Using asymmetric vibrations for feedback on flight envelope protection

Van Baelen, Dirk; Ellerbroek, Joost; van Paassen, Rene; Abbink, David; Mulder, Max

DOI
10.2514/6.2020-0409

Publication date
2020

Document Version
Final published version

Published in
Proceedings AIAA Scitech 2020 Forum

AIAA SciTech Forum
6-10 January 2020, Orlando, FL
AIAA Scitech 2020 Forum

10.2514/6.2020-0409

Using Asymmetric Vibrations for Feedback on Flight Envelope Protection

Dirk Van Baelen*, Joost Ellerbroek†, M.M. (René) van Paassen‡, David A. Abbink§ and Max Mulder¶
Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

Modern aircraft use a variety of fly-by-wire control devices and combine these with a flight envelope protection system to limit pilot control inputs when approaching the aircraft limits. The current research project aims to increase pilot awareness of such a protection system through the use of force feedback on the control device, i.e., haptics. This paper describes a new iteration of a design with the specific aim *to warn* the pilot when approaching a limit *and provide a clear direction* of suggested control input. This is achieved by using vibrations asymmetric in both amplitude, i.e. the mean of the signal is non-zero, *and* time, i.e. a cue which has a rise time different from the fall time. An evaluation is performed where 24 active PPL/LAPL pilots flew a challenging vertical profile and encountered a windshear. The pilots are divided in two groups: one group performing four flights with haptic feedback, followed by four without, the other groups has a reversed order. Although acceptance ratings slightly improved when providing haptic feedback, the other metrics are unchanged when switching between haptic feedback conditions, due to a large training effect during the first four runs. The results do show that enabling the haptic feedback does seem to improve the learning rate over the first runs, and no after effects are present when feedback is removed. As such, next to the fact that most pilots indicated that they expect an improved safety, this experiment shows a potential training benefit of haptic feedback.

Nomenclature

Symbols

b	Damping, Nms/rad
I	Amplitude of the discrete tick, Nm
k	Spring, N/rad
m	Mass, kg
n	Load factor, g
q	Pitch rate ($\dot{\theta}$), rad/s
V	Velocity, m/s
α	Angle of attack, rad
δ	Control device deflection, rad
θ	Pitch angle, rad
ϕ	Bank angle, rad

Subscripts

br	Breakout
lat	Lateral value
lon	Longitudinal value
max	Maximum value
MO	Maximum operational value
min	Minimum value
nom	Nominal value
prot	Protected region value
stall	Value when stall occurs

I. Introduction

International aviation safety boards, such as the European Union Aviation Safety Agency EASA and the International Air Transport Association IATA, identify loss of control in flight as one of the key risk areas resulting in most fatalities within aviation. [1, 2] A safety issue contributing to such a loss of control is identified as the inadequate monitoring of the main flight parameters and automation modes. To ensure and improve current safety levels, loss of control events should be prevented at all times, especially looking at the expected growth of the aviation industry.

*PhD student, Delft University of Technology - Control & Simulation, d.vanbaelen@tudelft.nl. Student Member AIAA.
†Assistant Professor, Delft University of Technology - Control & Simulation, j.ellerbroek@tudelft.nl.
‡Associate Professor, Delft University of Technology - Control & Simulation, m.m.vanpaassen@tudelft.nl.
§Professor, Delft University of Technology - Cognitive Robotics, d.a.abbink@tudelft.nl.
¶Professor, Delft University of Technology - Control & Simulation, m.mulder@tudelft.nl. Associate Fellow AIAA.

Improving the information presented to pilots is expected to help reducing the loss of control occurrences. The most straightforward measure would be to change the cockpit displays, through showing the flight-critical states on, e.g., the Primary Flight Display (PFD). This display can be augmented with information on the limits of the aircraft, i.e., the Flight Envelope (FE), which can improve safety by reducing the risk of violations of those limits. [3] Research on improving pilot understanding of the current status of their automation shows promising designs, yet a simple indication like a cross was not conclusively shown to be effective. [4, 5] On the other hand, once the limits are exceeded, for example in a stall, the information on the PFD can be augmented with recovery guidance which delivers recovery performance improvements as shown in three simulator evaluations. [6]

Apart from the visual channel, pilots can also perceive information through the sense of touch. An example is the haptic interface, which provides force feedback through the control device. This form of information can have a significant positive effect when a pilot is guided along the approach path. [7, 8] Additionally it can be used to show a set of predicted controllability limits, which was shown to be used by pilots in an experiment. [9] Furthermore, our previous research showed that haptic feedback can be used to show the pilot information on the Flight Envelope Protection (FEP) system which can limit the input of the pilot to ensure that aircraft is flying within acceptable limits. [10] The evaluation of this feedback system showed a potential benefit, yet lacked conclusive data. The experiment indicated that not all haptic feedback cues used were equally effective. [11]

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

This paper first discusses the new haptic design iteration in Section II. To evaluate this new design, Section III presents an experiment where the pilots are required to operate the aircraft at the limits. In Section IV and V, results of the experiment are described and discussed. Finally, the conclusions are shown in Section VI.

II. Haptic Display

The haptic feedback design is based on the Airbus A320 control structure. Full details are given in our earlier work [10] on the design of a haptic feedback system, only the most important elements will be explained in this section. Using the Airbus control law structure, the working principles of the new iteration of haptic feedback is elaborated.

A. Airbus A320 Control Structure

Modern-day Airbus aircraft, like the A320 and the A330, all employ a Fly-By-Wire (FBW) system. This means that there is no physical connection between the control surfaces and the control device. The latter acts as an interface for the pilot to provide inputs to the Flight Control Computers (FCCs) which then command the control surfaces with hydraulic actuators. This allows a Flight Envelope Protection (FEP) system to be used, which can check and, if necessary, limit the pilot inputs, this 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) [12–15]. On top of this control law, a hard envelope limit is employed which protects the pilot from exceeding limits on angle of attack (α), load factor (n), and maximum velocity (V_{MO}). This protection is depicted in Fig. 1, where the nominal flight envelope is the extreme limit which can not be exceeded, the safe flight envelope is the point where protections start acting. The envelope is constructed by the maximum (n_{max}) and minimum (n_{min}) load factor, their protection limits ($n_{\mathrm{max}_{\mathrm{prot}}}$ and $n_{\mathrm{min}_{\mathrm{prot}}}$, respectively), the maximum operation velocity (V_{MO}, and protection $V_{\mathrm{MO}_{\mathrm{prot}}}$), and minimum velocity (V_{stall}, and protection V_{prot}).

