maximum speed limits, as well as in the maximum angle of attack. 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 exceeded the maximum angle of attack limit very briefly, but he was in the angle of attack protection zone for circa 5 seconds. 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.

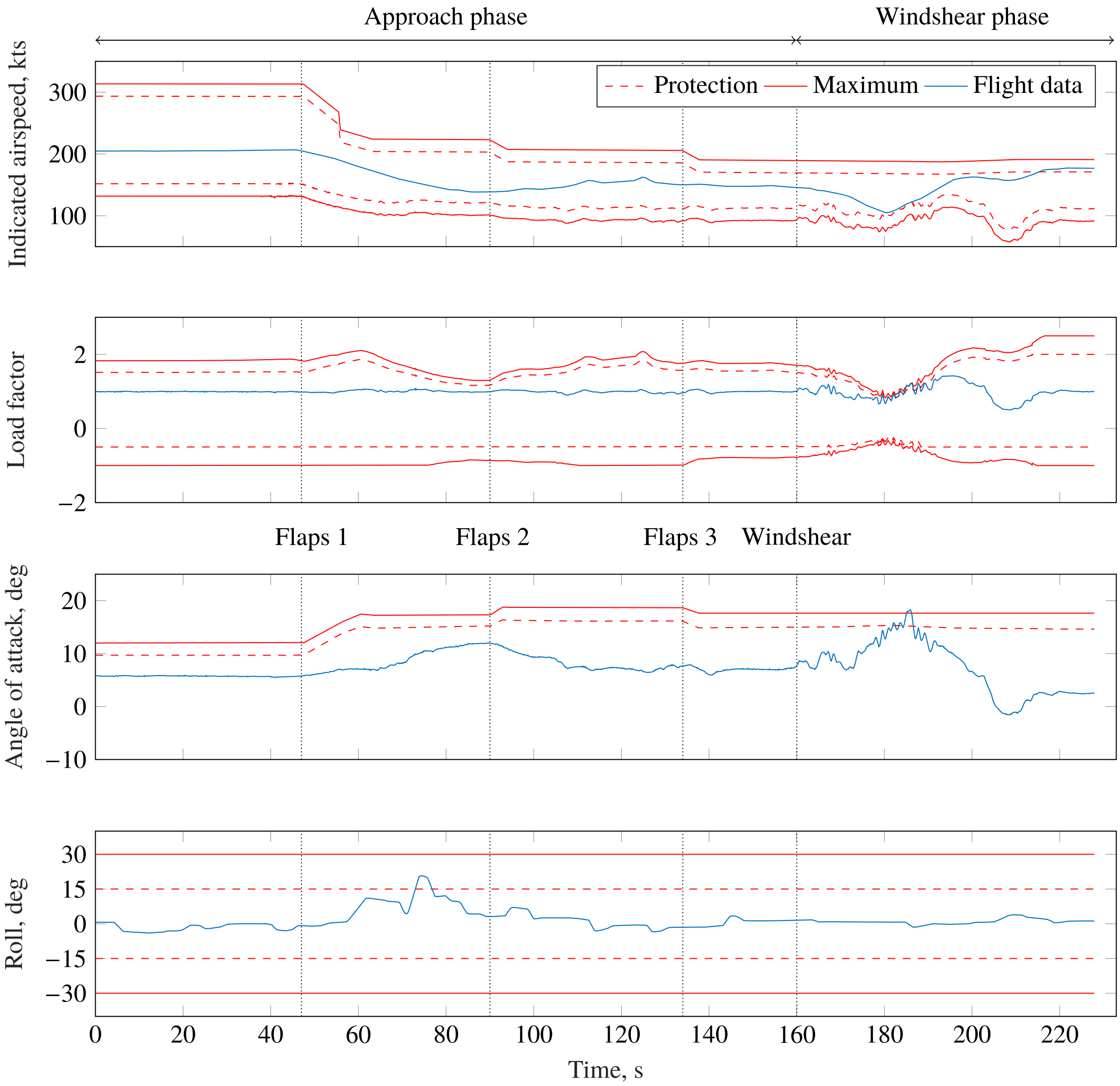


Fig. 22 Typical flight data: pilot A2 flying a windshear scenario at EGLL with the PFD+.

Figure 23 zooms in on the windshear section, showing the angle of attack during and after the windshear for all flights. Two flights stand out with a very high AoA of up to 28°. In one of the highlighted flights the pilot (B8) inadvertently thought he was flying in normal law and therefore initially provided full back stick upon encountering the shear. In the end he did manage to save the aircraft from crashing despite loosing some 1200 ft of altitude. The pilot of the other flight (A8) did not provide an explanation for the excessive AoA in his flight. A1 is an example of a very mild altitude loss (due to a high initial airspeed, note the low AoA) and large missed approach altitude overshoot.

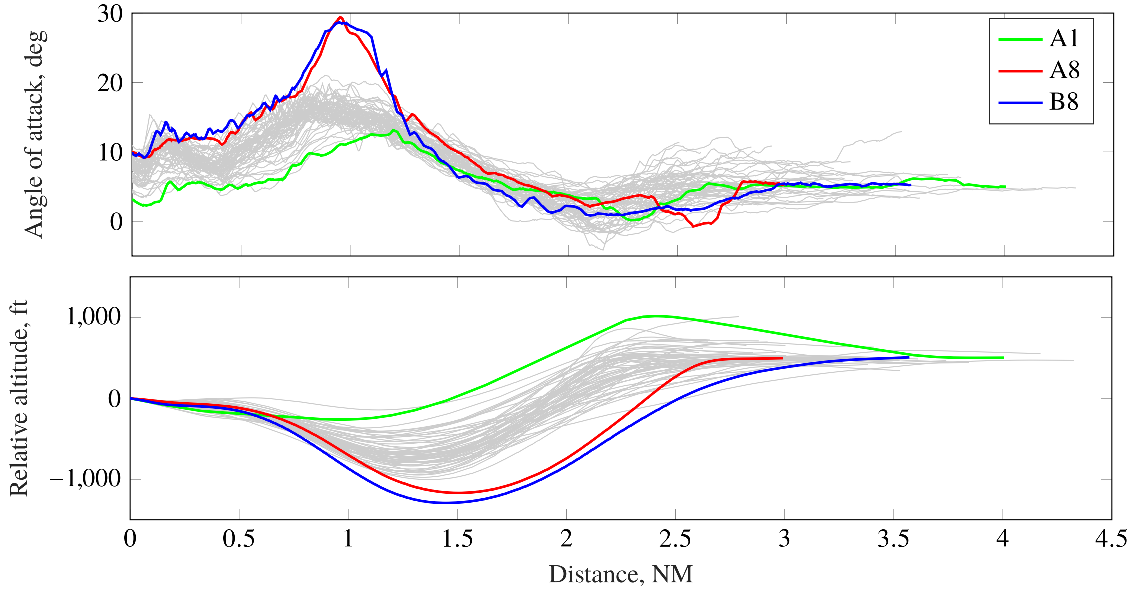


Fig. 23 Angle of attack and altitude in windshear for all flights combined. Three outliers are highlighted.

As can be seen from Fig. 24, not all pilots managed to fly around the approach speed of 140 kt when the windshear was triggered. Notably pilots A1 and A5 had much higher velocities. A higher airspeed makes the windshear escape procedure easier and generally corresponds to a smaller loss of altitude as shown in Fig. 23 for pilot A1. These pilots are consistently flying fast though, irregardless of the display variant (Fig. 25). Both fast-flying pilots were in group A, causing a considerable difference between the two groups. In both groups the airspeed is (slightly) lower in the second series of flights.

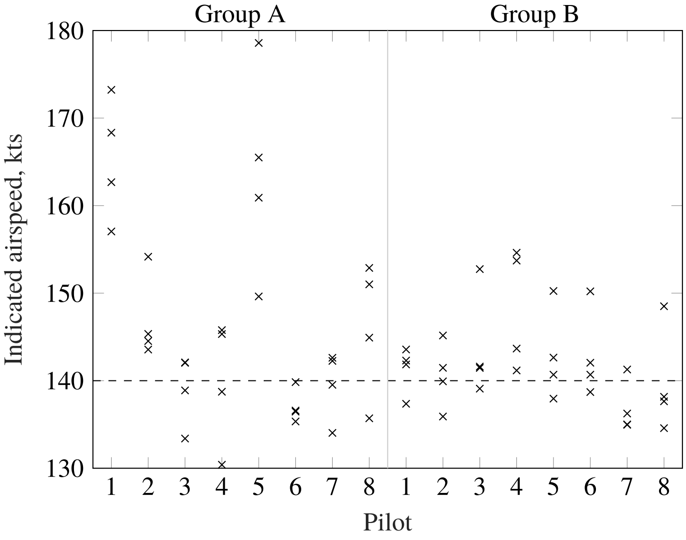


Fig. 24 Indicated airspeed at start of windshear per pilot. V_{APP} = 140 kt is indicated by the dashed line.

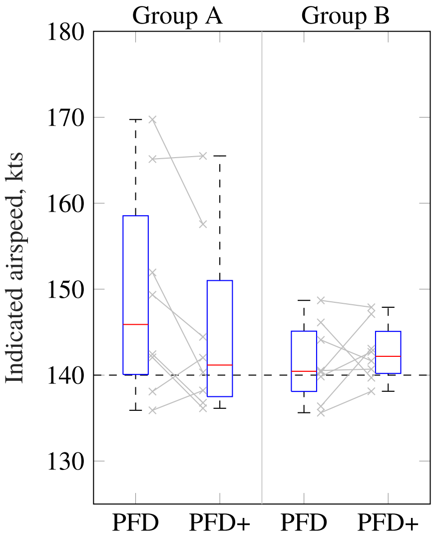


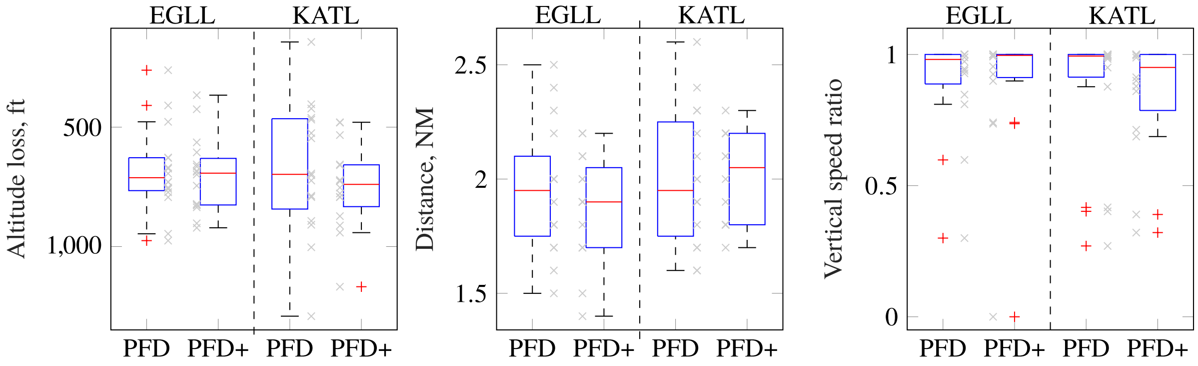
Fig. 25 Mean indicated airspeed per pilot at start of windshear split per display option.

Another non-constant factor is the extension of flaps. Some pilots extend them much earlier than others. On his first flight, pilot A1 was still in flaps 2 configuration when the windshear was triggered. Combined with the higher speed this made the windshear easier to handle. In all other flights the aircraft was in flaps 3 configuration during the scenarios.

2. Performance

The performance scores for the three scenarios as also communicated to the pilots after each flight are shown in Fig. 26. Overall there seems to be little effect of the display on the 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+. Such a difference is not observed at EGLL. The sidestep scores also show a slightly different pattern for the two airports. At EGLL the PFD+ leads to a slightly lower score, while at KATL the PFD+ has a higher score. Finally the go-around also shows a small difference between the two airports, with more low scores at KATL than at EGLL. One pilot (A1) scored particularly low on go-around performance, only one of his go-arounds scored higher than 50%. Several pilots indicated that it was ‘unusual’ to maintain 2000 ft/min on go-around so they sometimes forgot to pay attention to the vertical speed. Another possible cause of the low scores is the fact that it is 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 100 ft (ca. 5%) below the missed approach altitude.

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). Go-around at EGLL (Z = -0.035, p = 0.972) and KATL (Z = -0.175, p = 0.861).



(a) Windshear. **(b) Runway sidestep.** **(c) Go-around.**

Fig. 26 Mean performance scores per pilot.

3. Secondary task

Combining the flights of all pilots, there were 734 ATC calls that required a reply. Just 22 of those were not answered by the pilots. 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. The pilot can not be blamed for missing these calls. The ratio of correct replies is therefore not a useful means to measure workload in this experiment.

4. Roll

Figure 27 shows the maximum roll angles obtained during the various flight sections. Roll angles were particularly large during the approach and sidestep. Maximum roll angles appear to be slightly smaller with the PFD+ for all phases except windshear, where the maximum roll angle was generally larger with the PFD+. In the approach phase this is a significant reduction according to a Wilcoxon’s signed-rank test (Z = -2.223, p = 0.026), while the change is not significant in the sidestep (Z = -0.465, p = 0.642) and windshear (Z = 1.396, p = 0.163).

As shown in Fig. 28 roll protection limit excursions (ϕ > 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. In both approach and sidestep the excursions get 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 that in the sidestep is not (Z = -1.034, p = 0.301). For the maximum roll limit (ϕ > 30°), there were too little violations to run a similar analysis.

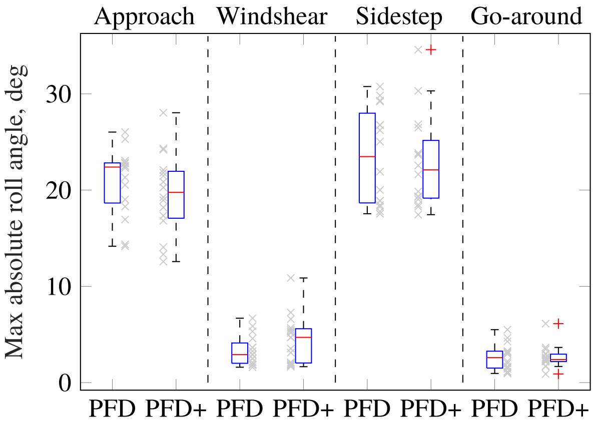


Fig. 27 Mean maximum absolute roll angle per pilot.

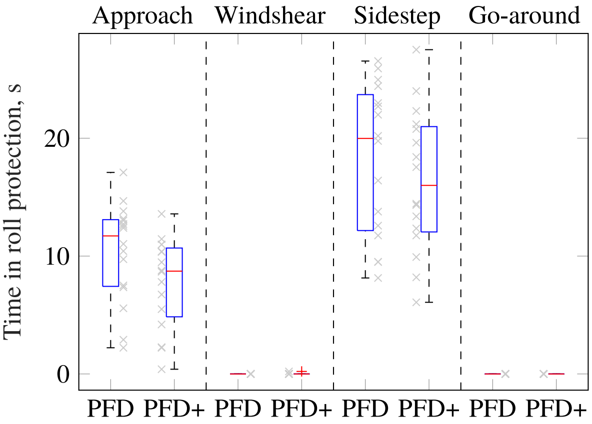


Fig. 28 Mean time in roll protection per pilot.

5. Overspeed

Figure 29 shows the time spent in overspeed protection for each of the four flight sections. Most speed excursions were seen during windshear and approach. In the approach these excursions were almost always 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 the windshear scenario, pilots seem to spent less time in the high speed protection with the PFD+, but this decrease is not significant (Z = -1.619, p = 0.105). A similar effect is seen during the approach phase, but here the decrease is significant (Z = -2.521, p = 0.012). In the sidestep and go-around there were too little overspeeds for any statistical analysis. The maximum speed was only exceeded in one flight, during a windshear with the original PFD.

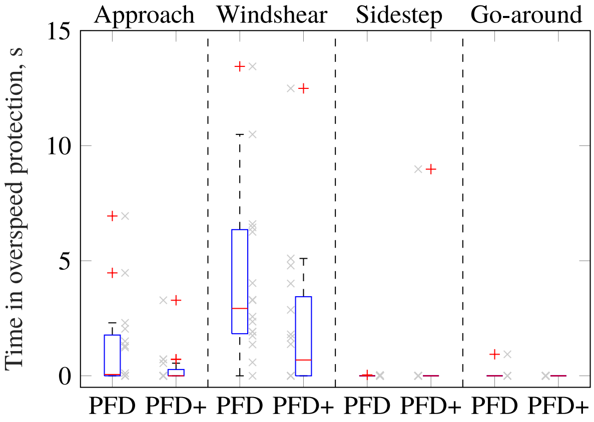


Fig. 29 Mean time in overspeed protection per pilot.

6. Angle of attack

As expected, the angle of attack limits are almost only exceeded during the windshear. Figures 30 and 31 show the time spent above the protection and maximum limits, respectively. Only one pilot (A1) never exceeded the AoA protection limit. For both limits there was a small decrease in time with the PFD+ that is not significant (protection: Z = -0.795, p = 0.427, maximum: Z = -1.020, p = 0.308).

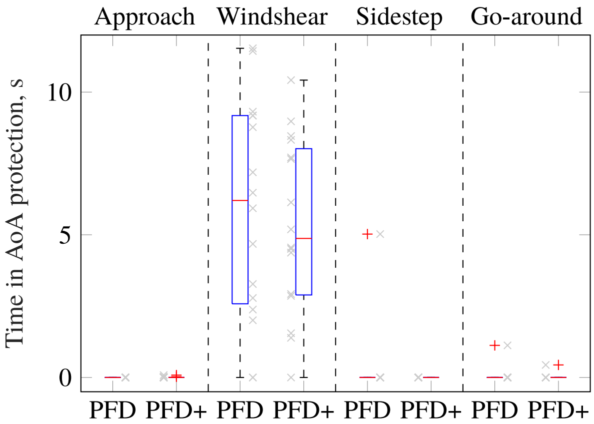


Fig. 30 Mean time in AoA protection per pilot.

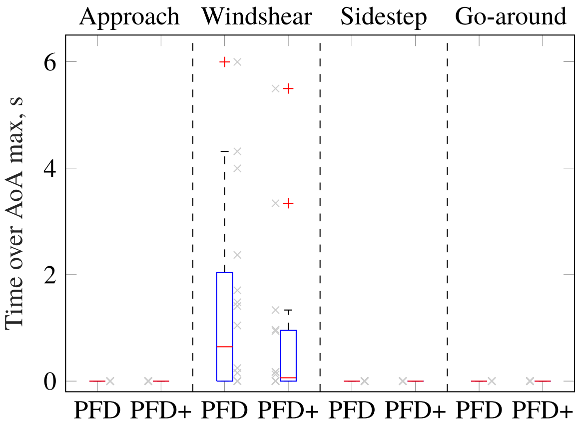


Fig. 31 Mean time over AoA max per pilot.

7. Control activity

The root mean square (RMS) control deflections of the side stick are given in Fig. 32 and 33 for pitch and roll respectively as a measure of control activity. During the windshear scenario control activity is highest in the pitch axis. In the roll axis, most control activity is seen during the sidestep and to a lesser extent during the approach phase which includes the roll onto the localizer. 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).

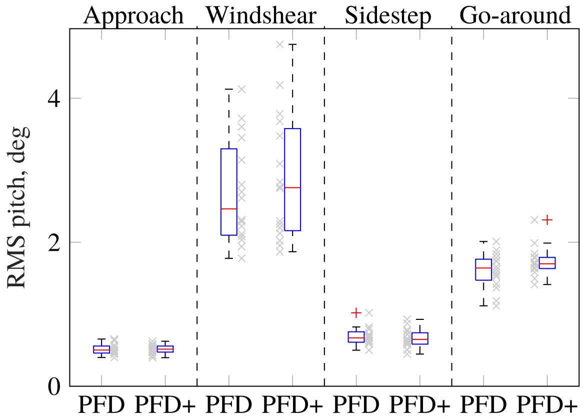


Fig. 32 Mean RMS pitch input per pilot.

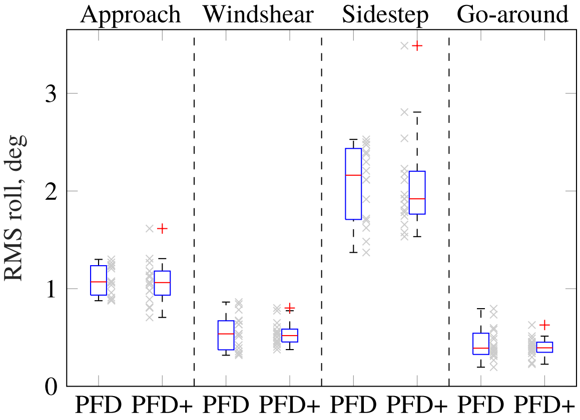


Fig. 33 Mean RMS roll input per pilot.

C. 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.

1. Post-run questionnaire

A short questionnaire after each single run allows to see how the display and haptics are experienced in the three scenarios. Figure 34 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 11 of the 16 pilots indicated less lack of essential information in the presence of the PFD+ and 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.

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. 35). 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.

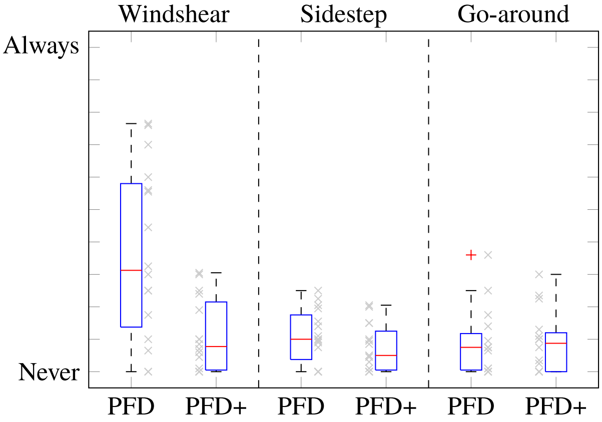


Fig. 34 Post-run question: *Did you have the feeling you missed any essential information?*

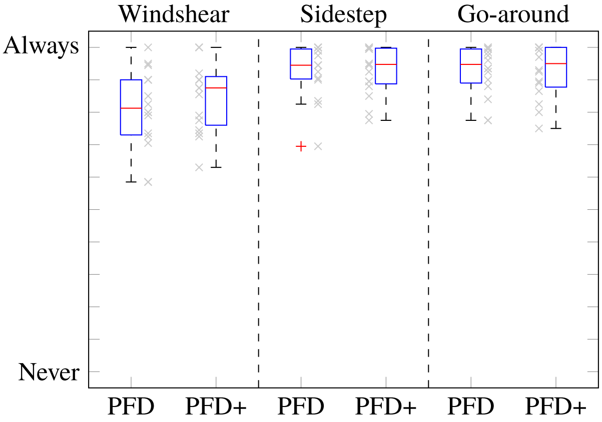


Fig. 35 Post-run question: *Did you have the feeling you were in control?*

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. 36). 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.

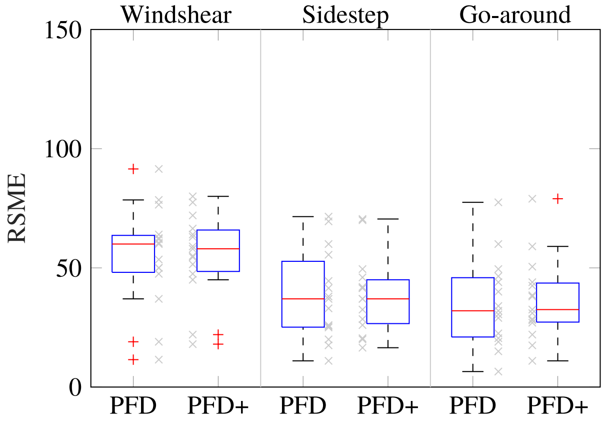
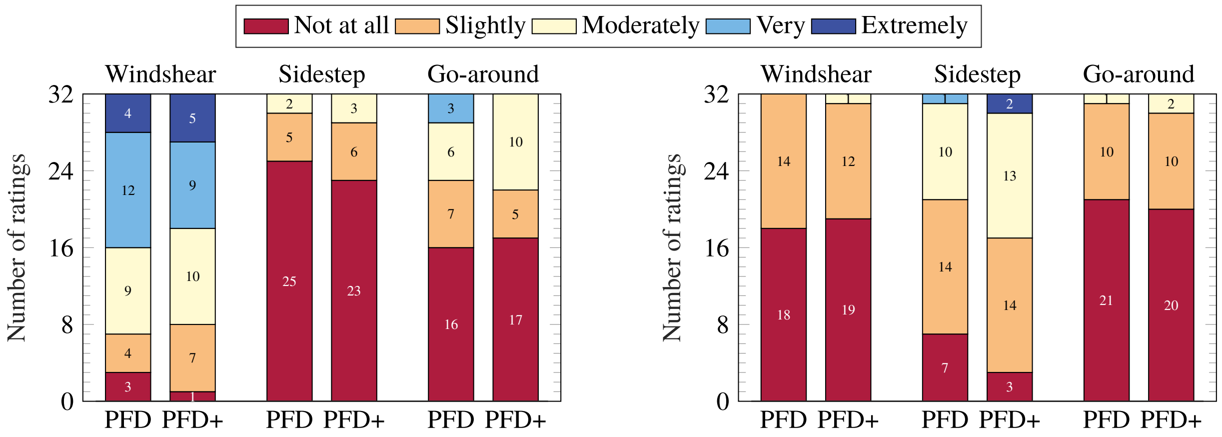


Fig. 36 Mean RSME scores per pilot.

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. 37). Pitch did not help in the sidestep scenario but provided some help in the go-around scenario. Roll was somewhat helpful during the sidestep, but much less 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.**

Fig. 37 Subjective usefulness ratings of the two 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. 38. It reveals that pilots consider the angle of attack indication most useful in the windshear scenario and to some extent also in the go-around. Overall, the airspeed indication is considered useful by a large portion of pilots in all scenarios, especially in windshear. The bank angle limit indication is somewhat helpful during the side step 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.

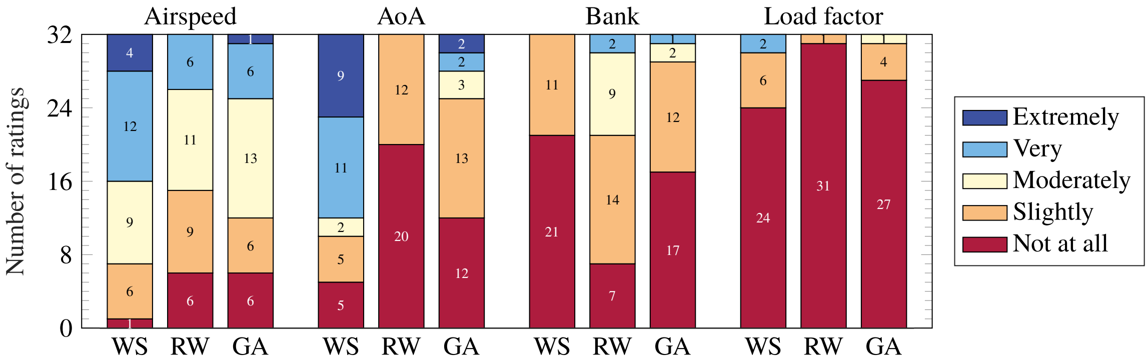
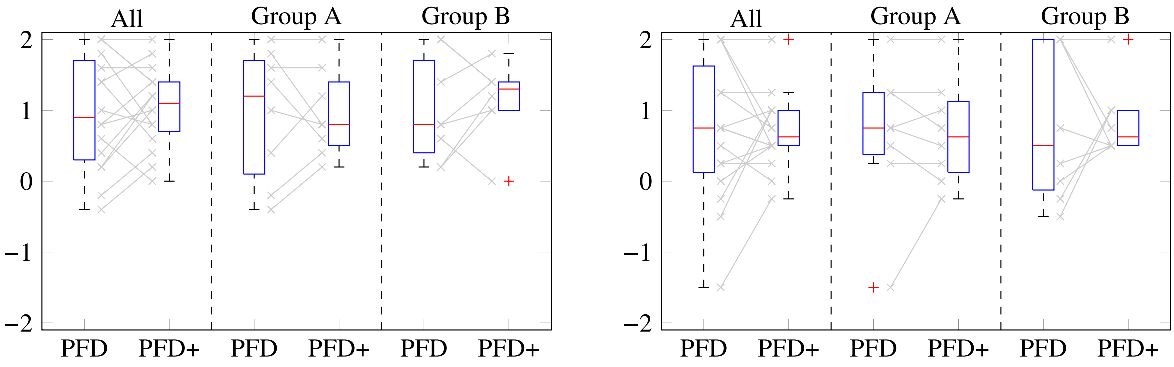


Fig. 38 Subjective usefulness ratings of display elements in helping to stay inside the flight envelope limits.

2. 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. 39 after being averaged per category [21]. The ratings show a small insignificant positive effect of the PFD+ on usefulness No such difference is observed in the acceptance of the system. 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+.



(a) Usefulness. **(b) Acceptance.**

Fig. 39 Van der Laan ratings per group.

As shown in Fig. 40, 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+ ($\rho = 0.757$).

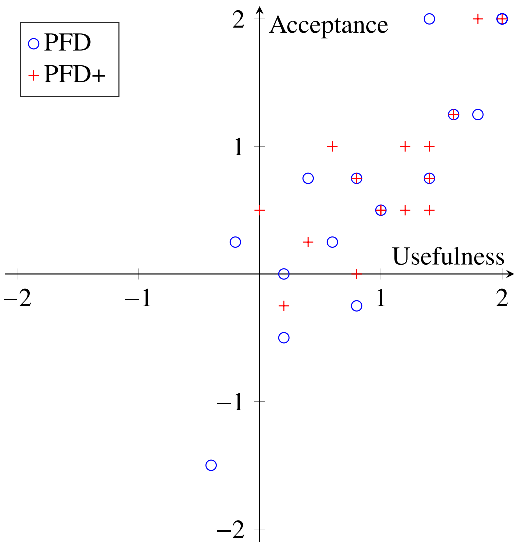
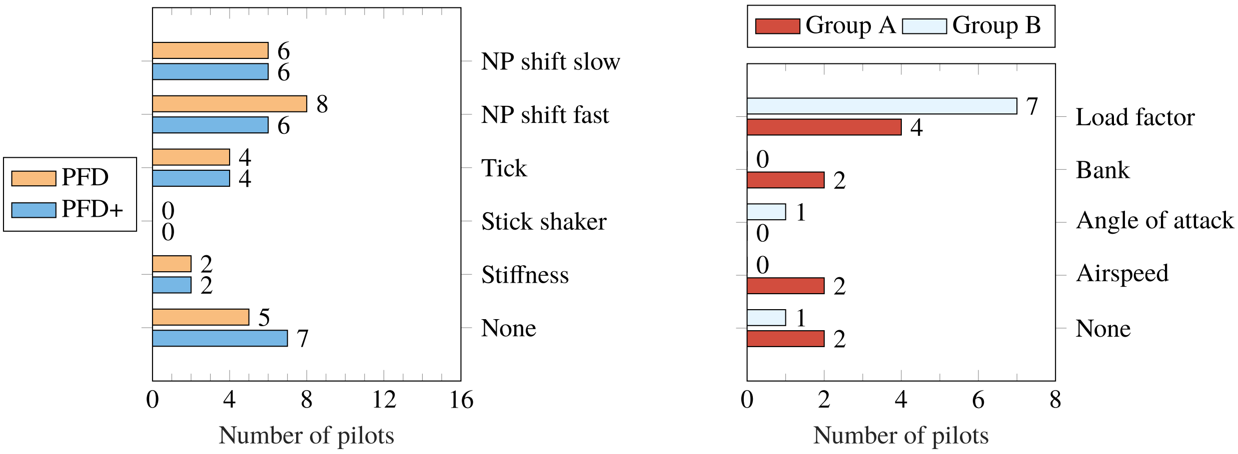


Fig. 40 Van der Laan ratings.

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 (Fig. 41). The neutral point shifts were often said to be removable. Most pilots explained they did not notice the stick's neutral position moving unless they explicitly paid attention to it. One pilot mentioned that he is used to 'flying with my finger tips' and as such did not feel the shift. All four pilots that would like to see the tick removed from the haptic system (same pilots for both displays) explained that they 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. Concentrating on the tick itself, it was said to have the potential of being a good attention grabber, as long as the limits are set to realistic values. Another attention grabber, the stick shaker, was unanimously praised as something that should not be removed from the system. With the PFD+ two more pilots indicated that nothing should be removed. When looking at the individual pilot level, it emerges that both of these would have liked to see the neutral point shift at high speed removed when they were flying with the PFD. It is also worth noting that three of the four pilots that would like to see the tick removed would like to keep all other cues.



(a) Haptics. **(b) Display.**

Fig. 41 Post-block question: *What indication should be removed?*

The same question was asked regarding the display indications, assuming that the haptics would not change. Seven out of eight pilots from group B indicated that they would remove the load factor indication from the display, while only four pilots from group A would like to see the indication removed. The most often mentioned reason for removal is that it was not used during the flights. It is said to be outside the pilot's scan pattern as the original display has nothing to the left of the speed tape. 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. The only pilot that said to remove the AoA, indicated that he does like to see the AoA and load factor indications in certain critical situations though, like windshear or terrain avoidance maneuvers.

The Modified Cooper-Harper (MCH) ratings in Fig. 42 show little differences between the old and new PFD, except that the spread is less with the new display and there are less ratings higher than 3. 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 2 indicates that this question was answered with '*yes*', while a rating of 3 can only be chosen when the question is answered with '*no*'.

