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Evaluation of a Haptic Feedback System for Flight Envelope Protection

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Modern fly-by-wire aircraft use flight envelope protection systems, whose actions are not always clear to pilots. To promote situation awareness, proximity to the limits of the flight envelope can be communicated using haptic feedback, by providing forces through the control device. Such a system was developed and this paper reports on the evaluation experiment. Professional pilots were invited to fly an Airbus A320 model in the Delft University of Technology Simona research simulator. A windshear and an icing scenario were flown using a full and degraded control law, with and without the haptic feedback system. The objective results show that the haptic feedback system does not lead to significant improvements in either performance or safety metrics, but also does not interfere with nominal pilot tasks. In the debriefing questionnaire, however, pilots expressed a clear preference for the haptic system. Recommendations for future research include the addition of visual support to complement the haptic cues, and the redesign of the scenarios to allow pilots more freedom in control.

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Acronyms

AL	Alternate Control Law
ATC	Air Traffic Control
EASA	European Aviation Safety Agency
FBW	Fly-By-Wire
FCC	Flight Control Computer
FCU	Flight Control Unit
ILS	Instrument landing system
ND	Navigation Display
NL	Normal Control Law
PFD	Primary Flight Display
RSME	Rating Scale Mental Effort
SFE	Safe Flight Envelope
Simona	SImulation, MOtion and NAvigation
TOGA	Take Off/Go Around

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Nomenclature

Greek Symbols

α	Angle of attack, rad
δ	Control device deflection, rad
θ	Pitch angle, rad
ϕ	Roll angle, rad

Roman Symbols

x	Distance from starting position, m
F	Force, N
n	Load factor, g
q	Pitch rate ($\dot{\theta}$), $rads^{-1}$
k	Spring, $Nrad^{-1}$
t	Time, s
V	Velocity, ms^{-1}

Subscripts

br	Breakout
max	Maximum value
MO	Maximum operational value
min	Minimum value
np	Neutral point
nom	Nominal value
prot	Protected region value
stall	Value when stall occurs

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I. Introduction

Civil aviation in the last 20 years showed an increasing trend in the number of passengers transported, together with a decreasing number of proportional fatalities.[1] Although the increase in safety can only be celebrated, the European Aviation Safety Agency (EASA) identified a set of priority key risk areas which should be improved to further increase the safety level, where preventing aircraft upset is on top of the list. Additionally, the main safety issue was stated to be the perception and situation awareness of the pilot. As the number of flights is expected to increase in the coming years, these key risk and safety issues must be investigated to maintain, and improve, the current safety level.

The relation between upset and situation awareness was investigated in a simulator study. It showed that an upset condition (a stall) is more difficult to manage when it is presented unexpectedly, possibly due to a reduced situation awareness, showing that prevention training should include elements of surprise.[2]

An addition to better pilot training could be an improved way of presenting information in the cockpit, such that an upset is prevented. Several research projects focused on this, approaching the problem through a visualization of the flight envelope limits. Combining the limits on the Primary Flight Display (PFD) with the limits of the flight envelope protection was indeed found to help improve safety by reducing the risk of flight envelope violations.[3,4] Presenting the limits on the PFD of a real-time updating flight envelope was also found to increase the safety margins in dealing with an icing scenario.[5] Nevertheless, only providing more visual support in an already heavily visually-loaded cockpit environment might not be sufficient.

Another source of information for the pilot can be through applying force feedback through the control device: haptics. Haptics showed to have a significant positive effect on a tracking task during approach.[6] Combining the haptic feedback with a visual addition on the PFD caused pilots to maintain larger safety margins.[7,8] Following this initial haptic feedback design, a new design iteration was made and described in our previous paper.[9]

This paper describes the experiment and its results for the evaluation of the updated haptic feedback design. Using this analysis, it can be decided whether the current design indeed leads to improving safety, or needs to be further improved.

The paper starts with a brief description of the haptic feedback design in Section II. The experiment is elaborated in Section III. Results are shown in Section IV and discussed in Section V. Conclusions and recommendations are given in Section VI.

II. Haptic Display

The haptic feedback design is based on the Airbus A320 control structure as briefly elaborated in this section. First the basic control structure is explained followed by the haptic feedback itself. Note that more details on the control laws and the haptic feedback design can be found in our previous paper.[9]

II.A. Airbus A320 Control Structure

Modern day Airbus aircraft like the A320 and the A330 employ a Fly-By-Wire (FBW) system. This means that there is no physical connection between the control surfaces and the control device, yet the latter acts as an interface for the pilot to give inputs to the Flight Control Computers (FCCs) which then command the control surfaces with hydraulic actuators. As such, a Flight Envelope Protection (FEP) system can be used, which can limit the inputs of the pilot to ensure that no limits are violated.

Longitudinal control in a FBW Airbus when all sensors are functioning (so called Normal Control Law (NL)) is provided using C^*-control, which is a combination of both pitch rate (q) and load factor (n).[10–13] On top of this control law, a hard envelope limit is employed which protects the pilot from exceeding limits on angle of attack (α), load factor (n), and maximum velocity (V_{MO}). This protection is depicted in Figure 1, where the nominal flight envelope is the extreme limit which can not be exceeded, the safe flight envelope is the point where protections start acting. The envelope is made by the maximum (n_{max}) and minimum (n_{min}) load factor, their protection limits ($n_{\text{max}_{\text{prot}}}$ and $n_{\text{min}_{\text{prot}}}$, respectively), the maximum operation velocity (V_{MO}, and protection $V_{\text{MO}_{\text{prot}}}$), and minimum velocity (V_{stall}, and protection V_{prot}).

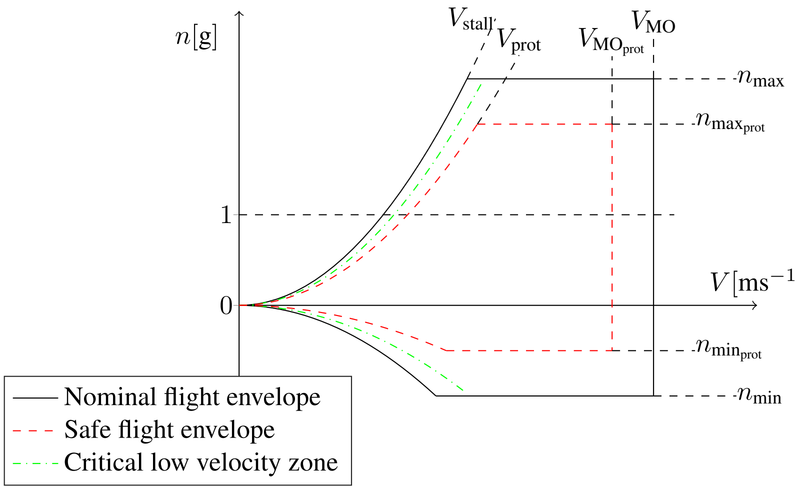

Figure 1. Flight envelope, velocity (V) versus load factor (n)

When an FCC fails, or when a sensor failure occurs, the control is reverted to a degraded control law. In this research, next to NL, we will also consider the Airbus Alternate Control Law (AL) without reduced protections, where the same protections apply as before, only the angle of attack protection is lost. Hence, in AL the aircraft can be stalled, yet giving the pilot more extreme control.

Lateral control is a rate command from $-33°$ till $+33°$ of roll. Beyond these limits, positive roll stability is achieved such that the aircraft rolls back to $\pm 33°$. The maximum achievable roll, with full lateral side stick deflection is $\pm 66°$ of roll. More details on the control laws and degraded control laws can be found in Ref. [9].

II.B. Haptic Feedback Design

In this subsection the haptic feedback is discussed. For this research, haptic feedback is defined by changing the haptic profile of the control device. That is, changing the amount of force required (F) to achieve a certain deflection of the control device (δ). A typical nominal haptic profile is given in Subfigure 2(a): a breakout center (δ_{br}) with an increased spring coefficient (k_{br}), followed by symmetric spring behaviour (k_{nom}) untill the maximum deflection (δ_{max}).

In the experiment described in this paper, haptic feedback is provided with four cues:

- Discrete forcing function: when the pilot exits the safe flight envelope (anywhere outside the red dashed line in Figure 1), a discrete forcing function is added to the stick resulting in a perceived 'tick on the stick'. This is visualized on the haptic profile with the inset graph in Subfigure 2(b).
- Periodical forcing function: for velocities close to the lower velocity limit V_{prot}, a stick shaker activates, a sinusoidal function, to communicate the risk of stall.
- Spring coefficient: to communicate the relative distance to the limit, the spring coefficient increases when moving from the safe flight envelope to the actual limit (black line on Figure 1). Maximum spring coefficients

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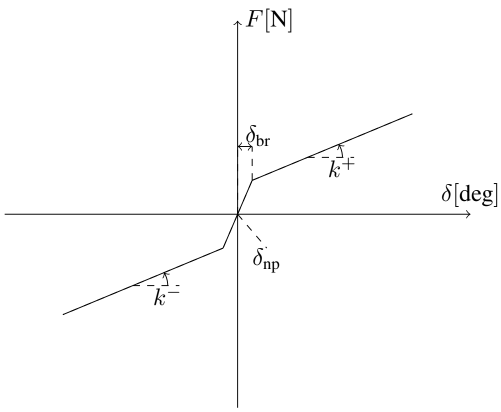
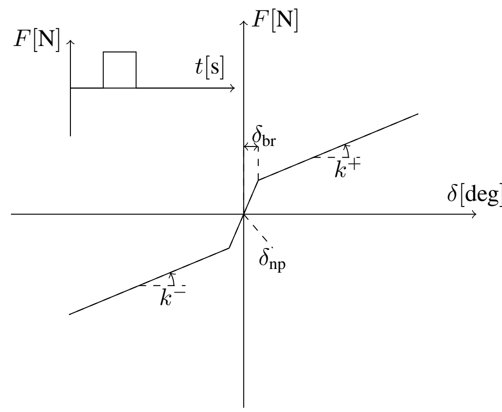
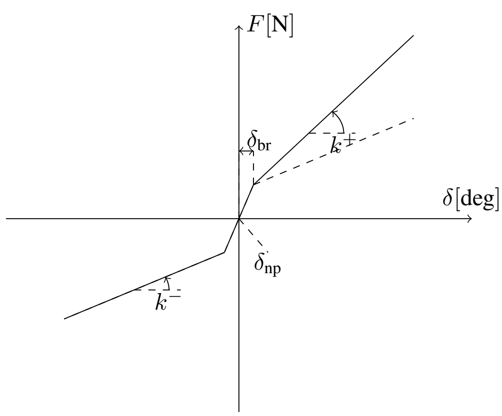


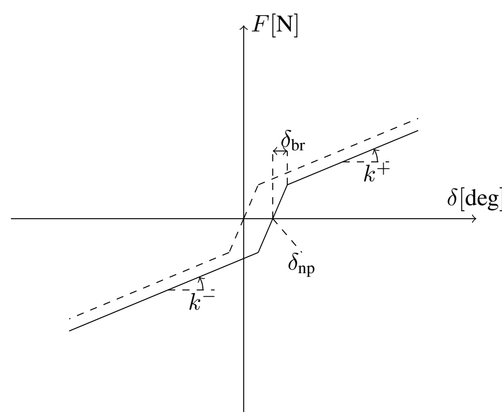
(a) Nominal case



(b) Added positive (push) pulse



(c) Increased spring coefficient for positive deflections



(d) Positive shift in position of the neutral point

Figure 2. Control device profiles

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are determined by the tuning parameters K_α, K_n and $K_{V_{\mathrm{MO}}}$ for angle of attack, load factor and maximum velocity, respectively as shown in our design paper. The increased spring coefficient results in a situation where pilots must exert more force to move the stick in a particular direction, as in Subfigure 2(c).