When an FCC fails, or when a sensor failure occurs, the control is reverted to a degraded control law. In this research, we will 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 allowing the pilot more extreme control actions.

Lateral control in NL is a bank (ϕ) rate command from $-33°$ till $+33°$ of bank. Beyond these limits, positive roll stability is achieved such that the aircraft rolls back to the protection value (ϕ_{prot}) of $\pm 33°$. The maximum achievable bank, with full lateral side stick deflection is $\pm 66°$ of bank. In AL, lateral control reduces to a pure rate command, irrespective of the actual bank angle. More details on the control laws and degraded control laws can be found in Ref. [10].

Given that for both longitudinal and lateral control, a degradation of the control law results in a different effect for a

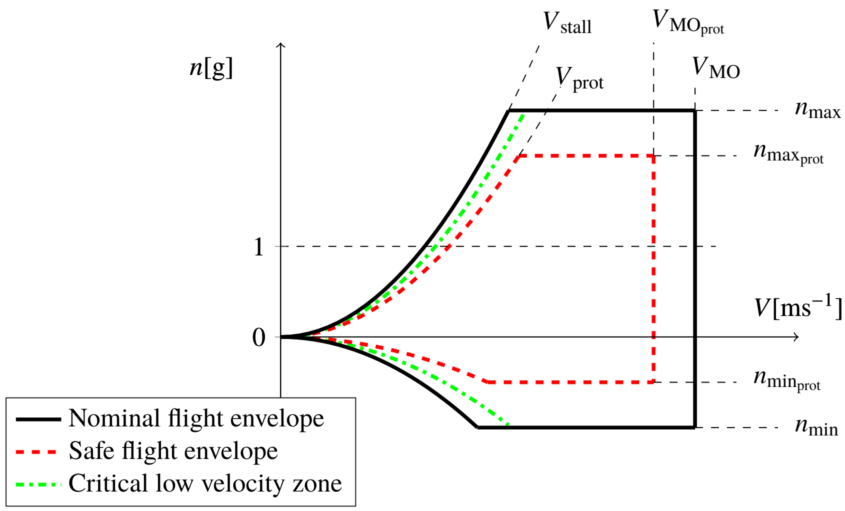


Fig. 1 Flight envelope, velocity (V) versus load factor (n)

given control input, a clear indication of both the limits and the active protections of the FE is required. Nevertheless, accidents did occur in the past where pilots were not aware of what control law was active, and what protections were still there. [16] As such, a clear and intuitive way of presenting this information can be found in haptic feedback and a new design is proposed in the following.

B. Haptic Feedback Design

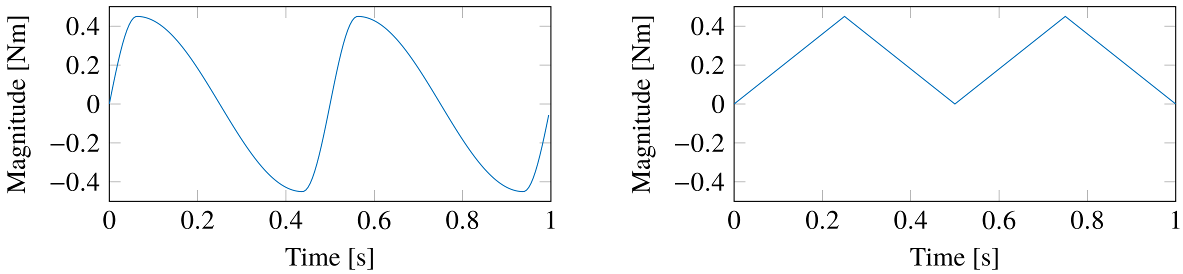
The design rationale of the haptic feedback presented in this paper is based on the results of an evaluation with a previous design. We found that the majority of pilots appreciated a discrete cue when leaving the Safe Flight Envelope (SFE), therefore additionally indicating when the FEP starts acting as indicated above. Furthermore, the stick shaker close to a stall, was considered to be very valuable. Although the other haptic cues used in the initial design – such as the increased stiffness of the side stick, the change of the position to which the stick returns when no force is applied – were appreciated, these were not received as well as the discrete indications. [11]

Looking at the cockpit implementation of a haptic feedback system with variable stiffness and changing neutral point, the verification, validation and certification procedure might present a huge hurdle to overcome. On the other hand, adding a 'simpler' discrete cue might be easier to implement as similar systems already exist, such as a stick shaker in Boeing aircraft, or an indication of angle of attack by a soft stop in the Gulfstream G500/G600 *. [17] Additionally, the discrete cue might be incorporated in the grip of the side stick such that it can be retro-fitted to current passive side sticks. Combining the preference by the pilots, and the potential market, we considered it to be worthwhile to investigate whether a haptic feedback system using *only* discrete cues might already yield an improvement.

Although the discrete cues were the preferred way of communication, it was not always clear to pilots in our previous experiment what *direction* of control input was required. This is no surprise, since the discrete cues were not designed to indicate direction, but it was a good incentive for us to investigate whether discrete cues *can* indicate direction. Therefore, an investigation into a number of forcing functions was performed to find a new candidate function. Previous research showed that an asymmetric-in-time forcing function, i.e., the forcing function has a different rise-time and fall-time (see Fig. 2a), provides more accurate directional haptic cues to operators holding a magnetic flotor. [18] This latter experiment was performed when the operators where just holding the control device (here a magnetic flotor), whereas on the flight deck, the pilots are actively controlling the control device.

A domain where operators are actively using the control device is automotive. Here, haptic feedback is, for example, used for communication of a lane departure warning system. To this end, similar to our previous design, research using pulse inputs when a lane departure was imminent showed that drivers were more inclined to follow these commands as they act as 'motor-priming' elements. [19] More recent, a study compared different forcing function shapes (pulses, square, triangular), magnitude, and frequencies, which showed that a combination of a small amplitude, square shape and mid-frequency was the best compromise for their intentions. [20] The forcing functions used here, are

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



(a) Asymmetric-in-*time* forcing function. [18]

(b) Asymmetric-in-*amplitude* forcing function. [20]

Fig. 2 Asymmetric forcing functions found in literature.

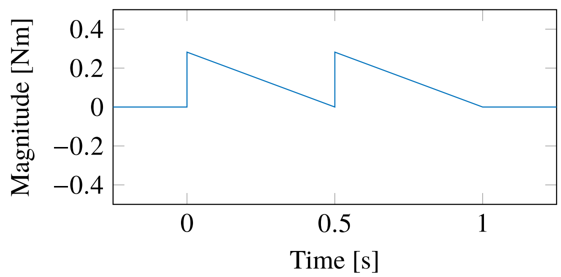


Fig. 3 Sawtooth-shaped forcing function used.

all asymmetric-in-amplitude, i.e., the oscillation is around a non-zero point (see Fig. 2b).