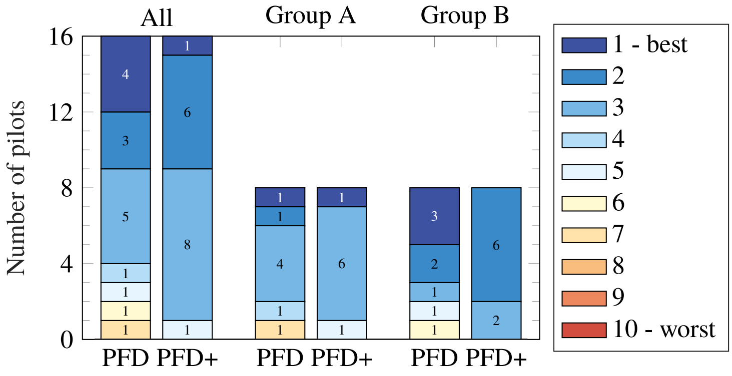


Fig. 42 Modified Cooper-Harper ratings.

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. 43). 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 large number of '*not at all*' ratings for the tick and neutral point shifts correspond to the large number of pilots in Fig. 41a that indicated that these should be removed from the system.

The same question was asked about the various elements of the display indications (Fig. 44). The indication of the protected limit (beyond which the SFE 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.

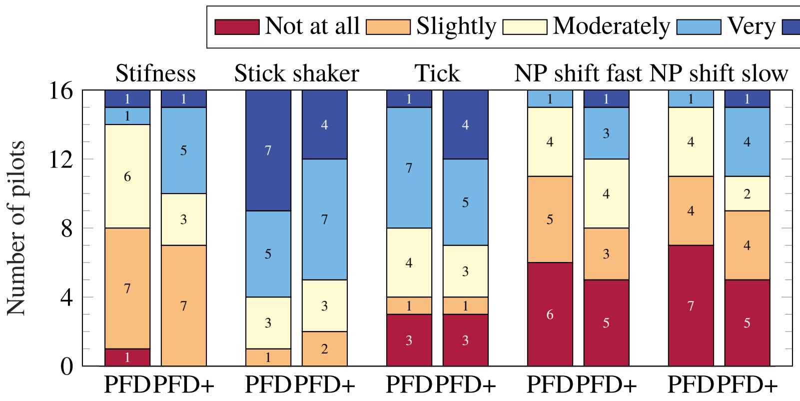


Fig. 43 Usefulness of haptic feedback cues.

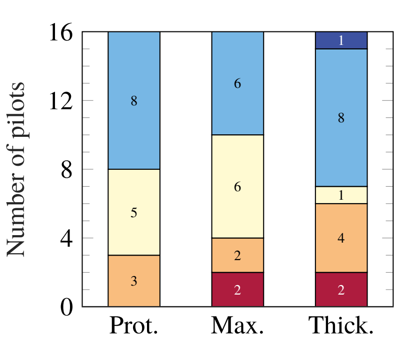


Fig. 44 Usefulness of display cues.

3. 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 indicated that they would like to see the haptics combined with the PFD+ (Fig. 45). 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.

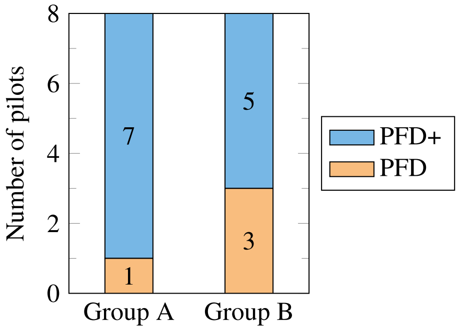


Fig. 45 Preferred display.

Apart from this binary question, several theses were posed to get a better understanding of how the pilots experienced the system and the experiment itself. The results of which are shown in Fig. 46, where the theses about training and distraction have been converted from a negative to a positive form for easier interpretation. 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 20 kts below the maximum speed, numerous pilots experienced ticks in the stick that they could not explain. Pilots also indicated to be able to return faster to the SFE 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. Almost all pilots thought implementation of such a system would have a positive effect on safety; only one pilot thought the safety would be unchanged. Finally, there is no consensus on whether the display is too much of a distraction. Pilots that were of the opinion that it was too 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.

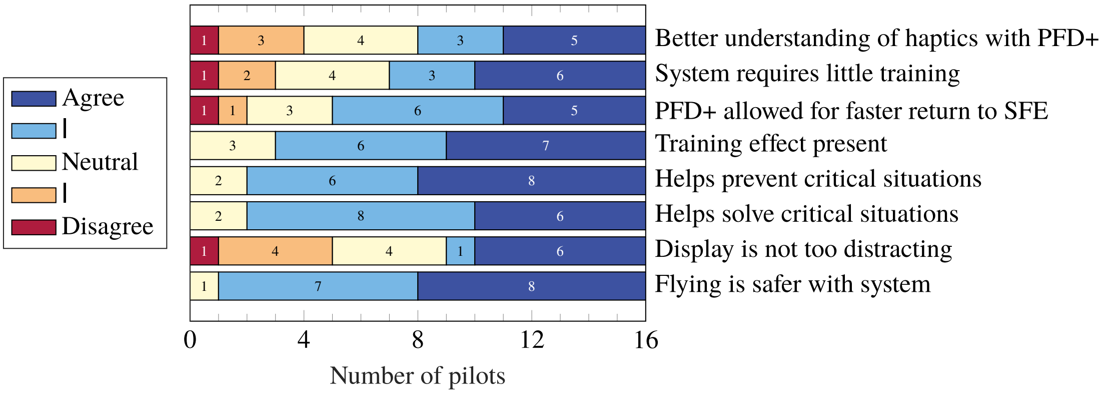


Fig. 46 Subjective post experiment ratings.

In terms of simulation fidelity, all aspects of the experiment are considered acceptable or better by the vast majority of pilots (Fig. 47). 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 navigation display. The other ‘*unrealistic*’ rating for weather was by pilot A8. Throughout the experiment day, there were considerable comments on the flight dynamics model. The most heard comments were about the thrust setting not matching that of a real Airbus and a too high sensitivity in pitch, which were also primary complaints in earlier research utilizing the same flight model [6]. In terms of weather, some pilots thought the windshears were too strong compared to their usual training scenarios and some attributed the effect of wind on the dynamics of the aircraft to the weather system. The projected environment (terrain, airport and sky) was rated acceptable or better by all pilots.

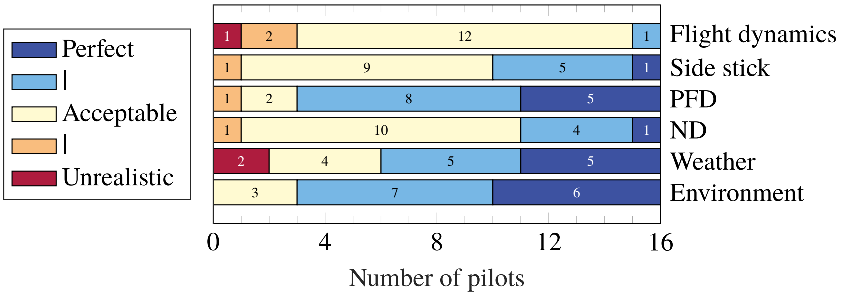


Fig. 47 Subjective simulation ratings.

When taking a closer look at the two 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.

VI. Discussion

Previous research has indicated that adding visualizations to haptic feedback improves user acceptance and possibly also performance and safety metrics [7]. The experiment discussed here 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, following the hypotheses on workload, performance, safety, pilot appreciation of haptic feedback and the display design itself. It concludes with a section on the experiment setup and an overall system evaluation.

A. Workload

When it comes to 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 an experiment with a similar setup [6], therefore future research should make use of a different secondary task to aid measuring 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.

B. Performance

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 for that 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) [18] – 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.

C. Safety

During windshear, pilots spent slightly less time outside the SFE at high angles of attack and airspeeds. 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. A similar effect was seen in overspeed protection. The decrease in time in overspeed protection during the approach phase clearly shows that the stringent 20 kts high speed margin, that was only visible to pilots with the PFD+, changed pilot behavior when clearly communicated. Similar behaviour was seen 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+. Pilots also used significantly smaller maximum bank angles to intercept the localizer when using 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. Previous research 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 [6].

D. 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 research did include such a baseline condition, but did not use the Van der Laan and MCH rating scales [6, 26]. Based on the preceding, hypothesis H4 cannot be unequivocally accepted.

E. 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. 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 angle of attack indication on the other hand was much more appreciated by the pilots. Although it did not bring the expected performance benefit, it did give 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 the stall information is now also communicated through the AoA indciation. Hypothesis H5 is thus accepted.

F. Experiment

Looking back at the experiment itself, several observations can be made. First of all, 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. A large part of this can probably be attributed to the learning effect. The 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 the researched systems as the experiment progressed. Subjective results may have also been effected 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 several challenges in the data analysis. It could be helpful to limit this freedom in future experiments. For example by showing the complete route on the ND, all the way from the start, rather than only drawing the route 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 occurrence of an event may also help and is an accepted method in flight training [27]. 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, and ensure that training effects were reduced as much as practically possible, pilots were given considerable time to familiarize themselves. Together with the focus of this research on the primary flight display 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 experiment 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. 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.

G. 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. At least in approach scenarios, while 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.

VII. 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 in displaying not only the limits of the flight envelope or the limits of the control inputs, but both in one display. In addition to that, 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 SFE 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 SFE.

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. On the opposite, especially the angle of attack indication appears to be a useful addition, 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.

Acknowledgments

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References

[1] "Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations | 1959 – 2016," Tech. rep., Boeing Commercial Airplanes, Jul. 2017.

[2] CAST/ICAO Common Taxonomy Team, "Aviation occurence categories - Definitions and usage notes," , Dec. 2017.

[3] "Aircraft Accident Investigation Report," Tech. rep., Komite Nasional Keselamatan Transportas, 2015.

[4] "Final report on the accident on 1st June 2009 to the Airbus A330-203 registered F-GZCP operated by Air France flight AF 447 Rio de Janeiro - Paris," Tech. rep., BEA, Jul. 2012.

[5] Van Baelen, D., Ellerbroek, J., Van Paassen, M. M., and Mulder, M., "Design of a haptic feedback system for flight envelope protection," *AIAA Modeling and Simulation Technologies Conference, 2018*, , No. 209959, 2018. doi:10.2514/6.2018-0117.

[6] Van Baelen, D., Ellerbroek, J., Van Paassen, M. M., and Mulder, M., "Evaluation of a Haptic Feedback System for Flight Envelope Protection," *AIAA Scitech Conference, 2019*, 2019. doi:10.2514/6.2019-0367.

[7] Ho, V., Borst, C., van Paassen, M. M., and Mulder, M., "Increasing Acceptance of Haptic Feedback in UAV Teleoperation by Visualizing Force Fields," *IEEE International Conference on Systems, Man, and Cybernetics*, 2018.

[8] Meuleau, N., Neukom, C., Plaunt, C., Smith, D. E., and Smith, T., *The Emergency Landing Planner Experiment*, NASA, 2011.

[9] Rijndorp, A. D. T., Borst, C., de Visser, C. C., Stroosma, O., Mulder, M., and van Paassen, M. M., "Aviate, navigate: Functional visualizations of asymmetric flight envelope limits," *AIAA Information Systems-AIAA Infotech at Aerospace*, 2017.

[10] Lombaerts, T., Schuet, S., Acosta, D., Kaneshige, J., Shish, K., and Martin, L., "Piloted simulator evaluation of safe flight envelope display indicators for loss of control avoidance," *Journal of Guidance, Control, and Dynamics*, Vol. 40, No. 4, 2017, pp. 948–963. doi:10.2514/1.G001740.

[11] Lombaerts, T. J. J., Looye, G., Ellerbroek, J., and y Martin, M. R., "Design and piloted simulator evaluation of adaptive safe flight envelope protection algorithm," *Journal of Guidance, Control, and Dynamics*, Vol. 40, No. 8, 2017, pp. 1902–1924. doi:10.2514/1.G002525.

[12] Ackerman, K. A., Seefeldt, B. D., Xargay, E., Talleur, D. A., Carbonari, R. S., Kirlik, A., Hovakimyan, N., Trujillo, A. C., and Gregory, I. M., "Flight envelope information-augmented display for enhanced pilot situation awareness," *AIAA Infotech at Aerospace*, 2015.

[13] Rustenburg, J. W., Skinn, D. A., and Tipps, D. O., "Statistical Loads Data for the Airbus A-320 Aircraft in Commercial Operations," Tech. rep., FAA, Apr. 2002.

[14] Corps, S. G., "Airbus A320 Side Stick and Fly By Wire - An Update," *Proceedings of the Aerospace Technology Conference and Exposition, Long Beach (CA)*, 1986, p. 13. doi:10.4271/861801.

[15] *A318/A319/A320/A321 Flight Crew Operating Manual*, Airbus, Aug. 2015.

[16] Wickens, C. D., Lee, J., Liu, Y., and Becker, S. G., *An Introduction to Human Factors Engineering*, 2nd ed., Pearson Prentice Hall, 2004.

[17] "Electronic Flight Displays, Advisory Circular 25-11B," Tech. rep., FAA, Jul. 2014.

[18] "Operational use of Angle of Attack on Modern Commercial Jet Airplanes," *Aero*, edited by J. Langer, 12, Boeing Commercial Airplanes Group, 2000.

[19] van Paassen, M. M., Stroosma, O., and Delatour, J., "DUECA - Data-Driven Activation in Distributed Real-Time Computation," Modeling and Simulation Technologies Conference, 2000, pp. 1–7. doi:10.2514/6.2000-4503.

[20] OpenStreetMap contributors, "OpenStreetMap maps," `https://www.openstreetmap.org`, 2019.

[21] van der Laan, J. D., Heino, A., and de Waard, D., "A simple procedure for the assessment of acceptance of advanced transport telematics," *Transportation Research Part C: Emerging Technologies*, Vol. 5, 1997, pp. 1–10. doi:10.1016/S0968-090X(96)00025-3.

[22] Cummings, M. L., Myers, K., and Scott, S. D., "Modified Cooper Harper Evaluation Tool for Unmanned Vehicle Displays," *Proceedings from UVS Canada: Conference on Unmanned Vehicle Systems Canada '06*, 2006.

[23] "Windshear Training Aid," Tech. rep., Federal Aviation Administration, 1990.

[24] Zijlstra, F. R. H., "Efficiency in work behaviour: A design approach for modern tools," Ph.D. thesis, Delft University of Technology, Nov. 1993.

[25] Wilde, G. J. S., "Risk homeostasis theory and traffic accidents: propositions, deductions and discussion of dissension in recent reactions," *Ergonomics*, Vol. 31, No. 4, 1988, pp. 441–468. doi:10.1080/00140138808966691.

[26] Ellerbroek, J., Rodriguez y Martin, M., Lombaerts, T., van Paassen, M., and Mulder, M., "Design and evaluation of a Flight Envelope Protection haptic feedback system," *IFAC-PapersOnLine*, Vol. 49, No. 19, 2016, pp. 171 – 176. doi: 10.1016/j.ifacol.2016.10.481, 13th IFAC Symposium on Analysis, Design, and Evaluation ofHuman-Machine Systems HMS 2016.

[27] *Airplane Upset Prevention & Recovery Training Aid for Transport Category Airplanes*, ICAO, Feb. 2017. Rev. 3.

II

Preliminary thesis

Previously graded under AE4020.

1

Introduction

Although aviation is already one of the safest forms of transport, there are still improvements to be made. In the last decade, loss of control in-flight (LOC-I) has been the most common cause of fatal aircraft accidents[1]. In some cases, aircraft were inadvertently brought down by pilots that did not realise what their aircraft was doing when automation failed. Air Asia flight 8501 in 2014 is an example of such an occurrence[2]. 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 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 extremer 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.

The accident investigators concluded that the pilot's inability to control the aircraft in alternate law led the plane to depart the normal flight envelope. In the comparable Air France flight 447 accident from 2009, a lack of understanding of what control law the aircraft was in and what protections were lost was found to be a key factor in the failure of the flight crew to regain control of the aircraft[3]. Both investigations recommend that more emphasis is placed on flying in alternate law in flight training. Flight instruments might be able to further support the crew flying in degraded laws. When nothing is done, the continuous growth in air traffic means that maintaining the current safety level would result in more accidents, which is not acceptable for the public.

Airbus aircraft currently do not completely inform pilots about the (un-)availability and activation of flight envelope protection systems that can limit their control inputs. Besides, once protections are lost, pilots lack clear cues on their position with respect to the flight envelope. Previous research on haptic feedback as a way to communicate information to human operators through tactile sensations has shown that haptic cues might close this gap and decrease LOC-I incidents[4]. Nevertheless it was found that pilots were confused as to what triggered the haptic feedback and what corrective action to take. It is expected that a visual representation of the flight envelope will help pilots understand what the aircraft is doing when automatic flight envelope protection is active[5]. In combination with haptic feedback, this may assist pilots recognising the edges of the flight envelope and act accordingly. Investigating the design and added value of such a display is the main goal of this project.

1.1. Research question

This research project attempts to reduce loss of control occurrences by improving the pilot's situation awareness with respect to flight envelope boundaries. This is achieved by developing a visual display to support or replace haptic feedback as a means to communicate the boundaries of the flight envelope as well as the corrective action(s) to take when the boundaries are exceeded. The research question of this thesis is therefore:

How can a visual display augment or replace haptic feedback to communicate the boundaries of the flight envelope to pilots?

To be able to answer this question, it is essential to gain extensive knowledge of the current situation. Leading to the following questions to be answered during literature research:

- What control laws are used for flying the aircraft?
    - How is the active control law communicated to the pilot?
- What flight envelope boundaries are there?
    - How are these boundaries communicated to the pilot?
- What flight envelope protections do aircraft manufacturers (not) provide?
    - How is the availability and activation of these protections communicated to the pilot?

Based on the knowledge gained during the literature review, the following questions are to be answered in the design and experiment phase:

- What would a display dedicated to the flight envelope look like?
- How can the display be integrated with the existing primary flight display?
- Does a visual display assist the haptic cues?
    - Does a visual display improve the performance of pilots flying with haptic feedback?
        - How does the control activity change when the display is added?
        - How does the workload change when the display is added?
    - Does the subjective acceptance of pilots for the haptic system increase by adding a visual display?
- Can a visual display replace the haptic cues?

1.2. Research approach and report structure

This preliminary report follows the research approach taken to come up with a novel display design. The project can be divided in a literature study phase and a preliminary design phase.

In order to acquire a sound basis for the research, an extensive literature study is performed. Focus is in particular on the existing flight envelope protection system and control laws of Airbus aircraft. Other manufacturers are briefly touched upon to see what industry has come up with so far (Chapter 2). The available research on solutions to visualise the flight envelope is examined in Chapter 3. This also includes more details on the haptic feedback system that is considered a baseline for the current research. Next, a closer look is taken at flight instrument design to see what is considered best practice and what legislation is relevant (Chapter 4).

Based on this knowledge a display design is proposed. The design is integrated in the existing Airbus primary flight display and presented in detail in Chapter 5. The design will be tested and evaluated in a simulator experiment involving professional pilots further discussed in Chapter 6. The hypothesis is that the addition of a visual display will greatly help pilots take full advantage of the haptic cues. The report concludes with some closing remarks and an outlook on future work in Chapter 7.

2

State of the art

To be able to come up with a valuable addition to existing instruments it is essential to get a good grasp of current the state of the art. As the airliner market is dominated by Airbus and Boeing, a closer look is taken at those two while other manufacturers are only briefly touched upon. The way aircraft are controlled is explained in Section 2.1. Section 2.3 provides details on the various flight envelope protection systems in Airbus and Boeing aircraft. Haptic feedback as it is in use on commercial aircraft is discussed in Section 2.4. Section 2.5 continues with the state of current instruments and displays. The chapter ends with a discussion on what is missing or can be improved in today's aircraft.

2.1. Control laws

Traditionally aircraft are controlled by the pilot through a system of cables and rods. With the introduction of the Airbus A320 in 1988, Airbus initiated the era of commercial fly-by-wire (FBW) aircraft. Over the past 30 years, more and more manufacturers have incorporated FBW in their designs.

2.1.1. Airbus

Unlike their traditional counterparts, FBW aircraft — like all Airbuses currently flying around — have no direct linkage between the pilot's controls and the control surfaces. Inputs by the pilot are electronically fed to a computer that translates and augments the commands before they are sent to actuators driving the control surfaces. Information on Airbus' control laws is scarce but it is known that pitch control works approximately according to Eq. 2.1[6].

$$C^* = (\Delta n_z)_{pilot} + \frac{V_{co}}{g} q \tag{2.1}$$

Where $(\Delta n_z)_{pilot}$ is the vertical load factor at the pilot's station, q the pitch rate and g the gravitational constant. Crossover speed V_{co} is chosen such that the parts on both side of the plus are equally weighted ($V_{co} \approx 240$ kt). This C^* handling criterion assumes that pilots mainly use pitch rate as a cue to control their aircraft at low speeds and load factor at high speeds. Airbus uses a slightly adapted version of the C^* algorithm. Instead of a fixed pitch rate gain it is a function of airspeed.

In normal flight a sideways deflection of the side stick commands a certain roll rate. With the stick at neutral, the roll rate is reduced to zero and the aircraft will thus maintain its bank angle. Yaw control is similar to that of a conventional aircraft with the rudder pedals directly corresponding to a certain rudder deflection.

2.1.2. Boeing

Most Boeing aircraft are still conventionally controlled with cables and rods but more recent aircraft like the Boeing 777 and 787 are FBW. For the pitch control of these aircraft Boeing uses an algorithm that is a normal C^* algorithm (Eq. 2.1) combined with an extra airspeed feedback loop[6]. This C^*U algorithm is captured by Eq. 2.2, where U_{err} is the difference between the aircraft's airspeed and the reference trim speed. The trim speed is commanded by the pilot when manipulating the trim switches on the yoke. In conventional aircraft, trimming is done by changing the horizontal stabiliser position until a moment equilibrium is reached at which the aircraft no longer pitches up or down without external disturbance. If the aircraft is statically stable, it will even automatically return to the trimmed state after a disturbance.

$$C^* U = C^* - K_V U_{err} \tag{2.2}$$

The control law also acts as a speed stability mechanism. For small deviations in air speed, the aircraft automatically pitches up or down to maintain the current air speed. In practice this means that the aircraft maintains a certain flight path, until the pilot provides a control input or the airspeed changes. In the latter case the aircraft will change pitch in order to restore the airspeed. As with Airbus, pitch rate dominates at low airspeeds, while load factor is the controlling factor at high air speeds. At low speeds, deflecting the control column results in a given pitch rate, proportional to the column deflection force. At high speeds a certain push corresponds to a certain load factor. Turn compensation is provided to relief the pilot of applying a pitch input to maintain altitude during a turn. Until 30° no additional pitch input is required to maintain altitude[7]. Pitch changes caused by turbulence, thrust changes and gear configurations are also automatically minimised.

Roll and yaw control on the B777 is no different from conventional aircraft in that control wheel and pedal movements are directly proportional to control surface deflections. On the B787 roll control is roll rate based similar to Airbus, while yaw control is yaw rate based[8].

2.2. Flight envelope

The longitudinal performance limits of an aircraft are often captured in a flight envelope (FE). FEs exist with various relations but the one used here relates velocity (V) to load factor (n). Load factor is an indication for the ratio between lift and weight ($n = \frac{L}{W}$). It not only depends on the magnitude of these two forces, but also on the angle between them. In straight level flight, lift and weight are equal in magnitude and act along the same line (albeit in opposite direction). This corresponds to a load factor of 1. In a level banked turn, the lift vector points away from the neutral and is increased to keep the aircraft levelled. The load factor is now larger than 1. When lift and weight are equal, the load factor is 1. Negative load factors relate to inverted flight.

Aircraft are designed to withstand certain load factors. A common FE shape denoting these limits is depicted by the solid line in Fig. 2.1. The upper velocity limit is dictated by the maximum velocity that can be attained by the aircraft respecting aerodynamic and vibration limits. Structural limits, indicated by horizontal lines, put a minimum and maximum on the load factor independent of airspeed. At low speeds a quadratic relation limits the minimum velocity according to Eq. 2.3. Flying below the minimum speed at a too high load factor will make the aircraft stall.

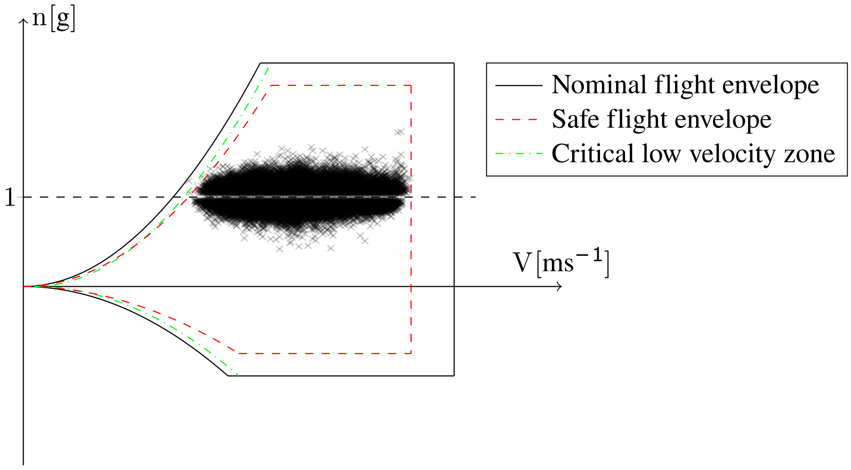


Figure 2.1: Typical flight envelope with velocity (V) versus load factor (n)[4]. Augmented with load factor data for 10,066 A320 flights[9]. The actual envelope depends on the aircraft's configuration and loading.

$$L = \frac{1}{2}\rho V^2 S C_L \tag{2.3}$$

When a safety margin is added to the flight envelope a so called safe flight envelope (SFE) is created, indicated by the red dashed line in Fig. 2.1. This margin is chosen such that the pilots have sufficient time to steer the aircraft away from the boundaries after being alerted of leaving the SFE. Another margin can be distinguished near the lower velocity limit. When the critical low velocity zone is reached, the aircraft is close to entering a stall (dashed green line).

The maximum and minimum load factor encountered during the flaps up phase of 10,066 Airbus A320 flights is shown in Fig. 2.1. It can be seen that aircraft in general stay well away from the boundaries. Nevertheless a significant number of flights does get close to the limits. Note that the flight envelope shown here is for illustration purposes only and does not precisely match the actual envelope corresponding to particular flights.

2.3. Flight envelope protection

The introduction of FBW opened up a whole range of possibilities to flight control enhancements including flight envelope protection systems. Aircraft manufacturers each have their own FBW design philosophies and thus provide different forms and levels of protection.

One of the biggest differences between Airbus and Boeing is the hardness of the protection. Airbus actively prevents the pilot from commanding the aircraft outside the flight envelope. Boeing's design philosophy for the 777 and 787 on the contrary is "to inform the pilot that the command being given would put the airplane outside of its normal operating envelope, but the ability to do so is not precluded."[10] In short this means that as the aircraft approaches the limits of the flight envelope, back pressure is progressively increased on the controls requiring the pilot to exert more force to steer the aircraft towards the limits. Another significant difference is that Boeing provides haptic and visual feedback to the pilots by moving the control column when the aircraft is flown by the autopilot keeping the pilot in the loop. In an Airbus, the pilots cannot feel or easily see what control outputs are delivered by the autopilot or FEP.

2.3.1. Airbus

When an Airbus experiences sensor or computer failures, it can switch to different control laws that provide less protection and support to the pilot. Information on these control laws and their associated protections is mostly acquired from the FCOM[11]. The availability of flight envelope protection functions depends on the active control law and is listed in Table 2.1. The indications associated to these protections and control laws are summarised in Table 2.2.

Table 2.1: Availability of flight envelope protections and warnings for Airbus and Boeing in the various control laws and modes[7, 11, 12].

	Airbus						Boeing			
Control law/mode	Normal	ALTN1	ALTN2	Direct	Mechanical	Abnormal	Normal	Secondary	Direct	Mechanical
Bank angle	✓	🟥	🟥	🟥	🟥	🟥	✓	🟥	🟥	🟥
Load factor	✓	✓	✓	🟥	🟥	✓	N/A	N/A	N/A	N/A
Overspeed	✓	~	🟥	🟥	🟥	🟥	✓	🟥	🟥	🟥
Pitch attitude	✓	🟥	🟥	🟥	🟥	🟥	N/A	N/A	N/A	N/A
Stall (high AoA)	✓	~	🟥	🟥	🟥	🟥	✓	🟥	🟥	🟥
Stall warning	N/A	✓	✓	✓	🟥	✓	✓	N/A	N/A	N/A
Overspeed warning	✓	✓	✓	✓	🟥	✓	✓	N/A	N/A	N/A

The various control laws and their impact on the availability or workings of flight envelope protections are outlined below.

- **Normal law**
  Full system functionality. The aircraft has the highest level of protection and cannot be stalled.

- **Alternate law with reduced protections (ALTN1)**
  The first degraded law is triggered when two computers fail and is called alternate law with reduced protections (ALTN1). The positive roll stability and bank angle protection are lost and lateral inputs are now directly related to control surface position. The autopilot disconnects when the bank angle exceeds 45°.

  Longitudinal control does not change from normal law. Angle of attack protection is lost though, so the aircraft can be stalled in alternate law. High speed protection is replaced by a high speed stability, which can be overruled by the pilot.

Table 2.2: Airbus A320 warnings related to flight envelope protection[11, 13].

	ECAM	PFD	Aural	Warning
Alpha floor	A FLOOR	A FLOOR	-	
Alpha prot	-	Black/amber bar along speed scale	-	
Stall	-	Red/black bar along speed scale	Cricket + "STALL"	
Overspeed	O/SPEED	Barber pole along speed scale	Continuous repetitive chime	MASTER WARNING
Alternate law	F/CTL ALTN LAW (PROT LOST) MAX SPEED........320 KT	= symbols change to X	Single chime	MASTER CAUT
Direct law	F/CTL DIRECT LAW (PROT LOST) -MAN PITCH TRIM.....USE	USE MAN PITCH TRIM	Single chime	MASTER CAUT
Mechanical law	-	MAN PITCH TRIM ONLY	Single chime	MASTER CAUT

- **Alternate law without reduced protections (ALTN2)**
  In more extreme cases the control laws degrade even more. While most is similar to the previous law, alternate law without reduced protections lacks low speed and high speed stabilities. There is no cockpit indication to distinguish between the two variants of alternate law.

- **Direct law**
  Another level of degradation is achieved in direct law. It is most likely experienced when the landing gear is lowered after an in-flight degradation to alternate law. Stick inputs are directly controlling control surface deflections in this law. All protections are lost in this case. Automated pitch trim is lost (indicated with USE MAN PITCH TRIM on the PFD), so the pilot has to manually trim the aircraft through the trim wheel.

- **Mechanical backup**
  The most basic law is a mechanical backup. This temporarily mode kicks in when for example electrical power is completely lost, rendering the side stick inoperative as its transducers are electrically powered. Longitudinal control is only possible through manual adjustments of the trimmable horizontal stabiliser using the pitch trim wheel and – in lesser extent – thrust. Lateral control is now achieved by operating the rudder pedals. This leads to a very slow roll response.

- **Abnormal attitude law**
  One final law is the abnormal attitude law. This law is added as a safety feature in case the aircraft ends up outside the flight envelope and is only activated under extreme conditions not reachable without "an extraordinary unpredictable external event (e.g. mid-air collision)" according to Airbus[11]. Nevertheless it is possible to reach abnormal attitudes with control inputs alone, as Air Asia flight 8501 showed in 2014[2]. The abnormal attitude law is similar to ALTN2, i.e. load factor protection is still available, but without autotrim.

In normal law, the aircraft is protected throughout the flight envelope in five ways:

- **Load factor limitation**
  Load factor is limited to -1g and +2.5g in clean configuration and 0g and +2g in any other configuration. When the load factor enters an unpublished margin from these limits, the control law is altered such that it becomes zero upon reaching the limit.

- **Bank angle limitation**
  Lateral stick inputs command roll rate up to bank angles of 33°. Between 33° and 67° the stick deflection corresponds to an actual roll angle. Positive spiral stability rolls the aircraft back to 33° when the stick is released above 33° bank. Bank angles larger than 67° cannot be reached. Fig. 2.2 shows the roll control law in a visual form. The maximum bank angle is indicated on the PFD by two green = symbols on either side of the attitude indicator (see Fig. 2.4). Bank angle is limited to 45° when high-angle-of-attack protection is active and to 40° when high speed protection is active. The limit symbols are always fixed at 67° though.

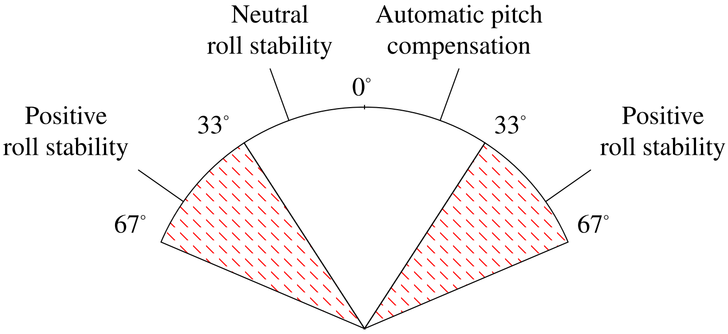
  

  Figure 2.2: A320 lateral control in normal law[4].

  Flight director indications are removed when bank angle exceeds 45° and are restored when the bank angle drops below 40°.

- **Pitch attitude protection**
  In normal law, pitch is limited to:

  - 30° nose up in configuration 0 to 3 (reducing to 25° at low speed).
  - 25° nose up in configuration FULL (reducing to 20° at low speed).
  - 15° nose down.

  When approaching one of either pitch limits, pitch rate is gradually reduced to reach zero upon reaching the pitch limit. No stick input can pitch the aircraft beyond this angle. The pitch limits are indicated on the PFD by two green = symbols along the pitch ladder as visible in Fig. 2.4. Flight director indications disappear when pitch exceeds 25° up or 13° down.

- **High-angle-of-attack protection**
  The high-angle-of-attack protection considers various angles of attack rather than a single stall angle. These angles are shown in Fig. 2.3 and vary with aircraft weight and configuration. The associated speeds that the aircraft will be flying at upon reaching some of these angles are displayed on the speed tape.