- Neutral point shift: when the autopilot makes inputs (e.g., an automatic 'pitch up' command to avoid an over-speed situation), or when the pilot has to perform an input (e.g., when the aircraft has a critically low velocity, and the stick neutral position is not sufficient to return to the safe flight envelope), the required stick deflection is communicated to the pilot by a change in neutral point of the stick as indicated in Subfigure 2(d). The automatic 'pitch up' command close to overspeed is designed in our design paper and contains one tuning parameter ($\tau_{overspeed}$).

More details on our haptic design rationale can be found in the previous paper, Ref. [9]. This paper focuses on the human-in-the-loop experiment evaluation, discussed next.

III. Method

To evaluate the haptic interface design as proposed in the previous section, an experiment is described in this section.

III.A. Subjects & Instructions to Subjects

The participants of the experiment were all professional pilots (all males) with a current license; their experience is shown in Table 1. They are instructed to fly as in normal operations, and to voice their thoughts as much as possible. Additionally it was mentioned that each run would stop at $50ft$ of altitude irrespective of any other event/performance due to limitations of the simulation.

Table 1. Participants in the experiment

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

III.B. Experimental Setup

The experiment is performed in the SImulation, MOtion and NAvigation (Simona) research simulator (SRS) of TU Delft. It is a full-motion capable, near $180°$ outside field-of-view, generic cockpit, used in the first officer position of which an inside-picture is shown in Figure 3.

Since the pilot is sitting in the first officer position, the display to his front-left is the Navigation Display (ND) showing a top-down view, shown in Subfigure 4(a). The display right in front of the pilot is the PFD showing the critical flight states, shown in Subfigure 4(b) for NL and Subfigure 4(c) for AL.

A control-loaded two degrees-of-freedom electrical Moog FCS Ecol-8000 resembling the Airbus side stick is the main control input, a Boeing 777 center console with throttles and flap-lever provides engine and high-lift device inputs, and a Boeing 737 Mode Control Panel (Airbus terminology: Flight Control Unit (FCU)) enables the interface with the heading/velocity/altitude references on the displays.

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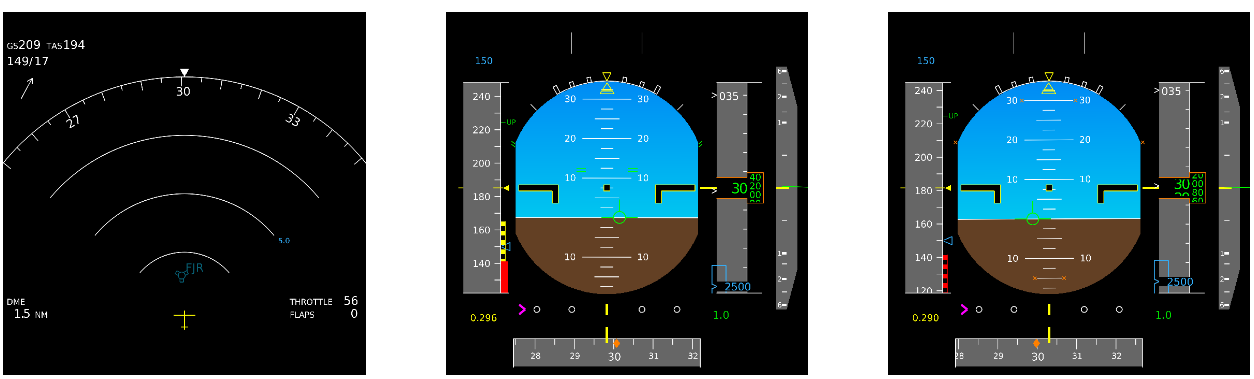
Figure 3. Inside view of the SRS cockpit (picture by Thierry Schut)



(a) ND

(b) PFD for NL

(c) PFD for AL

Figure 4. Cockpit display setup used in the experiment

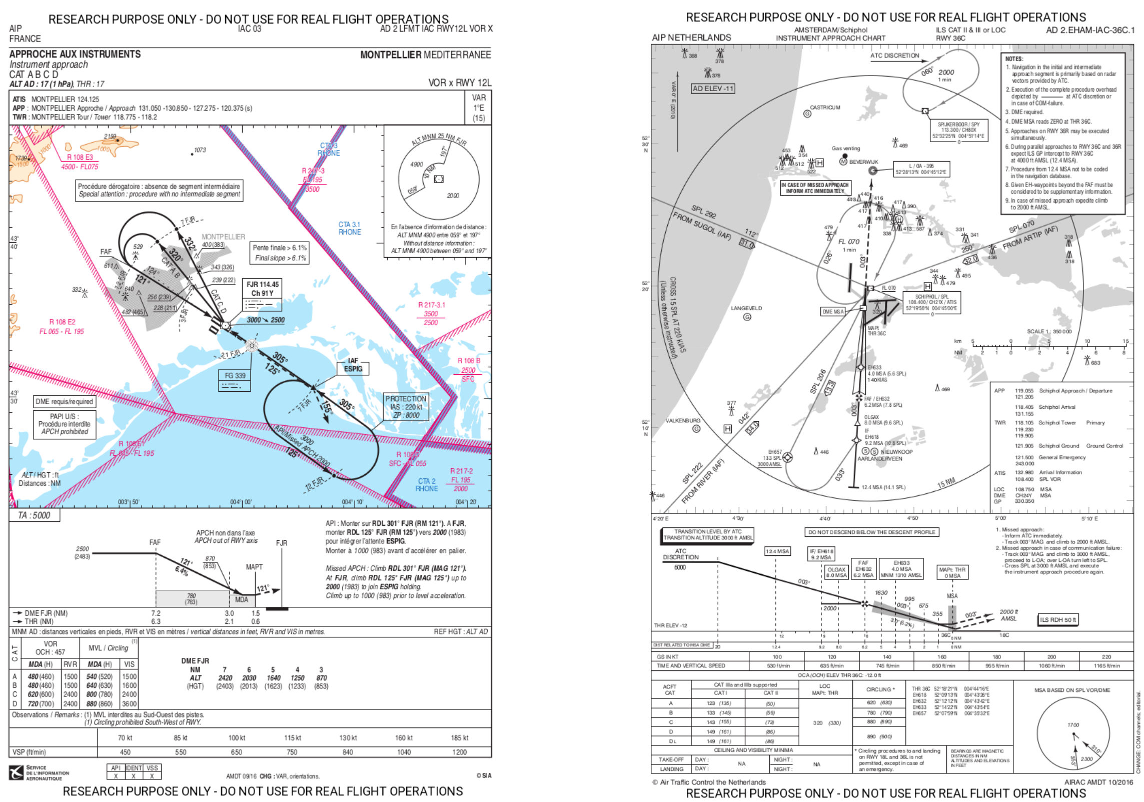
The nominal control device settings, and the haptic feedback settings for this experiment are given in Table 2. Forcing functions used in the experiment are a discrete block function of $0.1s$ and $10N$ when exiting the safe flight envelope, and a stick shaker for low velocities as a sinusoid with frequency of $20Hz$ and magnitude $5N$.

Table 2. Control device and haptic settings in the experiment

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

III.C. Experiment Scenarios

The haptic feedback system is designed to communicate the 'proximity of the flight envelope limits' to the pilot. Thereby it is expected that it supports the pilot by providing both a control aid when maneuvering close to the limits, as well a warning aid when moving (unknowingly) to the limits. To facilitate the two potential use cases, two experiment scenarios are designed: a case where the pilot has to maneuver close to the limits of the aircraft: a windshear event, and another case where the flight envelope shrinks, and the limits slowly move to the pilot: icing. Both scenarios were extensively discussed and prepared with the help of an experienced A330 captain (and instructor). They are elaborated in the following.



(a) Approach to Montpellier

(b) Approach to Amsterdam

Figure 5. Approach plates used in the experiment (printed on A4 size for pilots)

1. *Windshear*

During a windshear the pilot has to move as close to the stall limit as possible to prevent further descent while on the approach to the runway.

In the measurement phase of the experiment, a tear-drop approach is flown into Montpellier, to runway 12L. A

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tear-drop was chosen to increase the workload of the pilot due to the accurate timing of the maneuvers required. The approach starts at $3,000ft$ altitude, $180knots$, $1.6nm$ South-East of the airfield, and the pilot has to perform a procedure as indicated on the approach chart in Subfigure 5(a):

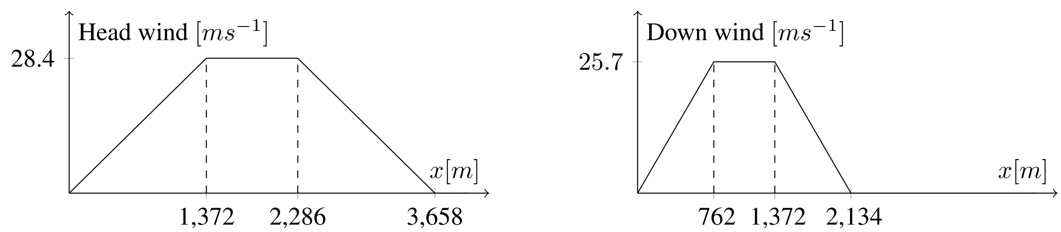
1. Fly overhead the airfield while descending to $2,500ft$,
2. Follow radial 332 outbound of the FJR VOR,
3. Slow down to $150knots$,
4. At $7.0nm$ radial distance from FJR, make a left turn to heading 121,
5. Change the heading using a 'rate one turn' (2 minutes per 360°), using the rule-of-thumb: $\phi = \frac{V}{10} + 7$,[14]
6. Maintain heading, velocity and altitude until instructed by Air Traffic Control (ATC).

At the end of this procedure, and when the velocity and altitude were 'stable' as judged by the experimenter, the windshear is initiated. Following the visual and aural warning, the pilot has to apply the windshear recovery procedure as stipulated by the aircraft manufacturer. This includes the following items:[13]

1. Maintain configuration (flaps/slats/gear),
2. Set thrust to Take Off/Go Around (TOGA),
3. Pitch up to $17.5°$,
4. Increase pitch to eliminate descent rate,
5. Closely monitor flight path and speed,
6. Recover smoothly when clear of the windshear.