These research efforts lead to the hypothesis that a forcing function which has an asymmetry in both time *and* amplitude would be the most effective in communicating a preferred control input direction to pilots. To test this hypothesis, an experiment was performed where a subject was holding the side stick and, while the subject was exerting a constant force, we investigated what the lowest forcing function magnitude is where that subject can still indicate the correct direction. This analysis confirmed our hypothesis, indicating that a sawtooth-shaped forcing function had best performance. [21]

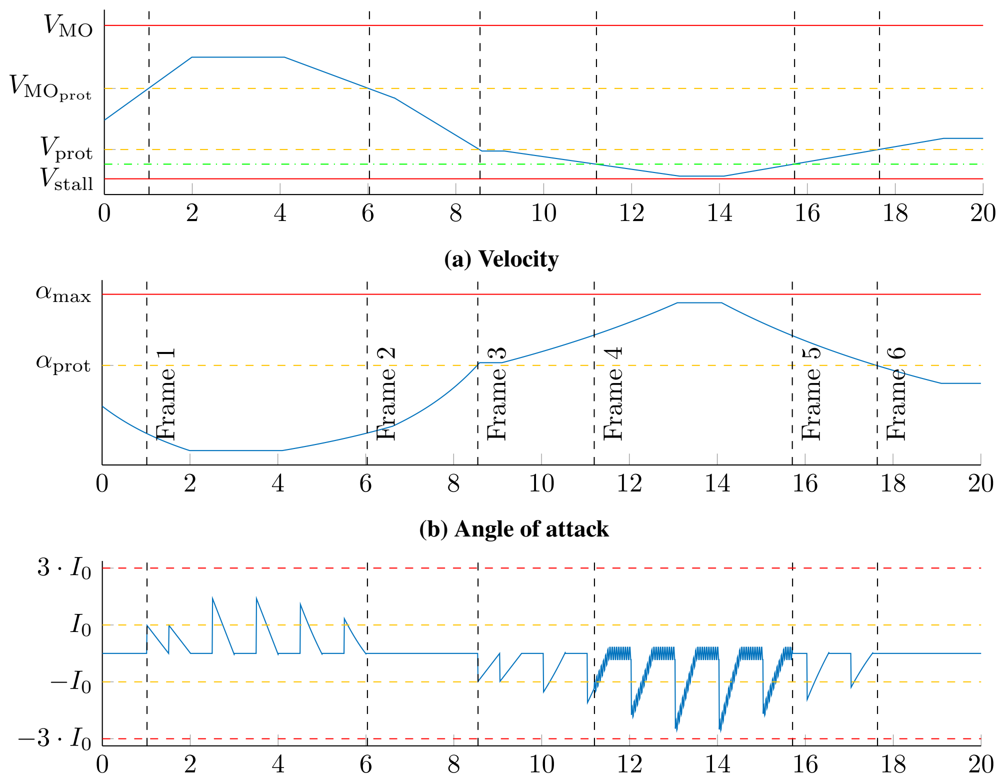
Additionally, the experiment showed the minimal required amplitude where the subjects could just indicate a direction, which was determined to be $0.094Nm$. As the subjects only focused on the side stick and the perceived direction, the minimal amplitude for use in a cockpit is expected to be larger. Therefore the amplitude is multiplied with a 'safety factor' of three. The resulting forcing function has a sawtooth-shape with amplitude (I_0) $0.282Nm$, frequency $2Hz$, lasts for one second, and is shown in Fig. 3. Although it has a discrete start, combining the forcing function with the actual side stick-dynamics results in an experience of similar shape to Fig. 2a, with a non-zero average.

Equal to the discrete cue provided in the previous analysis, this discrete cue is provided to the pilots when the aircraft leaves the Safe Flight Envelope (SFE) and the FEP becomes active, and the direction of the cue is the required direction to avoid the approaching limit. As such, a positive roll (i.e., to the right) cue is provided when $\phi < -\phi_{\text{prot}}$, a negative roll (left) cue is provided when $\phi > \phi_{\text{prot}}$. A positive pitch (push) cue is provide when one or multiple of the following conditions are met: (i) $\alpha > \alpha_{\text{max}_{\text{prot}}}$ or (ii) $n > n_{\text{max}_{\text{prot}}}$. A negative pitch (pull) cue is provided when at least one condition is met of the following: (i) $V > V_{\text{MO}_{\text{prot}}}$, (ii) $n < n_{\text{min}_{\text{prot}}}$, or (iii) $\alpha < \alpha_{\text{min}_{\text{prot}}}$.

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

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

To clarify the expected working principle of the haptic feedback system, Fig. 4 shows the time trace of an illustrative example: Fig. 4a, 4b and 4c show, respectively, the time traces of the velocity, angle of attack and resulting force supplied to the control device, i.e., the haptic feedback.



(a) Velocity

(b) Angle of attack

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

Fig. 4 Illustrative example of haptic feedback triggering on changing states.

At the start of the example, the aircraft accelerates to a value just below its maximum velocity. When the protection velocity is exceeded at Frame 1, as shown on Fig. 4a, the two initial ticks are supplied to the side-stick visible on Fig. 4c. These initial discrete cues have a set intensity of I_0 and are positive/backwards: indicating a pulling-action is required. While remaining in the upper velocity protection, the ticks are repeated every second, and the intensity is adjusted to reflect the relative distance from the protection limit to the ultimate flight envelope limit. Upon decelerating outside this upper velocity protection in Frame 2, the ticks are stopped and the nominal side-stick feeling is resumed.

When the angle of attack increases above the protection value at Frame 3 shown on Fig. 4b, two more ticks are provided on the side-stick as illustrated on Fig. 4c. Note that the direction of the tick is opposite from the previous: these ticks at intensity I_0 are negative/forward, indicating that the current problem can be resolved by pushing. By decelerating more, the velocity drops below the green dash-dotted line on Fig. 4a, i.e., halfway between the lower protection and lower flight envelope velocity, at Frame 4. At that point, the stick shaker is activated as shown by the added oscillations on the force to the side-stick on Fig. 4c. The intensity of the discrete cues is again adjusted to reflect the relative distance to the ultimate flight envelope. Increasing the velocity/lowering the angle of attack, stops the stick shaker at Frame 5 and the discrete ticks at Frame 6, resuming nominal side-stick feeling again.