  When the AoA becomes greater than α_{prot}, the system switches elevator control from normal mode to a protection mode, in which the AoA is proportional to side stick deflection. That is, from α_{prot} to α_{MAX}, the side stick commands α directly. The AoA will never exceed α_{MAX} though, even if the pilot pulls the side stick all the way back. If the pilot releases the side stick, the AoA returns to α_{prot} and stays there.

  Independently from α_{prot} and α_{MAX}, another AoA protection can be triggered. When the AoA exceeds α_{floor}, takeoff/go-around (TOGA) thrust is automatically selected irrespective of throttle lever position and autothrust engagement. α_{floor} is a fixed angle depending on aircraft configuration as listed below and is decreased in case of windshear when not in clean configuration[14]. Alpha floor protection can be triggered at any airspeed, even significantly higher than $V_{\alpha_{prot}}$.

  - 9.5° in configuration 0.
  - 15° in configuration 1, 2 and 3.
  - 14.5° in configuration FULL.

  This protection against stall and windshear disconnects the autopilot and has priority over all other protections. When active, the following indications are shown to the pilot:

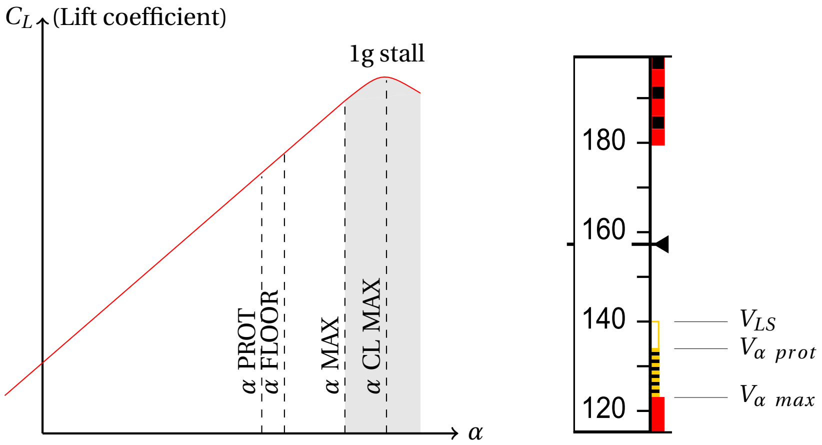


Figure 2.3: Airbus' angle of attack protection angles and associated indications on the speed tape. Adapted from [11].

  - As long as the alpha floor conditions are true:
    - "A FLOOR" (green) surrounded by a flashing amber box on the flight mode annunciator (FMA) on the PFD.
    - "A FLOOR" (amber) on the electronic centralised aircraft monitor (ECAM).
  - When leaving the alpha floor condition:
    - "TOGA LK" (green) surrounded by a flashing amber box on the FMA. TOGA thrust is now frozen (locked).

  To cancel the α_{floor} protection or the locked TOGA thrust, the flight crew must disconnect the autothrottle.

- **High-speed protection**
  Depending on the flight conditions (high acceleration, low pitch attitude), high speed protection is activated at/or above VMO + 6 kts / MMO + 0.01. The protection speed is indicated by a green = symbol on the speed tape. When activated the autopilot disconnects. The horizontal stabiliser is limited between the setting at the aircraft's entry into this protection and 11° nose-up. Positive spiral static stability is introduced to 0° bank angle (instead of 33° in normal law), so that with the sidestick released, the aircraft always returns to a bank angle of 0°. The bank angle limit is reduced from 67° to 40°. As the speed increases above VMO/MMO, the sidestick nose-down authority is progressively reduced, and a permanent nose-up order is applied to aid recovery to normal flight conditions. High speed protection is deactivated, when the aircraft speed decreases below VMO/MMO, where the usual normal control laws are recovered.

2.3.2. Boeing

As more information is available on the B777 than the B787, the B777 is explained here on the basis of its FCOM[7]. The B787 has been designed to closely resemble the B777 in terms of flight controls and envelope protections but supposedly has an additional stall protection limiting high angles of attack[15, 16]. Similarly to Airbus' various control laws, the B777's Primary Flight Control System has three operating modes outlined below[7, 10]. The difference in flight envelope protection availability between these various modes is listed in Table 2.1. Apart from the indications listed below and in Table 2.3, the active control mode is shown on the flight controls page of the secondary EICAS.

- **Normal mode**
  Full system functionality.

- **Secondary mode**
  Control laws are simplified, leading to more sensitive rudder and elevator at some speeds. No envelope protection functions available. Autopilot disengages. When the secondary mode is active, a "FLIGHT CONTROL MODE" caution message is shown on the EICAS.

- **Direct mode**
  Approximately similar airplane handling characteristics as in secondary mode but without control laws. Pilot inputs are directly converted to control surface deflections. The caution message "PRI FLIGHT COMPUTERS" is shown on the EICAS. Additionally, the degraded mode is shown on the non-normal Flight Control Synoptic which is automatically called. Lastly an amber "DISC" indicator lights up on the overhead panel when the flight computers are disconnected and the aircraft is in direct mode.

- **Mechanical backup**
  Basic control is available through the cable-connected stabiliser and some spoilers in the case of complete electrical failure.

Table 2.3: Boeing 777 warnings related to flight envelope protection[7].

Message logic	EICAS message	Level	Aural
Autopilot is operating in a degraded mode. Engaged roll and/or pitch mode may have failed, or the autopilot has entered envelope protection.	`AUTOPILOT`	Caution	Beeper
Flight control system is operating in the secondary mode.	`FLIGHT CONTROL MODE`	Caution	Beeper
Pitch down authority is limited.	`PITCH DOWN AUTHORITY`	Caution	Beeper
Pitch up and flare authority is limited.	`PITCH UP AUTHORITY`	Caution	Beeper
Flight control system is operating in the direct mode.	`PRI FLIGHT COMPUTERS`	Caution	Beeper

There are three forms of flight envelope protection on the B777, listed below. An AUTOPILOT caution message on the EICAS and roll or pitch mode failures alert the pilot if the envelope is exceeded and the autopilot prevents further envelope violations[7].

- **Stall protection**
  Stall protection is implemented in the form of a minimum on the reference trim speed. The column force to fly at a speed below this limit is progressively increased. The pitch flight director bar will disappear on the PFD when stall protection is active. Autothrottle can engage automatically to increase speed when approaching the stick shaker speed. Engagement depends on the pitch mode.

- **Overspeed protection**
  Overspeed protection works similar to stall protection. Instead of a minimum trim speed, a maximum trim speed is enforced by prohibiting nose down trimming. The pitch flight director bar disappears on the PFD when the protection is activated.

  Autopilot overspeed protection activates above V_{MO} + 20 knots or M_{MO} + 0.03 Mach. The autopilot will pitch up to reach and maintain V_{MO} -5 knots.

- **Bank angle protection**
  The bank indicator on the PFD indicates excessive bank angles exceeding 35° by changing colour to amber. If approximately 35° is exceeded, control wheel forces increases considerably. When the control wheel is released the autopilot gives a roll command back to 30°. This roll back can be disabled through the autopilot disengage bar on the flight control unit (FCU).

2.4. Haptic feedback

Traditional aircraft always provide haptic feedback to the pilots, since the control are directly linked to the control surfaces. When a control surface is deflected it generates an aerodynamic force. The larger the deflection and/or airspeed the larger the force. Pilots feel this force and are thus made aware of the state of the aircraft. With fly-by wire the direct link and thereby this form of feedback is lost.

To control Airbus aircraft the pilot manipulates a so called passive side stick. The stick is connected to a simple spring. The force felt by the pilot is linearly related to the stick deflection and independent of aircraft configuration and state. Apart from this cue for amount of stick deflection, the stick does not give any feedback to the pilot. The sticks of both pilots are not linked and when the autopilot is active, the sticks are locked in neutral position.

Active side sticks provide pilots with haptic feedback on the state of the aircraft and possibly autopilot, much like the linked controls on traditional aircraft. After being used on military aircraft for several decades, such sticks are now slowly reaching the civil market. As of July 2018 the Gulfstream G500 is the first certified civil aircraft with active control side sticks, developed by BAE Systems[17].

On its fly-by-wire aircraft (B777/B787) Boeing provides an artificial feedback force[10]. The required column force is increased with increasing airspeed and/or column displacement in normal mode. This force helps pilots recognise and stay away from excessive manoeuvres as control forces get progressively larger. The pilot can push through this soft form of protection though if he considers it necessary. In secondary and direct mode, only two discrete force levels are available, one for flaps up and one for flaps down. A stall warning is implemented in the form of stick shakers on the control column[7]. This alerts the pilot of an impeding stall. Both pilots' columns are linked to each other, as well as to the autopilot.

Other manufacturers have implemented other forms of haptic feedback. A relatively rare example is the stick pusher[18]. When the angle of attack approaches the stall angle, first the stick shaker is enabled to alert the crew. If the crew does not respond and the AoA exceeds a certain angle, the stick pusher automatically pushes the controls forward. This is a form of active guidance, helping the pilot to stay within or return to the flight envelope. Stick pushers do raise concerns as to what happens if they are activated inadvertently due to a malfunction.

2.5. Displays

Current generations of airliners have limited display of flight envelope boundaries. Angle of attack is only shown on a small number of aircraft, even though it has been recommended by many researchers over the past couple of decades. Most famously by the investigation of flight AF447[3]. Both Airbus and Boeing do offer optional angle of attack indicators on their aircraft but only a small number of clients chooses to have them installed. In order to nevertheless give pilots an indication of angle of attack limits, both manufacturers translate critical angles to associated airspeeds at which that angle would be reached[7, 11]. An excerpt of the Airbus speed tape with these indications is shown in Fig. 2.3.

2.5.1. Primary flight display

The most important instrument in any glass cockpit is the primary flight display. It provides the pilot with critical flight information on the aircraft's state like altitude, attitude and speed. Information is usually grouped to resemble the classical T layout that is seen on nearly all aircraft. Fig. 2.4 shows the PFD of an A320. Its corresponding grouping is shown in Fig. 2.5.

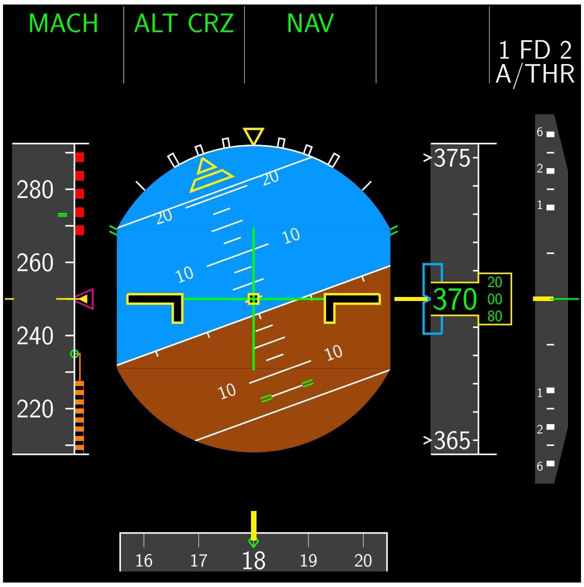


Figure 2.4: Airbus A320 PFD.

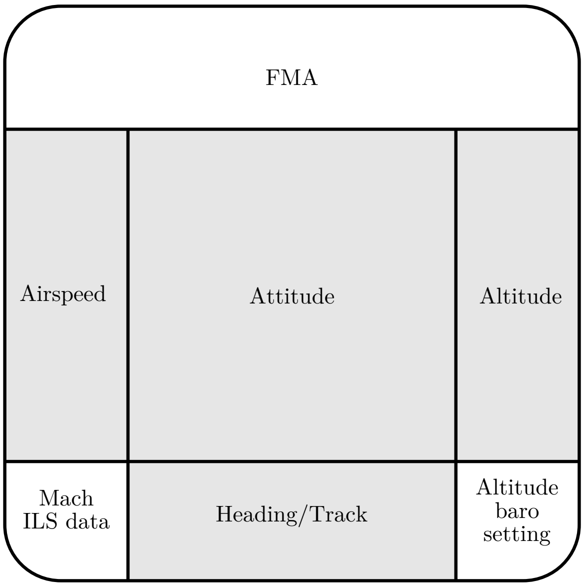


Figure 2.5: Sections on the Airbus PFD. Adapted from [11]

2.5.2. Angle of attack displays

Most commercial airliners do not provide a dedicated display for angle of attack (AoA). Both Airbus and Boeing do offer such instruments as options, but most airlines choose not to include them in their fleet. One of the reasons for that could be that a pure angle of attack indicator is a knowledge cue, requiring further processing by the human and thus increases workload. A rule based approach on the other hand (telling the pilot what to do) would increase performance and reduce workload[19].

Dedicated angle of attack displays can be classified into two categories, those of the normalised type and those that are not normalised. A normalised display scales the AoA to an arbitrary unit, such that zero corresponds to zero load factor and stall to one. A disadvantage of a normalised display is that it requires Mach data, which may be faulty when pitot tubes are blocked[20]. Both Airbus and Boeing therefore provide non-normalised dials.

Airbus' solution has a separate analogue dial as shown in Fig. 2.6 that is installed to the left and down of the PFD. The dial ranges from -5 to +25 degrees and has tick marks on every degree. It lacks any indication on whether the current angle of attack is safe or not. Boeing incorporates a similar dial in the top right corner of the PFD (Fig. 2.7). Boeing's indicator has a digital readout, ranges from -5 to +20 degrees and has tick marks every five degrees. It is supplemented by a red indicator of the stall warning angle and a green reference band corresponding to the safe AoA on approach that is only shown when landing flaps are selected. An identical colourless dial is offered by Rockwell Collins on some of its head up displays[21]. Note that both dials shown in Fig. 2.6 and 2.7 indicate an AoA of 6 degrees while pointing in completely different directions. There is clearly no industry wide standard.

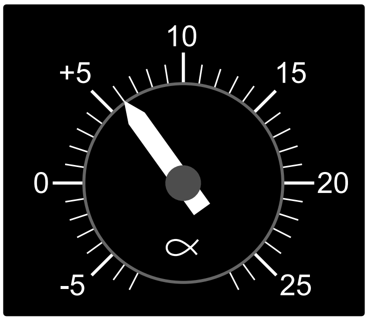


Figure 2.6: Airbus A320 AoA indicator.

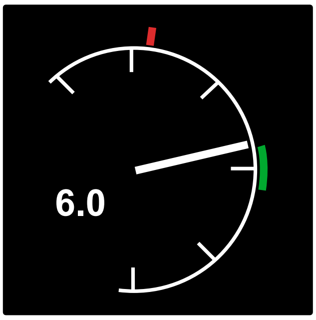


Figure 2.7: Boeing AoA indicator with approach reference band (green) and stall angle (red).

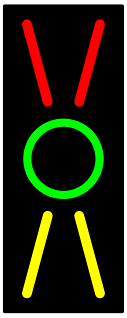


Figure 2.8: AoA indexer.

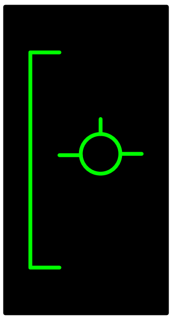


Figure 2.9: AoA bracket on a HUD.

What both manufacturers do provide by default is a flight path vector (FPV). This vector shows the aircraft's flight path angle and drift on the PFD. Since angle of attack (α), pitch angle (θ) and flight path angle (γ) are related through Eq. 2.4 the distance between the fixed aircraft symbol and the FPV is an indication for angle of attack[19]. The FPV can be switched on/off by the pilots but may be mandatory per standard operating procedures.

$$\alpha = \theta - \gamma \tag{2.4}$$

Boeing additionally has a pitch limit indicator (PLI) on its PFD, visible in Fig. 2.10 as two yellow "whiskers". The PLI was originally developed to help windshear escape training[20]. Its vertical displacement with respect to the fixed aircraft symbol is an indication for the margin from the current AoA to the stall AoA. To prevent excessively high pitch angles when encountering a windshear at high speed, the PLI is limited to 30° pitch. Note the difference with Airbus' maximum pitch indication, which does not relate to angle of attack and is always fixed at 30 degrees pitch. The PLI is attached to the aircraft symbol and does not rotate with bank. It is shown when the flaps are extended or when the AoA is within 1.3 g of the stall warning due to speed or load factor.

There are many more designs on the market for a variety of aircraft. Normalised angle of attack indicators come in all sorts and shapes. They all rely on the same principle though: telling the pilot whether the AoA is low, high or safe. An example of such an "AoA indexer" commonly found in military and general aviation aircraft is shown in Fig. 2.8. Depending on the AoA, either one or two of the three colours displays while the other(s) are dimmed. Red corresponds to too high of an AoA, the green circle is the optimal AoA, while yellow indicates a low angle of attack. Combinations of two colours correspond to intermediate angles. This indicator can also be found with several extra red and yellow chevrons to be able to show more intermediate steps.

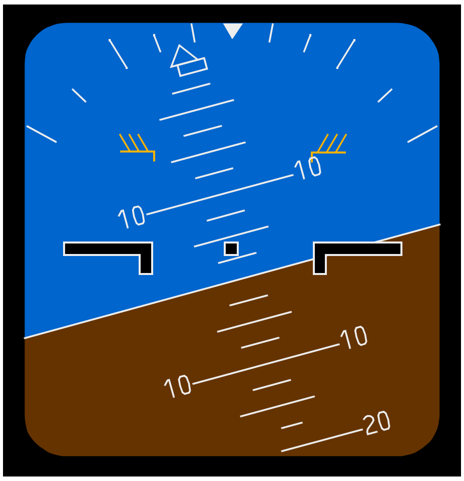


Figure 2.10: Boeing 777 PFD attitude indications[7].

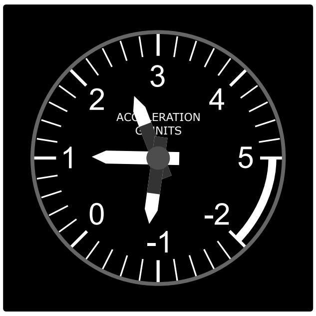


Figure 2.11: Acceleration meter.

Another angle of attack indicator that is frequently seen on the head-up displays (HUD) of military aircraft is the angle of attack bracket[21]. An example of such a bracket is given in Fig.2.9. It consists of a "bracket" that is located adjacent to the FPV. The relative position of the bracket with respect to the FPV is an indication for angle of attack. In general the center of the bracket corresponds to the optimum AoA for landing the aircraft. The upper and lower extremes are not flight envelope limits, but mere fixed deviations from this optimum. This principle is comparable to that of the AoA indexer.

Concluding, the general opinion seems to be that AoA indicator can be an useful addition to the flight deck, but there is no consensus on what such an indicator should look like.

2.5.3. Load factor displays

Load factor displays (also known as "g meters" and "accelerometers") are not common on airliners. Airbus does display the load factor as a digital readout at the bottom of the ECAM when the value is above 1.4g or below 0.7g. It remains visible for five seconds after the value returns to the normal range. Its location on the flight deck makes it unusable as an indicator to base control inputs on. As discussed in Section 2.3.1 the FEP system protects the aircraft from exceeding the normal load factor limits in all laws but direct and mechanical law, so there is generally no need to display it.

A much more prominent indication is provided on widebody aircraft from FedEx[22]. A large font digital readout of the load factor is displayed on the HUD, directly in front of the pilot. Research has indicated that such a display improves pilot response in upset situations leading to faster recovery. Nevertheless FedEx is unique in the airliner world in offering g meters.

One class of aircraft that have widely embraced accelerometers are aerobatics. Most of these instruments follow the MIL-A-25719B specification and exist of three pointers: one showing the instantaneous acceleration and two showing the minimum and maximum acceleration encountered since the last reset of the instrument[23]. An example of such an indicator is given in Fig. 2.11. Indicators showing a time-trail of g load are also available.

2.6. Discussion

Modern day airliners are complex machines. Airbus aircraft have several control laws with various levels of protection that may not always be present. The current displays do not provide a complete and unambiguous picture to the crew as to what protections are active.

Looking at Airbus and other aircraft manufacturers it is clear that there is no industry-wide consensus on how to display flight envelope limits and protections. The limited information that is currently displayed only shows information in the output space, while pilots operate in the input space. There is thus a gap to be filled by novel solutions.

3

Novel display solutions

The current solutions as discussed in Chapter 2 are considered inadequate as they do not show all flight envelope limits and do not relate to the input space. Various research projects have resulted in novel designs for more complete systems. These are discussed in detail below.

3.1. Industry current state of development

Both Airbus and Boeing are working or have worked on flight envelope instruments that are not yet available in service. Airbus patented a dial-like instrument that shows the angle of attack with respect to flight envelope protections[24]. While angle of attack is one of the most critical limits, the proposed instrument does not provide an overall solution for all of the flight envelope boundaries.

Boeing has filed a patent on the display of flight envelope information to pilots and the current location of the aircraft with respect to that envelope [25]. The envelope in question is a display dedicated to a 2D performance envelope, relating for example altitude and turn rate to speed. Like existing instruments it only shows information in the output space as opposed to the input space that the pilot is controlling in.

3.2. Flight envelope visualisation

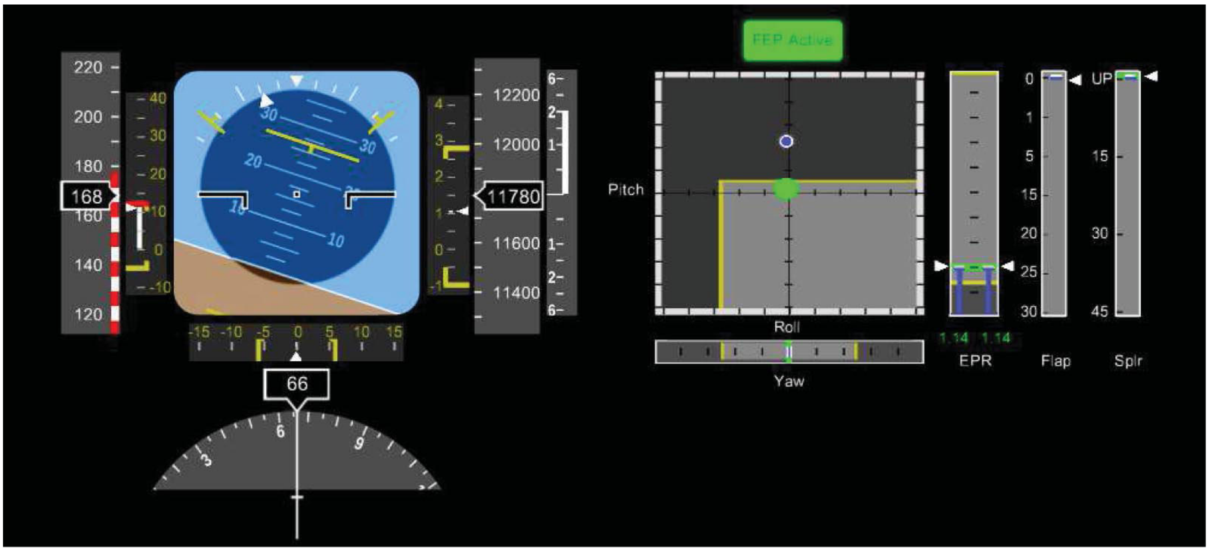


Figure 3.1: Displays proposed by Ackerman et al. [26]. The extended PFD is shown on the left and the envelope protection and simplified engine/warning display on the right. In this example FEP actively modifies pilot input to prevent a violation of the angle of attack limit.

Ackerman et al. have proposed a complementary display showing information about the aircraft state and automation [26]. This complementary display is shown on the right of Fig. 3.1. Rather than the common output-state like visualisation of the PFD, the control inputs are given overlaid with the actual output of the control system to visualise automatic flight envelope protection. In this particular figure, the pilot input (blue circle) is outside the flight envelope (yellow box) and thus the actual control input is limited to the green dot. The PFD on the left of Fig. 3.1 is enhanced with limits for bank and pitch angle on the attitude indicator (AI). Additional indicators are added for angle of sideslip below the AI, angle of attack left of the AI and load factor right of the AI.

To assess the newly designed instrument, a pilot experiment was set up in a simulator. Two pilots underwent scenarios involving standard and aggressive flight manoeuvres as well as adverse weather. Each experiment run started with the aircraft in a trimmed state. Pilots were then instructed to maintain a certain heading, altitude and speed that may be different from the trimmed state while encountering wind gusts of various magnitudes and directions.

The results of Ackerman's research indicate a possible reduction in unsafe command inputs when using the display. While Ackerman's research is a promising start, the human brain cannot easily switch between input and output space. A separate display may attract attention away from the PFD in critical situations. The authors stress that their display is not intended to be the best format. Their main focus was on the information itself rather than the way it was presented[27].

3.3. Visualisation of flight envelope limits

When researching an emergency landing planner, Meuleau and all stated that it was helpful to show flight envelope limits on the PFD to prevent control surface saturation[28]. Fig. 3.2 shows their design with colour bands on the speed tape, vertical speed indicator and bank angle scale. The green bands indicate safe flight where the aircraft is fully controllable. When the airspeed decreases into the lower yellow band (not visible) the green bands of bank and vertical speed shrink. The display was a small part of a bigger research project and no conclusions were drawn about the PFD enhancements.

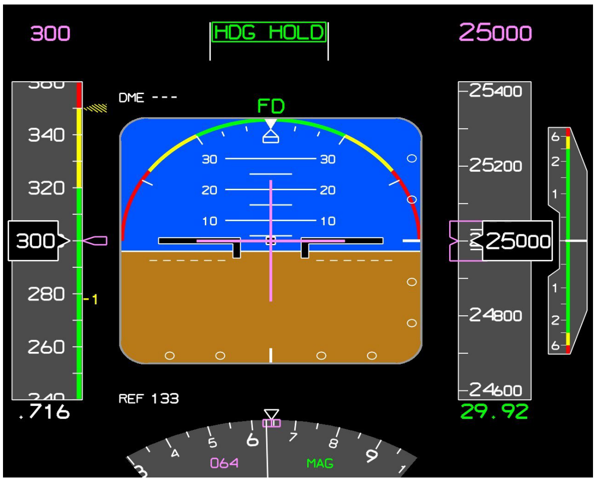


Figure 3.2: PFD showing bank angle, pitch, airspeed, vertical speed, altitude and heading[28].

3.4. Visualisations of asymmetric flight envelope limits

Another flight envelope display is proposed by Rijndorp in his research on the presentation of an altered asymmetric flight envelope due to damage to the aircraft[29]. He added limits for bank angle and roll rate to the PFD (Fig. 3.3). The green band is a measure for the maximum attainable roll rate. The arrow in this band shows a five-second forecast of the bank angle at the current roll rate. The roll angles that are reachable within ten seconds are indicated by the two blue triangles below the bank scale. The maximum bank angle limit is given by the solid white triangles, as well as a red dotted line. The red arrow indicates the bank angle at which the aircraft would roll out to if maximum opposite stick input is given. With an asymmetric flight envelope this angle is not necessarily zero. Rijndorp hypothesised that this indicator would help pilots understand why the roll rate is limited in aircraft with FEP before the maximum bank angle is reached. In addition to the PFD enhancements, a navigation envelope was added to the navigation display (ND) showing a sixty-second preview of the reachable navigation space (Fig. 3.4)[29].

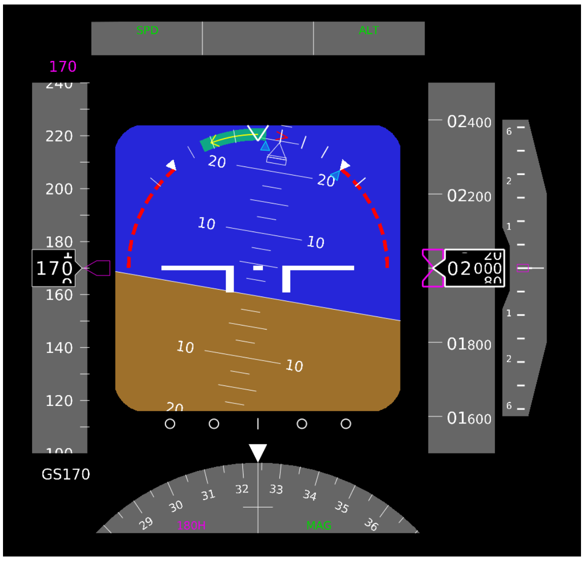


Figure 3.3: Boeing style PFD with limits for bank angle and roll rate, and roll and bank angle previews[29].

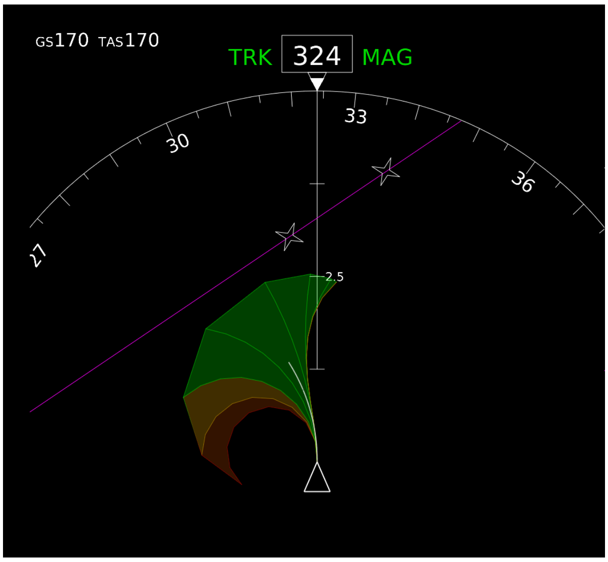


Figure 3.4: Boeing style ND navigation envelope showing the reachable navigational space[29].

In a simulator experiment involving nine pilots, Rijndorp found that they preferred to look at the ND rather than the PFD when tasked with flying an approach with a last-minute runway change. Pilots were also found to fly closer to the limits of the flight envelope when presented with a visual representation of those limits. It is noted though that the addition of soft limits might produce desired control behaviour. With a severely altered flight envelope, the PFD additions lead to an increase in the reported workload. With moderate failure the altered PFD showed a small benefit compared to the baseline PFD. In both cases the new ND had a much larger impact. In a questionnaire, the participating pilots said they mostly used the ND and the attainable roll rate bar on the PFD to control the aircraft. The other symbology on the PFD had little added value and was mostly cluttering the display while not providing useful information.

3.5. Adaptive safe flight envelope protection algorithm

Lombaerts researched the live adaption of flight envelope limits[30]. Similar to Ackerman, a SFE is used. In Fig. 3.5 the maximum bank angle is displayed by a barber-pole line extended with a yellow line. The yellow marker is fixed at a bank angle of 35°, as that is the angle that airliners normally do not exceed. The maximum angle markers move towards each other as the air speed drops, corresponding to the narrowing flight envelope at low speed. The two lines touch when the aircraft has reached the stall speed.

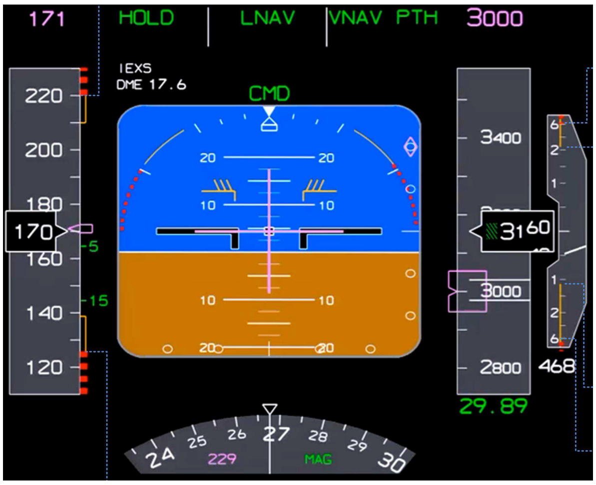


Figure 3.5: PFD from Lombaerts showing bank angle, vertical speed and airspeed limits[30].

Ten two-person cockpit crews were put in a full flight simulator to test the display, each flying four approaches to an airport. During one of the approaches the aircraft encountered icing and the crews had to prevent the aircraft from stalling. In another approach a stabiliser failure was encountered leading to a strong nose-up moment. In a subsequent go-around the crews had to recognise the failure and reduce their speed to prevent elevator saturation. The other two approaches involved high and low energy states and were less relevant for the flight envelope research.

In the icing scenario it was found that pilots used the display to deploy flaps earlier in the approach and thereby increase the margin to the SFE boundaries. The stabiliser scenario showed no clear improvement. Pilots were thought to have ignored the limit indications mostly due to the procedural nature of go-arounds. Despite the added information, no increase in workload was found for both scenarios. Pilots commented that they considered the limits information a welcome addition to improve awareness of events and energy state.

In follow-up research, Lombaerts combined a slightly different visual display with haptic feedback on the stick[31]. The flight envelope boundaries for airspeed, bank angle and vertical speed are indicated on the PFD as shown in Fig. 3.6. Bank angle limits are based on the angle at which a stall would occur. The flight path angle limit is translated to a corresponding vertical speed. In addition to the display, the boundaries are communicated through haptic feedback. In current Airbus aircraft, the side stick does not provide tactile feedback, other than a force delivered by a spring. The spring force is proportional to the displacement of the stick and therefore identical at all speeds, aircraft configurations and attitudes[32]. With Lombaerts' system, the stiffness of the stick is progressively increased as the aircraft leaves the SFE and gets closer to the boundaries of the flight envelope. The pilot can still ignore this suggestion by applying sufficient force. This soft protection is comparable to what Boeing does on the 777[10]. A stick shaker following a sinusoidal forcing function is enabled as additional warning when the aircraft approaches the stall speed. Unlike Boeing, Airbus does not yet have a stick shaker.