As for every approach, a missed approach procedure was added: maintain runway heading ($121°$), climb to $2,500feet$, and inform ATC.

The windshear itself was modeled by both a head-on and top-down component as shown in Figure 6.[15]



(a) Headwind component

(b) Downwind component

Figure 6. Windshear component distribution

For training of the procedure, an approach to Nice was flown which involved an agile GNSS approach. The final procedure was equal: when the aircraft was considered stable in terms of altitude, velocity and heading before the turn to base, the windshear was initiated. Here, the missed approach procedure consisted of turning South, climbing to $2,000feet$, $185kts$ and reporting to ATC. Aside from the initial part of the approach, all procedures were equal.

2. *Icing*

If icing occurs, the aerodynamic properties of the airplane degrade and can result in a loss of control, when the degradation of control authority is not anticipated by the pilot.

In the measurement phase of the experiment, an Instrument landing system (ILS) approach is flown into Amsterdam (EHAM) for runway 36C. The approach starts at $3,000ft$, $150knots$, $10.3nm$ radial distance from touch down point, slightly right of the localizer, and below the glide slope. From this point, the pilot has to intercept the localizer and glide slope as indicated on Subfigure 5(b). Approximately $100s$ after the start of the run, the aircraft was stabilized on the localizer/glide slope and icing was initiated. The stable approach after $100s$ was checked visually by the experimenter, and was indeed the case for all runs and for all pilots.

The instructions for the pilots in this scenarios were to follow the localizer/glide slope until an altitude of $50ft$ where the simulation automatically stops, and to fly as slow as possible due to heavy traffic. It was the pilots' responsibility to decide what the slowest velocity was, and the information they had was the minimum velocity indicated on the PFD and the haptics (if enabled).

During the approach, there was a stable and a variable wind component present. The stable wind was different for each of the runs the pilots performed: values can be found in Table 3. As the runway in use is 36C (heading North, actual heading 003), all wind instances give a headwind with a slight crosswind (approximately equal to the

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East component). The four wind states are distributed using a (four-by-four) Latin square, which is repeated every four pilots.

Table 3. Wind components during the icing scenario

Wind realization	North [mps]	East [mps]	Down [mps]	Variable heading [°]
1	5.44	-4.36	0	331
2	5.17	-2.72	0	342
3	5.17	2.72	0	017
4	5.44	4.36	0	028

Variable wind ($w_{variable}$) is added to the experiment to mask the change in aerodynamic properties, and to increase pilot workload. It is modeled with a sinusoidal shape, given by Equation 1, where I is the intensity, $T_{duration}$ the duration of one period, and $T_{trigger}$ the time between the end of one shape and the start of the next. When $t > (T_{trigger} + T_{duration})$, time is reset to zero, and the parameters are re-initialized. It is finally applied by converting to North-East-down components using the direction specified in Table 3.

$$w_{variable} = \begin{cases} 0 & \text{if } t < T_{trigger} \\ \frac{I}{2.0} \cdot \left(1.0 - \cos\left(2 \cdot \pi \cdot \frac{(t - T_{trigger})}{T_{duration}}\right)\right) & \text{if } t <= (T_{trigger} + T_{duration}) \\ \text{reset properties and time} & \text{else} \end{cases} \quad (1)$$

The re-initialization of the parameters is to prevent recognition of the variable wind, and performed by taken them from a random distribution. I is taken from a Weibull distribution with $\lambda = 4.9$ and $k = 2.3$, $T_{duration}$ from a Weibull with parameters $\lambda = 9.0$ and $k = 5.5$, and $T_{trigger}$ from a normal distribution with $\mu = 6.5$ and $\sigma = 1.0$. To enable reproducibility of the results, and equal variable wind over the participants, four realizations of the stochastic process are made and each is coupled to one of the four cases specified in Table 3.

III.D. Secondary task: ATC requests

As a secondary task, pilots were instructed to listen and, if required, respond to ATC requests throughout the scenarios.

In the simulation, each of the ATC requests is characterized by three variables: a callsign, a command, and a trigger time. The callsign is the unique name of each aircraft which is used by ATC to communicate and consists of a company specific name (for example 'Speedbird' for British Airways, or 'Easy' for EasyJet), and a flight number. All callsigns used in the experiment have the same company name, being the same company of which the pilot is an employee. At the start of the experiment day, each pilot is asked what his preferred flight number is, and if no preference, flight number '107' is used. Two other flight numbers are used: 685 and 713, which results in three possible combinations of callsigns.

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

To prevent recognition and anticipation of the requests, random realizations are made of the above; one realization is coupled to one condition. Using a uniform distribution, a callsign and a command is selected. Next the trigger time is determined by a normal distribution ($\mu = 20$ and $\sigma = 2.5$ seconds) indicating the time after the previous command.

On the trigger time, the command is sent to a text-to-speech generator, in this simulation the 'festival' library by The University of Edinburgh is used.[16] It is set to give the requests with a synthetic American-English, female voice to the pilots, to remove the effect of accent of the experimenter.

III.E. Experiment design

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

1. Familiarization

After a briefing on the simulator safety procedures, controls and displays, the model was introduced to pilots by flying a traffic pattern to a final approach at Schiphol (EHAM) as shown on Figure 7. Pilots were instructed to follow the instruction as indicated, unless company policy deviates. This to focus on the model familiarization, not procedures.

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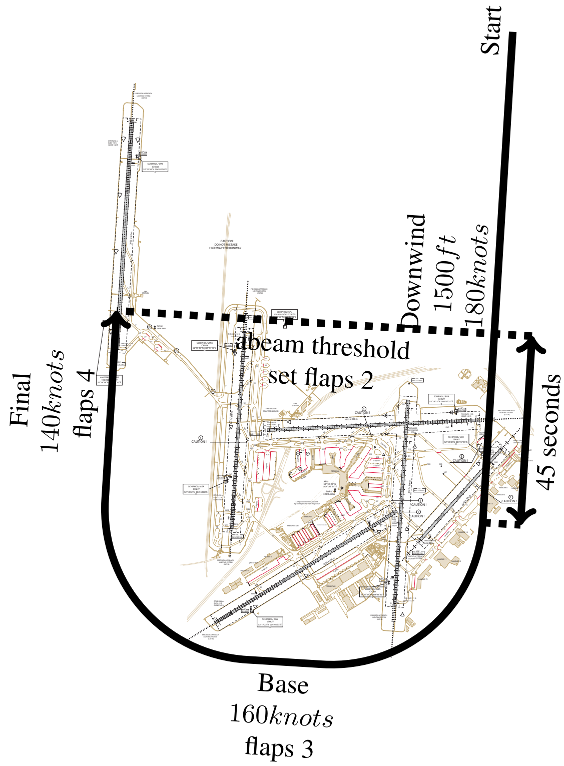


Figure 7. Traffic pattern flown to runway 36L at Schiphol (Schiphol layout from AIP[17])

The traffic pattern was flown three times in visual approach weather conditions: twice in NL without wind, and once in AL with variable wind similar to the winds used in the icing scenario.

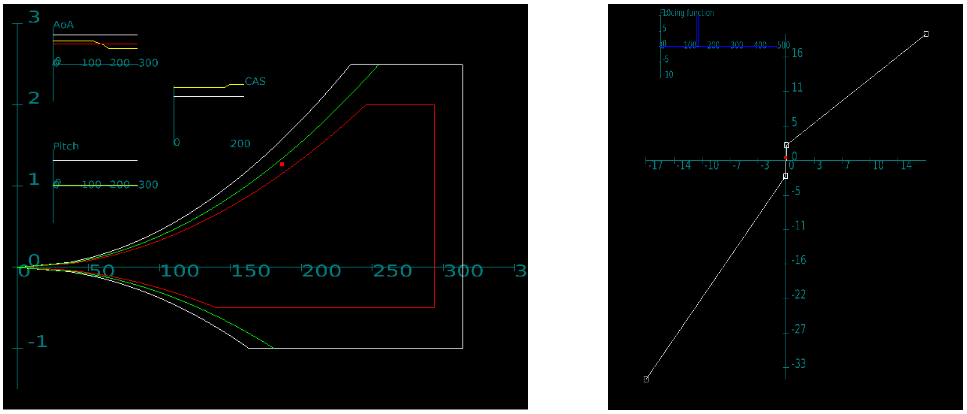
After model familiarization, the pilots *feel* the design rationale behind the haptic feedback design. This is done by presenting both the flight envelope (Subfigure 8(a)), haptic profile (Subfigure 8(b)), and the PFD (Subfigure 4(b)) to the pilot. In this setup, no aircraft model is used, yet the flight envelope state is changed directly (hence changing the velocity and load factor) and all cues are elaborated.

Following the static demonstration, the pilots *fly* the haptic feedback design using the full Airbus simulation. The pilot is asked to fly a set of maneuvers (stall, overspeed, high load factor, climbing stall) three times. Once in NL without haptics such that the pilot can see how the aircraft reacts. Secondly in NL with haptics enabled such that the pilot can feel how the haptics reacts in all these cases. Finally, it is flown once more in AL with the haptics enabled. After this last set of maneuvers, the pilot is asked to pitch again to $5°$ nose down, followed by closing his eyes and pitching up as far as possible while not crossing the limits. The rationale behind the latter is to see whether the pilot can indeed feel the limits of the aircraft: if he stalls the aircraft, the haptic cues are not understood, if the pilot is able to keep pitching up while not exceeding the limits, the pilot understands how the haptics communicates the limits.

2. *Training and Measurements*

The training and evaluation phase has the scenarios as described with the independent variables below. These eight conditions were flown in a randomized fashion, using a Latin-square distribution. The pilot has to respond to ATC requests during the run, as explained before. After each run, pilots were asked to give a Rating Scale Mental Effort (RSME) rating, and fill-in the post-run situation awareness questionnaire. Once the task was completed, the respective performance score is communicated to the pilot.

After all runs were completed, pilots were asked to complete a post-experiment questionnaire, which contained a number of questions on how pilots experienced the haptic feedback system.



(a) Flight envelope, red lines indicate protection limits, white lines the flight envelope limits. Inset graphs, from top to bottom, show angle of attack, calibrated airspeed and pitch.

(b) Haptic profile, increased stiffness for backwards deflection. Inset graph shows the forcing function: a recent discrete cue.

Figure 8. Cockpit setup used in the familiarization. This time frame shows a recent protection value excursion.

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III.F. Independent variables

The experiment had three independent variables. First, the haptic feedback was either present (HF), or not (NH). Second, two levels of protections in the control law were used: the default Airbus NL where all protections are present, and the degraded AL where a stall is possible. See Subsection II.A for more details on the control laws. Third, two scenarios were used: windshear (WS) and icing (IC), as elaborated above. This results in eight different experiment conditions, flown by each subject.