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

III. Method

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

A. Participants & Instructions to Participants

For this experiment, 24 pilots (1 female, 23 male) with a current Private Pilot License (PPL) or Light Aircraft Pilot License (LAPL) license are invited. As these pilots are not necessarily active Airbus pilots, they are reminded that

Table 1 Participants in the experiment

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

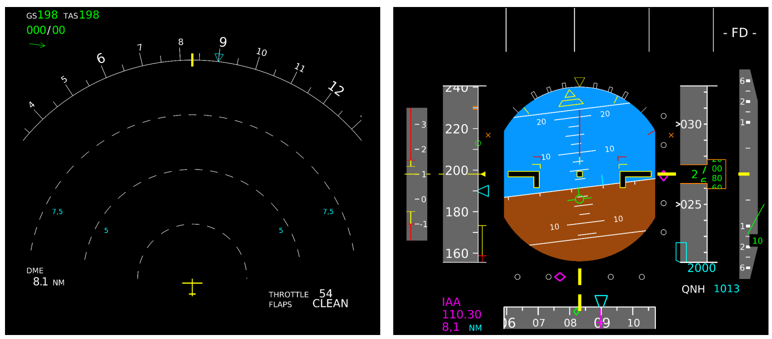
the aircraft model used has a mass of $64,000 kg$ and has to be handled with more care than a general aviation aircraft. Additionally, they are instructed to always stay within the nominal limits of the FE (black line on Fig. 1) which are shown on the PFD using the red indications proposed in Ref.[22]. Additionally it was mentioned that each run would stop at $50 ft$ above ground level irrespective of any other event/performance due to limitations of the simulation.

B. Experimental Setup

The experiment is performed in the Human Machine Interaction (HMI) research simulator of Delft University of Technology. It is a fixed-base, near 180° outside field-of-view, used in the first officer position of which an inside-view is shown in Fig. 5. 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 overview of the situation, shown in Fig. 6a, combined with a basic engine N1-indication and slats/flaps indication. The display right in front of the pilot is the PFD showing the critical flight states, shown in Fig. 6b, which includes display indications used to show *why* and *when* the haptic feedback is active. [22] Next to the visual information, auditory warnings are presented when the angle of attack is above the maximum value, and when the velocity is above the maximum velocity.

A custom-made, hydraulically driven side-stick with programmable dynamic properties is located at the right-hand side and configured to Airbus side stick properties. [23] To the left, a throttle quadrant is present which can be used to control the throttle and high lift device settings. Centrally placed, a Boeing 737 Mode Control Panel (Airbus

Fig. 5 Inside view of the HMI cockpit



(a) ND **(b) PFD**

Fig. 6 Cockpit display setup used in the experiment

terminology: Flight Control Unit (FCU)) enables the interface with the heading/velocity/altitude references on the displays. Outside visuals are generated using FlightGear† and show the airport infrastructure, terrain and important buildings at the airport. A proprietary A320 flight dynamics model, including control laws from the German Aerospace Center (DLR), is used as the simulated aircraft. [24]

The nominal control device settings for this experiment, including mass (m), spring coefficient (k), damping coefficient (b) and maximum deflection ($\delta_{\max}$), for both longitudinal and lateral side stick axes are given in Table 2. Forcing functions used in the experiment are: (i) a sawtooth shape of intensity $0.282Nm$, duration $1s$ and frequency $2Hz$ when exiting the safe flight envelope, (ii) a sawtooth shape with varying intensity proportional to the relative distance of the protection and flight envelope limit, duration $0.5s$ and frequency $2Hz$ when remaining outside the safe flight envelope and (iii) a stick shaker for low velocities as a sinusoid with frequency of $20Hz$ and magnitude $0.426Nm$.

C. Experiment Scenarios

The haptic feedback system is designed to communicate the 'proximity of the flight envelope limits' to the pilot and therefore requires an evaluation at these limits. In previous work, this was achieved by presenting the pilots with a

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

Table 2 Control device in the experiment

	m	$k_{\mathrm{lon}_{\mathrm{nom}}}$	b_{lon}	$\delta_{\mathrm{lon}_{\max}}$	$k_{\mathrm{lat}_{\mathrm{nom}}}$	b_{lat}	$\delta_{\mathrm{lat}_{\max}}$	k_{br}	δ_{br}
Value	0.2	36.3	0.4	0.279	21.8	0.4	0.314	544	$8 \cdot 10^{-4}$
Unit	kg m^2	Nm/rad	Nm s/rad	rad	Nm/rad	Nm s/rad	rad	Nm/rad	rad

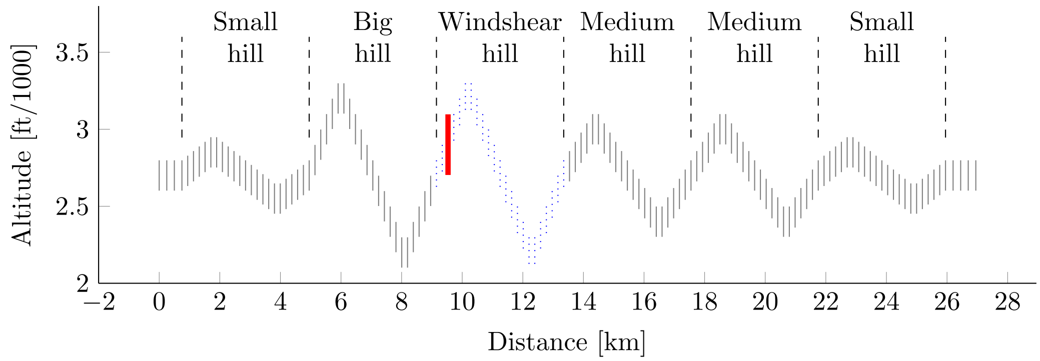
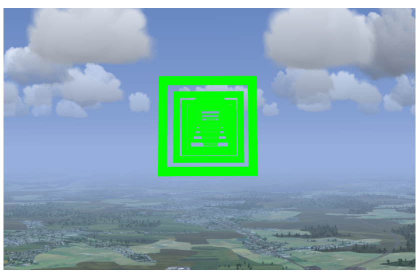
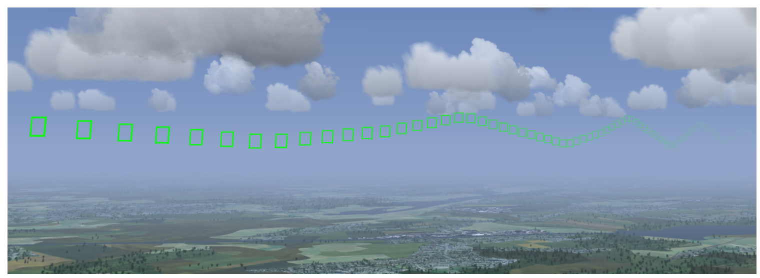


Fig. 7 Flight path side-view, solid black vertical lines indicate "fly-through gates" shown on the outside visual; the thick red line indicates the trigger point of the windshear (not shown on the outside visual); the dotted blue lines lines indicate the windshear section used in our evaluation.