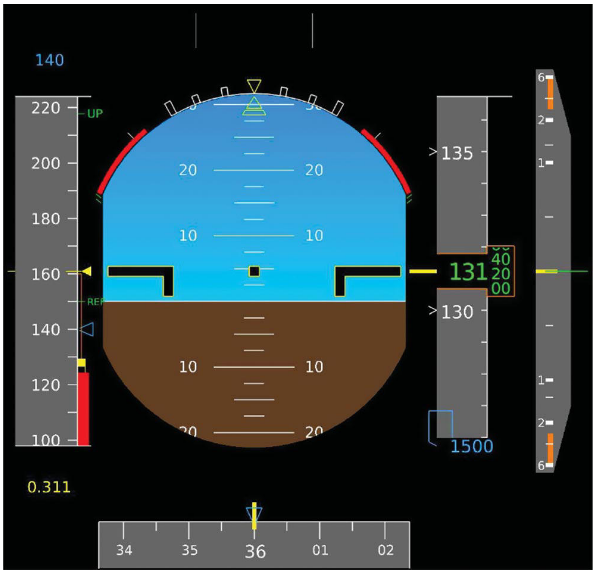


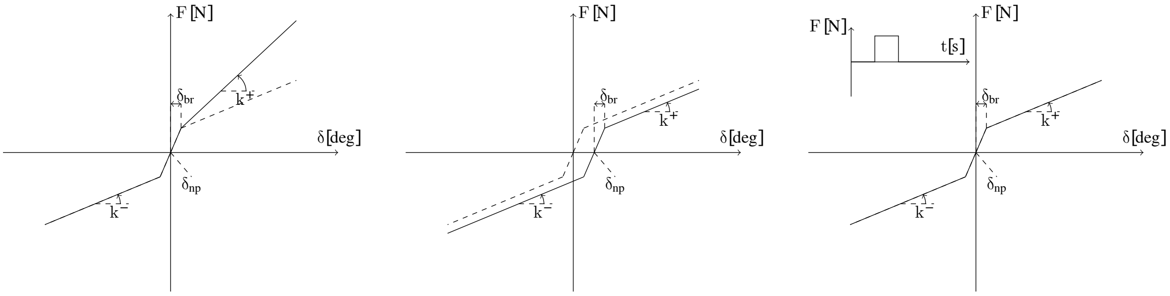
Figure 3.6: Airbus style PFD with envelope boundary information for airspeed, bank angle and vertical speed[31].

This system was evaluated in a simulator experiment on the Simulation, Motion and Navigation (SIMONA) Research Simulator (SRS) at Delft University of Technology. Seven professional Airbus A330 pilots took part in the experiment. An icing scenario was mainly set up to test whether the flight envelope estimation and protection algorithm improved pilot performance when combined with haptic feedback. In it a pilot was approaching runway 27 at Schiphol on a base leg, before making a 90 degree turn to line up with the runway. A second scenario investigated a wind shear on final approach to runway 22 at Nice Airport involving several left and right turns while descending the aircraft from 6000 ft.

The limited number of pilots and broad range of technologies that were investigated reduced the statistical relevance of the results. Nevertheless some trends could be observed. In the icing scenario, pilots were more confident to bank. The extra information on the PFD also helped with deciding to increase airspeed as a means to enlarge the envelope when icing started to occur. The margins of angle of attack, airspeed and bank angle with respect to the flight envelope were significantly larger with the new PFD and haptics. The stick deflection was not found to be much different, but the deflection rate dropped indicating decreased pilot activity. This is further supported by subjective measures of workload that were obtained through a NASA-TLX questionnaire.

3.6. Haptic feedback system for flight envelope protection

The haptic system from Lombaerts has been further enhanced by Van Baelen[4]. The altered control device profiles are given in Fig. 3.7. Apart from changing the stick's stiffness (Fig. 3.7a) like in the previous system, Van Baelen's system suggests a corrective control input to the pilot by shifting the neutral point of the stick (Fig. 3.7b). This works similar to a stick pusher in the case of stall protection as discussed in Section 2.4. In an overspeed situation the stick is shifted such that it mimics the automatic pitch up command as long as the aircraft is accelerating. The system also warns the pilot of exiting the SFE with a discrete force cue in the direction that would bring the aircraft back to the SFE (Fig. 3.7c). In the original research only longitudinal haptic feedback was considered but lateral feedback is based on the same principles and has since been implemented.



(a) Increased spring coefficient for positive deflections.

(b) Positive shift in position of the neutral point.

(c) Added positive (push) pulse.

Figure 3.7: Altered control device profiles[4].

The system was tested by 11 professional pilots flying two scenarios in the SRS in Delft: wind shear and icing similar to Lombaerts' experiment discussed in Section 3.5. The experiment setup is shown in Fig. 3.8. The wind shear scenario was flown in both normal and alternate law, while the icing scenario was only flown in alternate law due to simulation issues. Haptic feedback was enabled on some of the flights. The Airbus-like PFD was not enhanced with extra indications.

It was found that pilots in general like the system, but they indicated it was unclear what the system was trying to suggest to them[5]. In some situations, the haptic system gave a cue while there was no supporting visual indication. Visualising the boundaries and consequential haptic feedback might solve this. The haptic feedback did not result in performance or safety improvements, not did it cause a change in workload. Neither subjective nor objective.

Figure 3.8: Experiment setup of Van Baelen, with side stick on the right[5].

3.7. Labview airplane display system

While not strictly a novel solution, Boeing uses a Labview Airplane Display System (LADS) on its test flights to provide the pilots with information on flight envelope limits[16]. The LADS is installed next to the PFD (Fig.3.9) and only used on test flights so it can be considered ’novel’ to commercial operations.

An example of a LADS page is shown in Fig. 3.10. The actual layout of the display depends on the manoeuvre being tested. Amongst others it can display angle of attack, load factor and flight control mode. The two vertical bars indicate the current AoA and load factor, while the horizontal lines on the corresponding scales denote certain limits. When these limits are passed, the bar changes its colour corresponding to that limit. The respective digital readout also changes colour to further alert the crew of a limit violation. .

Figure 3.9: LADS installed next to the PFD[16].

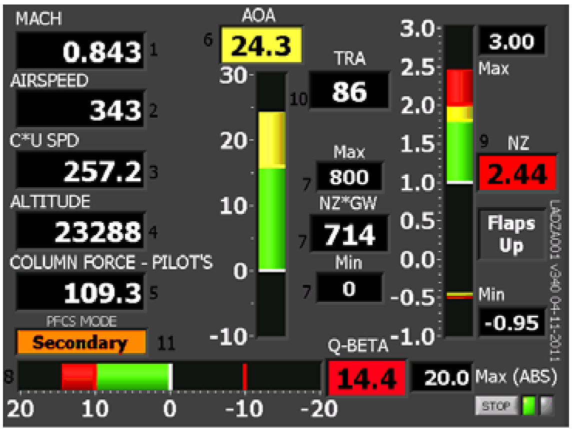


Figure 3.10: Example of a LADS display[16].

3.8. Discussion

Combining insights from all of the novel solutions, several observations can be made that can help in developing another solution. Experiment results indicate that the addition of flight envelope information helps pilots keep their aircraft in the flight envelope. A multi-modal approach might be beneficial, combining various forms of feedback (e.g. haptic and visual). When the flight envelope information is to be integrated with current displays, the PFD seems to be the preferred display. None of the existing research has integrated the input and output space in a single display so far.

To fill this gap, the research of this thesis project builds further on the work done by Lombaerts and Van Baelen. Visualising the boundaries of the flight envelope, the boundaries where haptic feedback kicks in and what the haptics are doing at that point is expected to help pilots appreciate the haptics more. It may even be found that haptics are not required at all and a display could be all that is needed. This has the benefit that implementing haptic feedback in (existing) aircraft is costly, while a simple software update on existing displays is much cheaper. Greatly increasing the chance of the system being adopted by the industry.

With regards to testing it can be noted that all of the solutions were evaluated in experiments involving wind disturbances as a means to provoke flight envelope excursions. Another common scenario in the experiments with the same objective is icing.

4

Design rules and guidelines

Aviation is a strictly governed industry. New instruments or changes to existing instruments must meet a plethora of rules to be accepted by the regulatory authorities. While the preliminary design is supposed to have a considerable level of design freedom, applying guidelines early on in the design process can help develop an acceptable and efficient display.

Various frameworks have been developed that can help with the design of an interface. The Ecological Interface Design (EID) framework conceptualised by Jens Rasmussen and Kim Vicente is just one example that is often used[33]. The display of this project however does not fit in the common approach, since most of the information is not new but already available through haptics. Following the complete EID design cycle is therefore not necessary.

At the start of the design, it is nevertheless wise to consider what kind of information processing will be relevant. The display is supposed to support pilots when the aircraft is close to the edges of the flight envelope in time-critical situations. As such, the display should be intuitive in the most swift way. When considering the skill, rule and knowledge taxonomy that is used in EID[33], the haptic feedback without additional (visual) cues triggers knowledge-based behaviour (KKB) as the pilot is trying to understand what the haptics are communicating. KKB puts a significant cognitive load on the pilot which is undesired in time critical situations. Visualising the haptics and the limits that the haptics are acting on can bring the pilot back to rule-based behaviour, requiring less mental processing capacity and less time.

4.1. Regulations

An important regulatory document for display design is advisory circular (AC) 25-11B of the FAA. It "provides guidance for showing compliance with certain requirements of Title 14, Code of Federal Regulations part 25 for the design, installation, integration, and approval of electronic flight deck displays, components, and systems installed in transport category airplanes"[34]. Items from this AC that are particularly relevant for flight envelope indications on the PFD are briefly discussed below.

- It is in general not allowed to place information between the primary attitude indication and the speed and altitude tapes. An arrangement like Ackerman's from Section 3.2 would therefore require special approval.
- When it comes to colours, AC 25-11B suggests red or yellow/amber for displaying flight envelope limits. As mentioned in Section 2.3.1 Airbus deviates from this by using green indicators for bank, pitch and speed limits in its current displays. These indications are always green = symbols to distinguish them from other indications. The AC further states that scales and other information, like axis labels, are best shown in white.
- Items that are not essential at all time can be hidden. They should pop up automatically when required. A bank angle limit can for example pop up when the aircraft starts banking into that direction while being invisible as long as the aircraft is well away from the limit.
- When an item pops up, it should be prominent enough by itself, or be accompanied by another attention grabber such as an auditory cue.

- If an item that pops up obscures other information, that information should not be relevant during the condition for which the overlaying item is shown.

4.2. Thirteen principles of display design

Apart from complying to regulations, a good design adheres to several design principles. Wickens et al. defined thirteen principles of display design in their book on human factors engineering outlined below[35]. Using these principles can reduce errors and required training time while increasing efficiency and user satisfaction. Design choices in Chapter 5 refer back to these principles.

- Perceptual principles
    1. **Make display legible (or audible)** chose right contrast, visual angle etc.
    2. **Avoid absolute judgement limits** use no more than five to seven levels of colours, shapes or sizes.
    3. **Support top-down processing** highlight the unexpected in a series of signals.
    4. **Redundancy gain** present the same information in alternative forms (e.g. both in colour and location).
    5. **Discriminability** avoid similar appearing signals.
- Attention principles
    6. **Minimise information access cost** place frequently accessed sources close to each other to reduce time or effort to scan between them.
    7. **Proximity compatibility principle** place related sources close to each other to ease mental integration.
    8. **Principle of multiple resources** divide information across resources (e.g. visual, auditory, haptic)
- Mental model principles
    9. **Principle of pictorial realism** present information that is mentally represented in analogue fashion in analogue format.
    10. **Principle of the moving part** moving elements in a display should move in a pattern and direction compatible with the user's mental model.
- Memory principles
    11. **Replace memory with visual information** balance knowledge in the head against knowledge in the world.
    12. **Principle of predictive aiding** provide a preview to help users become proactive instead of reactive.
    13. **Principle of consistency** the design should be consistent with other displays the uses is using concurrently or may have used in the past.

5
Preliminary design

This chapter discusses the preliminary design of a display solution that is integrated in the existing A320 PFD and that adheres to the regulations and principles from Chapter 4. After discussing the driving principle behind the design, the complete design is presented before the various indicators are discussed in more detail.

5.1. Design principle

According to the principle of multiple resources, it is important to use multiple resources when presenting information. Combining haptic feedback with a visual display fulfills this principle. In order to support the haptic system, the display has to match with the forces felt through the side stick. The system provides four different kind of haptic cues as discussed in Section 3.6:

- Change in spring coefficient
- Discrete tick
- Stick shaker
- Shift of neutral position

The first two cues can be visualised by an ordinary spring (upper part of Fig. 5.1) that is positioned next to the side stick. When the aircraft approaches the edge of the SFE as discussed in Section 2.2 the spring moves towards the stick. Upon leaving the SFE the free end of the spring – visualised by the left-most vertical line – barely touches the stick. At this point the haptic feedback gives a discrete tick on the stick. 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. 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. The spring coefficient does not change any further beyond that maximum.

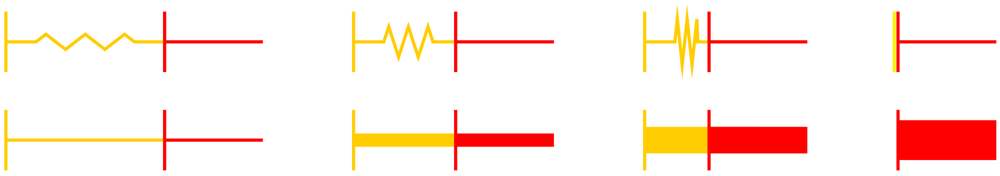


Figure 5.1: Spring (top) and piston (bottom) symbols with increasing levels of compression.

To ease implementation in the display and reduce clutter, the spring can instead be visualised in the form of a piston cylinder whose thickness is similar to the width of the spring (lower part of Fig. 5.1). Apart from visualising the "feel" from the haptics, 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 SFE. No existing research is known on such a visualisation of haptic feedback.

Since the stick shaker is merely a trigger to bring the pilot's attention to the low speed, no extra indication is added. The shift of the neutral position is neither explicitly visualised, as it always comes in combination with an increased stick stiffness and thus one of the other indications.

This basic analogy is used throughout the enhanced display. The symbols and colours that are used are kept uniform over the various indications to adhere to the 13th design principle of consistency. Yellow is used to indicate the the protection limit, beyond which the aircraft is outside the SFE but still within the flight envelope. 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. Fig. 5.2 shows the PFD with all of the flight envelope indications in place. The various elements are discussed in greater detail below.

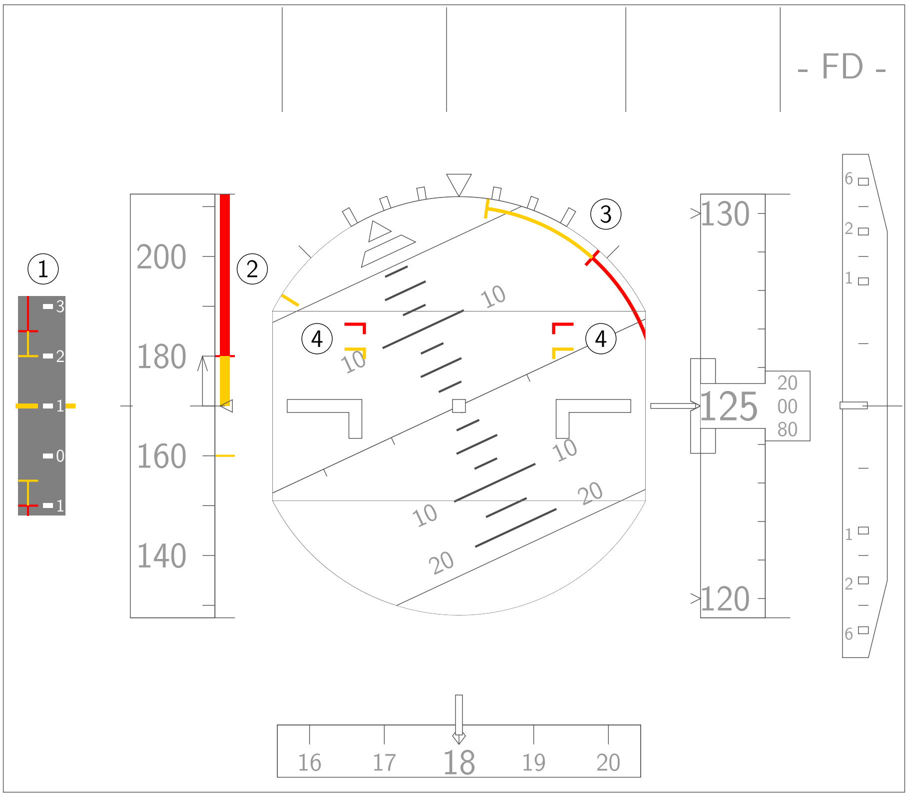


Figure 5.2: Airbus A320 PFD with additional load factor indicator ① and flight envelope limits for overspeed ②, bank ③ and angle of attack ④.

5.2. Load factor

Airbus has fixed load factor limits at -1 and +2.5 in clean configuration and 0 and +2 in all other configurations. For the proposed display, the load factor limits are directly derived from the haptic flight envelope and therefore change with air speed in the low speed regime (see Section 2.2). While load factor and stall speed are closely related, the load factor of the safe flight envelope is only directly related to the stall speed in the low speed regime. At higher speeds, it is possible to exceed the load factor while maintaining an acceptable speed.

A load factor indicator is therefore added to the left of the airspeed tape (Fig.5.3). The 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 hard limit is indicated in red, while the soft limit is shown in yellow. When the aircraft enters the soft limit region, the thickness of the vertical lines 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 manoeuvre is shown in the sequence of Fig. 5.3. The big red line at the top of the scale on the rightmost figure gives a clear cue to the pilot that he should pitch down. Approaching and crossing the lower load factor limit exhibits a similar but mirrored sequence on the lower part of the scale.

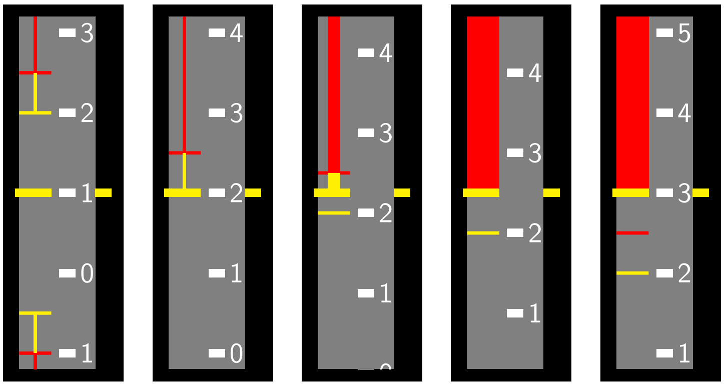


Figure 5.3: Load factor indicator progressively reaching and eventually exceeding the upper limit.

The indicator is placed left of the speed tape for a number of reasons:

- According to FAA AC 25-11B nothing must be added between the attitude indicator and the altitude or speed tapes[34]. Since in normal flight the load factor requires no attention, such a prominent spot would not be appropriate anyway.
- Extreme load factors should always be avoided, but especially at high air speeds this quickly becomes a danger to the structure of the aircraft. Similarly at low air speed, a very low load factor places the aircraft close to entering a dangerous stall. Placing the indicator next to the speed tape is therefore a logical choice, as the pilot's attention should be drawn to the speed tape as well.
- To maintain a more or less symmetric display with respect to the vertical speed indicator on the right. This yields an aesthetically pleasing balanced display with the attitude indicator in the middle.

5.3. Pitch limit / angle of attack

Airbus offers a flight path vector (FPV) that can be toggled by the pilot. Once enabled, a green ghost plane is shown on the attitude indicator. Its vertical displacement with respect to the horizon indicates the flight path angle, while the horizontal displacement corresponds to the drift (difference between heading and track)[11]. The vertical distance between the fixed aircraft symbol and this ghost plane equals the angle of attack that the aircraft is currently flying at.

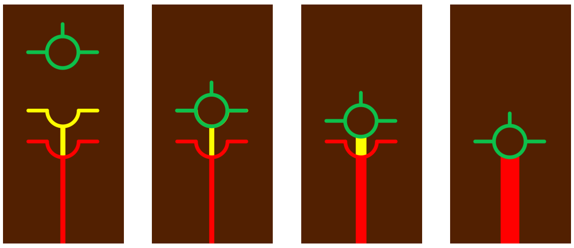


Figure 5.4: Angle of attack limit utilising the FPV progressively reaching the limit.

It would be logical to make use of this representation to display the angle of attack limits. One way to do that is to add the piston symbol below the FPV to indicate the maximum angle of attack limit (Fig. 5.4). Since a horizontal line like in the other flight envelope indicators would be ambiguous in combination with the circle-shaped FPV, the limits are here displayed with a small "seat" shape mimicking the lower side of the FPV. When the angle of attack limit is exceed, the piston width increases similar to the load factor indicator. An indication like this could result in adverse pilot response though. When the angle of attack needs to be reduced, the FPV should go up but the aircraft should be pitched down. Since pilots control pitch, the primary cue should be pitch based.

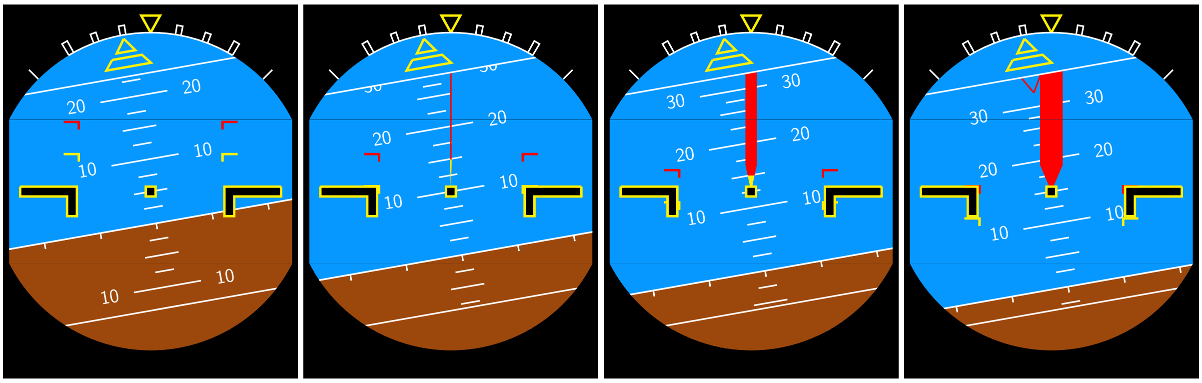


Figure 5.5: Angle of attack indicators relative to the fixed aircraft symbol progressively reaching the AoA limit.

A less ambiguous presentation is to place the piston symbol above the fixed aircraft symbol and convert maximum AoA to an associated maximum pitch angle, similar to Boeing's PLI "whiskers" (Section 2.5.2). This improved design is shown in Fig. 5.5. A small bank angle is introduced to demonstrate the non-interference with the pitch ladder. The indication is now no longer dependant on the presence of the FPV. To ensure that the limits are clearly visible and do not interfere with the pitch ladder they are placed directly above the wings of the fixed aircraft symbol in a shape analogous to the wings. The presence of the piston indicator in the middle of the pitch ladder could interfere with the flight director bars in normal law. The indications are only shown in alternate law though when the FD is unavailable. To put even more 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.

5.4. Bank angle

For the bank angle protection, yellow and red regions are indicated below the bank indicator scale (Fig. 5.6). The yellow line perpendicular to the scale corresponds to the soft limit of the haptic system, at which a discrete force cue is generated to alert the pilot of the excessive bank angle. When the aircraft banks further, the stick force is progressively increased to suggest the pilot to decrease the bank angle. Synchronous to this increase in required stick force, the curved line's thickness increases as the yellow region is compressed. An example of an extreme bank is shown in Fig. 5.6. In this particular example, the pilot should roll left to lower the bank angle.

The protection regions rotate with the horizon, as to provide a proper incentive to the pilot to correct the excessive angle. Due to the inside-out setup of the attitude indicator, if the regions were to be fixed to the display, with the bank indicator rotating, an opposite reaction could be provoked in stressful situations.

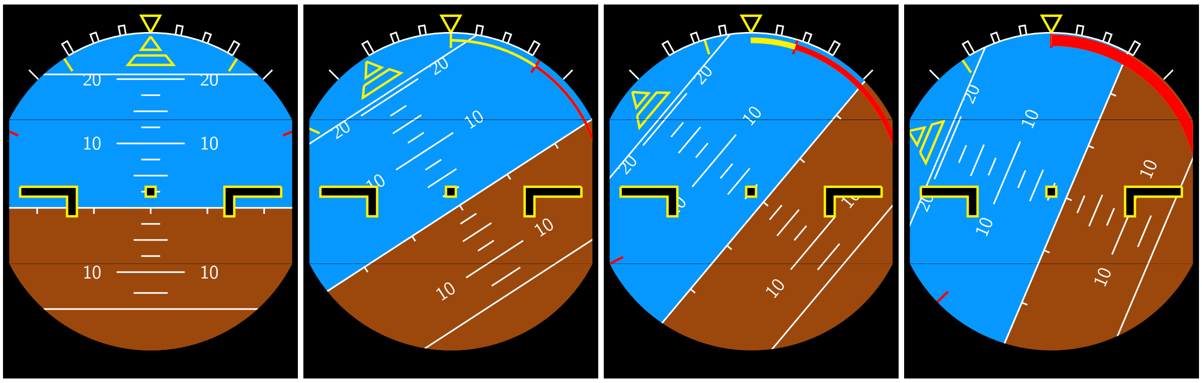


Figure 5.6: Bank angle indicator progressively reaching the limit.

5.5. Airspeed

For the overspeed protection, the standard overspeed barber pole is replaced by a hard and soft limit indication similar to that of the load factor. Once the aircraft crosses the soft limit, a gentle nose up command is encouraged by the haptics and the vertical line increases in thickness. At the maximum speed limit, the vertical line has reached its maximum thickness, giving a strong alert to the pilot that the aircraft's speed is too high.

A similar indication on the lower side of the speed tape corresponds to the low speed part of the flight envelope. When the aircraft decelerates into the yellow region of this indication, the haptics will 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.

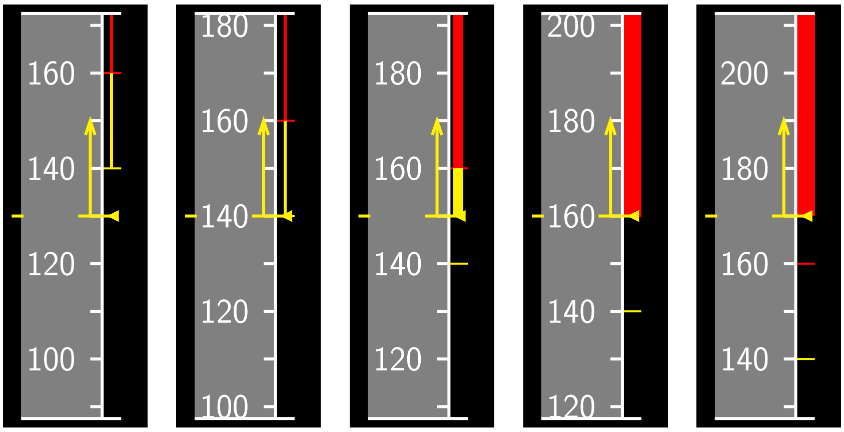


Figure 5.7: Overspeed indicator progressively reaching and eventually exceeding the limit.

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 orientated leads to indications that are not adhering to the principle of the moving part. A big red line at the top of the speed tape might be interpreted as a nose down cue when 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. Since the speed tape on the A320's PFD already has an indication for overspeed that is similar in direction to this new piston-symbol, it is expected not to be a large problem.

It might nevertheless be beneficial to link speed and pitch to replace the piston indication on the speed tape by a nose up indication on the pitch ladder when the aircraft is in an overspeed situation. Care has to be taken though when mixing angle of attack and speed limits to not create conflicting commands.

6

Experiment approach

To evaluate the design from Chapter 5, a simulator experiment is to be executed. The goal of the experiment is to see if the new display supports haptic feedback in communicating flight envelope boundaries.

6.1. Participants and instructions to participants

A number of professional Airbus pilots from various airlines will be invited to conduct the experiment. Because of the Airbus-like display design and control characteristics non-Airbus pilots do not qualify. Due to the large commonalities between Airbus types, pilots from A320, A330, A340 and A380 all qualify.

The pilots are asked to fill in a questionnaire on their flying hours, previous experience with haptic feedback and previous experience with flight envelope displays to ensure that the possible influence of these factors can be weighted. They are told that the experiment aims to evaluate a new display, not the skills of individual pilots.

6.2. Apparatus

The experiment will be set up in the Simulation, Motion, and Navigation (SIMONA) Research Simulator (SRS) at Delft University of Technology. The simulator's exterior and interior are shown in Fig. 6.1 and 6.2. SIMONA is a six degrees of freedom motion simulator with a full fledged cockpit shell. The interior can be configured to resemble any modern glass cockpit transport aircraft. For this particular experiment the motion system is not used.

Figure 6.1: Exterior of SIMONA at TU Delft.

Figure 6.2: Interior of SIMONA at TU Delft.

An electrically controlled Moog FCS Ecol-8000 side stick with force feedback capabilities as described in [4] will be located on the right hand side of the pilot who is seated in the right seat. The pedals are 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) complement the interior. The outside visuals will be provided by FlightGear[1]

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

and show the runway(s), airport infrastructure, surrounding terrain and important buildings at the airport. A proprietary A320 flight dynamics model including control laws from DLR is used as the simulated aircraft. The entire simulation is run using the Delft University Environment for Communication and Activation (DUECA) software[36]. DUECA is a framework written in C++ allowing for easy real-time distributed simulations. The displays are drawn using OpenGL.

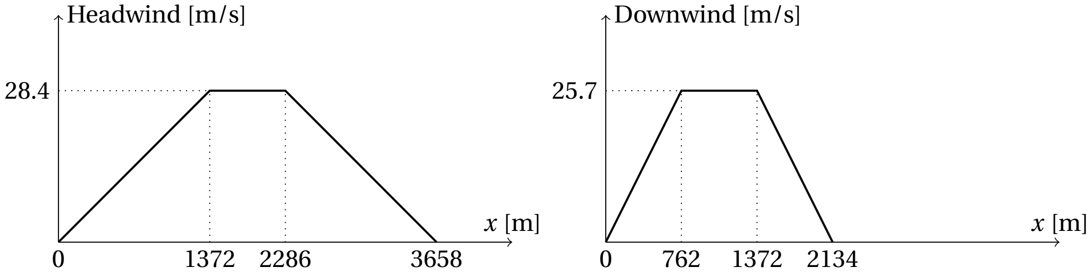
The pilot will have an Airbus A320 primary flight display (PFD) and generic navigation display (ND) in front of him in the standard right-seat configuration. The ND will show the route to be flown. The PFD will be augmented in some of the runs as discussed in Section 5. Both displays are designed in DUECA. Since the goal of the project is to support haptic feedback, the haptics are always enabled.

6.3. Scenarios

The experiment consists of a number of professional pilots hand flying flight envelope critical conditions. To examine the use of the display, it is essential that pilots approach the limits of the flight envelope. In normal law Airbus does not allow pilots to get close to the flight envelope limits. The experiment is therefore executed in alternate law without reduced protections. Since pilots stay away from the boundaries in normal flight, the experiment must be set up such that it forces them to fly at the edges of the envelope. This requires special scenarios.

6.3.1. Windshear

One scenario that is well understood and readily available in the simulator is windshear. When an aircraft encounters windshear, it first experiences a strong headwind causing a rapid increase in airspeed. Shortly thereafter, the aircraft is pushed towards the ground by a strong vertical wind component. Finally the wind changes to a strong tailwind drastically lowering the airspeed placing the aircraft close to or even in a stall. When encountered in low level flight, windshears can have severe consequences when not properly recognised and dealt with. A generic windshear model from the FAA is already implemented in the simulator according to Fig. 6.3 and can be tuned for this specific experiment[37].



(a) Headwind component

(b) Downwind component

Figure 6.3: Windshear model, based on [37].

6.3.2. Icing

Another scenario that many projects discussed in Chapter 3 have used is icing. When an aircraft encounteres icing its flight envelope shrinks. Icing is however not properly implemented in the A320 model and therefore not considered.

6.3.3. Runway sidestep

Apart from external triggers, one could also let the pilots fly certain manoeuvres that place the aircraft close to the flight envelope limits. For example have the pilot fly an approach to a certain runway while the aircraft is aligned to a parallel road or ditch. When the pilot spots the runway he has to make two steep banks to properly align the aircraft with the runway while maintaining the correct rate of descent. Since the aircraft will be low in altitude and airspeed, the flight envelope is small. Pilots are told that they have to land due to being fuel critical; going around is not an option. Simulator tests revealed that aircraft do not get close to the bank angle limits, even with considerate banking when side stepping to a parallel runway at the very last moment. To ensure pilots do encounter the limits and activate the haptic system, the bank limits are artificially reduced in the experiment. Pilots are told that their bank limits are more stringent than normally due to some failure.

In order to help the pilots recognise these reduced limits, the bank limit indications on the PFD (two amber **X** symbols in alternate law) that are normally fixed at 67°are moved to the reduced limits.

6.3.4. Go-around

To bring extra variation to the experiment and prevent pilots recognising conditions, a go-around scenario can be added in which the pilot is told by ATC to execute a go-around. This scenario is not expected to put the aircraft near its limits and is merely designed to also have experiment runs in which the haptic system and novel display are not extensively used.

6.4. Independent variables

Based on the above considerations, the experiment has two independent variables, with respectively two and three levels:

1. Display configuration
    (a) D1: The standard A320 PFD
    (b) D2: The standard A320 PFD with flight envelope enhancements
2. Experiment scenarios
    (a) S1: Windshear
    (b) S2: Runway sidestep
    (c) S3: Go-around

In both scenarios the pilots are instructed to approach and land at a runway. To prevent pilots from recognising scenarios and basing their actions on that, runs where nothing happens and the aircraft continues uneventful to the runway are performed in between. The approaches take place in reduced visibility to control the distance at which pilots will be able to see the runway. Approaches are alternated between Hartsfield–Jackson Atlanta International Airport (KATL) and London Heathrow (EGLL). Both airports have runways on either side of the terminal buildings with comparable runway spacing (KATL: 1340 m, EGLL: 1420 m). The airport layouts can be found in Fig. 6.4 and 6.5. An instrument landing system (ILS) is available on the approach runway, with corresponding ILS guidance indications visible on the PFD.