III.G. Dependent Measures

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

1. Objective measures

The objective measures were directly retrieved from the experiment data:

- Performance: how well the pilot performed is measured differently for the two scenarios:
  - Windshear: starting from the windshear initiation, until the lowest point in the recovery, the total altitude loss is determined.
  - Icing: after the initiation of the icing until the end of the simulation, the deviation from the ILS glide slope/localizer in meters is tracked and the root-mean-square is determined.
- Safety (metrics visualized in Figure 9):
  - Closest distance to limit: from the α data, the 10% closest to the limit is taken and the average is calculated, safer if further away from the maximum value.
  - Time in protected zone: from the data, the amount of time spend in the protected zone is determined, less time is safer.
  - Integration of α in protected zone: combination of time in protected zone and distance over limit.
- Workload: the performance in the secondary task – responding to ATC requests – is evaluated in order to measure workload.

Previous research showed a relation between performance and safety called risk homeostasis: the perceived level of risk is kept constant with increasing support.[18] An example is the increase in driving speed when being supplied with haptic feedback for lane keeping in an automotive study.[19] In this experiment, risk homeostasis is evaluated as an increase in performance, yet a degradation of the objective safety metrics. Here it is assumed that with haptics, the objective safety metrics actually become worse because pilots obtain a better awareness of the risk involved.

2. Subjective measures

Subjective measures are obtained by asking the pilot for an opinion, or how it has been experienced. The categories and measures in this experiment are:

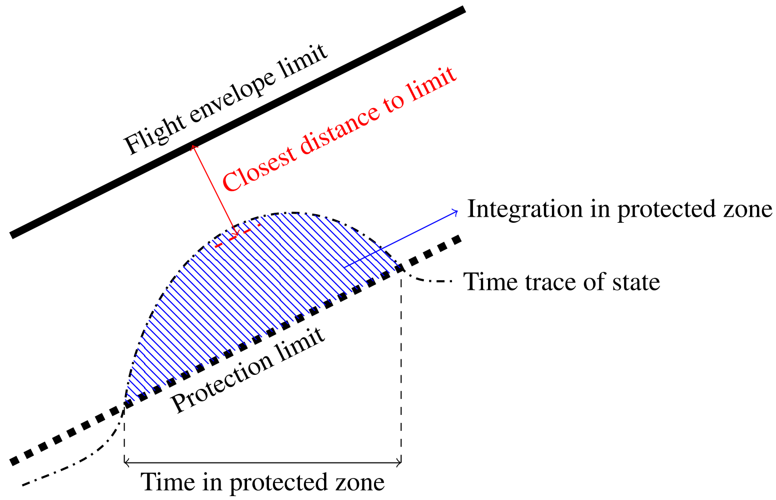

Figure 9. Safety metrics indicated on time trace

- Workload: after each run, the pilot is asked to provide a RSME[20]
- Situation awareness questions: after each run, the pilot is asked to answer two questions on a linear scale (0–100) ranging 'Never' left (0), and 'Always' right (100):
  1. Did you have the feeling you were in control of the situation?
  2. Did you have the feeling you missed critical information?
- Pilot experience: after the experiment, the pilot is asked to fill in a questionnaire regarding the experience with the haptic feedback system. The questionnaire was provided in Dutch, used a five point Likert-scale where the extreme and middle points are labeled. It included the following questions, and three labels:
  1. What is your general feeling on the haptic feedback as an information cue about the flight envelope?
     Negative ↔ Neutral ↔ Positive
  2. The haptic interface affected my workload.
     Less ↔ Neutral ↔ More
  3. Using the haptic system, my knowledge on the edges of the aircraft performance changed.
     Less ↔ Neutral ↔ More
  4. If a critical event occurs, the haptic interface helps to mitigate the consequences.
     Disagree ↔ Neutral ↔ Agree
  5. The haptic interface changes the likelihood of human error.
     Decreased ↔ Neutral ↔ Higher possibility
  6. The haptic interface changed my behavior.
     Disagree ↔ Neutral ↔ Agree
  7. The haptic interface distracts me.
     Disagree ↔ Neutral ↔ Agree
  8. I was fighting the haptic interface.
     Never ↔ Sometimes ↔ Always
  9. Do you expect any adverse impact on outcomes when using this technology? (on a two point scale)
     No ↔ Yes
  10. How would you grade the A320-alike dynamics?
      Unrealistic ↔ Acceptable ↔ Perfect
  11. How would you grade the controls? (sidestick with nominal feeling)
      Unrealistic ↔ Acceptable ↔ Perfect
  12. How would you grade the displays?
      Unrealistic ↔ Acceptable ↔ Perfect
  13. How would you grade the weather?
      Unrealistic ↔ Acceptable ↔ Perfect

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III.H. Hypotheses

1. With haptics enabled, risk homeostasis is present:
   (a) performance metrics improve.
   (b) safety metrics decrease.
2. With haptics enabled, the pilot awareness of the aircraft critical flight states is improved under high workload.
3. With haptics enabled, the pilot workload decreases.
4. The haptic feedback is equally effective when maneuvering the state towards the edges of the flight envelope (windshear revocery procedure) compared to a diminishing flight envelope (flight envelope is moving towards the state, icing scenario).
5. The haptic feedback is equally effective in both NL and AL in terms of performance and safety.
6. The haptic feedback does not interfere with nominal pilot behavior (executing normal tasks such as navigation and communication).

IV. Results

Subsection IV.A starts the results with time exerts showing a pilot making use of the haptic support system. For the remainder of the results, as mentioned in the method, the metrics are split in objective measures, presented in Subsection IV.B, and subjective measures, shown in Subsection IV.B, and the answers to the questionnaire in Subsection IV.D.

Note that no data are recorded for the icing scenario in NL, because during the simulations the control laws in the Airbus model did not function well in this situation. In addition, during the measurements for Subject 1 we found that the icing severity was too much reduced after pre-tests. Hence, the icing level was increased for the subjects which followed, and data for Subject 1 were removed.

IV.A. Time trace

This subsection gives an example where Subject 2 used the haptic feedback system. The exert used here is retrieved from the windshear scenario, flown in NL with the haptics enables (WSNLHF). Time traces for angle of attack, load factor, control device deflection and control device load can be found in Figure 10, which all start at the time of the windshear warning. Combining the control device deflection and load, results in the haptic profile, which is shown on Figure 11 for the time frames indicated on the previous figure.

At the start of the windshear recovery procedure, the pilot observes the states as can be seen on the constant zero control device load in Subfigure 10(d). After this, the pilot uses back pressure on the side stick to increase the pitch angle to $17.5°$ without reaching the limits. On reaching the target, he maintains the stick deflection and load as can be seen on the haptic profile for Frame 1 in Subfigure 11(a). In order to stop descending, the pilot increases pitch further until the angle of attack protection is encountered in Frame 2. As shown on Subfigure 11(b), after the 'tick on the stick', the pilot reduces the input, yet maintains back pressure on the stick.

Frames 3 and 4 show on Subfigure 11(c) and 11(d) that the back pressure is increased when the stiffness increases to maintain deflection. Arriving at Frame 5, the stick shaker is activated, and Subfigure 11(e) shows that the pilot reduces control input, even pitches down, to deactivate the shaker. Following the de-activation, the pilot intends to move the side stick backwards again, yet encounters again the stick shaker and has to pitch down more as on Subfigure 11(e). This is effectively 'riding the stick shaker'. Note that the way the pilot uses the haptic feedback system in this example, is in line with the expected usage from Ref. [9].

IV.B. Objective measures

The objective measures are determined based on the time traces of the experiment. Here the performance for both scenarios is shown, followed by the safety, and the secondary task.

1. Performance

The performance for the windshear events is shown in Subfigure 12(a), where it can be noted that no clear trend is visible. For the icing events, the performance is shown in Subfigure 12(b), where decreasing trend is visible yet no statistical significance is found. For all conditions, a grouping per subject seems to be present: each subject has a certain performance-level indifferent from the control law, or haptics state used.

Aside from the general trend, some subjects do stand out: the windshear scenario flown in NL shows that Subjects 1, 2 and 3 obtained a more noticeable difference in their performance. During the runs of Subjects 1, 2 with the haptics

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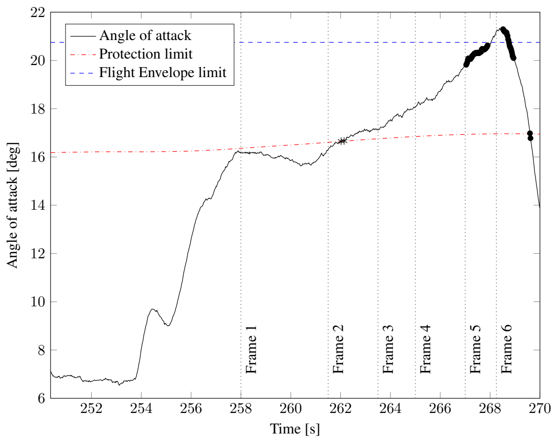
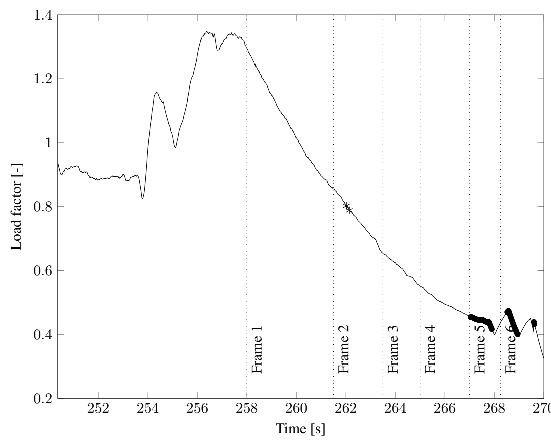
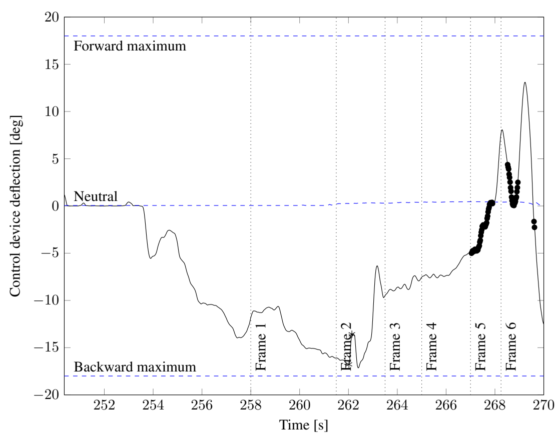


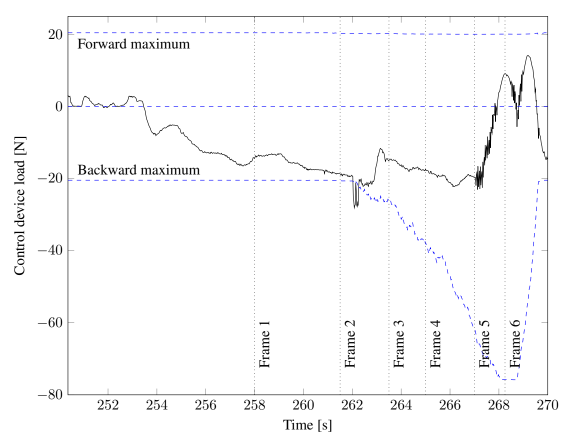
(a) Angle of attack



(b) Load factor



(c) Device deflection



(d) Device load

Figure 10. Time trace for Subject 2 in condition WSNLHF. Solid dots indicate stick shaker active, stars indicate a discrete tick.