(a) View at start of run.



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

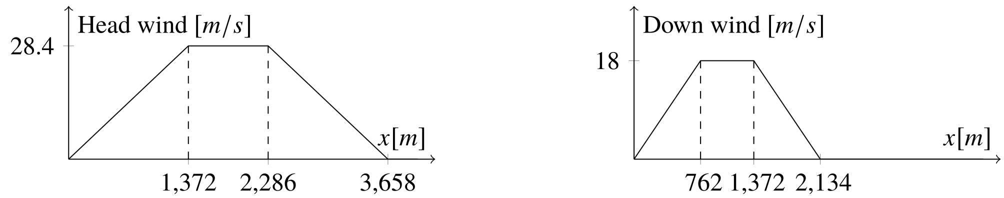
Fig. 8 Example of the outside visual flight path visualization.

scenario as realistic as possible: initializing the simulation right before the pilot would intercept the glide slope and localizer. An event was triggered after following the glide slope/localizer for several minutes. The analysis showed that, due to this initial part of the simulation, the aircraft state (velocity/altitude/heading) of each pilot when the events were triggered, were not equal and resulted in a large spread in the data. Therefore these experiments indicated that it was beneficial to reduce the degrees of freedom allowed to the pilot participants. [11, 22] Therefore, in the present experiment the required flight trajectory is more stringent, as will be discussed below, followed by the emergency scenario encountered.

1. Flight path

Each run is started when the aircraft is flying 140kts (72.0mps) at 2500ft (762m) with flaps setting 3, overhead the threshold of runway 23 of Zoersel (Belgium) and aligned with the respective runway. This location is chosen as it has no special terrain features close-by, and the runway is not visible from the starting position as illustrated on Fig. 8a. Additionally, the auto-throttle is set to 140kts and activated, reducing the variability of the initial aircraft state when the event is triggered and should provide more consistent results. From this position, pilots are presented with visual markers (squares of 60m by 60m) on the outside display to fly a flight profile consisting out of six 'hills', for which an example path is presented in Fig. 7 and the visualized on the outside visual illustrated by Fig. 8.

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



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

Fig. 9 Windshear component distribution

2. Emergency scenario

As the pilots of the experiments mentioned before did express the potential added value of the haptic feedback system in a windshear event, this event is re-used for this research. During a windshear event, a large cylinder of air is plunging towards the ground, resulting in winds pushing the aircraft to the ground. To recover from this event, the pilot has to move as close to the stall limit as possible to prevent further descent and utilize maximum performance of the aircraft.

The windshear is *always* started when the aircraft moves through the visual marker of the large amplitude hill at an altitude of $883.92m$ ($2900ft$). Each flight path contains two large hills, only one of them is selected at random to contain the windshear trigger point. The windshear itself is modeled by both a head-on and top-down component as shown in Fig. 9. [25] Once the windshear is initiated, the visual and aural warning trigger, and the pilot has to apply the windshear recovery procedure as stipulated in Fig. 10a, which is based on the Airbus Flight Crew Operating Manual. [15]

When providing only windshear as the emergency scenario, pilots might anticipate this event, even in the first run. To prevent this, two more checklists for an emergency are presented to the pilots: the actions required for a single engine stall (Fig. 10b), and for a sudden center of gravity shift (Fig. 10c). Note that the checklists presented in Fig. 10a and 10b are heavily modified from the FCOM, and the checklist for the sudden center of gravity shift is non-existing in the FCOM.

D. Experiment design

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

1. Familiarization

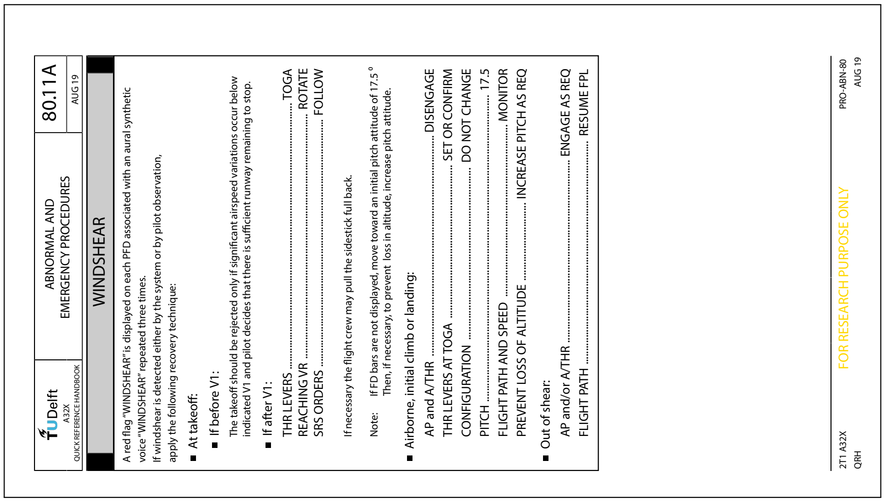
After a briefing on the simulator safety procedures, controls and displays, the pilots *feel* the design rationale behind the haptic feedback design. This is done by presenting the FE (an image similar to Fig. 1), the haptic feedback (a time trace of the forcing function on the side-stick), and the PFD (Fig. 6b) 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 visual, auditory and haptic cues are elaborated.

Next the model is introduced to the pilot by flying a traffic pattern twice to a final approach at Schiphol (EHAM) as shown on Fig. 11 without the haptic feedback, hence focusing on familiarization with the model. Pilots are instructed to follow the instructions as indicated. Some pilots did encounter a stall and/or an overspeed condition during these first runs. If the pilots did not hit one or both limits by accident, they are asked to deliberately explore those boundaries to ensure that all pilots encountered them before the measurement runs.