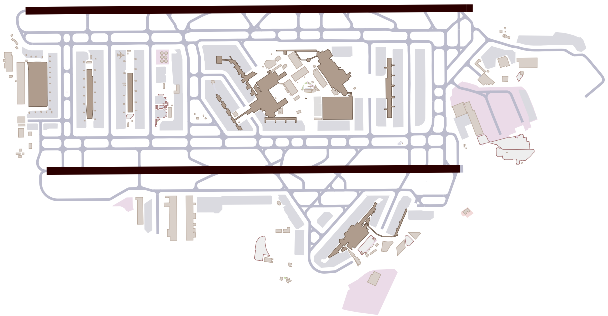


Figure 6.4: Airport diagram of EGLL[38].

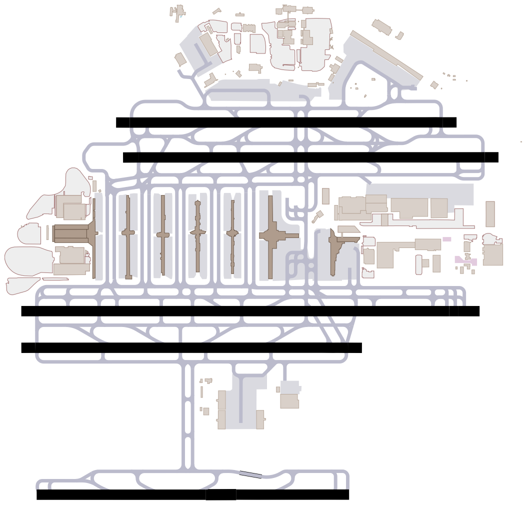


Figure 6.5: Airport diagram of KATL[38].

The experiment is set up as a within-subject experiment meaning that all participants will experience all conditions. This requires the least amount of participants while ensuring that all conditions are tested multiple times. Due to the two independent variables with two and three levels, a total of six different conditions can be set up. Therefore a multiple of six pilots is needed in a within-subjects experiment. To be able to run each scenario twice (once at both airports), the total number of conditions is twelve. A minimum of twelve pilots is therefore required to participate.

To take away order effects, a balanced Latin square distribution is used as shown in Table 6.1. The experiment is divided into two blocks of six runs with a break in between. Six subjects will get the new display in the first block and the old display in the second block, while six other subjects get the blocks in reversed order. Both groups of subjects will be assigned according to the

Table 6.1: Balanced Latin square distribution of airport (A) and scenarios (S).

		Run												
		1	2	3	4	5	6		7	8	9	10	11	12
Pilot	1	A1S1	A1S2	A2S3	A1S3	A2S2	A2S1	B	A2S2	A1S2	A1S1	A1S3	A2S1	A2S3
	2	A1S2	A1S3	A1S1	A2S1	A2S3	A2S2	R	A1S3	A2S3	A1S2	A2S1	A2S2	A1S1
	3	A1S3	A2S1	A1S2	A2S2	A1S1	A2S3	E	A1S2	A1S3	A2S2	A2S3	A1S1	A2S1
	4	A2S1	A2S2	A1S3	A2S3	A1S2	A1S1	A	A2S3	A2S1	A1S3	A1S1	A1S2	A2S2
	5	A2S2	A2S3	A2S1	A1S1	A1S3	A1S2	K	A2S1	A1S1	A2S3	A2S2	A1S3	A1S2
	6	A2S3	A1S1	A2S2	A1S2	A2S1	A1S3		A1S1	A2S2	A2S1	A1S2	A2S3	A1S3

6.5. Experiment procedure

Each experiment session consists of a couple of steps outlined below.

1. At the start of the experiment session, the pilot receives a briefing on the experiment. He will have to sign a consent form and write down a couple of personal details like the number of flight hours flown so far, types of aircraft and age.

2. During several training sessions the pilots are able to familiarise themselves with the design of the display, the haptic feedback and the simulated aircraft's handling characteristics. The pilots are asked to follow a trajectory that requires them to fly near to some of the flight envelope boundaries so they can clearly see and feel the display and haptics. Throughout the trajectory, the various parts of the haptic feedback and corresponding display indications are explained as they are encountered.

3. In the actual measured runs, the pilot will fly the six conditions. Irrespective of the condition, at the start of a run the aircraft will be placed in a steady straight and trimmed condition. A secondary task may be introduced to measure the objective workload.

4. After each condition pilots will undergo a questionnaire, such as the Rating Scale Mental Effort (RSME) to find out what their perceived workload is.

5. At the end of the experiment, each pilot will fill in an additional survey about their general opinion on the display and the experiment itself.

Halfway the experiment a lunch break is added to reduce pilot fatigue. The overall experiment is expected to take around four to five hours.

6.6. Dependent variables

Both objective and subjective measurements are taken from the experiment. The actual measurements depend on the choice of scenario, but will most likely include the following:

- Objective
    - Stick deflection
    - Stick deflection rate
    - Margins to flight envelope
    - Performance (e.g. altitude loss during windshear)
- Subjective

- Workload through a RSME questionnaire.
- System acceptance through a questionnaire.

After each run pilots will undergo a questionnaire to find out what their perceived workload is. There are several options for such a questionnaire, each with their own (dis-)advantages. NASA-TLX is often used in human factors research and frequently shows up in aviation studies. It gives an overall workload rating based on participants giving grades for a number of categories: mental demand, physical demand, temporal demand, performance, effort and frustration[39]. The Modified cooper-Harper questionnaire is less extensive and puts less load on the subject, which might be a reason to favour it over TLX. Another option is to make use of Rating Scale Mental Effort (RSME). RSME consists of a single 150 mm long line with nine descriptive markers along its length shown in Fig. 6.6. The markers range from "absolutely no effort" to "extreme effort". Pilots are asked to rate their mental effort on the line. This questionnaire is even simpler and therefore preferred over the other options.

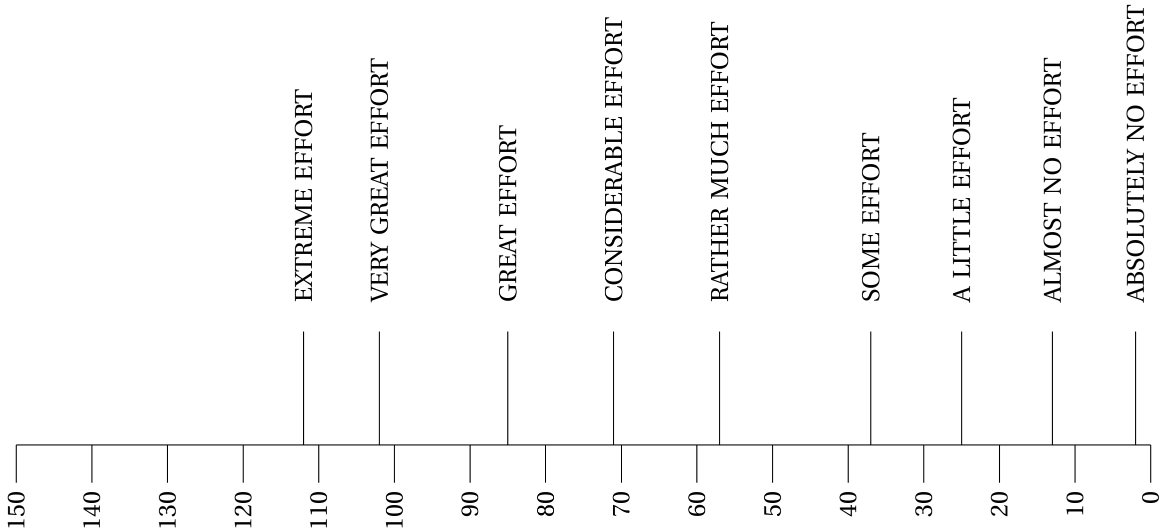


Figure 6.6: Rating Scale Mental Effort (RSME)[40].

At the end of the experiment, each pilot will fill in an additional survey about their opinion on the enhanced display in terms of symbology and overall usefulness. A questionnaire to measure usefulness and acceptance is developed by Van der Laan[41]. An example of such a test is given in Fig 6.7. Its advantages are mainly its ease of use requiring very little to no training. Additional ratings make use of the Likert rating scale[42].

My judgements of the novel display elements are... (please tick a box on every line)			
1	useful	☐ ☐ ☐ ☐ ☐	useless
2	pleasant	☐ ☐ ☐ ☐ ☐	unpleasant
3	bad	☐ ☐ ☐ ☐ ☐	good
4	nice	☐ ☐ ☐ ☐ ☐	annoying
5	effective	☐ ☐ ☐ ☐ ☐	superfluous
6	irritating	☐ ☐ ☐ ☐ ☐	likeable
7	assisting	☐ ☐ ☐ ☐ ☐	worthless
8	undesirable	☐ ☐ ☐ ☐ ☐	desirable
9	raising alertness	☐ ☐ ☐ ☐ ☐	sleep-inducing

Figure 6.7: Van der Laan usefulness and acceptance questionnaire[41].

6.7. Hypotheses

While the outcomes depend on the yet to be finalised experiment setup, some general hypotheses can already be made.

- Control activity for example is expected to go down with the extended display compared to the original display. The display shows the pilot in advance where the limits are, so he knows what to expect and can intervene timely without overshoot. This is favourable, since less control activity generally means less workload for the pilot and a smoother ride for the passengers.
- 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. For example requiring less altitude loss to recover from a windshear and less secondary stalls.
- On a subjective level, pilots are expected to show greater appreciation for haptic feedback when combined with the new display since the display helps them understand the haptic cues that they receive. It not only supports the corrective action needed to recover but also helps them identify the envelope boundary that triggered the feedback. These tackle the main issues raised by pilots on the haptic feedback project.
- With respect to safety is is hypothesised that the margins to the flight envelope boundaries will be larger when flying with the enhanced display and/or haptics because the pilots do not have to move all the way to the limits before recognising these limits through haptic cues.
- It is furthermore expected that the load factor display brings the least improvement compared to the old display. The load factor limits are almost only encountered in combination with other limits, so those limits already provide sufficient indication of what to do to unload (e.g. lower the nose).

6.8. Data analysis

From the measurements various analyses can be done. It would for example be interesting to look at the time it takes pilots to steer the aircraft back into the safe flight envelope after an envelope excursion. This does not necessarily has to go down when the display is added, as pilots may feel more secure when they see the aircraft is still relatively far from exciting the actual flight envelope and thus let the aircraft recover more slowly.

To draw conclusions from the data, it is essential that the data has statistical significance. This significance can be shown by performing a repeated-measures ANOVA for the objective data and a Friedman analysis for ordinal questionnaire data. The actual tests depend on the final selection of measurements.

7

Conclusion and outlook

In this preliminary report the work so far has been presented. A large portion of the research questions can be answered now. A literature study has revealed that current generations of aircraft are controlled using various levels of fly-by-wire. Each manufacturer has its own way of implementing flight envelope protections and communicating flight envelope boundaries to the pilots. There is no industry wide consensus on this topic. Research on other novel solutions has suggested that so far no completely satisfactory display has been conceived. Available solutions have successfully displayed flight envelope limits and the behaviour of the flight envelope protection system, but lack the indication of both the input and output space in a single display.

To fill this gap a novel instrument has been designed to visualise the boundaries corresponding to a haptic flight envelope protection system for Airbus aircraft. It not only shows the limits, but also visualises the haptic forces that the pilot feels in the stick. The instrument is integrated with the existing Airbus PFD to allow for easy adoption by the industry. Care has been taken to create a consistent display with similar indications for all flight envelope boundaries. The enhanced display is expected to result in greater pilot appreciation and better performance compared to a haptic system without such display.

Now that the preliminary phase is over, the display should be refined to ensure its working optimally in the simulator. Additional work should be put in the experiment design to make sure that the experiment delivers the desired data. Next the experiment should be executed to test the hypotheses and see if the display does augment the haptic feedback in helping pilots recognise and stay away from the flight envelope limits. Once the experiment data is in, it can be analysed to provide an answer to the remaining research questions. These answers will show whether the display is a promising step in supplementing haptic feedback to make aviation safer.

Bibliography

[1] “Statistical summary of commercial jet airplane accidents, worldwide operations | 1959 – 2016,” Boeing Commercial Airplanes, Tech. Rep., Jul. 2017.

[2] “Aircraft Accident Investigation Report,” Komite Nasional Keselamatan Transportas, Tech. Rep., 2015.

[3] “Final report on the accident on 1st June 2009 to the Airbus A330-203 registered F-GZCP operated by Air France flight AF 447 Rio de Janeiro - Paris,” BEA, Tech. Rep., Jul. 2012.

[4] D. Van Baelen, J. Ellerbroek, M. M. Van Paassen, and M. Mulder, “Design of a haptic feedback system for flight envelope protection,” *AIAA Modeling and Simulation Technologies Conference, 2018*, no. 209959, 2018.

[5] ——, “Evaluation of a haptic feedback system for flight envelope protection,” *AIAA Scitech Conference, 2019*, 2019.

[6] D. Niedermeier and A. Lambregts, “Fly-by-wire augmented manual control - basic design considerations,” *28th Congress of the International Council of the Aeronautical Sciences 2012, ICAS 2012*, vol. 4, pp. 3073–3086, 2012.

[7] *777 Flight Crew Operating Manual*, The Boeing Company, Mar. 2017.

[8] T. Dodt, “Introducing the 787,” *ESASI Lisbon*, Sep. 2011.

[9] J. W. Rustenburg, D. A. Skinn, and D. O. Tipps, “Statistical Loads Data for the Airbus A-320 Aircraft in Commercial Operations,” Apr. 2002.

[10] G. F. Bartley, “11 Boeing B-777: Fly-By-Wire Flight Controls,” in *The Avionics Handbook*, C. R. Spitzer, Ed. CRC Press, 2001.

[11] *A318/A319/A320/A321 Flight Crew Operating Manual*, Airbus, Aug. 2015.

[12] J. Pochandke, “A320 FLT CTRL Laws &. protections,” Dec. 2012.

[13] *A318/A319/A320/A321 Flight Crew Training Manual*, Airbus, Aug. 2015.

[14] *A319/A320/A321 Technical Training Manual*, Airbus, 2000.

[15] “Inovative 787 Flight Deck Designed for efficiency, comfort, and commonality,” in *Aero*, J. Langer, Ed. Boeing Commercial Airplanes Group, 2012, no. 12.

[16] P. J. Bolds-Moorehead, V. G. Chaney, T. Lutz, and S. Vaux, “Stalling transport aircraft,” *The Aeronautical Journal (1968)*, vol. 117, no. 1198, p. 1183–1206, 2013.

[17] M. Thurber. (2018, Aug.) Pilot Report: Gulfstream G500. AINonline. Accessed 19 November 2018. [Online]. Available: https://www.ainonline.com/aviation-news/business-aviation/2018-08-24/pilot-report-gulfstream-g500

[18] R. Rogers, *Pilot authority and aircraft protections*. Air Line Pilots Association, Mar. 1999.

[19] A. Karwal, “Angle-of-attack display in modern commercial aircraft. do we need that?” National Aerospace Laboratory NLR, May 2014, iCAO LOC-I Symposium, Montreal.

[20] “Operational use of Angle of Attack on Modern Commercial Jet Airplanes,” in *Aero*, J. Langer, Ed. Boeing Commercial Airplanes Group, Oct. 2000, no. 12.

[21] Lisa R. Le Vie, “Review of research on angle-of-attack indicator effectiveness,” NASA, Tech. Rep., Aug. 2014.

[22] Stephanie J. Harrison, “Review of research on guidance for recovery from pitch axis upsets,” NASA, Tech. Rep., Dec. 2016.

[23] “MIL-A-25719B,” Feb. 1990.

[24] J.-J. Toumazet and M. Vadillo, “Aircraft display management system for flight envelope protection,” U.S. Patent application US 2017/0 038 223 A1, Feb. 9, 2017.

[25] N. Barraci, “Flight envelope display,” U.S. Patent application US 2014/0 121 863 A1, May 1, 2014.

[26] K. A. Ackerman, B. D. Seefeldt, E. Xargay, D. A. Talleur, R. S. Carbonari, A. Kirlik, N. Hovakimyan, A. C. Trujillo, and I. M. Gregory, “Flight envelope information-augmented display for enhanced pilot situation awareness,” *AIAA Infotech at Aerospace*, 2015.

[27] K. A. Ackerman, D. A. Talleur, R. S. Carbonari, E. Xargay, B. D. Seefeldt, A. Kirlik, N. Hovakimyan, and A. C. Trujillo, “Automation situation awareness display for a flight envelope protection system,” *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 4, pp. 964–980, 2017.

[28] N. Meuleau, C. Neukom, C. Plaunt, D. E. Smith, and T. Smith, *The Emergency Landing Planner Experiment*. NASA, Jun. 2011.

[29] A. D. T. Rijndorp, C. Borst, C. C. de Visser, O. Stroosma, M. Mulder, and M. M. van Paassen, “Aviate, navigate: Functional visualizations of asymmetric flight envelope limits,” *AIAA Information Systems-AIAA Infotech at Aerospace*, 2017.

[30] T. Lombaerts, S. Schuet, D. Acosta, J. Kaneshige, K. Shish, and L. Martin, “Piloted simulator evaluation of safe flight envelope display indicators for loss of control avoidance,” *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 4, pp. 948–963, Apr. 2017.

[31] T. Lombaerts, G. Looye, J. Ellerbroek, and M. R. y Martin, “Design and piloted simulator evaluation of adaptive safe flight envelope protection algorithm,” *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 8, pp. 1902–1924, 2017.

[32] *A319/A320/A321 Flight deck and systems briefing for pilots*, Airbus, 1998.

[33] K. J. Vicente, *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*. CRC Press, Apr. 1999.

[34] FAA, “Electronic flight displays, AC 25-118,” 2014.

[35] C. D. Wickens, J. Lee, Y. Liu, and S. G. Becker, *An Introduction to Human Factors Engineering*, 2nd ed. Pearson Prentice Hall, 2004.

[36] M. M. van Paassen, O. Stroosma, and J. Delatour, “DUECA - Data-Driven Activation in Distributed Real-Time Computation,” in *Modeling and Simulation Technologies Conference*, Aug. 2000, pp. 1–7.

[37] “Windshear training aid,” Federal Aviation Administration, Tech. Rep., 1990.

[38] OpenStreetMap contributors, “OpenStreetMap maps,” https://www.openstreetmap.org, 2019.

[39] S. G. Hart and L. E. Staveland, “Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research,” *Advances in Psychology*, vol. 52, no. C, pp. 139–183, 1988.

[40] F. R. H. Zijlstra, “Efficiency in work behaviour: A design approach for modern tools,” Ph.D. dissertation, Delft University of Technology, Nov. 1993.

[41] J. D. van der Laan, A. Heino, and D. de Waard, “A simple procedure for the assessment of acceptance of advanced transport telematics,” *Transportation Research Part C: Emerging Technologies*, vol. 5, pp. 1–10, Feb. 1997.

[42] L. A. Haworth and R. L. Newman, “Test Techniques for Evaluating Flight Displays,” NASA, Tech. Rep., Feb. 1993.

III

Appendices

A

Balanced Latin square distribution

Three independent variables were used in the experiment: the airport which had two levels, the scenario which had three levels and the display that had two levels. In total there were therefore twelve different conditions. To mitigate order effects, a balanced Latin square was used. Twelve pilots each flew an unique series of flights. The four other pilots underwent series of flights that were duplicates of the series for pilots A1, A2, B1 and B2.

The table below shows the distribution of display (first digit) airport (second digit) and scenarios (third digit) per pilot. For example, 123 means the old display at KATL with a go-around scenario.

	Run											
Pilot	1	2	3	4	5	6	7	8	9	10	11	12
A1	111	112	123	113	122	121	222	212	211	213	221	223
A2	112	113	111	121	123	122	213	223	212	221	222	211
A3	113	121	112	122	111	123	212	213	222	223	211	221
A4	121	122	113	123	112	111	223	221	213	211	212	222
A5	122	123	121	111	113	112	221	211	223	222	213	212
B1	211	212	223	213	222	221	122	112	111	113	121	123
B2	212	213	211	221	223	222	113	123	112	121	122	111
A6	123	111	122	112	121	113	211	222	221	212	223	213
B3	213	221	212	222	211	223	112	113	122	123	111	121
B4	221	222	213	223	212	211	123	121	113	111	112	122
B5	222	223	221	211	213	212	121	111	123	122	113	112
B6	223	211	222	212	221	213	111	122	121	112	123	113
A7	111	112	123	113	122	121	222	212	211	213	221	223
B7	211	212	223	213	222	221	122	112	111	113	121	123
B8	212	213	211	221	223	222	113	123	112	121	122	111
A8	112	113	111	121	123	122	213	223	212	221	222	211

B

Pilot recruitment

In order to recruit pilots, the following flyer was shared with a large number of pilots from various airlines. Pilots who previously participated in the haptic feedback project [5] were also approached. In the end 19 pilots were scheduled to participate in the experiment, of which three pilots had to cancel due to various reasons outside the control of the experiment.

Gezocht: Airbus vliegers voor experiment TU Delft

Beste vliegers,

De Technische Universiteit Delft heeft recent onderzoek gedaan naar een nieuwe vorm van ondersteuning bij het besturen van een Airbus. De side stick is hiervoor voorzien van force feedback. Uit een simulatorexperiment bleek dat vliegers het een fijne toevoeging vonden maar niet altijd begrepen wat de force feedback probeerde te vertellen. Ter afronding van mijn studie Luchtvaart- en Ruimtevaarttechniek onderzoek ik manieren om dit duidelijker te communiceren. Dit wordt wederom getest in een simulator.

Omdat het om een Airbus configuratie gaat ben ik hiervoor **specifiek op zoek naar Airbus vliegers** (alle types, posities en vlieguren) die het leuk vinden een bijdrage te leveren aan de wetenschap en toekomstige cockpits. Vlieg een dagdeel in de geavanceerde onderzoekssimulator van de TU Delft en doe ervaringen op die tijdens normale vluchten niet mogen of kunnen!

- Het experiment vindt plaats **tussen 4 en 22 februari 2019** en duurt per vlieger één dag van 10:00 tot ca. 15:00. Datum (en tijd) is nader te bepalen in overleg.
- Locatie is de SIMONA Research Simulator van de TU Delft (Kluyverweg 1, 2628HS Delft).
- Reiskosten worden vergoed.
- Lunch wordt door ons verzorgd.
- Resultaten worden geanonimiseerd.

Mocht u interesse hebben dan hoor ik dat uiteraard graag! Ook vragen of opmerkingen zijn welkom, net als het delen van deze oproep met collega's. Ik ben te bereiken via g.derooij@student.tudelft.nl of 06-48579287. Alvast ontzettend bedankt!

Met vriendelijke groet,

Gijs de Rooij
MSc student

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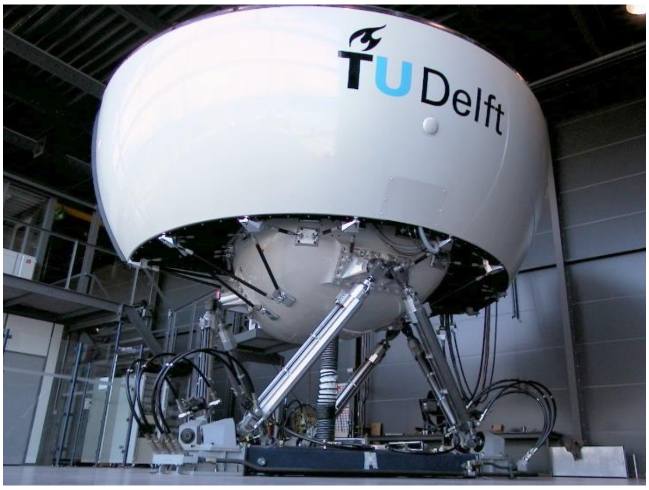


C

Briefing

A briefing was sent to the pilots several days ahead of the experiment day. The briefing contained some logistical information, a short description about the experiment and an explanation of the rights of the participants.

A320 experiment briefing

Beste deelnemer,

Ontzettend fijn dat u deelneemt aan mijn afstudeeronderzoek! Met dit experiment onderzoek ik de mogelijkheden van haptische feedback – ook wel bekend als force feedback – via de side stick in combinatie met een nieuw display. Dit document bevat essentiële informatie om u voor te bereiden op het experiment. Ik verzoek u het goed door te lezen voor aanvang van het experiment. Aarzel niet om contact op te nemen als u na het lezen nog vragen hebt.

Met vriendelijke groet,

Gijs de Rooij

1 Logistieke informatie

Datum	Dinsdag 5 maart 2019
Tijd	10:00 - circa 15:00
Locatie	Luchtvaart- en Ruimtevaarttechniek, Kluyverweg 1, 2629HS Delft Een routebeschrijving is te vinden op: tudelft.nl/over-tu-delft/contact-en-bereikbaarheid/plattegrond-en-gebouwen/gebouw-62/
Verzamelplaats	Servicebalie bij de hoofdingang, u kunt bij de balie naar mij (Gijs de Rooij) vragen
E-mail	g.derooij@student.tudelft.nl
Telefoon	06-48579287

Hoewel deelname vrijwillig is worden reiskosten vergoed. U kunt hiervoor op de dag zelf een formulier invullen.

2 Apparatus

Het experiment vindt plaats in de Simona Research Simulator (SRS) bij de faculteit Luchtvaart- en Ruimtevaarttechniek van de Technische Universiteit Delft. De SRS bestaat uit een volledig omsloten glass cockpit op een beweegbaar platform (Fig. 1a). De simulator zal in dit experiment niet bewegen. Een impressie van de cockpit is te zien in Fig. 1b. Tijdens het experiment zult u in uw eentje in de cockpit zitten en houden we contact via een headset.

(a) Exterieur van de SRS.

(b) Interieur van de SRS.

Figuur 1: Simona Research Simulator (SRS).

Omdat de simulator gebruikt wordt voor onderzoek zal hij anders zijn dan de simulatoren waar u aan gewend bent. U neemt plaats op de stoel van de first officer met een side stick aan uw rechterhand, voetenstuur, gashendels en een flight control unit die zoveel mogelijk een Airbus benaderen. De side stick is voorzien van force feedback zodat u haptische signalen kunt voelen die u helpen binnen de flight envelope te blijven. Op het instrumentenpaneel ziet u een A320 primary flight display (PFD) en een generiek navigation display die een vereenvoudigde weergave van de benodigde functies bevatten. Tijdens een deel van het experiment zal de PFD enkele nieuwe indicaties bevatten die u voorafgaand aan het experiment worden uitgelegd. De haptische feedback is altijd aanwezig.

U zult een Airbus A320-achtig model vliegen. Omdat het geen volledig accuraat model is krijgt u de tijd om u het model en de opstelling eigen te maken. Alle vluchten vinden in alternate law plaats zonder autopilot en auto throttle.

3 Experiment procedure

Het experiment start om 10:00 en eindigt omstreeks 15:00. Ik heb tijd ingepland voor pauzes en een lunch, maar laat het weten als u op enig moment extra pauzes nodig hebt.

In de ochtend ontvangt u een training om vertrouwd te raken met de simulator en het vliegmodel. De haptische feedback en de nieuwe elementen op het display zullen worden uitgelegd. U brengt de uitleg direct in de praktijk door een aantal oefenscenario's te vliegen. Als u vragen hebt tijdens de training of later op de dag hoor ik dat graag. Na de training zullen we pauzeren voor een (verzorgde) lunch.

's Middags simuleren we een serie vluchten die lijken op operationele vluchten. Elke vlucht wordt afgesloten met een aantal korte vragen. Aan het eind van het experiment vraag ik u tot slot een enquête in te vullen over de bruikbaarheid van de nieuwe display elementen en het experiment zelf. Tevens zal ik u uitleggen wat ik precies met het experiment probeer te onderzoeken.

4 Uw rechten

Deelname aan het experiment is volledig vrijwillig. U kunt u op elk moment terugtrekken uit het onderzoek voor elke reden, zelfs nog tijdens het experiment.

Data die tijdens het experiment worden verzameld zullen geanonimiseerd worden opgeslagen zodat ik als enige ze aan u persoonlijk kan linken. Door deelname gaat u akkoord met het publiceren van de data in geanonimiseerde vorm. Er worden geluidsopnamen gemaakt maar deze zullen niet worden gepubliceerd.

Op de dag van het experiment zal ik u vragen een verklaring te ondertekenen om er zeker van te zijn dat u het bovenstaande begrijpt en ermee akkoord gaat.

Tot snel in Delft!

D

Consent form

To ensure the pilots have read and understood the terms of the experiment they had to sign a consent form at the start of the experiment. On the form they could also provide their address details in order to receive travel reimbursement.

Onkostenvergoeding en verklaring van deelname

Dit formulier wordt apart van alle andere formulieren gehouden om de anonimiteit te waarborgen.

REISKOSTENVERGOEDING

Om aanspraak te maken op de reiskostenvergoeding gelieve onderstaande gegevens invullen.

Naam ____

Adres ____

E-mail adres ____

IBAN ☐☐☐☐ ☐☐☐☐ ☐☐☐☐ ☐☐☐☐ ☐☐

VERKLARING VAN DEELNAME

Onderteken onderstaande verklaring om te bevestigen dat u deelneemt aan het experiment.

Opgenomen data zal gescheiden worden van uw identiteit. Op geen enkel moment nu of in de toekomst zal informatie van u worden gepubliceerd die tot u persoonlijk te herleiden valt. Wij waarborgen dat we de verzamelde data zorgvuldig behandelen volgens degelijke ethische regels. We nemen de simulatiegegevens en geluiden in de cockpit gedurende het gehele experiment op. Er worden geen beeldopnamen gemaakt.

Hierbij verklaar ik dat ik de instructies en voorwaarden van het experiment begrijp en dat ik vrijwillig deelneem. Ik weet dat ik mij op elk moment kan terugtrekken zonder gevolgen.

Naam __________________________ Datum __________ Handtekening __________________________

E

Pre-experiment questionnaire

At the start of the experiment the pilots were asked to complete a questionnaire on their experience as a professional pilot.

vlieger

☐

Vragenlijst voorafgaand aan het experiment

1	**PERSONALIA**			
1.1	Leeftijd ________________			
1.2	Gender	☐ Man	☐ Vrouw	☐ Anders

2	**VLIEGERVARING**		
2.1	License type(s)	☐ PPL ☐ CPL	☐ ATPL ☐ ________________
2.2	Vlieguren	Totaal: ___________ Airbus: ___________	
2.3	Type-rating(s)	Huidig: ______________________________ Voormalig: ____________________________	
2.4	Huidige functie	☐ Second officer ☐ First officer	☐ Gezagvoerder ☐ ________________
2.5	Ben je een Airbus flight instructor?	☐ Ja	☐ Nee
2.6	Heeft u ooit windshear ervaren tijdens een echte vlucht?	☐ Ja	☐ Nee
	In een Airbus?	☐ Ja	☐ Nee
	Tijdens welke fase(s) van de vlucht?	☐ Take-off ☐ Climb ☐ Cruise	☐ Approach ☐ Landing ☐ ________________
2.7	Heeft u een upset prevention and recovery training (UPRT) gehad?	☐ Ja	☐ Nee
2.8	Heeft u ooit een degraded control law ervaren? ☐ Ja, in een simulator. Welke control law(s) was/waren het? ☐ Alternate law with reduced protection ☐ Alternate law without reduced protection ☐ Direct law ☐ Mechanical backup ☐ Ja, tijdens een echte vlucht. Welke control law(s) was/waren het? ☐ Alternate law with reduced protection ☐ Alternate law without reduced protection ☐ Direct law ☐ Mechanical backup ☐ Nee		

vlieger

3 WETENSCHAPPELIJKE ERVARING

3.1 Heeft u ooit deelgenomen aan een wetenschappelijk experiment? ☐ Ja ☐ Nee

Indien ja, wat voor soort onderzoek?

Einde vragenlijst

F

Post-run questionnaire

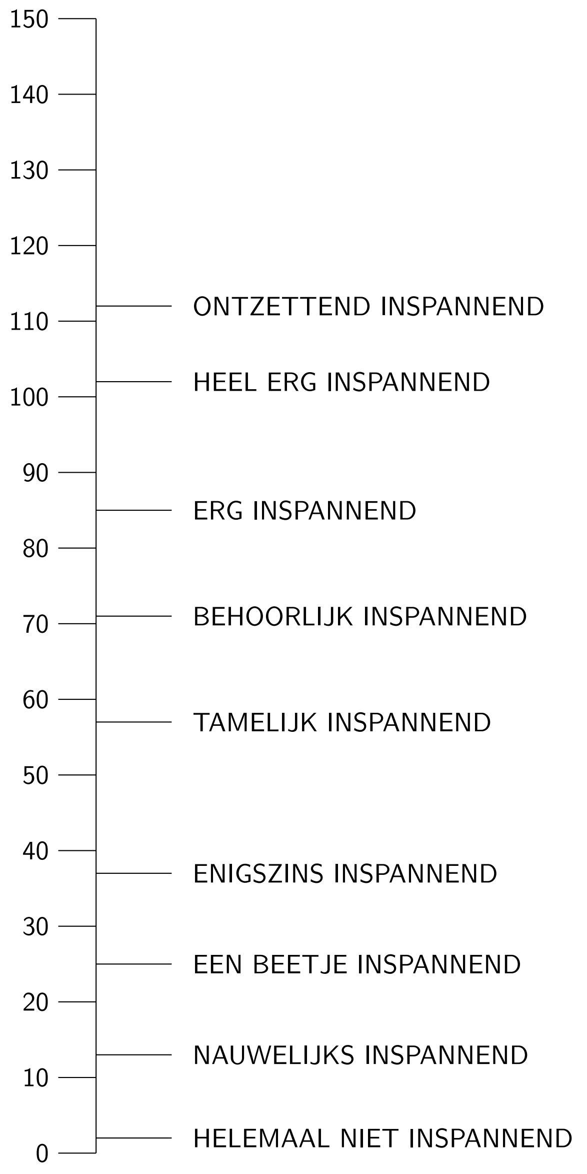
Directly after each run, the pilots had to complete one of the following questionnaires about the preceding run. The questionnaires were the same for all flights, except for a section on the display which was only present after runs in which the PFD+ was used, as shown here in the second questionnaire.

vlieger run

Vragenlijst na een run met alleen haptiek

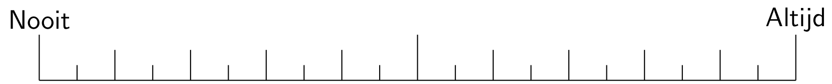
1 MENTALE BELASTING

1.1 Hoe inspannend vond u deze run?



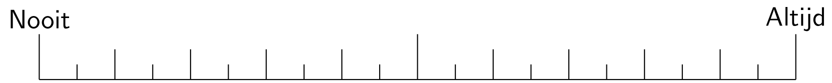
2 ALGEMEEN

2.1 Had u tijdens deze run het gevoel dat u controle had over de situatie?



Waarom wel/niet? ____________________

2.2 Had u tijdens deze run het gevoel essentiële informatie te missen?



Zo ja, welke? ____________________

3 HAPTIEK

3.1 Geef voor onderstaande haptiek assen aan hoezeer ze u hielpen binnen de limieten te blijven tijdens de noodsituatie in deze run (indien voorgekomen).