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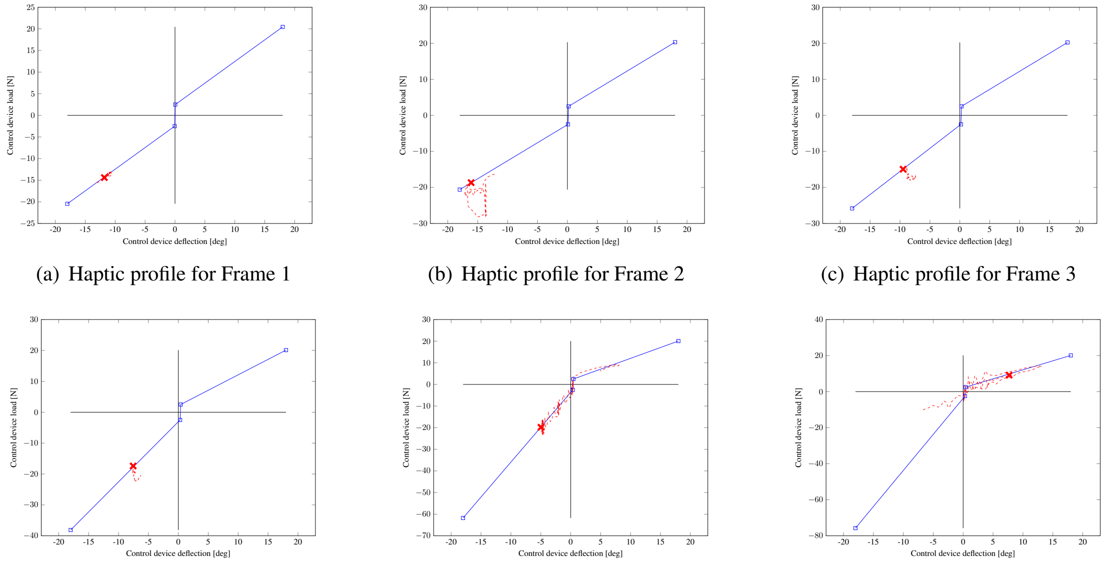
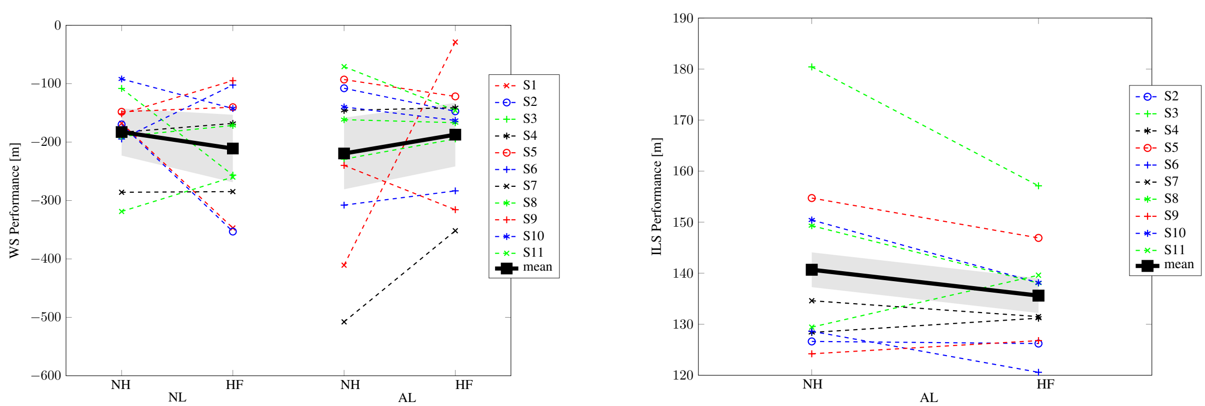


(a) Haptic profile for Frame 1 (b) Haptic profile for Frame 2 (c) Haptic profile for Frame 3

(d) Haptic profile for Frame 4 (e) Haptic profile for Frame 5 (f) Haptic profile for Frame 6

Figure 11. Haptic profile during windshear recovery of Subject 2 in condition WSNLHF. The current state is indicated with a cross, and a preview of the control device of 1.5s, frame numbers correspond to Figure 10.



(a) Windshear performance (b) Icing performance

Figure 12. Performance scores. Gray area indicates the 95% confidence interval (corrected for between-subject variability).

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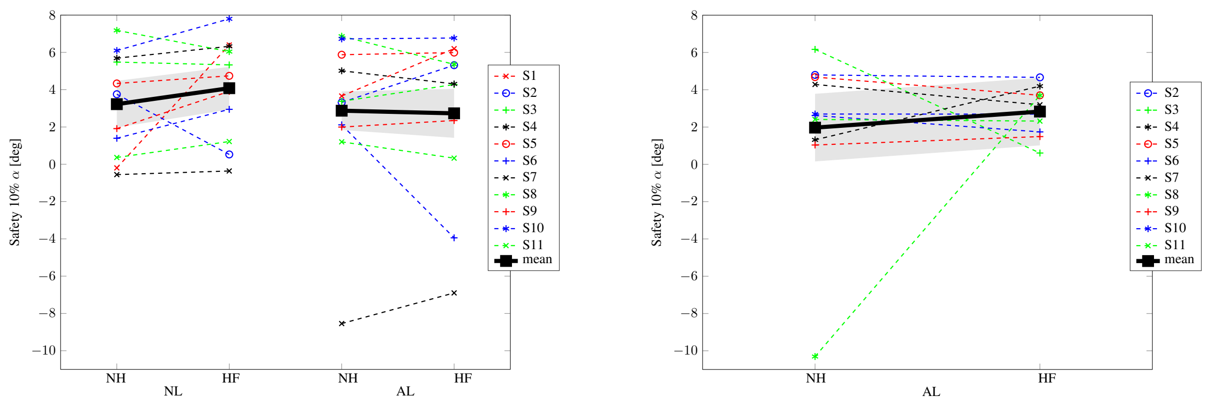
enabled, a problem with the control law simulation occurred resulting in an oscillating response, enlarged by the pilot control input. For Subject 3, the haptics enabled run in NL was one of the final runs, and a sign of fatigue showed: his initial reaction after the windshear warning was a reverted control input. Using his captain (left-hand) seat-routine he closed the throttles and pitched down, resulting in a low performance. When using AL, Subject 1 again shows a clear difference in performance: the control law oscillation showed again when the haptics were disabled, making him to use a more conservative control strategy for the next run with haptics. Subject 7 shows consistently the lowest performance for windshear. During the debriefing, he indicated that he prioritized the windshear over the stall warning and haptic cues by maintaining pitch up command albeit the visual/aural/haptic low velocity warnings.

On the icing plot in Subfigure 12(b), Subject 11 has a noticeable decrease in performance when enabling the haptic feedback, no confounding factors (such as the control law or fatigue) have been identified. Yet the pilot was not paying much attention to his altitude causing a larger deviation from the glide path. Additionally, Subject 3 has a lower performance score for the icing scenario in general. After the experiment, he noted that he did not recognize the presented case as icing and as such had difficulties to understand what was going on.

2. *Safety*

Objective metrics for safety are defined in relation to pilot behavior at or near the limits. The first metric, presented in Figure 13, looks at the 10% highest values for α, and takes the average of this data as the evaluation criteria. As stated, high numbers means more distance to the limit, hence safer flight. Similar to the performance of windshear, and now also for icing, no trend is present, yet a grouping per subject is observable.



(a) Windshear safety

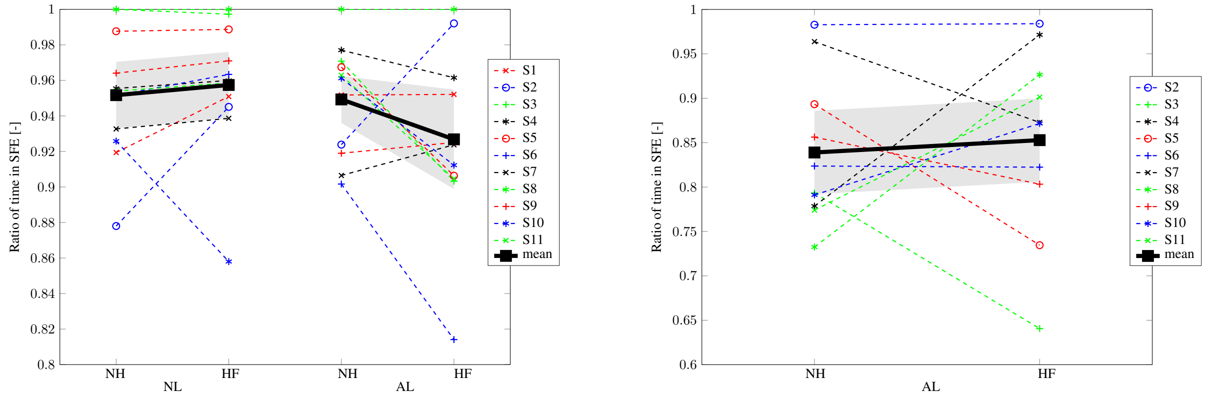
(b) Icing safety

Figure 13. Safety metric: Closest distance to the limit. Gray area indicates the 95% confidence interval (corrected for between-subject variability).

From this first safety metric, the windshear scenarios in NL show three noticeable differences. Subject 1 has a larger safety margin when the haptics is enabled. Do note that, as stated with the performance, this run contained an oscillation at and below the protection limit. The run without haptics shows the pilot pulling the side stick full backwards resulting in a high angle of attack for a long period of time. The safety margin for Subject 5 is lower without the haptics as in the turn speed was dropping without power being added. The haptics enabled run followed this run where he compensated this effect. Subject 2 encountered an oscillation in the haptic enabled run, which resulted in an extremely high angle of attack, hence low margin. Looking at the runs in AL, mostly the haptic enabled run of Subject 6 stands out: the safety margin dropped largely because he slowed down at the start of the run without a proper flap setting, resulting in a haptic cue which was used as trigger for selecting flaps.

In the icing scenarios, Subject 3 encountered a control law oscillation, resulting in high angles of attack hence major drop in safety margin. After dropping below the glide slope Subject 8, without haptics, tried to climb again yet stalled due to the presence of icing resulting in a crash.