2. Measurements

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

After each run, pilots are asked to indicate their workload using a Rating Scale Mental Effort (RSME) rating [27], and complete a post-run situation awareness questionnaire, to indicate how helpful the display and haptic (if supplied)



TU Delft A32X QUICK REFERENCE HANDBOOK | ABNORMAL AND EMERGENCY PROCEDURES | 80.11A | AUG 19

WINDSHEAR

A red flag "WINDSHEAR" is displayed on each PFD associated with an aural synthetic voice "WINDSHEAR" repeated three times.
If windshear is detected either by the system or by pilot observation, apply the following recovery technique:

- At takeoff:
  - If before V1:
    The takeoff should be rejected only if significant airspeed variations occur below indicated V1 and pilot decides that there is sufficient runway remaining to stop.
  - If after V1:
    THR LEVERS .... TOGA
    REACHING VR .... ROTATE
    SRS ORDERS .... FOLLOW

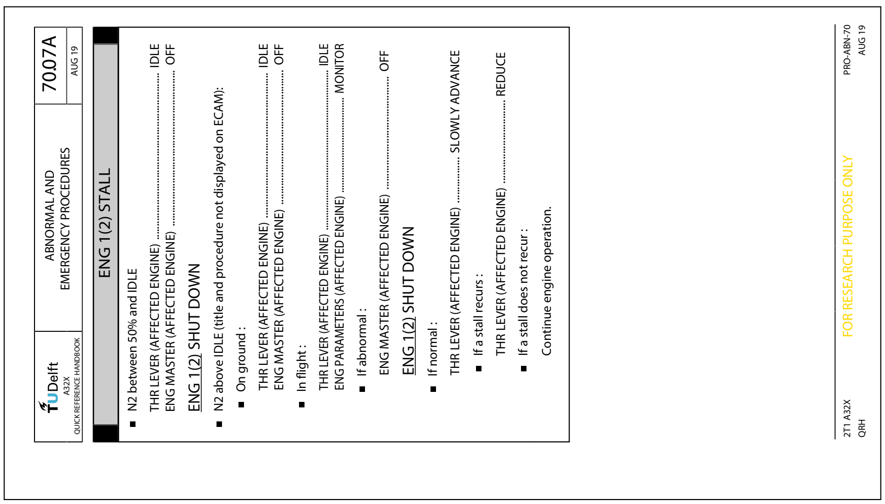
If necessary the flight crew may pull the sidestick full back.

Note: If FD bars are not displayed, move toward an initial pitch attitude of 17.5 °
Then, if necessary, to prevent loss in altitude, increase pitch attitude.

- Airborne, initial climb or landing:
  AP and A/THR .... DISENGAGE
  THR LEVERS AT TOGA .... SET OR CONFIRM
  CONFIGURATION .... DO NOT CHANGE
  PITCH 17.5
  FLIGHT PATH AND SPEED .... MONITOR
  PREVENT LOSS OF ALTITUDE .... INCREASE PITCH AS REQ
- Out of shear:
  AP and/or A/THR .... ENGAGE AS REQ
  FLIGHT PATH .... RESUME FPL

2T1 A32X QRH | FOR RESEARCH PURPOSE ONLY | PRO-ABN-80 AUG 19

(a) Windshear recovery



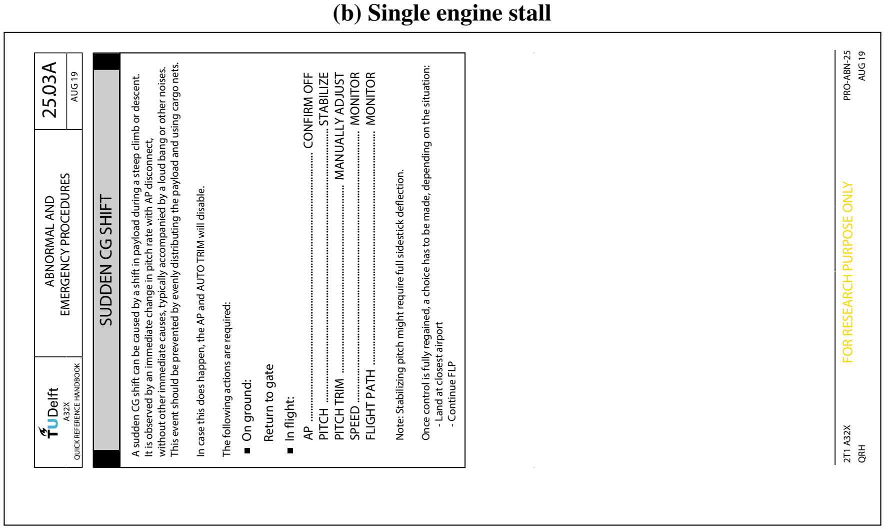
TU Delft A32X QUICK REFERENCE HANDBOOK | ABNORMAL AND EMERGENCY PROCEDURES | 70.07A | AUG 19

ENG 1(2) STALL

- N2 between 50% and IDLE
  THR LEVER (AFFECTED ENGINE) .... IDLE
  ENG MASTER (AFFECTED ENGINE) .... OFF
  ENG 1(2) SHUT DOWN
- N2 above IDLE (title and procedure not displayed on ECAM):
  - On ground :
    THR LEVER (AFFECTED ENGINE) .... IDLE
    ENG MASTER (AFFECTED ENGINE) .... OFF
  - In flight :
    THR LEVER (AFFECTED ENGINE) .... IDLE
    ENG PARAMETERS (AFFECTED ENGINE) .... MONITOR
    - If abnormal :
      ENG MASTER (AFFECTED ENGINE) .... OFF
      ENG 1(2) SHUT DOWN
    - If normal :
      THR LEVER (AFFECTED ENGINE) .... SLOWLY ADVANCE
      - If a stall recurs :
        THR LEVER (AFFECTED ENGINE) .... REDUCE
      - If a stall does not recur :
        Continue engine operation.

2T1 A32X QRH | FOR RESEARCH PURPOSE ONLY | PRO-ABN-70 AUG 19

(b) Single engine stall



TU Delft A32X QUICK REFERENCE HANDBOOK | ABNORMAL AND EMERGENCY PROCEDURES | 25.03A | AUG 19

SUDDEN CG SHIFT

A sudden CG shift can be caused by a shift in payload during a steep climb or descent.
It is observed by an immediate change in pitch rate with AP disconnect,
without other immediate causes, typically accompanied by a loud bang or other noises.
This event should be prevented by evenly distributing the payload and using cargo nets.

In case this does happen, the AP and AUTO TRIM will disable.

The following actions are required:

- On ground:
  Return to gate
- In flight:
  AP .... CONFIRM OFF
  PITCH .... STABILIZE
  PITCH TRIM .... MANUALLY ADJUST
  SPEED .... MONITOR
  FLIGHT PATH .... MONITOR

Note: Stabilizing pitch might require full sidestick deflection.