	Niet	Een beetje	Tamelijk	Erg	Heel erg
Pitch	☐	☐	☐	☐	☐
Roll	☐	☐	☐	☐	☐

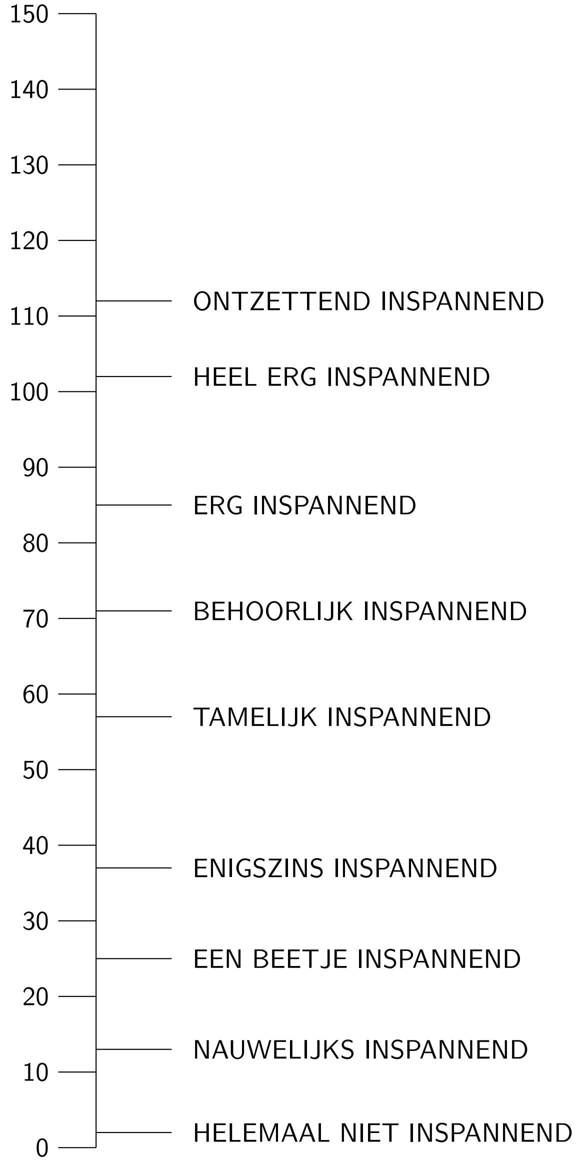
vlieger run

vlieger	run

Vragenlijst na een run met zowel haptiek als display

1 MENTALE BELASTING

1.1 Hoe inspannend vond u deze run?



2 ALGEMEEN

2.1 Had u tijdens deze run het gevoel dat u controle had over de situatie?

Nooit Altijd

Waarom wel/niet? ______

2.2 Had u tijdens deze run het gevoel essentiële informatie te missen?

Nooit Altijd

Zo ja, welke? ______

3 HAPTIEK

3.1 Geef voor onderstaande haptiek assen aan hoezeer ze u hielpen binnen de limieten te blijven tijdens de noodsituatie in deze run (indien voorgekomen).

	Niet	Een beetje	Tamelijk	Erg	Heel erg
Pitch	☐	☐	☐	☐	☐
Roll	☐	☐	☐	☐	☐

4 DISPLAY

4.1 Geef voor onderstaande nieuwe display elementen aan hoezeer ze u hielpen binnen de limieten te blijven tijdens de noodsituatie in deze run (indien voorgekomen).

	Niet	Een beetje	Tamelijk	Erg	Heel erg
Airspeed	☐	☐	☐	☐	☐
Angle of attack	☐	☐	☐	☐	☐
Bank	☐	☐	☐	☐	☐
Load factor	☐	☐	☐	☐	☐

G

Post-block questionnaire

After a block of six flights with a certain display option, the pilots were asked to exit the simulator and complete one of the following questionnaires about the six previous flights as a whole. The questionnaires were largely similar with the exception of some extra questions about the display that were only included after six flights with the PFD+, as shown here in the second questionnaire.

vlieger

☐

Vragenlijst na zes runs met enkel haptiek

1 ALGEMEEN

1.1 Hoe zou u het nieuwe systeem (haptiek) beoordelen? Kruis op elke regel één vakje aan.

nuttig	☐	☐	☐	☐	☐	zinloos
plezierig	☐	☐	☐	☐	☐	onplezierig
slecht	☐	☐	☐	☐	☐	goed
leuk	☐	☐	☐	☐	☐	vervelend
effectief	☐	☐	☐	☐	☐	onnodig
irritant	☐	☐	☐	☐	☐	aangenaam
behulpzaam	☐	☐	☐	☐	☐	waardeloos
ongewenst	☐	☐	☐	☐	☐	gewenst
waakzaamheidverhogend	☐	☐	☐	☐	☐	slaapverwekkend

2 HAPTIEK

2.1 Geef voor onderstaande haptiek elementen aan hoezeer ze u hielpen binnen de limieten te blijven.

	Niet	Een beetje	Tamelijk	Erg	Heel erg
Oplopende stijfheid naar de rand van de flight envelope toe	☐	☐	☐	☐	☐
Stick shaker in de stall regio	☐	☐	☐	☐	☐
Tik bij het verlaten van de beschermde zone	☐	☐	☐	☐	☐
Verandering van de neutrale positie bij een te hoge snelheid	☐	☐	☐	☐	☐
Verandering van de neutrale positie bij een stall	☐	☐	☐	☐	☐

2.2 Als u een indicatie zou kunnen toevoegen aan de haptiek, wat zou dat zijn en waarom?

2.3 Welk(e) haptiek element(en) zou u weglaten?

- ☐ Geen
- ☐ Oplopende stijfheid naar de rand van de flight envelope toe
- ☐ Stick shaker in de stall regio
- ☐ Tik bij het verlaten van de beschermde zone
- ☐ Verandering van de neutrale positie bij een te hoge snelheid
- ☐ Verandering van de neutrale positie bij een stall

Indien u iets zou weglaten, waarom?

____

____

____

____

3 STELLINGEN

		Oneens		Neutraal		Eens
3.1	De haptiek had invloed op mijn gedrag.	☐	☐	☐	☐	☐
3.2	De haptiek en de PFD gaven tegenstrijdige signalen.	☐	☐	☐	☐	☐

3.3 Heeft u nog opmerkingen over bovenstaande stellingen, of wilt u uw antwoorden verder toelichten?

____

____

____

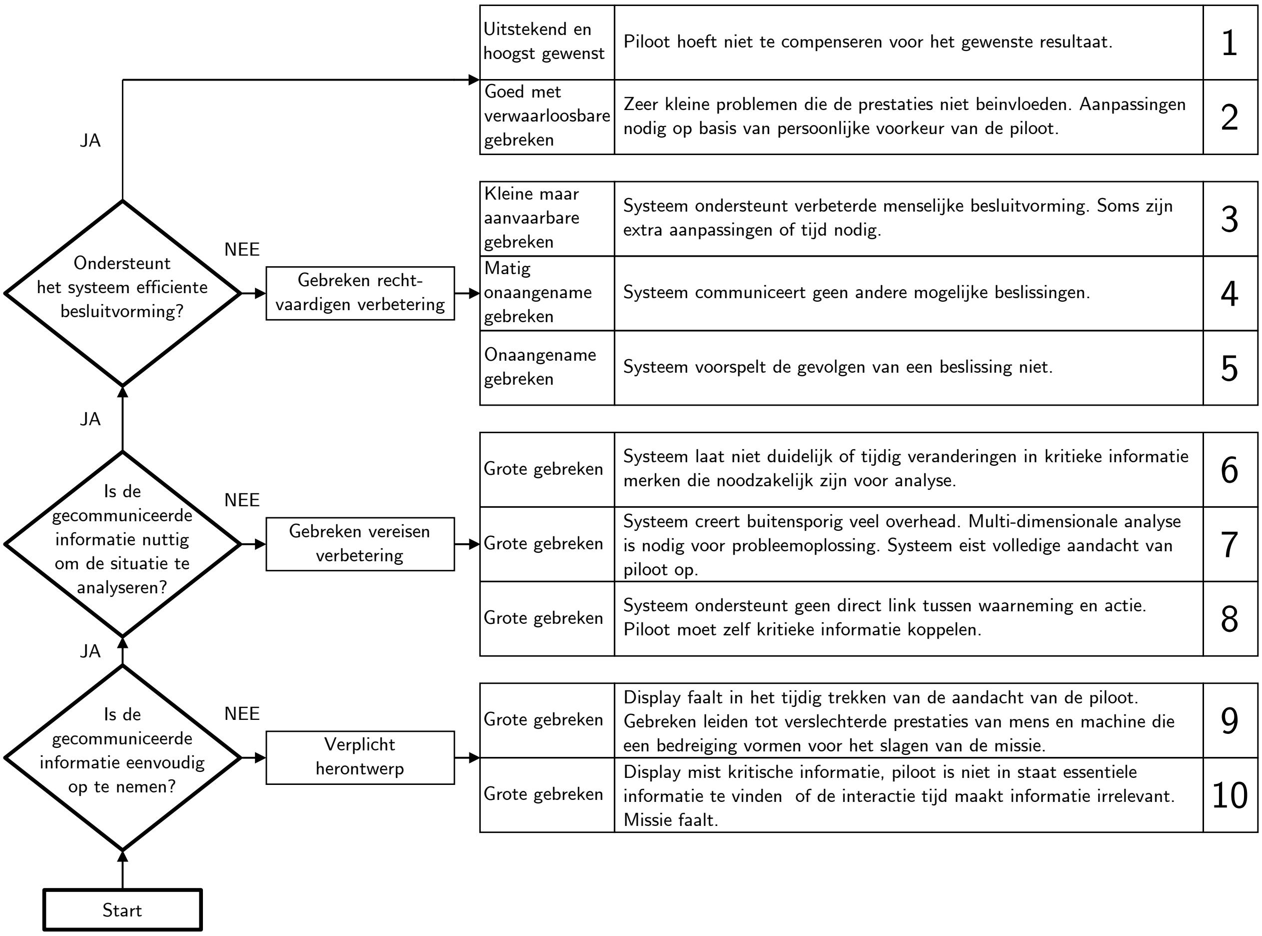
____

vlieger

☐

3.4 Welke beoordeling zou u het nieuwe systeem (haptiek) geven op basis van onderstaand schema als het gaat om het communiceren van de limieten van het vliegtuig?

1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐



Uitstekend en hoogst gewenst	Piloot hoeft niet te compenseren voor het gewenste resultaat.	1
Goed met verwaarloosbare gebreken	Zeer kleine problemen die de prestaties niet beinvloeden. Aanpassingen nodig op basis van persoonlijke voorkeur van de piloot.	2
Kleine maar aanvaarbare gebreken	Systeem ondersteunt verbeterde menselijke besluitvorming. Soms zijn extra aanpassingen of tijd nodig.	3
Matig onaangename gebreken	Systeem communiceert geen andere mogelijke beslissingen.	4
Onaangename gebreken	Systeem voorspelt de gevolgen van een beslissing niet.	5
Grote gebreken	Systeem laat niet duidelijk of tijdig veranderingen in kritieke informatie merken die noodzakelijk zijn voor analyse.	6
Grote gebreken	Systeem creert buitensporig veel overhead. Multi-dimensionale analyse is nodig voor probleemoplossing. Systeem eist volledige aandacht van piloot op.	7
Grote gebreken	Systeem ondersteunt geen direct link tussen waarneming en actie. Piloot moet zelf kritieke informatie koppelen.	8
Grote gebreken	Display faalt in het tijdig trekken van de aandacht van de piloot. Gebreken leiden tot verslechterde prestaties van mens en machine die een bedreiging vormen voor het slagen van de missie.	9
Grote gebreken	Display mist kritische informatie, piloot is niet in staat essentiele informatie te vinden of de interactie tijd maakt informatie irrelevant. Missie faalt.	10

Einde vragenlijst

vlieger

☐

Vragenlijst na zes runs met zowel haptiek als display

1 ALGEMEEN

1.1 Hoe zou u het nieuwe systeem (haptiek en display gecombineerd) beoordelen? Kruis op elke regel één vakje aan.

nuttig	☐ ☐ ☐ ☐ ☐	zinloos
plezierig	☐ ☐ ☐ ☐ ☐	onplezierig
slecht	☐ ☐ ☐ ☐ ☐	goed
leuk	☐ ☐ ☐ ☐ ☐	vervelend
effectief	☐ ☐ ☐ ☐ ☐	onnodig
irritant	☐ ☐ ☐ ☐ ☐	aangenaam
behulpzaam	☐ ☐ ☐ ☐ ☐	waardeloos
ongewenst	☐ ☐ ☐ ☐ ☐	gewenst
waakzaamheidverhogend	☐ ☐ ☐ ☐ ☐	slaapverwekkend

2 HAPTIEK

2.1 Geef voor onderstaande haptiek elementen aan hoezeer ze u hielpen binnen de limieten te blijven.

	Niet	Een beetje	Tamelijk	Erg	Heel erg
Oplopende stijfheid naar de rand van de flight envelope toe	☐	☐	☐	☐	☐
Stick shaker in de stall regio	☐	☐	☐	☐	☐
Tik bij het verlaten van de beschermde zone	☐	☐	☐	☐	☐
Verandering van de neutrale positie bij een te hoge snelheid	☐	☐	☐	☐	☐
Verandering van de neutrale positie bij een stall	☐	☐	☐	☐	☐

2.2 Als u een indicatie zou kunnen toevoegen aan de haptiek, wat zou dat zijn en waarom?

vlieger

☐

2.3 Welk(e) haptiek element(en) zou u weglaten?

☐ Geen

☐ Oplopende stijfheid naar de rand van de flight envelope toe

☐ Stick shaker in de stall regio

☐ Tik bij het verlaten van de beschermde zone

☐ Verandering van de neutrale positie bij een te hoge snelheid

☐ Verandering van de neutrale positie bij een stall

Indien u iets zou weglaten, waarom?

3 DISPLAY

3.1 Geef voor onderstaande nieuwe display indicaties aan hoezeer ze u hielpen binnen de limieten te blijven.

	Niet	Een beetje	Tamelijk	Erg	Heel erg
Indicatie van de beschermde zone	☐	☐	☐	☐	☐
Indicatie van de maximum waarde	☐	☐	☐	☐	☐
Dikker worden van de indicatie	☐	☐	☐	☐	☐

3.2 In het geval dat de haptiek blijft zoals in dit experiment. Voor welk(e) limiet(en) zou u dan de haptische indicatie(s) weglaten op het display?

☐ Geen

☐ Airspeed

☐ Angle of attack

☐ Bank

☐ Load factor

Indien u iets zou weglaten, waarom?

vlieger ☐

3.3	Als u een indicatie zou kunnen toevoegen aan het display, wat zou dat zijn en waarom? ____ ____ ____ ____

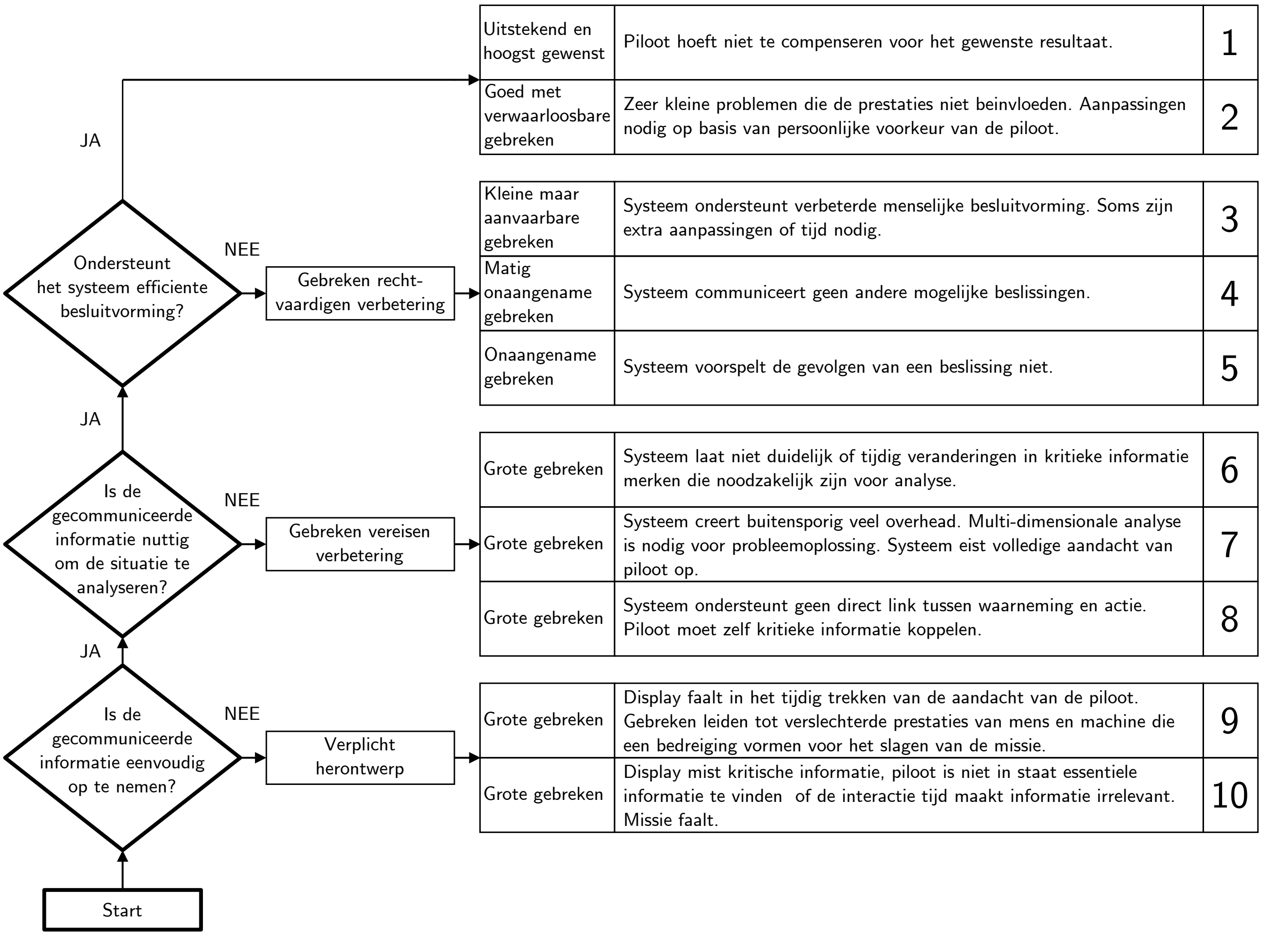
4 STELLINGEN

		Oneens		Neutraal		Eens
4.1	De haptiek had invloed op mijn gedrag.	☐	☐	☐	☐	☐
4.2	De haptiek en de PFD gaven tegenstrijdige signalen.	☐	☐	☐	☐	☐
4.3	De nieuwe display elementen hadden invloed op mijn gedrag.	☐	☐	☐	☐	☐

4.4	Heeft u nog opmerkingen over bovenstaande stellingen, of wilt u uw antwoorden verder toelichten? ____ ____ ____ ____

4.5 Welke beoordeling zou u het systeem (haptiek en display gecombineerd) geven op basis van onderstaand schema als het gaat om het communiceren van de limieten van het vliegtuig?

1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐



Uitstekend en hoogst gewenst	Piloot hoeft niet te compenseren voor het gewenste resultaat.	1
Goed met verwaarloosbare gebreken	Zeer kleine problemen die de prestaties niet beinvloeden. Aanpassingen nodig op basis van persoonlijke voorkeur van de piloot.	2
Kleine maar aanvaarbare gebreken	Systeem ondersteunt verbeterde menselijke besluitvorming. Soms zijn extra aanpassingen of tijd nodig.	3
Matig onaangename gebreken	Systeem communiceert geen andere mogelijke beslissingen.	4
Onaangename gebreken	Systeem voorspelt de gevolgen van een beslissing niet.	5
Grote gebreken	Systeem laat niet duidelijk of tijdig veranderingen in kritieke informatie merken die noodzakelijk zijn voor analyse.	6
Grote gebreken	Systeem creert buitensporig veel overhead. Multi-dimensionale analyse is nodig voor probleemoplossing. Systeem eist volledige aandacht van piloot op.	7
Grote gebreken	Systeem ondersteunt geen direct link tussen waarneming en actie. Piloot moet zelf kritieke informatie koppelen.	8
Grote gebreken	Display faalt in het tijdig trekken van de aandacht van de piloot. Gebreken leiden tot verslechterde prestaties van mens en machine die een bedreiging vormen voor het slagen van de missie.	9
Grote gebreken	Display mist kritische informatie, piloot is niet in staat essentiele informatie te vinden of de interactie tijd maakt informatie irrelevant. Missie faalt.	10

Einde vragenlijst

H

Post-experiment questionnaire

At the end of the experiment day, one final questionnaire was presented to the pilots. This questionnaire was mainly about the experience with haptic feedback and the display throughout the day, as well as the realism of the simulation.

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Vragenlijst na afloop van het experiment

1	**HAPTIEK EN DISPLAY**	
1.1	Welke variant heeft uw voorkeur? ☐ Alleen haptiek ☐ Haptiek met display indicaties	
1.2	De combinatie van haptiek met nieuwe display indicaties zorgde ervoor dat ik de haptiek beter begreep dan met alleen de traditionele display.	Oneens Neutraal Eens ☐ ☐ ☐ ☐ ☐
1.3	Het systeem vereist veel training.	Oneens Neutraal Eens ☐ ☐ ☐ ☐ ☐
1.4	Met de display indicaties wist ik sneller wat ik moest doen om terug te keren naar de safe flight envelope dan wanneer er alleen haptiek was.	Oneens Neutraal Eens ☐ ☐ ☐ ☐ ☐
1.5	Gedurende het experiment (na de training) ging ik de haptiek en display bij elke vlucht steeds beter begrijpen.	Oneens Neutraal Eens ☐ ☐ ☐ ☐ ☐
1.6	Het systeem helpt kritieke situaties te voorkomen.	Oneens Neutraal Eens ☐ ☐ ☐ ☐ ☐
1.7	Als zich een kritieke situatie voordoet helpt het systeem bij het oplossen van die situatie.	Oneens Neutraal Eens ☐ ☐ ☐ ☐ ☐
1.8	Ik denk dat toevoegingen aan het display zoals in dit experiment teveel afleiden om nuttig te zijn.	Oneens Neutraal Eens ☐ ☐ ☐ ☐ ☐
1.9	Wat voor effect zou het invoeren van dit systeem volgens u hebben op de veiligheid?	Onveiliger Ongewijzigd Veiliger ☐ ☐ ☐ ☐ ☐
1.10	Heeft u nog opmerkingen over bovenstaande stellingen, of wilt u uw antwoorden verder toelichten? ____________________ ____________________ ____________________ ____________________	

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2	**SIMULATIE**	
2.1	Hoe zou u de A320-achtige vliegeigenschappen omschrijven?	Onrealistisch Acceptabel Perfect ☐ ☐ ☐ ☐ ☐
2.2	Hoe zou u de sidestick omschrijven terwijl u niet in de limieten vloog?	Onrealistisch Acceptabel Perfect ☐ ☐ ☐ ☐ ☐
2.3	Hoe zou u de primary flight display omschrijven (afgezien van de nieuwe elementen) voor de gevlogen taken?	Onrealistisch Acceptabel Perfect ☐ ☐ ☐ ☐ ☐
2.4	Hoe zou u de navigation display omschrijven voor de gevlogen taken?	Onrealistisch Acceptabel Perfect ☐ ☐ ☐ ☐ ☐
2.5	Hoe zou u het weer omschrijven?	Onrealistisch Acceptabel Perfect ☐ ☐ ☐ ☐ ☐
2.6	Hoe zou u de geprojecteerde omgeving (landschap, vliegveld, lucht) omschrijven?	Onrealistisch Acceptabel Perfect ☐ ☐ ☐ ☐ ☐
2.7	Heeft u nog andere opmerkingen over de simulatie?	

3	**OVERIG**
3.1	Is er tot slot nog iets dat u genoemd wilt hebben maar wat niet in voorgaande vragen aan bod is gekomen?

Einde vragenlijst

Ontzettend bedankt voor het invullen van deze vragenlijst en uw deelname aan mijn onderzoek!
Mocht u nog vragen hebben naar aanleiding van dit experiment dan kunt u mij bereiken via g.derooij@student.tudelft.nl.

I

Approach charts

The pilots were provided with approach charts for each of the three airports that they visited during the experiment[1]. All charts included a schematic runway layout inset, which was explicitly mentioned in order to give the pilots a minimum chance of finding the correct runway whenever a sidestep was requested by ATC. The original charts have been edited such that all approaches had the same straight ahead go-around procedure.

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[1] Available from `https://www.faa.gov/air_traffic/flight_info/aeronav/procedures/` and `http://www.nats-uk.ead-it.com`

ILS or LOC RWY 16R

SEATTLE-TACOMA INTL (SEA)

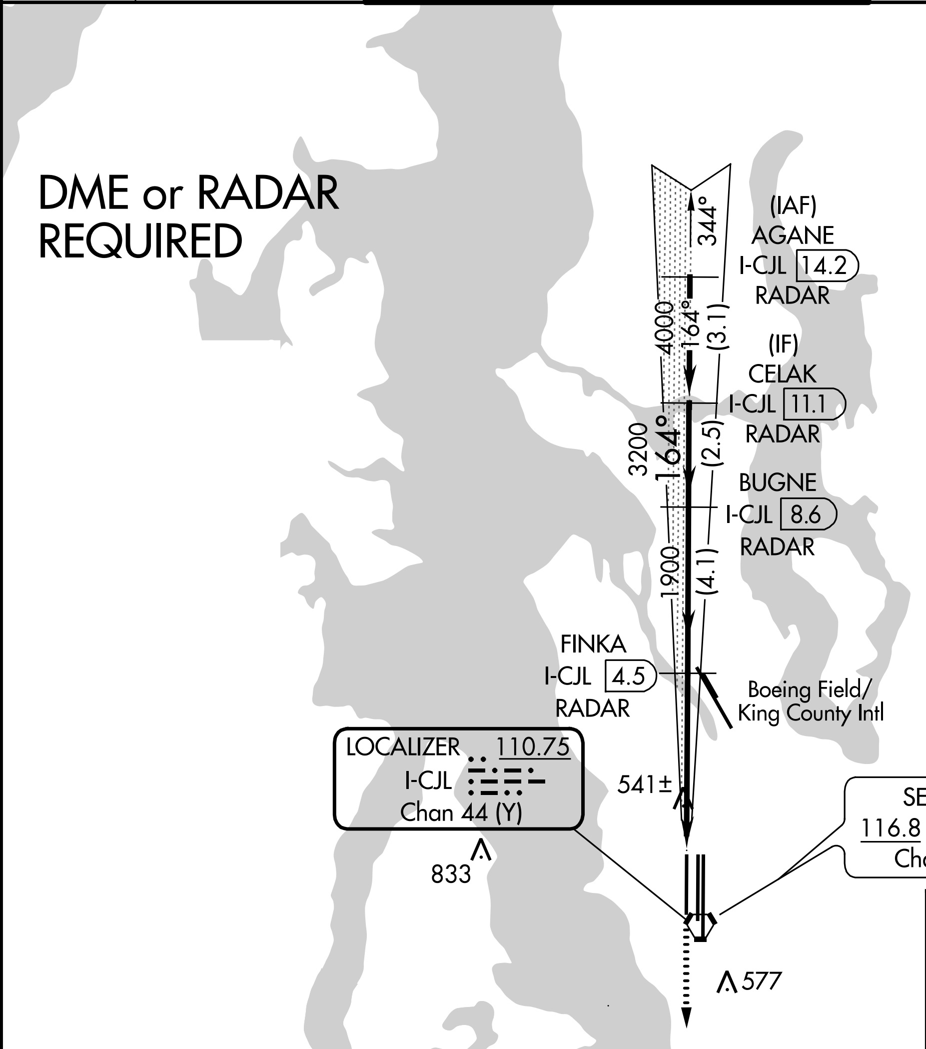
LOC/DME I-CJL **110.75** Chan **44** (Y)	APP CRS **164°**	Rwy ldg TDZE Apt Elev	**8500** **415** **433**

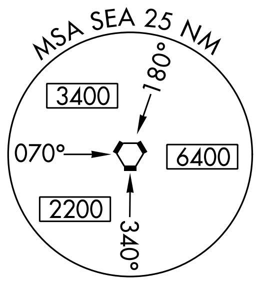
Simultaneous approach authorized with Rwy 16L and ILS or LOC RWY 16C. DME or RADAR required. Simultaneous operations with Rwy 16C require use of vertical guidance, maintain last assigned altitude until established on glideslope.

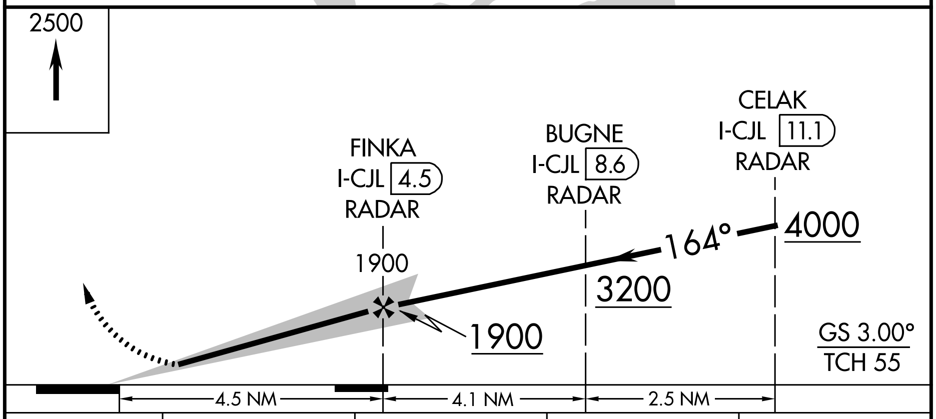
ALSF-2 Ⓐ

MISSED APPROACH: Climb to 2500

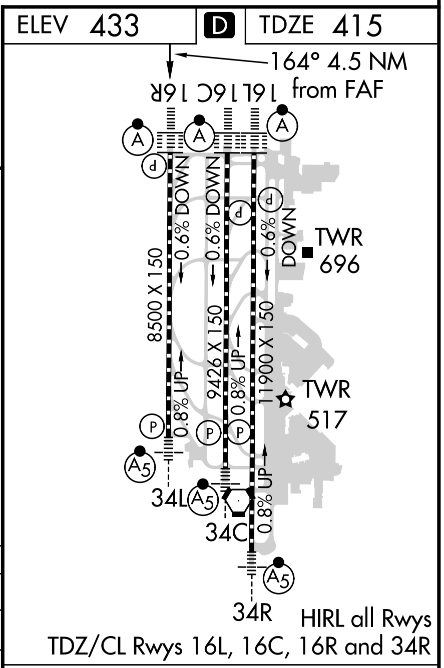
D-ATIS	SEATTLE APP CON	SEATTLE TOWER	GND CON	CLNC DEL	CPDLC
118.0	**133.65 273.45**	**119.9 239.3** (Rwys 16L, 16C, 34C, 34R) **120.95 239.3** (Rwys 16R, 34L)	**121.7**	**128.0**	







ELEV 433 D TDZE 415



TDZ/CL Rwys 16L, 16C, 16R and 34R

CATEGORY	A	B	C	D
S-ILS 16R	615/18 200 (200-½)			
S-LOC 16R	800/24 385 (400-½)		800/35 385 (400-⅝)	
C CIRCLING	1000-1 567 (600-1)		1000-1½ 567 (600-1½)	1000-2 567 (600-2)

FAF to MAP 4.5 NM

Knots	60	90	120	150	180
Min:Sec	4:30	3:00	2:15	1:48	1:30

ILS or LOC RWY 26L

HARTSFIELD-JACKSON ATLANTA INTL (ATL)

LOC/DME I-BRU	APP CRS		26L	26R
108.7	**275°**	Rwy ldg	**9999**	**8800**
Chan **24**		TDZE	**996**	**990**
		Apt Elev	**1026**	**1026**

Inoperative table does not apply to Sidestep Rwy 26R. For inop MALSR, increase S-ILS 26L visibility all Cats to RVR 4500 and S-LOC 26L Cat E visibility to 1¼ . Simultaneous approach authorized with Rwy 27L or 27R or 28.