Figure 14 gives the ratio of the time in the Safe Flight Envelope (SFE). The figure for icing shows again no clear trend, yet the windshear condition does show a different trend in both control laws. As such, the ratio of time steps in the SFE during control with NL increases when enabling the haptic feedback. In contrast, when looking at AL, the number of time steps in the SFE decreases. Statistical analysis using a repeated measure ANOVA did not show a significant difference for both conditions (the control law and haptics), yet a significant interaction effect was found confirming the observation (F=5.82, $p = 0.0037$).

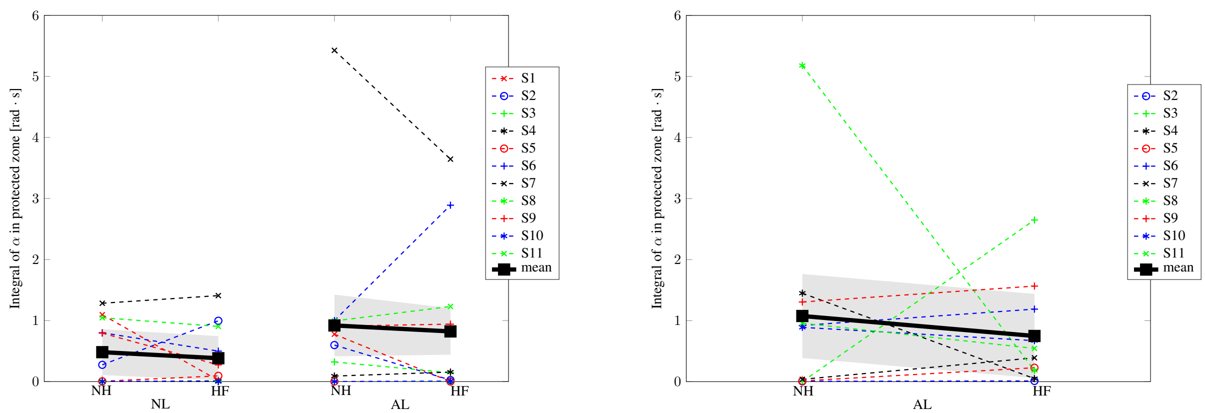


(a) Windshear (b) Icing

Figure 14. Safety: ratio of time in the safe flight envelope. Gray area indicates the 95% confidence interval (corrected for between-subject variability).

Subject 10, in all windshear conditions, did not enter the angle of attack protection, yet he did achieve a velocity above the maximum velocity protection ($V_{\text{MO}} - 20$, not indicated on the display). Without the haptics he was not informed as such, yet with the haptics he was informed by the haptics and remained longer in the speed regime. Using AL, Subject 6 again has a lower safety metrics for the same reason as the previous margin metric: he slowed down without proper flap settings.

As the time on previous plots does not take into account the proximity to the limit, the integral of α in the protected zone is shown in Figure 15. These safety metrics shown again no clear trend, yet do show the grouping per subject.



(a) Windshear (b) Icing

Figure 15. Safety metric: integral of α in protected zone. Gray area indicates the 95% confidence interval (corrected for between-subject variability).

The figure does show the previous mentioned control strategy during windshear of Subject 7: neglecting the low velocity and focusing on the windshear by maintaining full back stick resulting in a long time with considerable magnitude in the angle of attack protection. The run with haptic feedback in AL for Subject 6 is again higher integral as he did not set the flaps in time.

In the icing condition, Subject 3 shows the effect of the control law oscillation by an increased integral during the haptics enabled run. Subject 8 has an extreme value without haptics, this originates from the occurred crash.

3. *Secondary task*

During the run, the answers of the pilots to the requests of ATC were recorded. The ratio of correct answers can be seen in Figure 16 which shows that the pilots in each case are triggered, and give correct answers to ATC. No statistical

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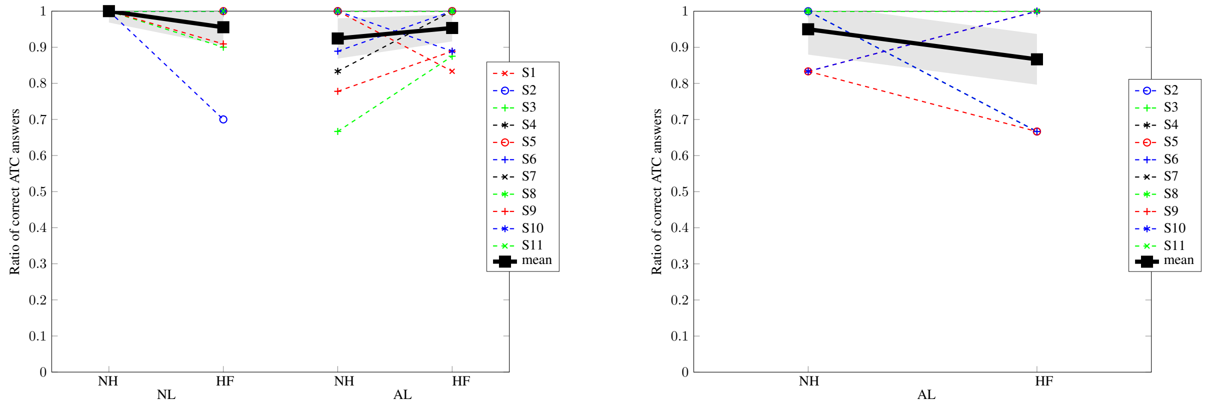
significant results are obtained.

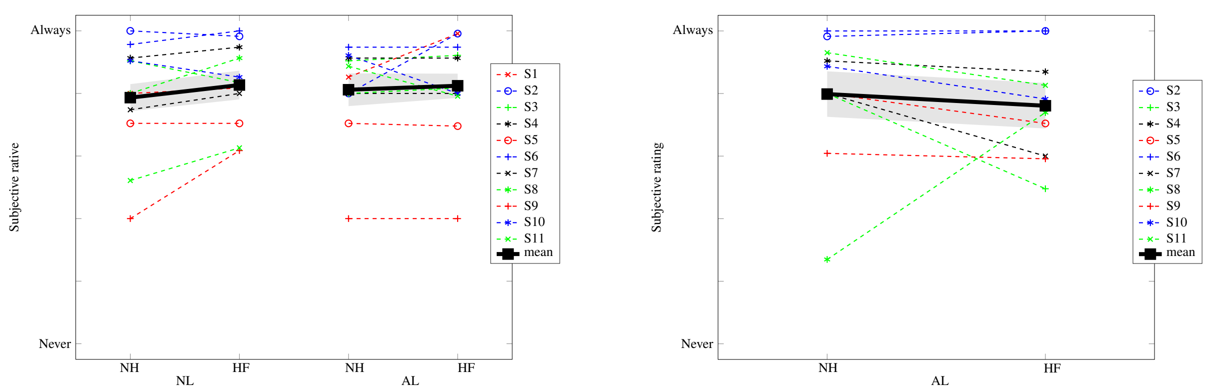


(a) Windshear (b) Icing

Figure 16. Secondary task: ratio of correct responses to ATC. Gray area indicates the 95% confidence interval (corrected for between-subject variability).

IV.C. Subjective measures

After each run, the subjects were asked to fill the subjective ratings, these include a measure of how well they were in control, Figure 17, a measure on whether they had all the critical information they needed, Figure 18, and a rating for their mental workload, Figure 19. As for the previous results, no statistically significant trend is present, and again a grouping per subject is observed.



(a) Is the pilot in control for windshear? (b) Is the pilot in control for icing?

Figure 17. Subjective situation awareness: is the pilot in control? Gray area indicates the 95% confidence interval (corrected for between-subject variability).

When asked whether the pilot was in control, enabling the haptics in the windshear scenarios seems to give most pilots a re-affirming feeling: they indicated to be more in control. In contrast, switching on the haptics in the icing scenario lowers the perceived level of being in control. Only Subject 8 indicated to be clearly more in control.

From the information missing according to the pilot during windshear, one subject does stand out: Subject 2. Looking at the windshear data in Subfigure 18(a), the pilot indicated that he was missing more information when enabling the haptics in NL, whereas the differences between both runs is less for the other pilots. In contrast, in AL, the Subject 2 experienced the run with haptic had less information missing showing that the haptics does provide the pilot with information.

In the icing condition, Subjects 3 and 8 are the only pilots who indicated a clear difference between both runs. Here it can be noted already that Subject 3 indicated that in AL, the triggering data of the haptics (mostly α_{prot} and

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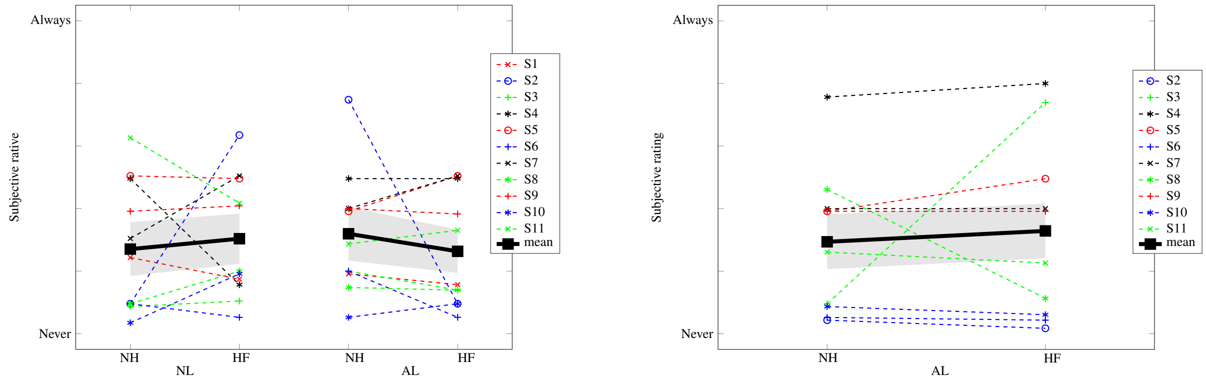
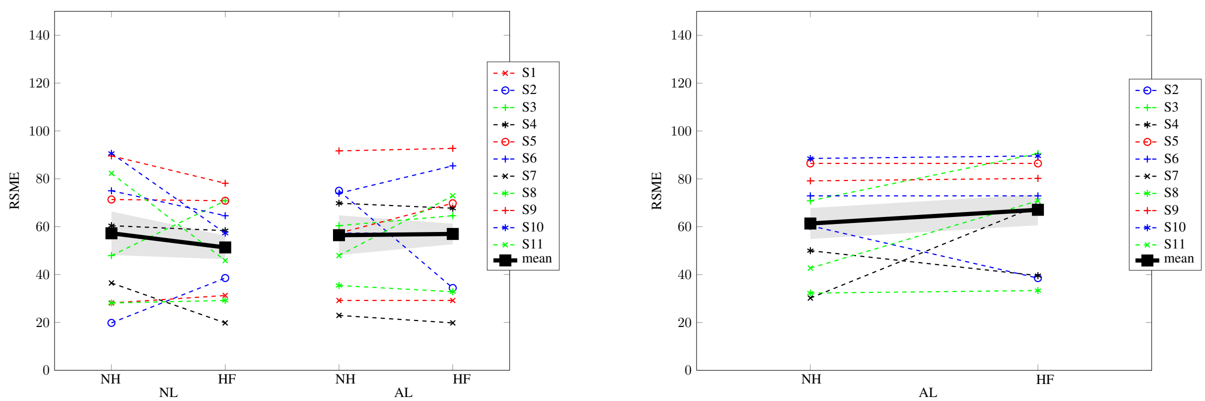


(a) Is the pilot missing information for windshear?