Once control is fully regained, a choice has to be made, depending on the situation:
- Land at closest airport
- Continue FLP

2T1 A32X QRH | FOR RESEARCH PURPOSE ONLY | PRO-ABN-25 AUG 19

(c) Sudden CG shift

Fig. 10 Provided checklists for the emergency scenario's (provided to pilots on A4 paper size)

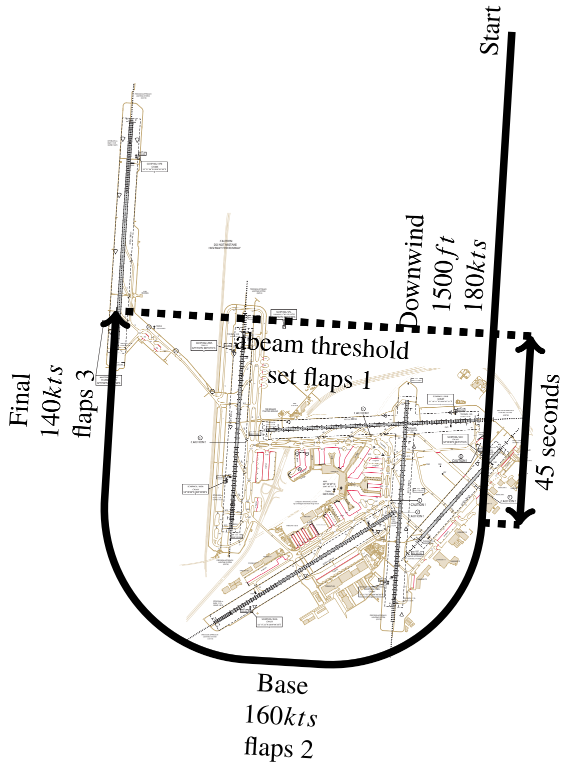


Fig. 11 Traffic pattern flown to runway 36L at Schiphol (Schiphol layout from AIP [26])

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

Fig. 12 Experimental design

elements are. They also provided a misery scale rating tracking effect of motion sickness. [28] Once this is completed, the pilots are informed on how much time they spent inside the FE, which they have to maximise.

After one block of four runs, the pilots are asked to complete a questionnaire with a modified Cooper-Harper rating scale ([29]), and a Van der Laan-rating scale. [30] After the experiment was completed, pilots are asked to complete a post-experiment questionnaire, which contained a number of questions with Likert-scales on how they experienced the haptic feedback system.

E. Independent variables

The experiment has two independent variables. First, the haptic feedback is within-subject either present (HF), or not (NH). Second, the subjects are between-subject divided in two groups: the haptics first group (HFG) receives haptic feedback for four runs, followed by no haptic feedback, the haptics second group (HSG) vice versa as shown in Fig. 12. All participants with an odd number in Table 1 are placed in the HFG, all even-numbered participants are part of the HSG.

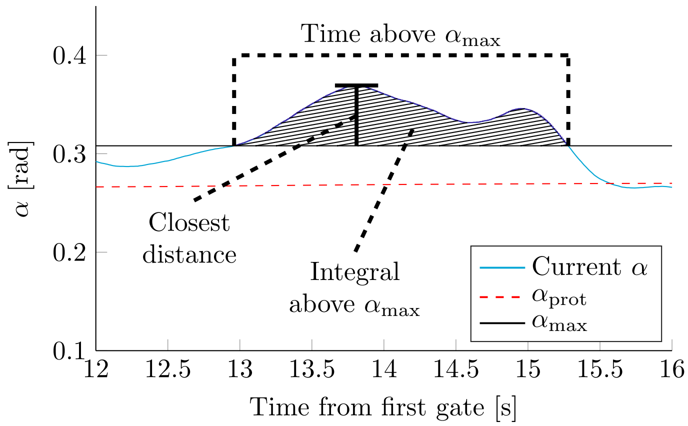


Fig. 13 Time trace of velocity with safety metrics indicated.

F. Dependent Measures

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

1. Objective measures

The objective measures are retrieved from the windshear recovery procedure, and focus on performance and safety. To show why metrics were chosen, a time excerpt of a windshear recovery is shown in Fig. 13. Another example is further elaborated in the results section, for now it is sufficient to understand that this shows a participant hunting for the best performance of the aircraft close to the maximum angle of attack.

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

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

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

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

Previous research shows that the perceived level of risk is mostly kept constant with increasing support, i.e., risk homeostasis, as exampled by a haptic feedback system in an automotive study. [31, 32] For the current paper, risk homeostasis can be defined by improved performance combined with a degradation of the objective safety metrics, as pilots obtain a better awareness of the risk involved when supplied with haptic feedback.

2. Subjective measures

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

- Workload: after each run, the pilot is asked to provide a RSME [27]
- 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?

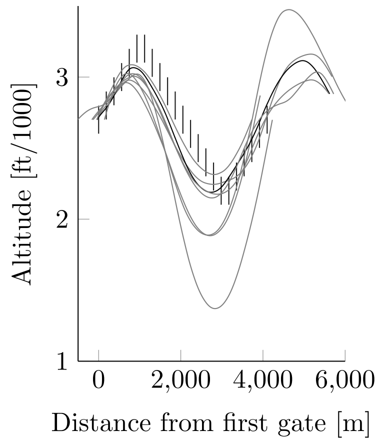


Fig. 14 Windshear recoveries flown by Participant 23, Run 3 indicated in black, vertical lines represent gates on the outside visual.

- Usefulness:
  1) Pilots are asked after each run to rate the usefulness of all display and haptic elements
  2) After a block of 4 runs, pilots are asked to provide a modified Cooper-Harper rating
  3) After a block of 4 runs, pilots are asked to fill a Van Der Laan-questionnaire
- Pilot experience: after the experiment, the pilot is asked to fill in a questionnaire regarding the experience with the haptic feedback system. It uses a five point Likert-scale where the all points are labeled.

G. Hypotheses

From the experiment, we expect the following when the pilot is provided with haptic feedback:

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

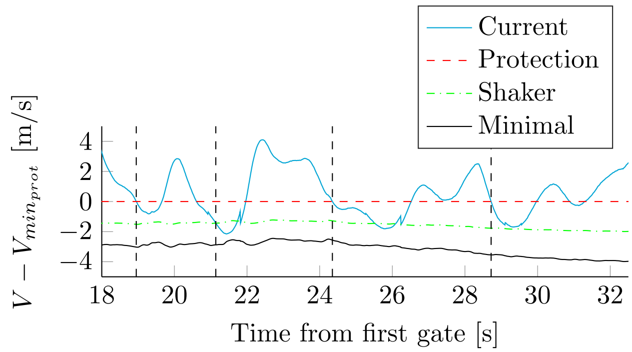
IV. Results

To see how a pilot can use the haptic feedback system, Subsection IV.A shows a time trace of a windshear recovery. Next, the objective and subjective measures are discussed in, respectively, Subsection IV.B and IV.C. Answers to the debriefing questionnaires are shown in Subsection IV.D. All flown trajectories for all flight paths used are included in Appendix A, together with one extra participant, a very experienced commercial airline pilot, who was included to check the performance of the 24 less experienced pilots.