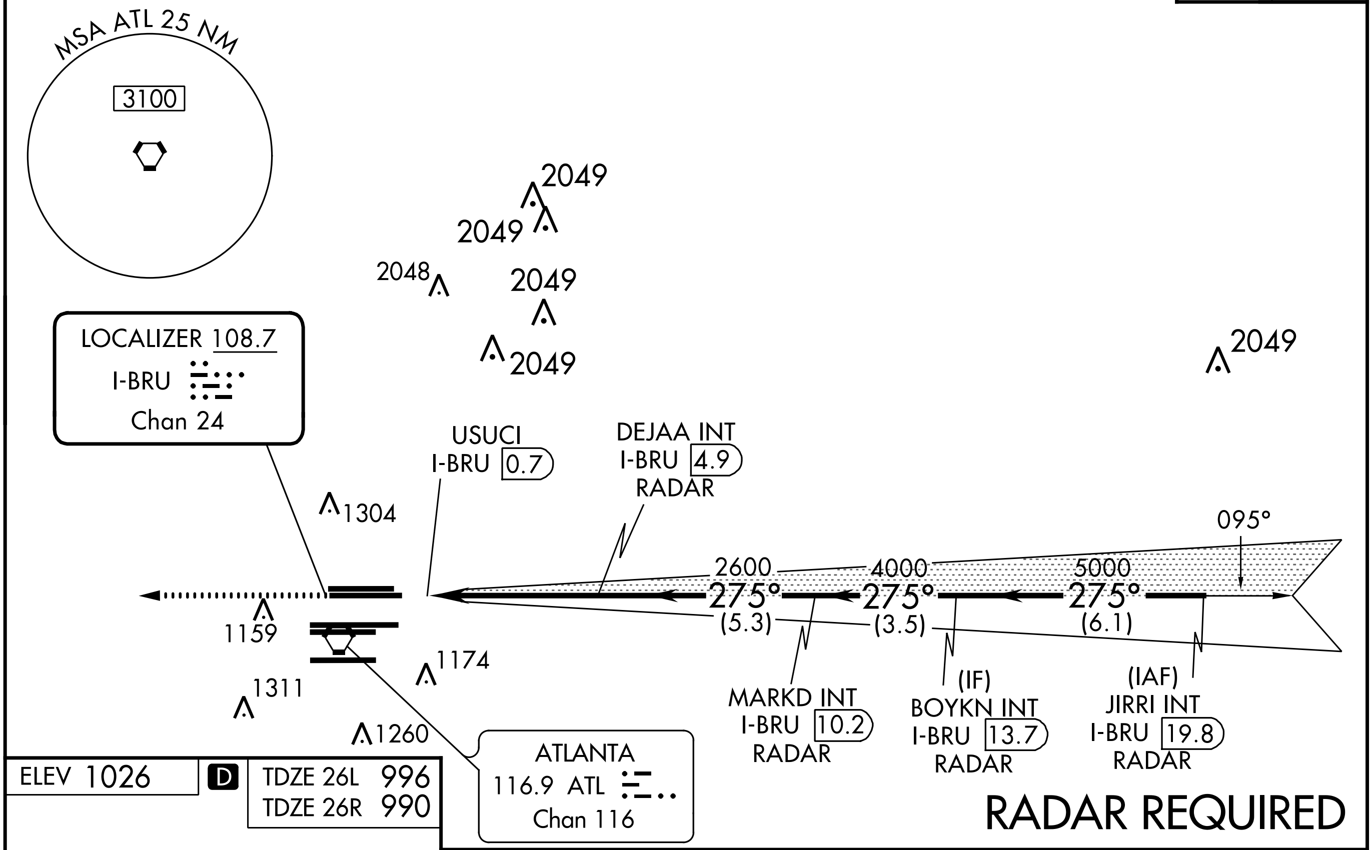
Rwy 26L MALSR Ⓐ5

Rwy 26R MALSR Ⓐ5

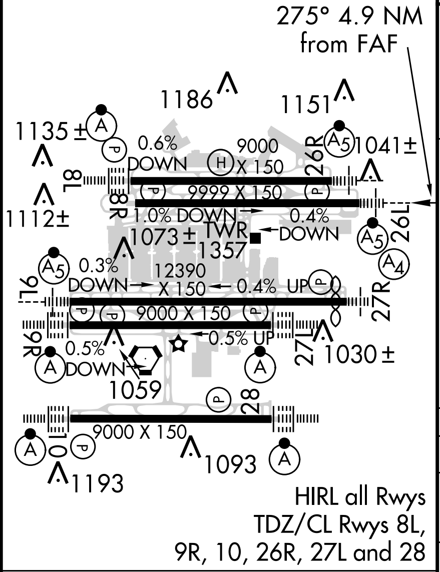
MISSED APPROACH: Climb to 3000

D-ATIS	ATLANTA APP CON	ATLANTA TOWER 8L-26R	8R-26L	9L-27R	9R-27L	10-28	ALL RWYS	GND CON (8L-26R,8R-26L)	(9L-27R,9R-27L)	10-28	ALL RWYS
ARR **119.65** DEP **125.55**	**127.9 379.9**	**119.1**	**125.325**	**123.85**	**119.3**	**119.5**	**254.4**	**121.9**	**121.75**	**121.65**	**254.4**

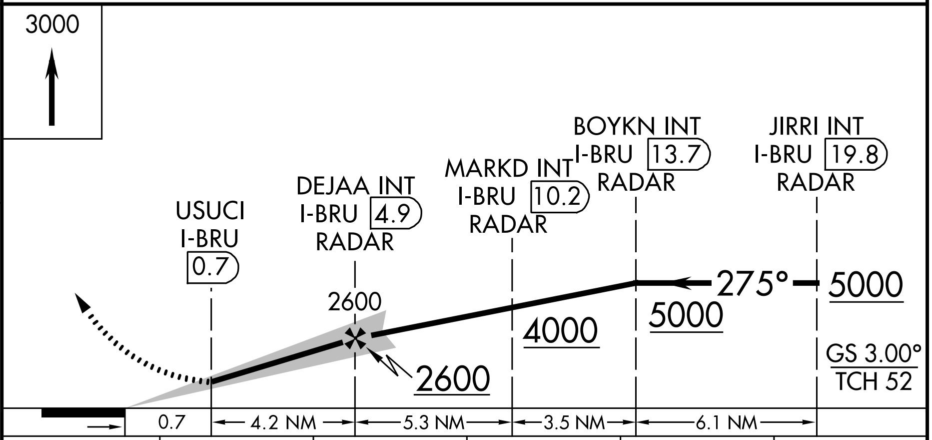
CLNC DEL	CPDLC
118.1	



ELEV 1026 D TDZE 26L 996 TDZE 26R 990



HIRL all Rwys
TDZ/CL Rwys 8L, 9R, 10, 26R, 27L and 28



CATEGORY	A	B	C	D	E
S-ILS 26L	1280/24 284 (300-½)				
S-LOC 26L	1420/24 424 (400-½)		1420/40 424 (400-¾)		

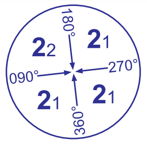
FAF to MAP 4.2 NM

Knots	60	90	120	150	180
Min:Sec	4:12	2:48	2:06	1:41	1:24

SE-4, 03 JAN 2019 to 31 JAN 2019

INSTRUMENT APPROACH CHART - ICAO

LONDON/HEATHROW
ILS/DME I-AA
RWY 09L
(ACFT CAT A,B,C,D)

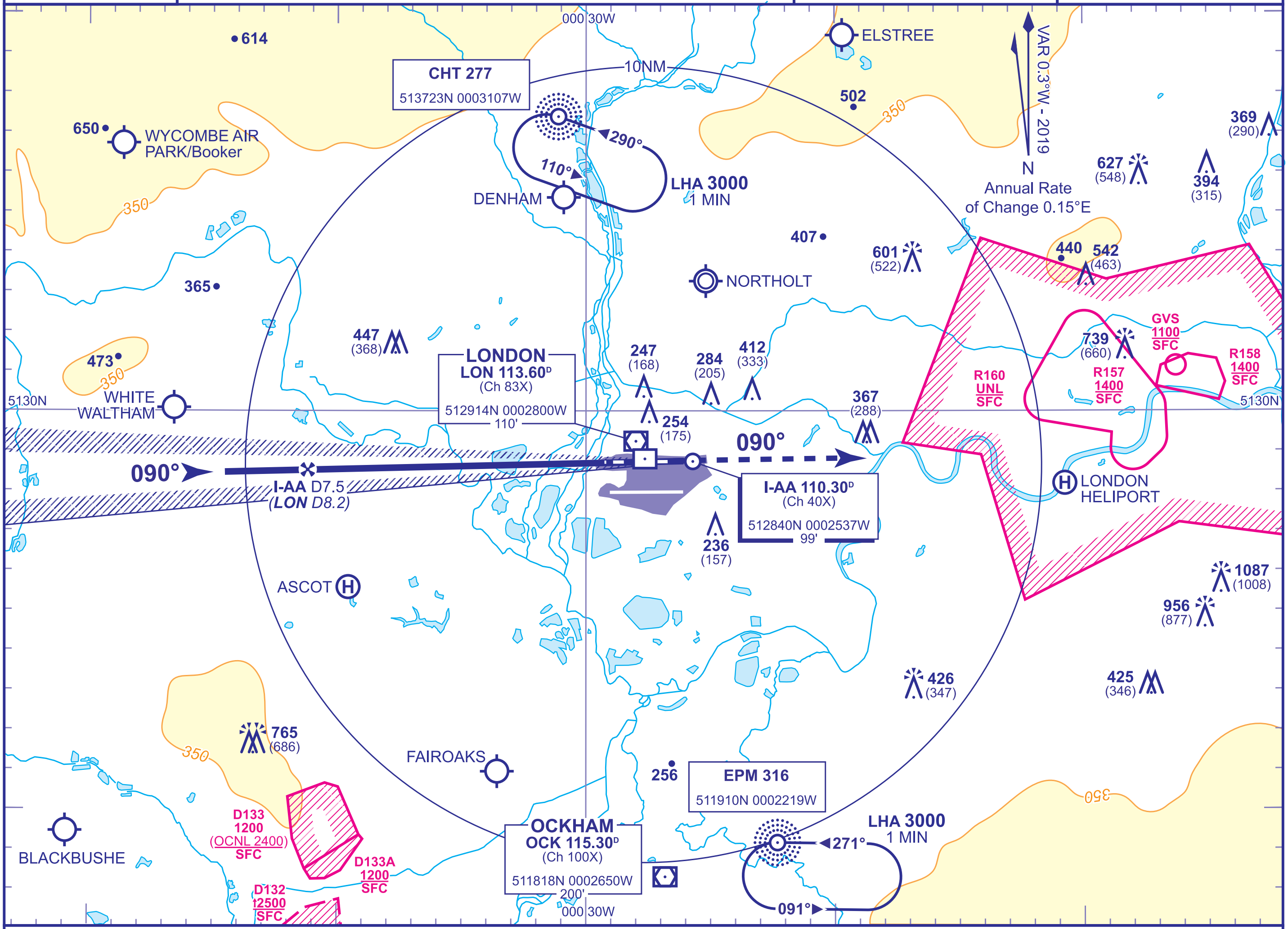


MSA 25NM LON VOR

APP 119.725, 120.400, 127.525, 134.980	HEATHROW DIRECTOR
TWR 118.500, 118.700, 124.475	HEATHROW TOWER
RAD 125.625, 127.525	HEATHROW RADAR
ATIS 128.075, 113.750, 115.100	HEATHROW INFORMATION

AD ELEVATION	83
THR ELEVATION	79
OBSTACLE ELEVATION **1087 AMSL** (1008) (ABOVE THR)	
BEARINGS ARE MAGNETIC	

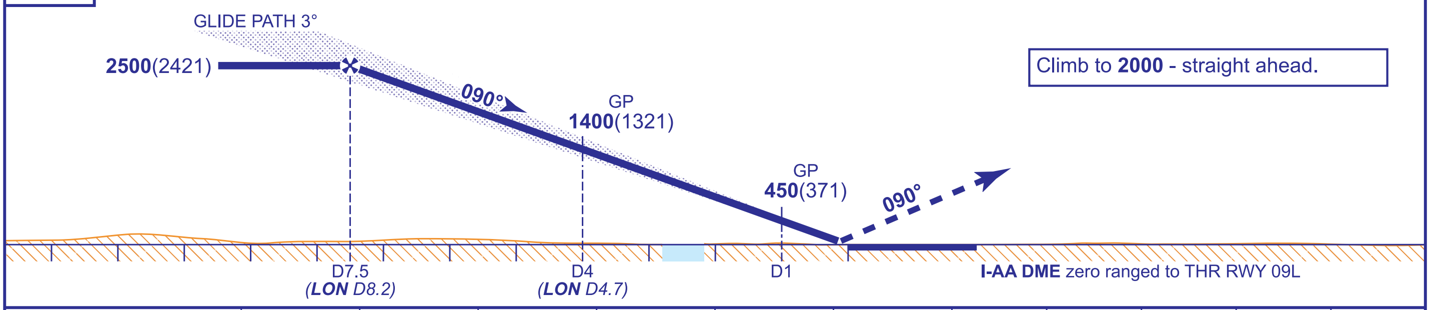
TRANSITION ALTITUDE
6000



RECOMMENDED PROFILE GLIDE PATH 3.0°, 318FT/NM

DME I-AA	7	6	5	4	3	2
ALT(HGT)	**2360**(2281)	**2040**(1961)	**1720**(1641)	**1400**(1321)	**1080**(1001)	**770**(691)

RDH 51



Climb to **2000** - straight ahead.

I-AA DME zero ranged to THR RWY 09L

Aircraft Category		**A**	**B**	**C**	**D**
OCA (OCH)	**CAT I**	**221**(142)	**232**(153)	**243**(164)	**257**(178)
	CAT II	**134**(55)	**145**(66)	**158**(79)	**174**(95)
VM(C)OCA (OCH AAL)	**Total Area**	**750**(667)	**750**(667)	**850**(767)	**850**(767)

Rate of descent	**G/S KT**	160	140	120	100	80
	FT/MIN	850	740	640	530	420

AIRCRAFT UNABLE TO RECEIVE DME I-AA
Advise ATC. Equivalent radar ranges will be provided when established on the localiser approaching the nominal FAP and 4NM points.

NOTES
1 Aircraft will normally be radar vectored from the STAR Holding/Initial Approach Fixes.
2 Ranging information is provided by ILS-dedicated DME facilities. DME values derived to the nearest 0.1NM from VOR DME LON are also provided for the FAP and 4NM check altitude/height.

CHANGE (11/18): APP FREQUENCY. MAG VAR. MAG TRACKS. R157 REDEFINED.

AERO INFO DATE 12 JUL 18

J

DUECA simulation interface

The complete simulation is included in the 'HapticFeedbackForFlightEnvelopeProtection' project under the version tag 'experiment_gijs'. It consists of a large number of modules outlined in the diagram on the next page. The user interface shown in Fig. J.1 was designed in Glade to control the experiment. It facilitates scenario initialization with a single click, greatly reducing the possibility of loading wrong settings.

Save current state

New condition

Initial Flight Conditions: KATL_26L_ILS.txt

Bank protection [deg]: CL prot: 90 DP prot: 15 DP max: 30

Subject: 13

Run number: 0

Experiment Scenario
- ○ Familiarization
- ● Wind shear
- ○ Icing
- ○ Runway sidestep
- ○ Go-around

Run timer [s]: 0.0 ☐ Training
Altitude loss [ft]: /
Total error RMS [m]: /
Within 50 ft offset [NM]: /
1500 < ROC < 2500 [] /

Flight Control Law: ○ Normal law ● Alternate law
Haptic Feedback: ● ON ○ OFF
Visual Protections: ● ON ○ OFF
Static Protections: ● ON ○ OFF

Scenario quickselect

EGLL	KATL	EHAM	KSEA
○ GA/OLD ○ RW/OLD ○ WS/OLD	○ GA/OLD ○ RW/OLD ○ WS/OLD	○ Circuit 36L	○ GA/OLD ○ RW/OLD ○ WS/OLD
○ GA/NEW ○ RW/NEW ○ WS/NEW	○ GA/NEW ○ RW/NEW ● WS/NEW	○ Training Area	○ GA/NEW ○ RW/NEW ○ WS/NEW

Atmospheric Conditions

Aircraft States Monitor

	Prot	Current State	Max
AoA [deg]	0.0	0.0	0.0
n [-]	0.0	0.0	0.0
V [TAS kts]	0.0	0.0	0.0
Thrust	0.0	%	
Flaps [deg]	0	Slats [deg]	0.0

Telnet Commands

set sim/rendering/precipitation-enable true

Automated ATC chatter settings

Automated messages: ○ n ● ff
Mean interval [s]: 20.0
Standard deviation of interval [s]: 2.5

ATC chatter list settings

● n ○ ff
ws_new_katl.atc

Priority ATC Command

Call sign / Command / Number

Sim limits

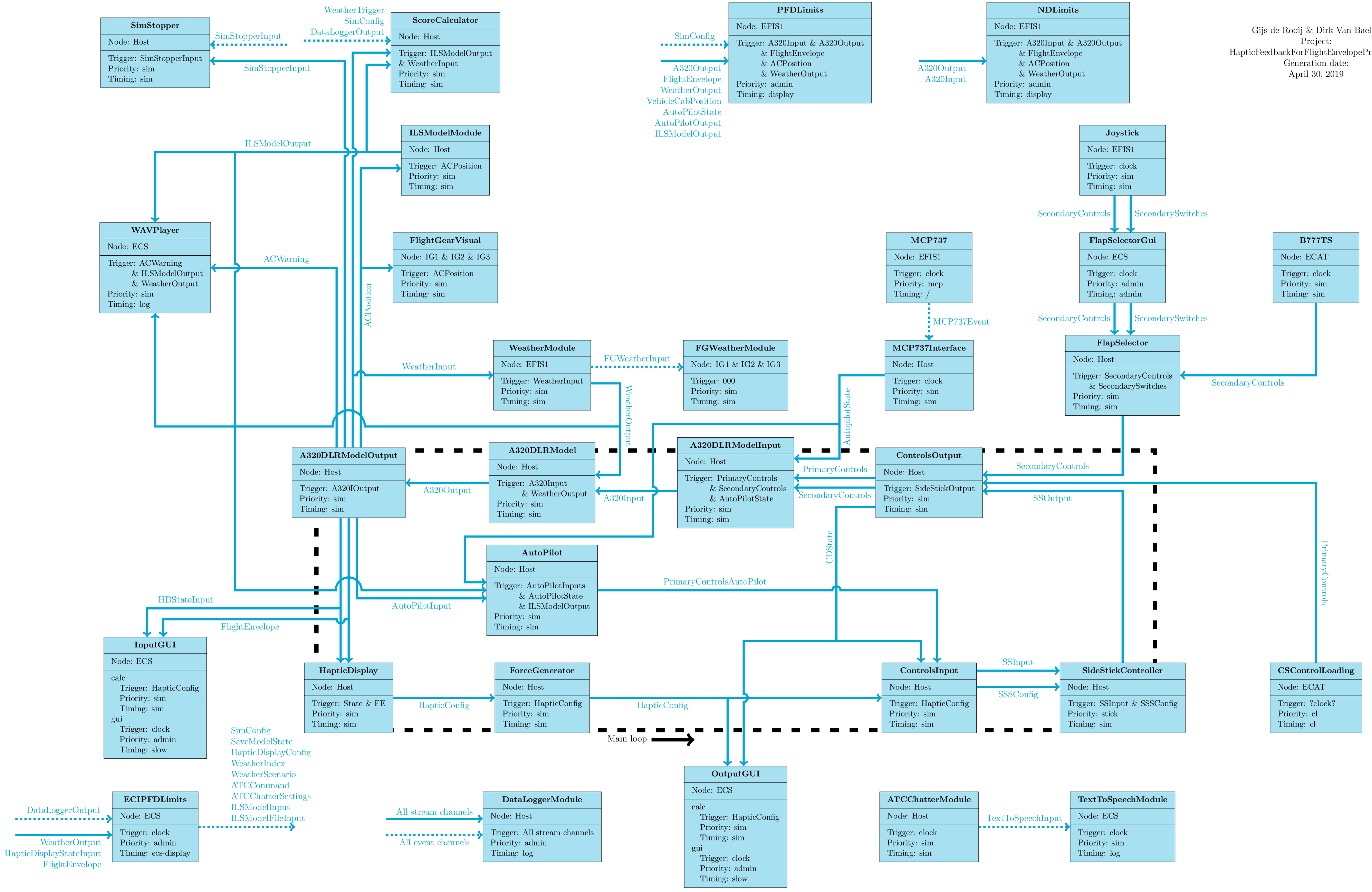
☑ Altitude [ft]	50	99000
☑ Pitch [deg]	-85.0	85.0
☑ Velocity [kts]	50	600
☑ Roll [deg]	-85	85
☑ Load factor [-]	-3.0	3.0

Weather scenario

Trigger weather

Figure J.1: Experiment control interface (ECI).

Gijs de Rooij & Dirk Van Baelen
Project:
HapticFeedbackForFlightEnvelopeProtection
Generation date:
April 30, 2019



K

Typical flight data

The following figures show flight data on the haptic feedback limited parameters for four pilots, each flying three scenarios with the PFD+. Every figure shows one parameter for one scenario with, from top to bottom, data from pilots A1, A6, B2 and B8 respectively. The figures clearly show the large variety in approach strategies when it comes to airspeed and the deployment of flaps. These in turn have impact on the limits, the maximum allowable angle of attack for example.

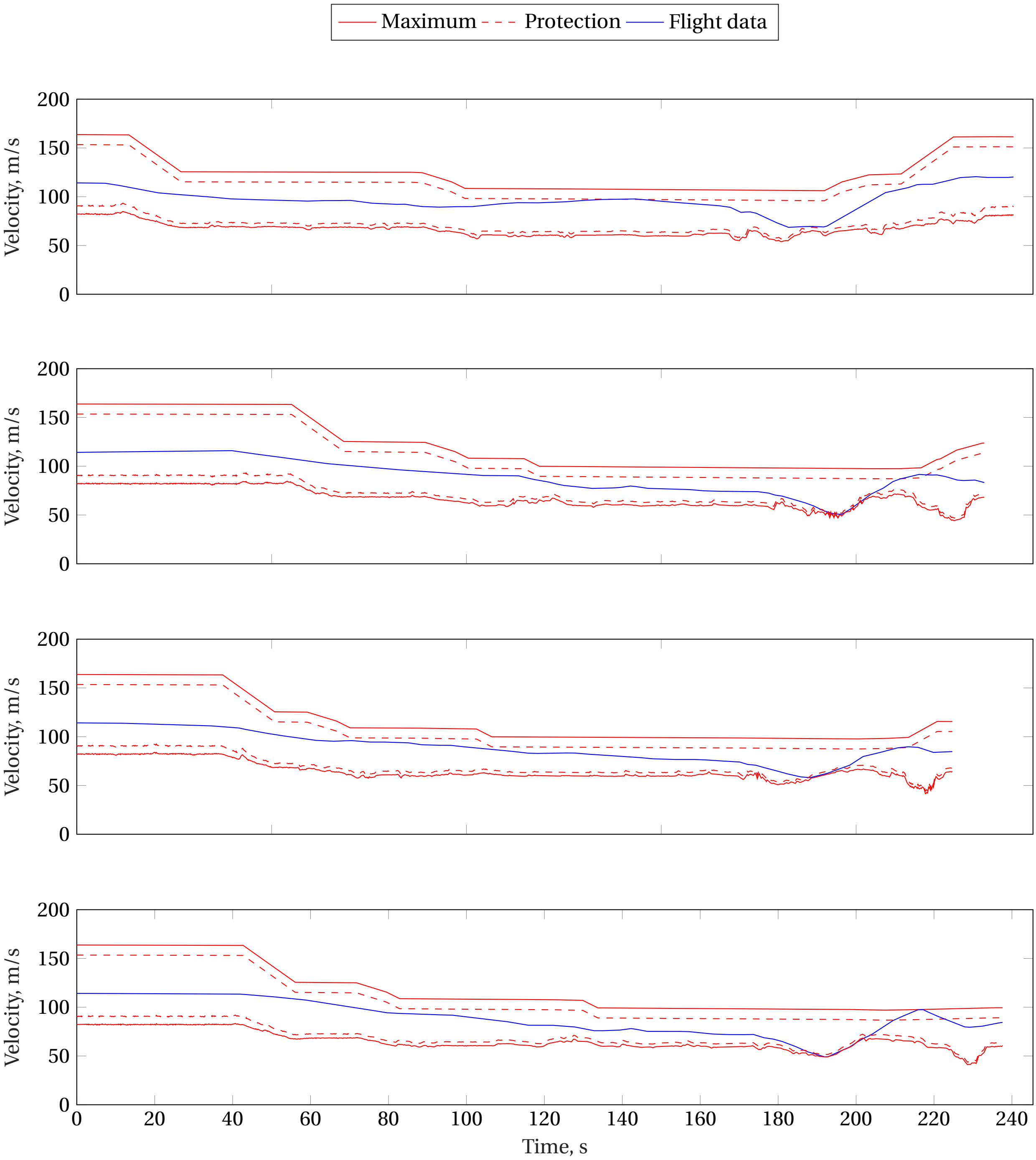


Figure K.1: Typical indicated airspeed data from the windshear scenario at KATL with PFD+.

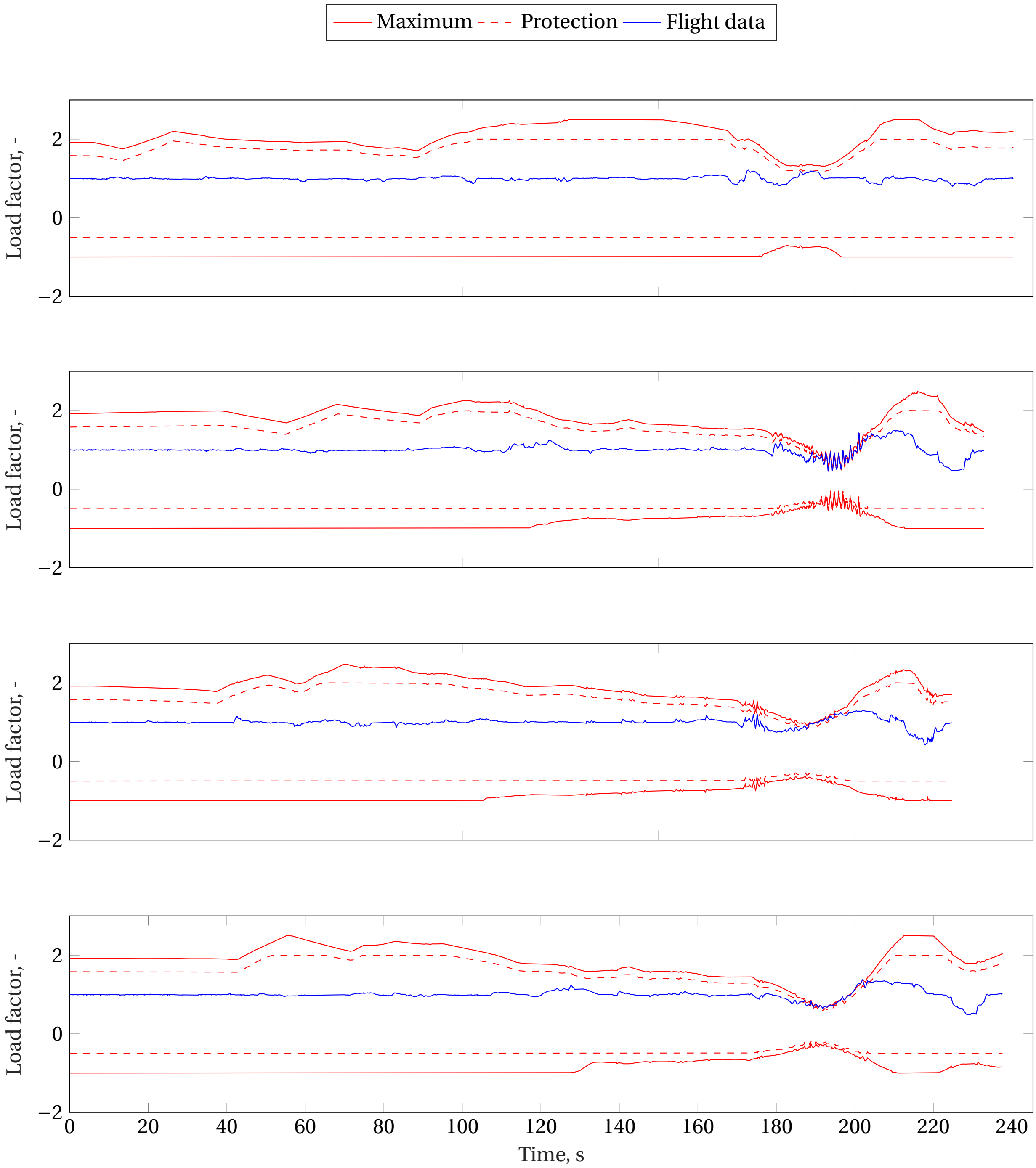


Figure K.2: Typical load factor data from the windshear scenario at KATL with PFD+.

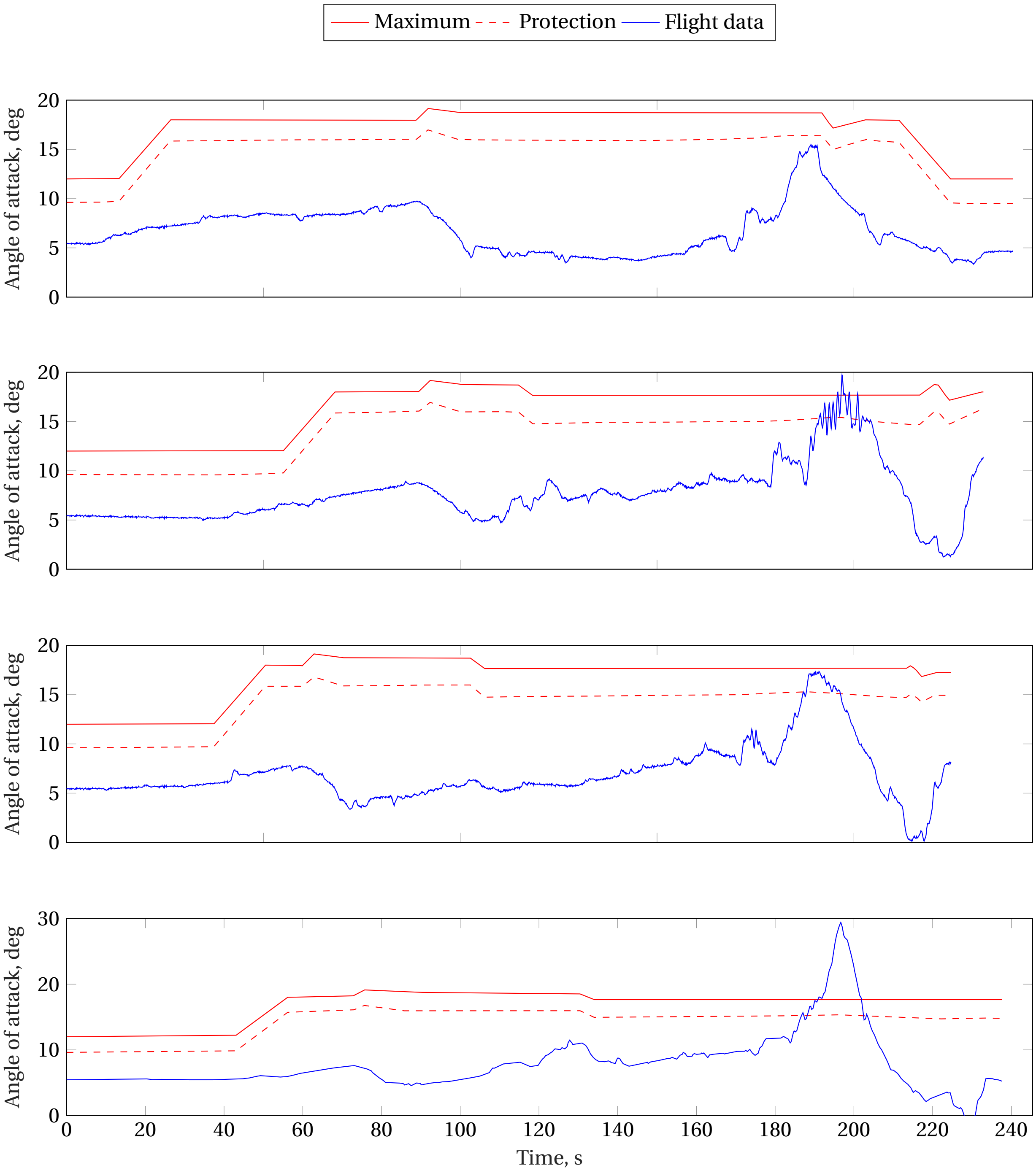


Figure K.3: Typical angle of attack data from the windshear scenario at KATL with PFD+.