(b) Is the pilot info missing for icing?

Figure 18. Subjective situation awareness: is the pilot missing information? Gray area indicates the 95% confidence interval (corrected for between-subject variability).

$V_{\mathrm{MO_{prot}}}$ for this case) was not clear as this is not available on the PFD. He therefore was not able to properly understand the haptic cues. Subject 8 did perceive the haptics as a cue for the approaching angle of attack.



(a) Windshear

(b) Icing

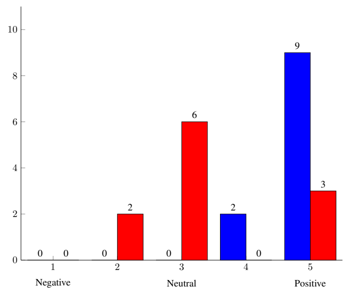
Figure 19. Workload: RSME. Gray area indicates the 95% confidence interval (corrected for between-subject variability).

IV.D. Post-run questionnaire

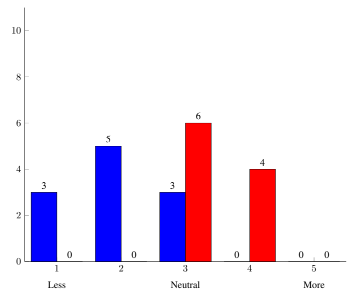
After the final run, the participants were asked to complete a questionnaire which mainly queried them about their experience with the system. It involved multiple questions which are shown before. The questions contain one entry for each pilot (hence eleven in total) for the windshear scenarios, and ten answers for the icing scenario since one pilot did not want to complete the questions for the icing scenario as he did not recognize it as such an event. Statistical analysis between both scenarios is performed using a Wilcoxon Signed Rank test with continuity correction for which $N = 10$ as the windshear entry of the previously mentioned subject is removed.

The first question asked what their general idea on the haptic system is, for which the results are shown in Subfigure 20(a). For the windshear scenario, the results are statistically significant more towards the positive side, whereas for the icing scenario the results are more centered around neutral ($V = 28$, $p = 0.021$).

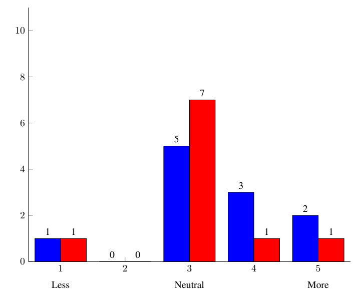
Another set of questions was asked to investigate the expected consequence of using the system according to the pilots. With a statistical significant difference from the icing answers, the pilots answered in case of windshear that with haptics their workload was less (Subfigure 20(b), $V = 0$, $p = 0.011$), the system has the ability to help mitigate consequences of critical events (Subfigure 20(d), $V = 15$, $p = 0.057$), and did not distract them (Subfigure 20(g), $V = 1.5$, $p = 0.040$). For the icing scenario the haptic system gave a neutral to increased workload, a more neutral opinion



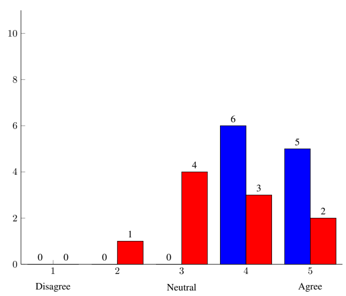
(a) What is your general feeling on the haptic feedback as an information cue about the flight envelope?



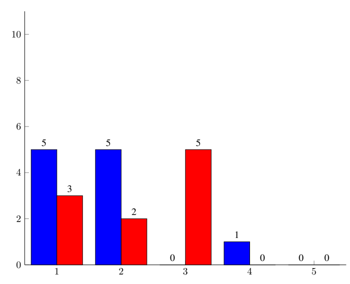
(b) The haptic interface affected my workload.



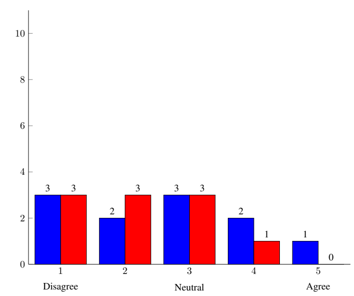
(c) Using the haptic system, my knowledge on the edges of the aircraft performance changed.



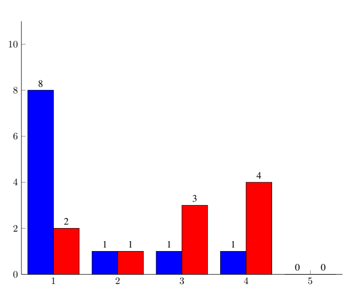
(d) If a critical event occurs, the haptic interface helps to mitigate the consequences.



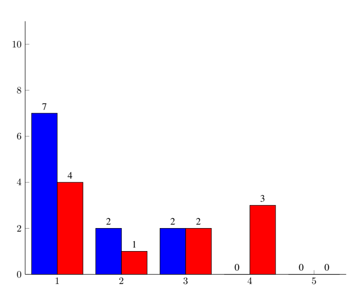
(e) The haptic interface changes the likelihood of human error.



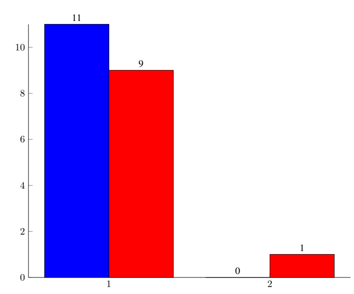
(f) The haptic interface changed my behavior.



(g) The haptic interface distracts me.



(h) I was fighting the haptic interface.



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

Figure 20. Subjective post-run ratings. Blue indicate answers for windshear, red for icing.

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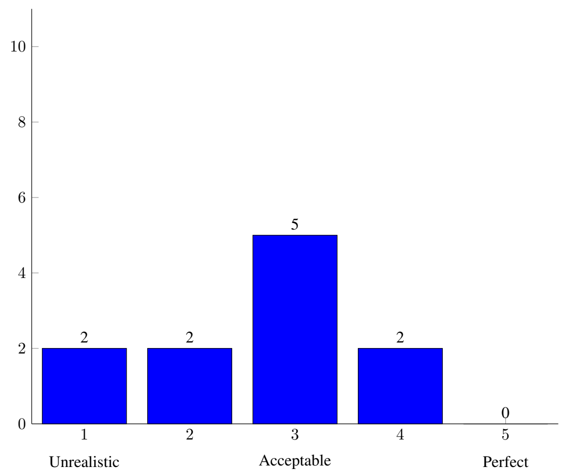
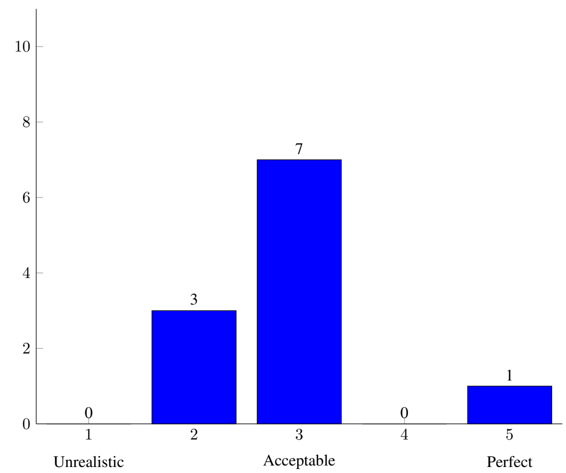
for the system to mitigate consequences of critical events, and a larger distraction. The pilots on both scenarios expect the possibility of human error to decrease (Subfigure 20(e)), in general were not fighting the haptics (Subfigure 20(h)), and expected no adverse impact (Subfigure 20(i)). Overall a neutral to positive change on their knowledge on the edges of the flight envelope was observed (Subfigure 20(c)), which should be kept in mind when considering the goal of the design. They did not provide a uniform answer to whether they changed their behavior (Subfigure 20(f)).

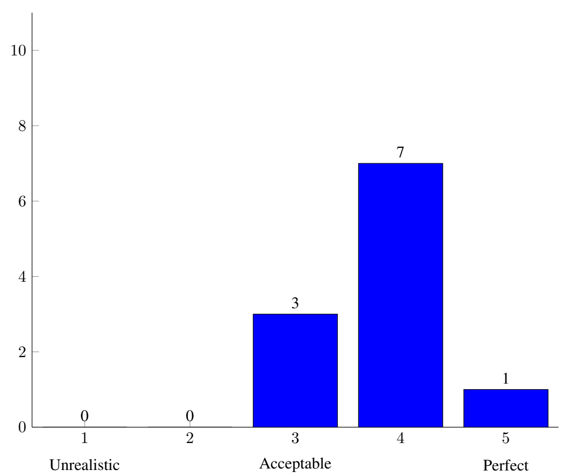
In order to evaluate whether the simulation was adequately representing an actual Airbus-aircraft, four questions on realism were asked for which the results are shown in Figure 21. It shows that the displays and the weather implementation were positively received, whereas the dynamics did lack realism. The realism of the controls shown in Subfigure 21(b), is more important as the experiment considers the design of the controls itself. Most pilots perceived the (nominal) feeling of the controls as acceptable.



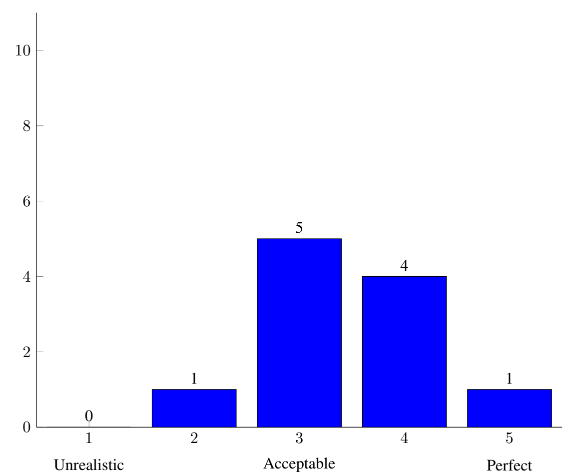
(a) How would you grade the A320-alike dynamics?



(b) How would you grade the controls?



(c) How would you grade the displays?



(d) How would you grade the weather?

Figure 21. Post-run questions on realism

V. Discussion

As before, the discussion is split in the objective, subjective and post-run criteria. After a discussion on the simulation, this section is concluded with the overall haptic feedback system evaluation in the final subsection.