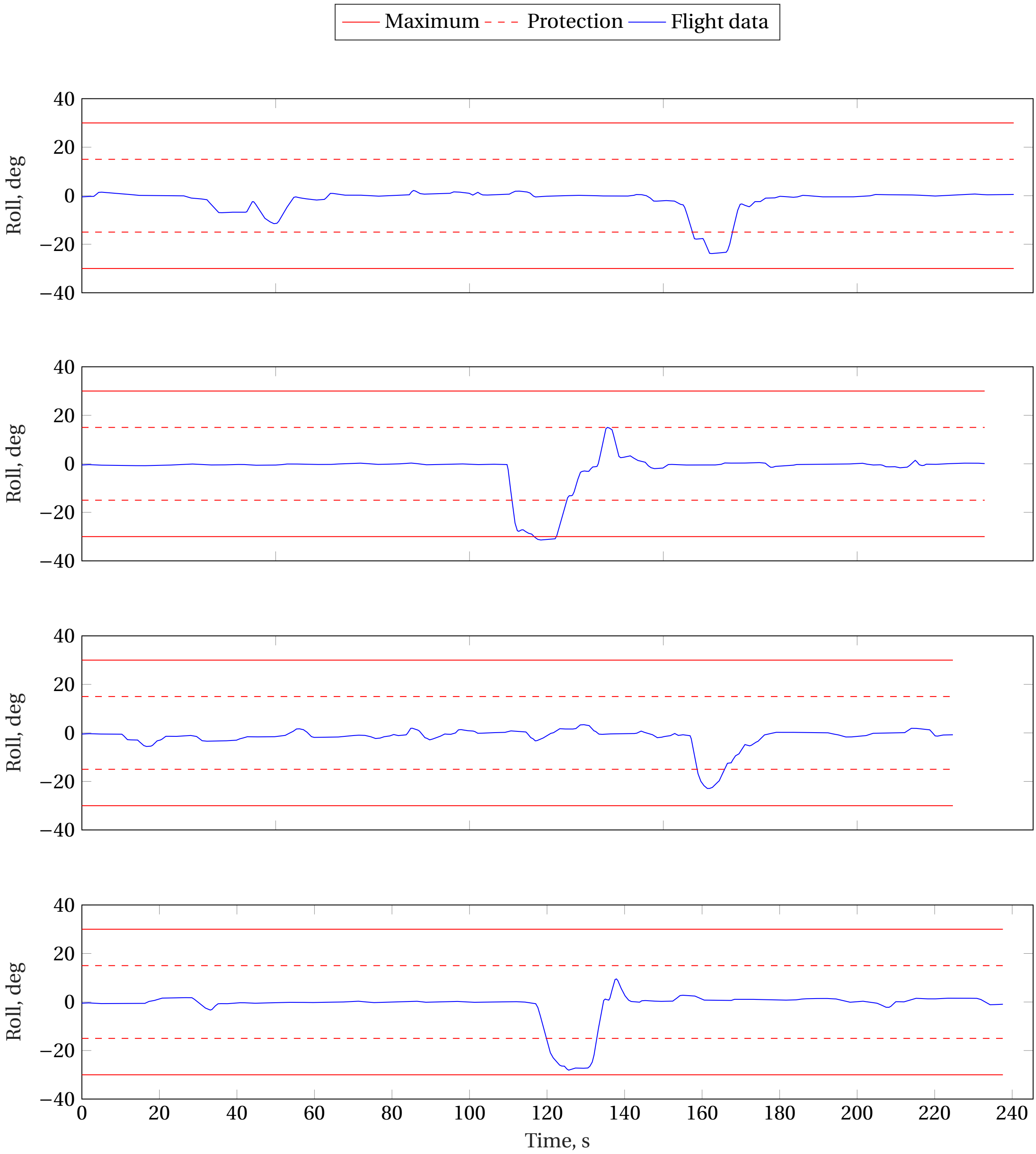


Figure K.4: Typical roll data from the windshear scenario at KATL with PFD+.

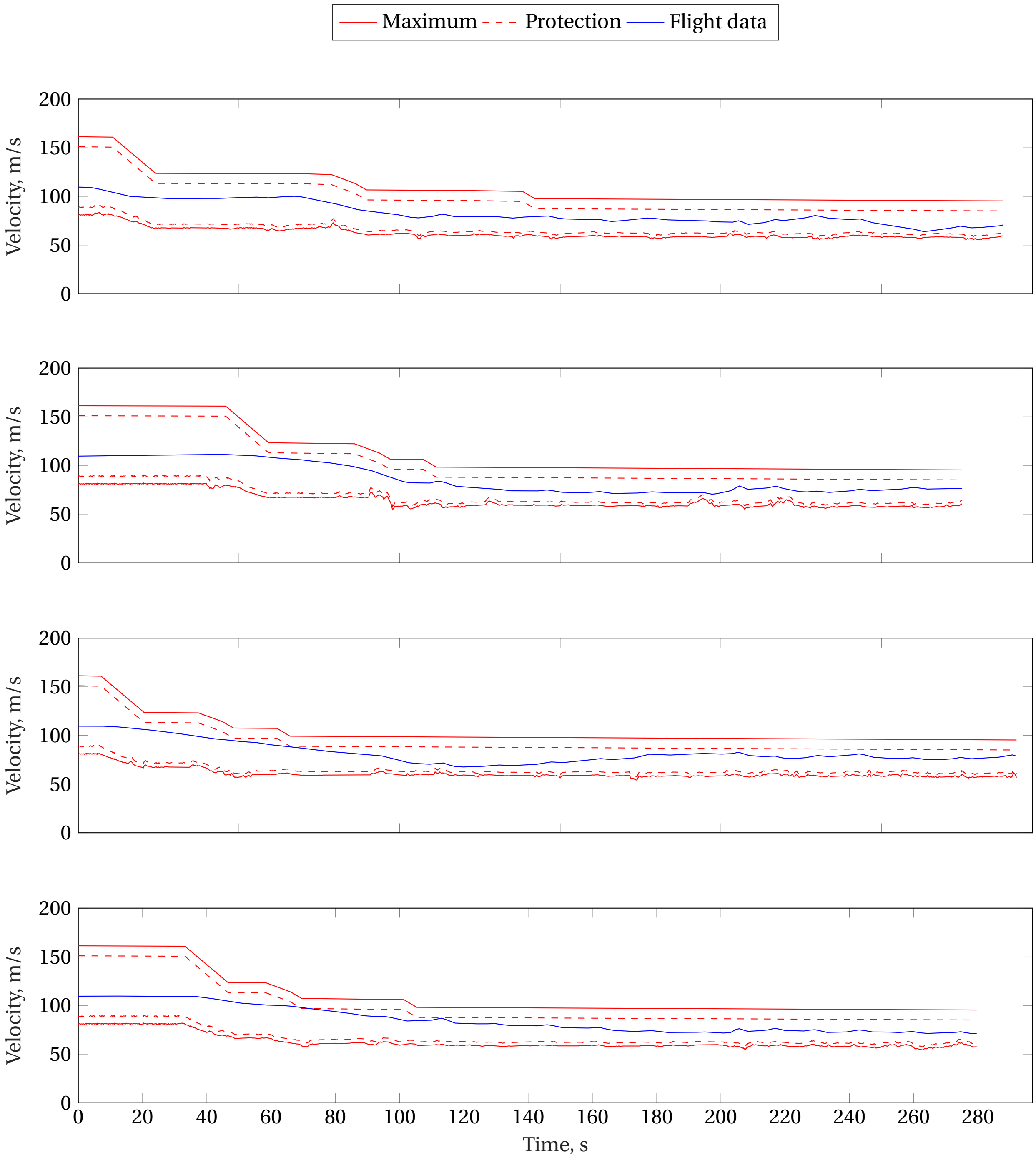


Figure K.5: Typical indicated airspeed data from the runway sidestep scenario at EGLL with PFD+.

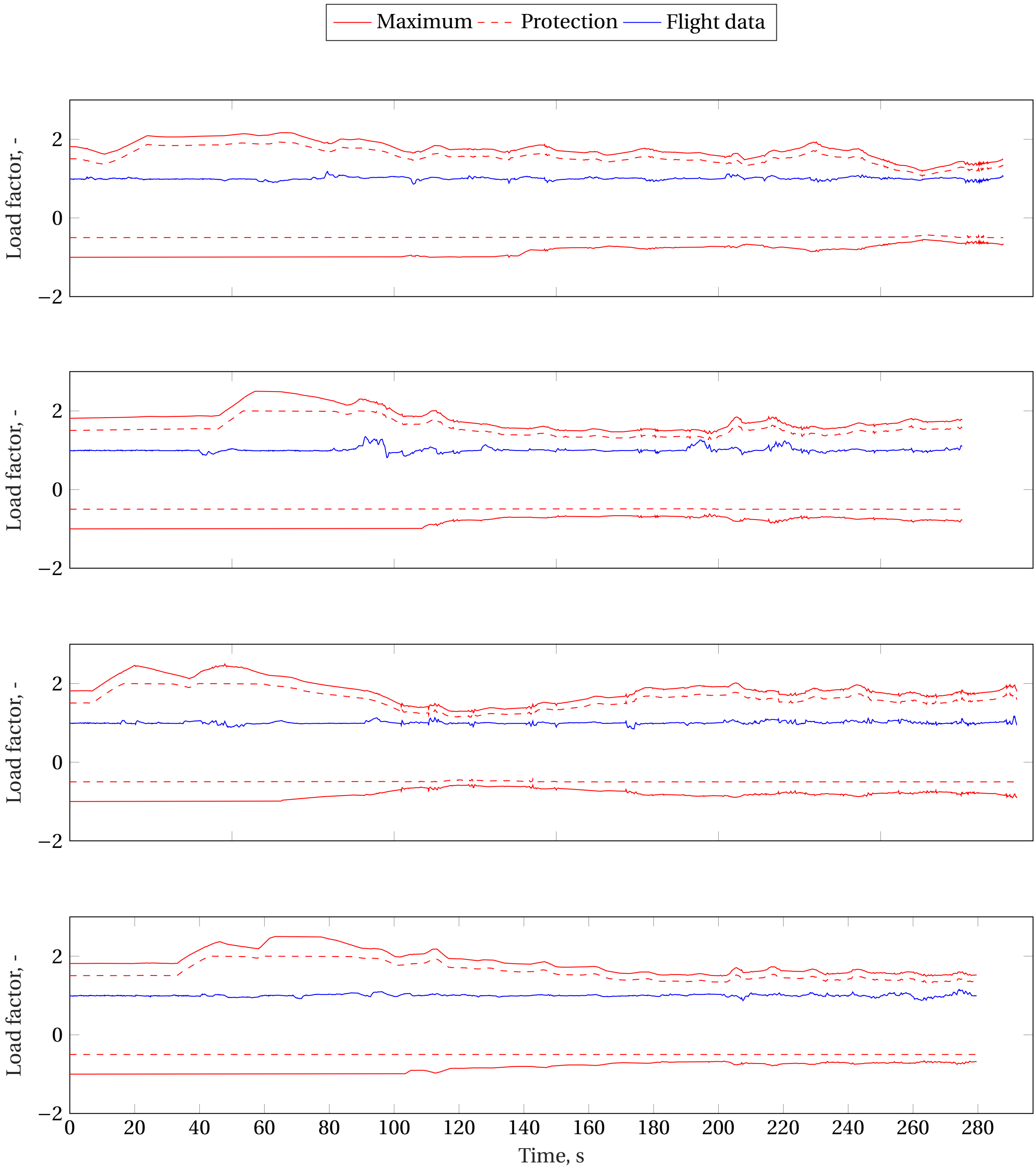


Figure K.6: Typical load factor data from the runway sidestep scenario at EGLL with PFD+.

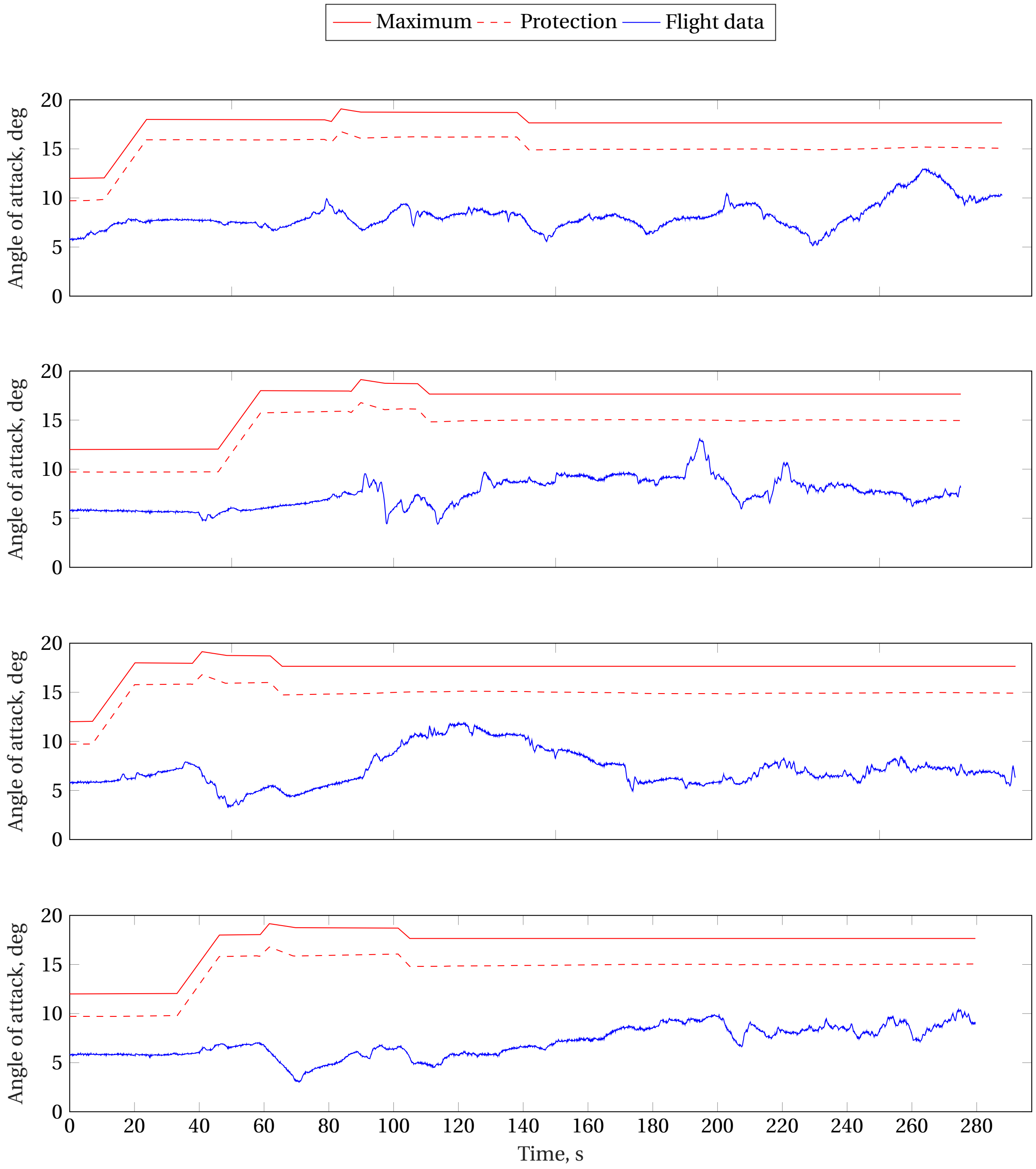


Figure K.7: Typical angle of attack data from the runway sidestep scenario at EGLL with PFD+.

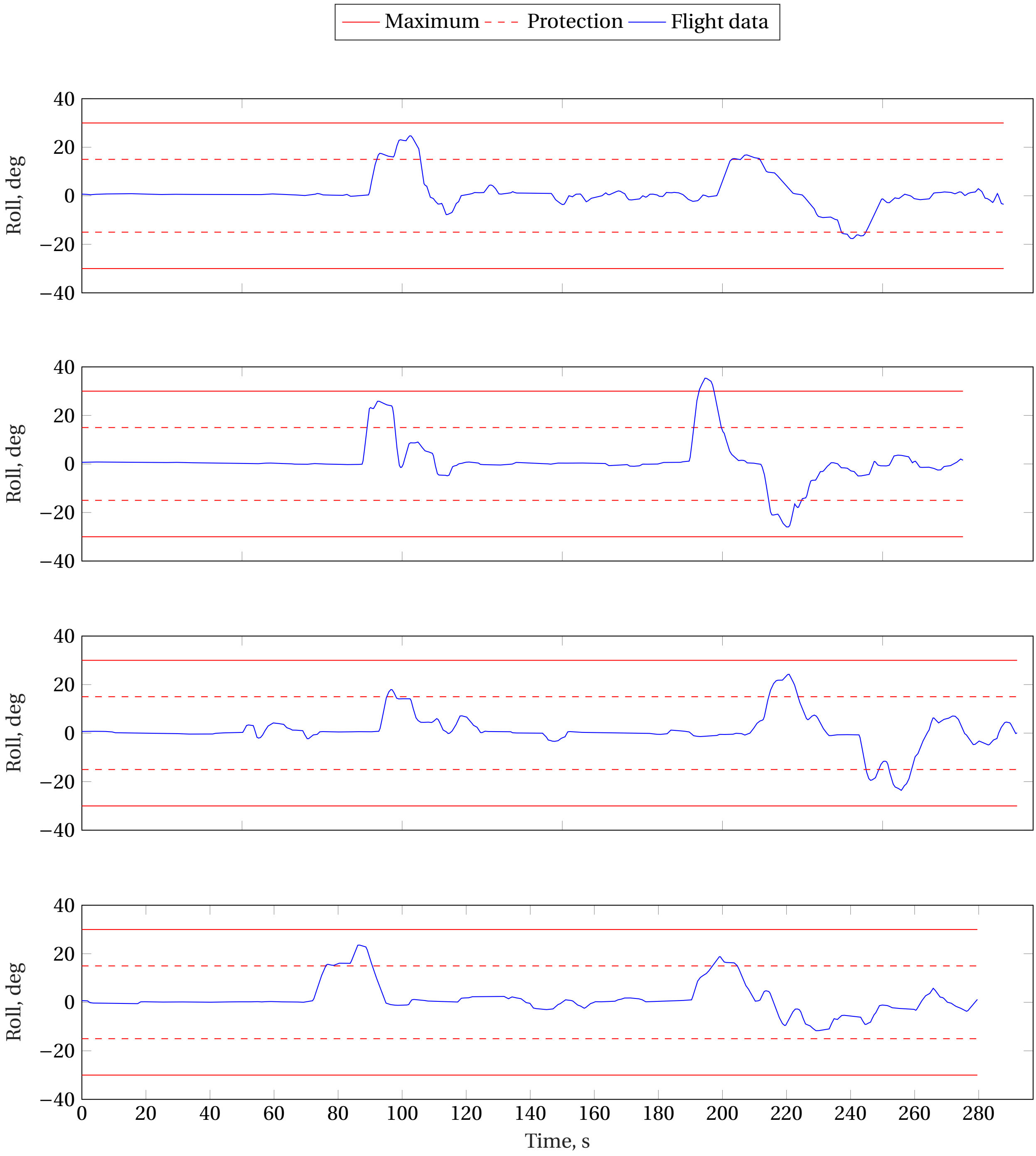


Figure K.8: Typical roll data from the runway sidestep scenario at EGLL with PFD+.

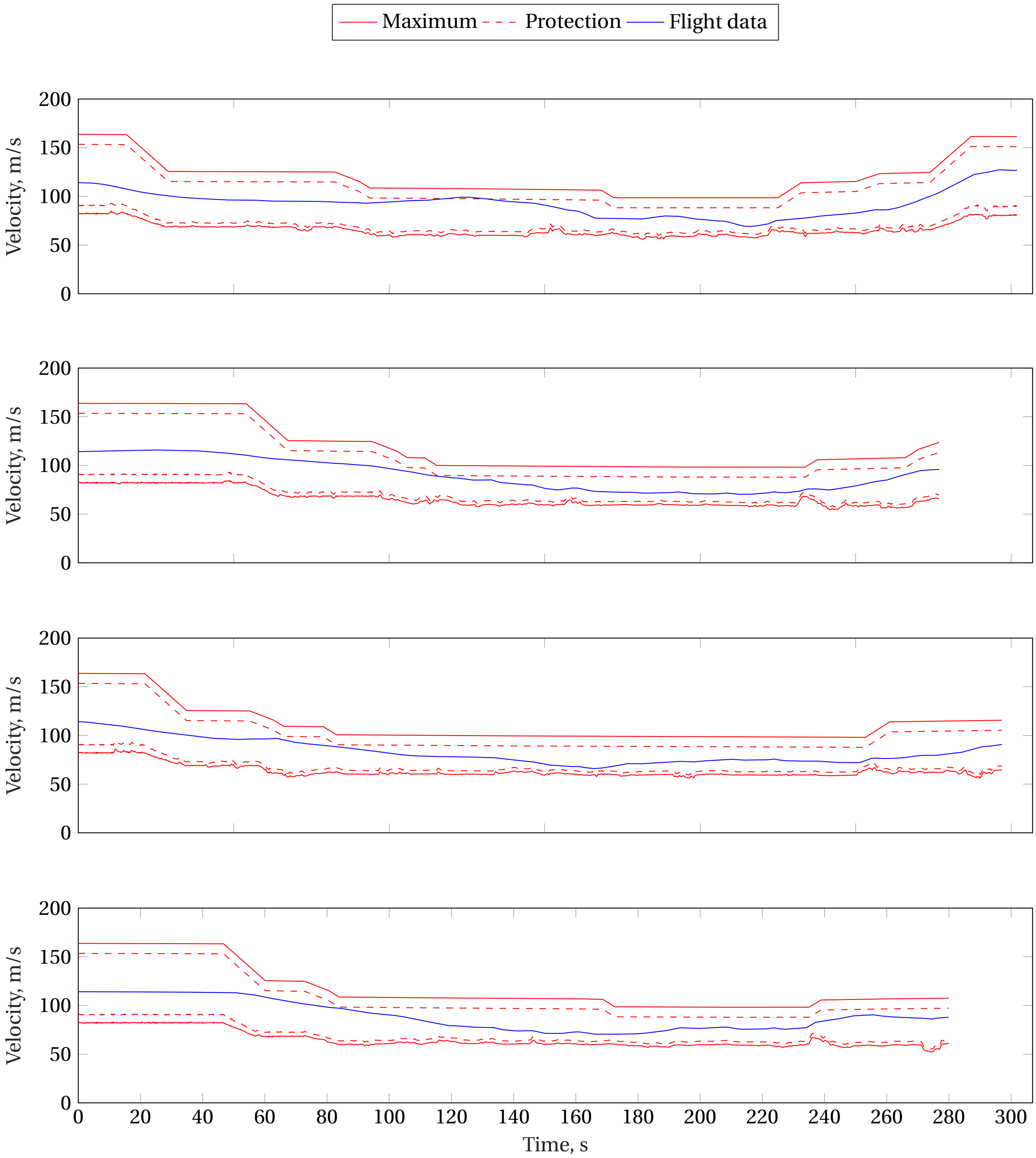


Figure K.9: Typical indicated airspeed data from the go-around scenario at KATL with PFD+.

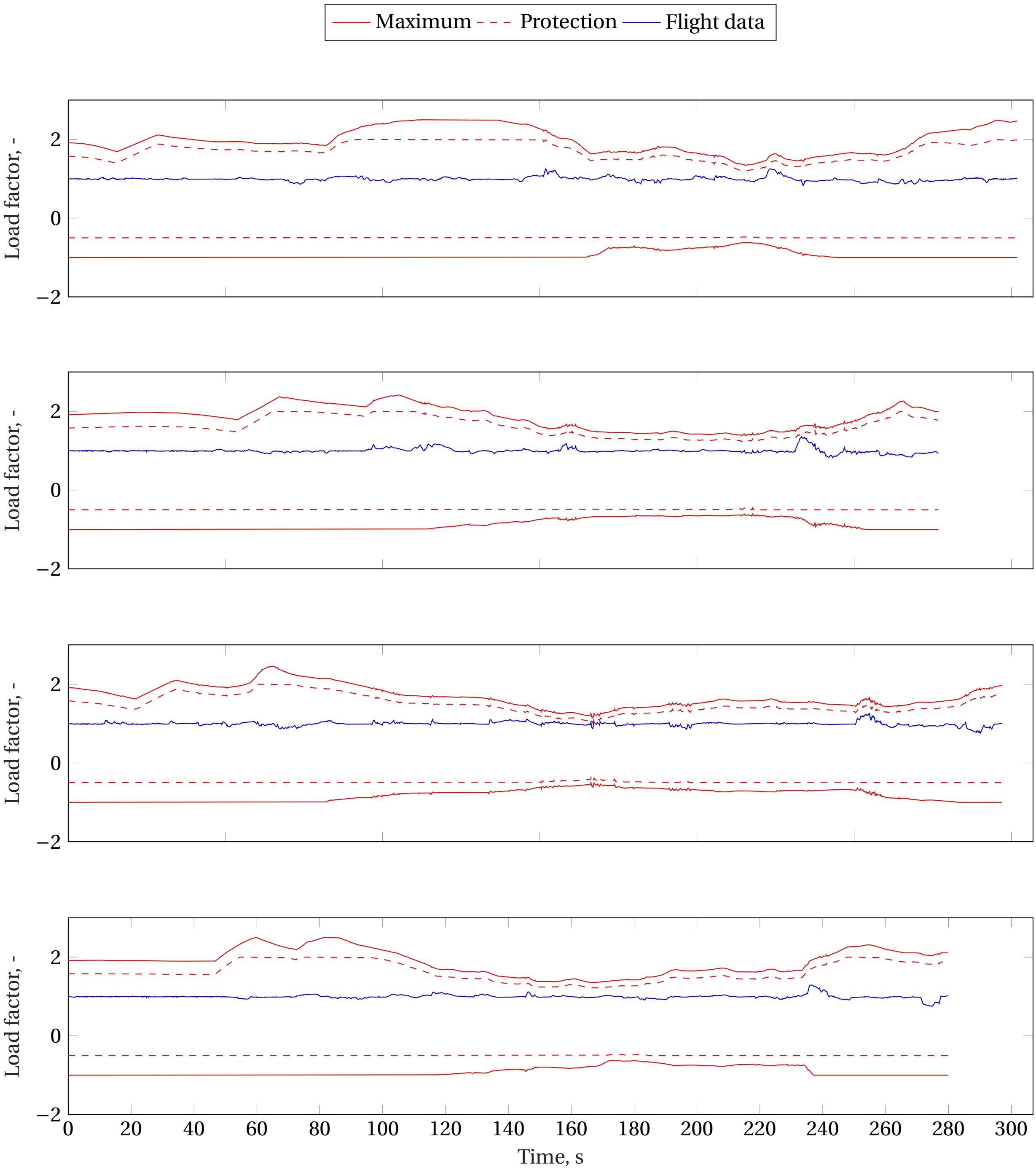


Figure K.10: Typical load factor data from the go-around scenario at KATL with PFD+.

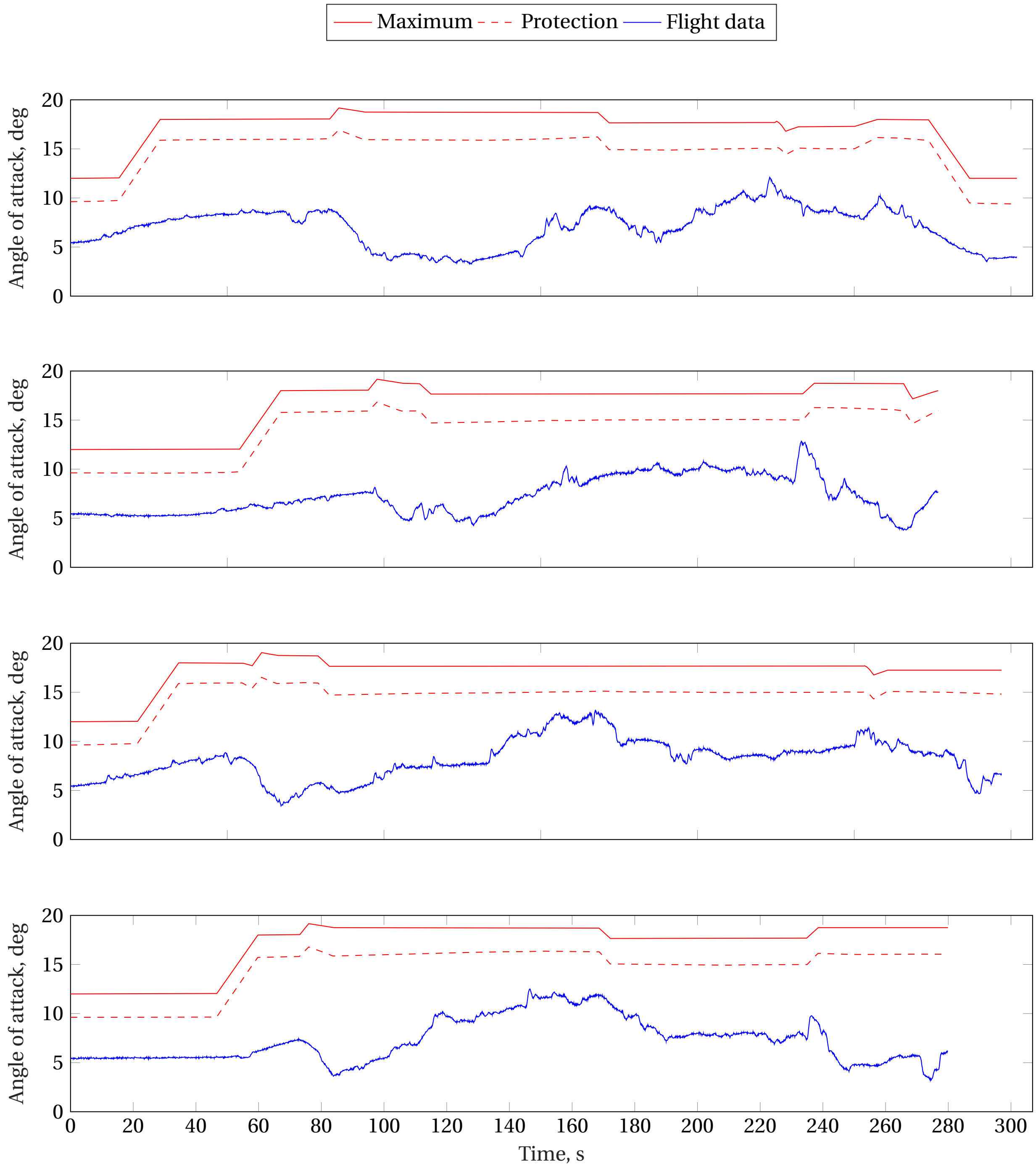


Figure K.11: Typical angle of attack data from the go-around scenario at KATL with PFD+.

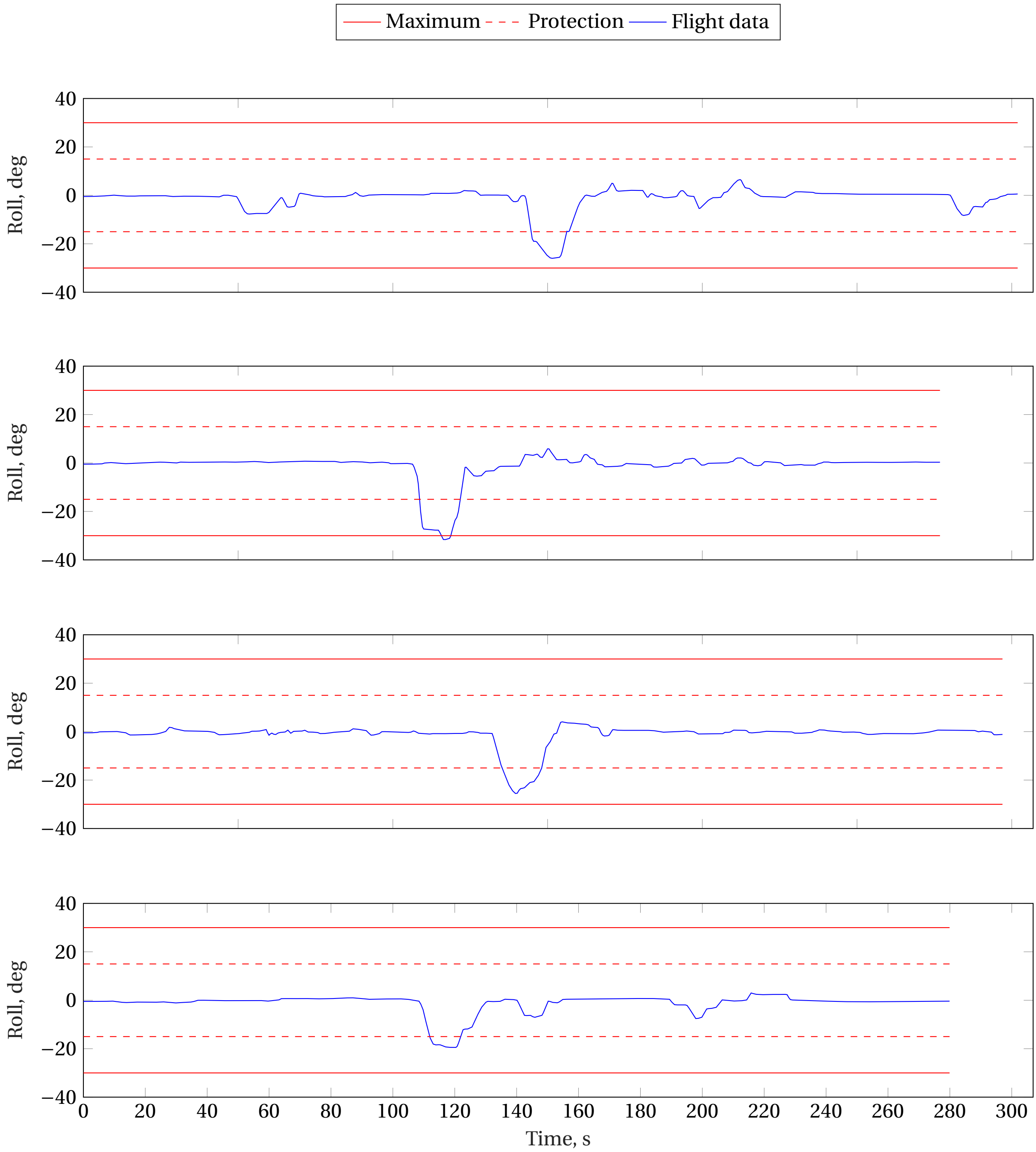


Figure K.12: Typical roll data from the go-around scenario at KATL with PFD+.

L

Experiment curiosities

- A total of 370 flights completed by 16 pilots.
    - Of which 98 approaches with windshear (including 2 crashes).
    - Of which 96 approaches with runway sidestep.
    - Of which 96 approaches with go-around.
    - Of which 48 familiarization circuits at Schiphol.
    - Of which 32 maneuver training flights.
- 5772 NM traveled, exceeding the distance from Amsterdam to Singapore.
- 30 hours, 23 minutes and 30 seconds of air time.
- 79.6 GB of flight data collected.
- 69 hours of audio recorded.
- 434 pages of questionnaires.
- 16 bottles of fine wine.