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V.A. Objective measures

The results for the objective performance metric showed no statistical difference for the scenarios, nor for the different control laws. Nevertheless, the icing scenario showed that the addition of the haptic feedback system did show a trend for an improved performance. Note that this scenario is only evaluated for AL, in which case the display shows minimal velocity, and no velocity protections. With the addition of the haptic feedback system, angle of attack information is added, as the haptic uses the protection angle of attack to trigger the discrete cue. This improvement of performance score is most likely caused by this inclusion of angle of attack information, not directly in the way of communicating it. Hence one can conclude that showing the angle of attack information, albeit the degraded control law, can be beneficial for the performance.

One safety metric did show a statistically significant result for the interaction of the control law and enabling of the haptic feedback system: in NL enabling the haptic feedback caused the pilot to spend more or equal time in the protected zone, whereas enabling it in AL caused the average time spend in the protected zone to decrease. The latter indicates that the pilots, on average, moved more in the protected zone when given the (haptic) protection information. Hence the first hypothesis stating that risk homeostasis is present cannot be rejected: as the pilot has more information on the limits, the perceived risk is lowered, and the pilot moves closer to the limits. Nevertheless the equalization effect of perceived risk is not visible in a change performance.

In NL, pilots can see the angle of attack protection on the display, yet do not move closer to the limits. This can indicate that the perceived level of risk is not changed by adding the haptic feedback and pilots are still relying on the information on the displays. A possible reason for not using the haptic feedback information can be a lack of experience with the haptic system while having abundance experience with the visual system, or a dislike for the haptic feedback information channel. The first can be mitigated by longer training of training which incorporates haptic feedback from the start. From the questionnaire, discussed below, we can infer that pilots did not disapprove on the system. Nevertheless, to avoid dislike of the system, the limits used by the haptics can be more clearly communicated to the pilot on the display. An example for this is the overspeed protection ($V_{mo} - 20$) used by the haptics, yet not visible on the PFD.

Results for both the performance and safety metrics show a grouping per subject: the metric for one scenario is in most cases of similar value irrespective of control law used or status of the haptic feedback system. This shows that the largest variation is the subject, not the intervention used. Hence the hypotheses that the haptic feedback is equally effective in NL and AL, and for moving towards the flight envelope as a diminishing the envelope cannot be rejected. Another conclusion from the lack of differences is that the scenarios might have to be reconsidered to eliminate the subject variation.

Finally, the ratio of correct answers to ATC did not show any difference over the conditions. Therefore this secondary task cannot confirm that the workload of the pilot decreases. It did show that the addition of haptic feedback still enabled to aviate, navigate the approaches, and communicate with ATC. Based on this data, the hypothesis that the haptic feedback does not interfere with nominal behavior cannot be rejected.

V.B. Subjective measures

The subjective measure for situation awareness involved two questions: “Is the pilot in control?” and “Is the pilot missing information?”. As stated, the pilots indicated that they feel less in control in the icing event. Following the debriefings with the pilots, this is traced back to the mis-match of the visual display, showing minimal velocity, and the haptic system giving information on the angle of attack. The latter was largely influenced by the icing causing the haptic cues to be triggered at much higher velocities. As this did not match the information on the visual display, the pilots experienced this a being sometimes unclear, resulting in a reduced feeling of being in control.

Looking at whether the pilot was missing information, the pilots do not seem to experience that they have more information available in the AL. The objective results before indicated that in the windshear scenario they moved more into the protected flight envelope, and they performed better with the icing scenario, which could only be caused by the added information by the haptics. Nevertheless, this was not experienced as such by the pilots.

Combining the two questions, this simplified subjective criterion cannot confirm that the haptic display increases the situation awareness of the pilots.

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

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V.C. Post-run questionnaire

The questionnaire asking the pilots for their experience with the system showed a clear difference between both scenarios (already rejecting Hypothesis 5). For the windshear scenario, the pilots clearly experienced the haptic feedback system as positive, whereas more neutral for the icing scenario, which follows the metrics shown before and the answers in the following.

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

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

No clear preference for the haptic feedback system was present for icing. This can be partially explained as some pilots noted that the condition was not recognized as icing, and the biased comparison of available information (as no angle of attack indication present in no haptics case). Additionally, the pilots remarked that the haptic cues were sometimes unclear: a haptic cue was provided while it was not supported by an item on the display. An example of this is the haptic cue for angle of attack, while the display does not show this, leading to a clear recommendation for follow-up designs.

As the pilots have to reflect more with the haptics, the workload increase rejects the hypothesis for workload decrease. The indication that the pilots have more knowledge on the edges, haptics helps to solve problems, and a decreased chance of human error, indicates that the addition of the angle of attack information through the haptics indeed helps the pilots. Nevertheless, as the haptics was experienced to be slightly distracting and sometimes pilots were fighting against it, the current design does not allow the pilots to maintain nominal behavior during the icing scenario.

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

V.D. Simulation evaluation

To put the simulation in relation to the real world, four questions were asked questioning the level of reality. The pilots did provide a mostly positive rating for the displays and the weather. For the latter, mostly the occurrence of icing was problematic.

The dynamics of the model are less realistically received. This is known as the drag of the model was significantly less as an actual aircraft. Additionally, often noted in the objective results, oscillations occurred probably due to issues with the implementation of the flight control law in the proprietary model. A probable result of this might be a more conservative control strategy of the pilots. Albeit these problems, the time trace in Subsection IV.A showed that the haptic feedback is used. For further research, further collaboration with the partners is planned to mitigate these problems.

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

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V.E. Overall system evaluation

As some of the hypotheses could be evaluated by both objective and subjective measures, this subsection summarizes the results for all of them and discusses a recommendation for further research.

Hypothesis 1 is fully based on the objective results, they indicate that risk homeostasis is partly present as pilots do spent more time in the protected zone for the haptics-enabled windshear condition with AL. For icing, this was not found and the hypothesis has to be rejected.

The pilot awareness of the aircraft critical flight states does not seem to increase based on the subjective questions asked after each run, nevertheless, in the debriefing questionnaire the pilot's answers indicate that they have an increased perceived situation awareness. Combing both givens, we cannot reject Hypothesis 2.

Workload was measured objectively with the ratio of correct answers to ATC and subjectively with a RSME evaluation, giving no difference for enabling haptics. Looking at the post-run questionnaire, the icing scenario showed an increase in workload due to the unclear cues, yet in the windshear scenario it was deemed decreasing workload. Hence, Hypothesis 3 must be rejected for the current design because of the lack of evidence.

To not reject Hypothesis 4, no differences should be found between the windshear and the icing scenario. This is true for both the objective and the subjective metrics. Nevertheless the post-run questionnaire indicates that the current haptic feedback design is not equally effective for both scenarios. This is partly to blame of the remaining simulation problems, yet is attributed as well to the missing visual information in AL as stated by the pilots.

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

Finally as the pilots we able to aviate, navigate and communicate throughout all runs, the haptic feedback system does not interfere with nominal behavior and Hypothesis 6 is not reject. As the system does not interfere, one could consider whether a combination of the two uses of haptics described in the introduction can be combined: providing both haptic feedback for flight envelope protection, as for guidance during a tracking task.

The results shown above give the indication that the haptic feedback system in the current design does not lead to the expected result in terms of hypothesis. Nevertheless, all pilots indicated that they liked the system.

Possible reasons for the generally positive responses of pilots, while dependent measures lack significance, are the low number of subjects but also perhaps the experiment itself. In the icing scenario, the haptic disabled runs did not have angle of attack indication as elaborated above, giving a different set of states to the pilot. For the windshear scenario, the solution space is quite small, giving the pilot little space for maneuvering. Providing the pilots with a scenario in which they have a little more freedom in their solution, could result in more prominent use of the haptic cues.

VI. Conclusion

To increase pilot situation awareness about flight envelope limits we investigated haptic feedback – force feedback through the control device. Our haptic interface communicates the proximity to the flight envelope limits using several cues. When approaching the limit, the first cue when crossing the flight envelope protection boundaries is a discrete cue: a 'tick on the stick'. Moving further in the protected zone, the stiffness of the control device is increased. To clearly communicate an imminent stall, a stick shaker is added. Finally, the control device is moved to a desired position when a zero input is not sufficient for continuous safe flight.

To evaluate the haptic feedback system, professional Airbus pilots were invited to fly an Airbus A320 model in TU Delft's Simona research simulator. Two scenarios are used: a windshear where the pilot has to move as close to the limit as possible, and an icing scenario where icing degrades the flight envelope hence the limit is moving to the pilot. The windshear scenario was flown in both the normal, fully protected Airbus control law, as well as an alternate control law which allows the pilot to stall. As the icing implementation in the model showed unexpected issues in the normal control law, this scenario was flown with the alternate law only. All scenarios were flown both with and without the support of the haptic feedback system.

For the experiment, several hypotheses were formulated. First, it was expected that enabling the haptic feedback would increase the performance and decrease the (objective) safety metrics, caused by a constant perceived risk by the pilots. Results showed this only for the degraded control law during the windshear scenario were less visual information is present. Second, pilots indicated after the experiment that they experience an increased situation awareness, yet this is not confirmed with the subjective questions after each run. Third, the objective metrics, the ratio of correct ATC answers, and the subjective rating scale did not show a decreased workload. Nevertheless, the pilots indicated in the

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debriefing that the haptic feedback system is expected to decrease workload. Fourth, equal trends were expected for the haptic feedback when moving towards the flight envelope limits, as when the flight envelope limits are decreasing. As the trends in both scenarios, windshear and icing, are not equal this hypothesis has to be rejected. Fifth, based on the windshear scenario, the difference in visual information causing different trends with the use of haptics, indicates that the equal effectiveness for the NL and AL, again has to be rejected. Finally, as the pilots was able to aviate, navigate and communicate throughout all runs, we conclude that the haptic feedback system does not interfere with nominal behavior, supporting the final hypothesis which can therefore not be rejected.

During the experiment two major issues did appear: firstly the model showed an oscillatory response which might have influenced the pilot to maintain a more conservative control strategy. Secondly, the pilot did not always understand the haptic feedback system as it did provide cues when no visual confirmation was provided, resulting in pilot confusion.

As this experiment does show some promising results, especially when considering the high pilot appreciation for the haptic feedback, for future research it is recommended to design a visual display which complements the haptic feedback cues. Doing so can result in more acceptance of the haptic feedback system. Additionally, by designing scenarios in which the pilots have more freedom of choosing a control action, more observable results could be obtained. Finally, as the current system does not interfere with nominal pilot behavior, it should be investigated whether haptic feedback for flight envelope protection can be combined with haptic feedback for a tracking tasks, such as during an instrument landing.

In conclusion, this paper presented the evaluation of the haptic feedback for flight envelope protection. Especially from the pilot experience, it was found to show a clear potential benefit. Therefore the design should be more developed and improved for future implementations in the modern fly-by-wire cockpit.

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