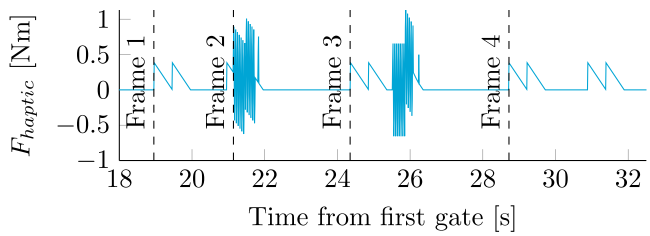
When presenting data using box plots, medians are indicated using a horizontal thick line, outliers are indicated using plus-signs; all individual data points are presented next to the boxes using crosses. Furthermore, statistical analysis is performed in R ([33]) and a significance level of 0.05 is used. When comparing the means of the haptic versus no haptic feedback conditions (HF vs NH), or within one group on different runs, a Friedman test is performed. Within single runs and between groups, results are compared using the Wilcoxon Rank Sum test.

A. Time trace

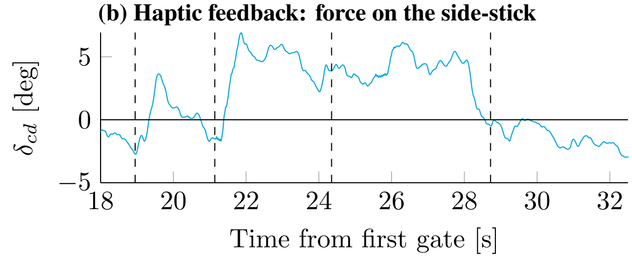
Fig. 14 illustrates all windshear recoveries from Participant 23, and shows that they all follow a similar pattern in terms of altitude. The black line indicates a situation where the pilot made use of the haptic feedback, as shown on



(a) Velocity relative to the minimal protection velocity.



(b) Haptic feedback: force on the side-stick



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

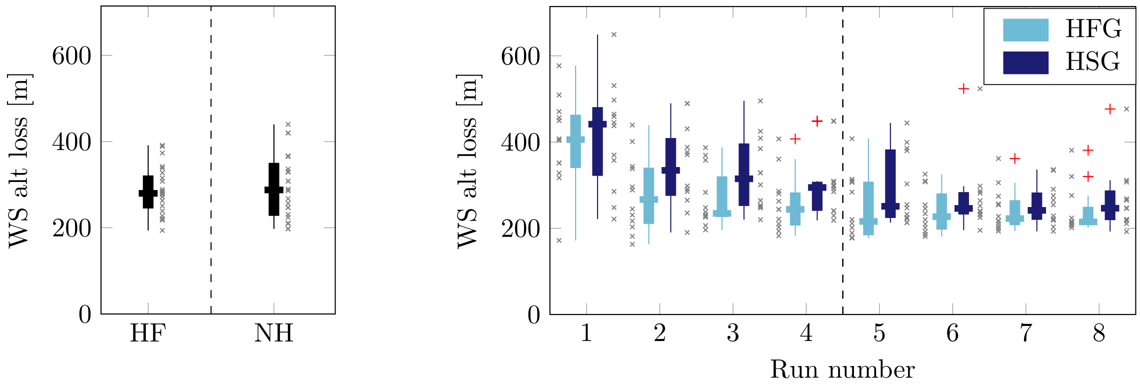
Fig. 15 Example of Participant 23 using the haptic feedback during the windshear recovery in Run 3.

Fig. 15. During the windshear recovery, the goal is to stay as close to the limit as possible, while not surpassing it during the highly dynamic recovery phase. During the recovery performed in this example, shown on Fig. 15, at Frame 1 the haptic feedback (Fig. 15b) informs the pilot of the approaching limit (Fig. 15a), the pilot reacts by reducing the input (Fig. 15), even pushing the side-stick. When clear of the limit, a more negative input is given again, resulting in a quick encounter of the stick shaker at Frame 2. The pilot reacts by pushing hard on the side stick and succeeds in increasing the aircraft velocity. In the dynamic situation, the wind is changing and the state of the aircraft is moving closer to the limit even though a positive/push input is provided. In Frame 3, the pilot is informed of the protection zone, yet decides not to act on it yet, only at the subsequent stick shaker, the positive input is increased and the state moves out of the protection zone. After Frame 4, two more occurrences of the initial tick occur on which the pilot reduces the input slightly.

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

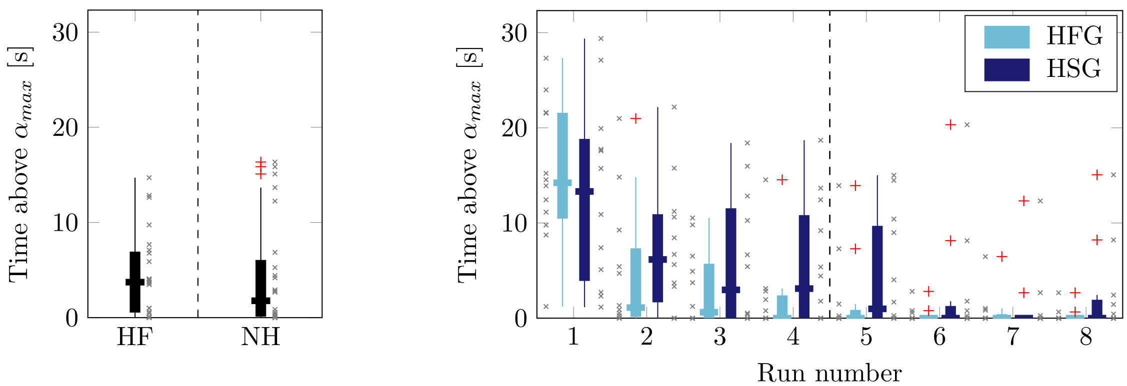
B. Objective measures

For the windshear recovery, the difference in altitude between the windshear trigger point and the lowest point encountered during the windshear is calculated and averaged over the four runs in one block (following the block/run structure in Fig. 12). The results in Fig. 16a show that there is no difference in performance when comparing the HF and NH conditions, which is supported by no statistical significance of a Friedman test. This result is found despite the fact that during the experiment the final runs with haptic feedback seemed better compared to the runs without haptic



(a) Initial analysis **(b) Individual runs**

Fig. 16 Altitude lost during windshear recovery



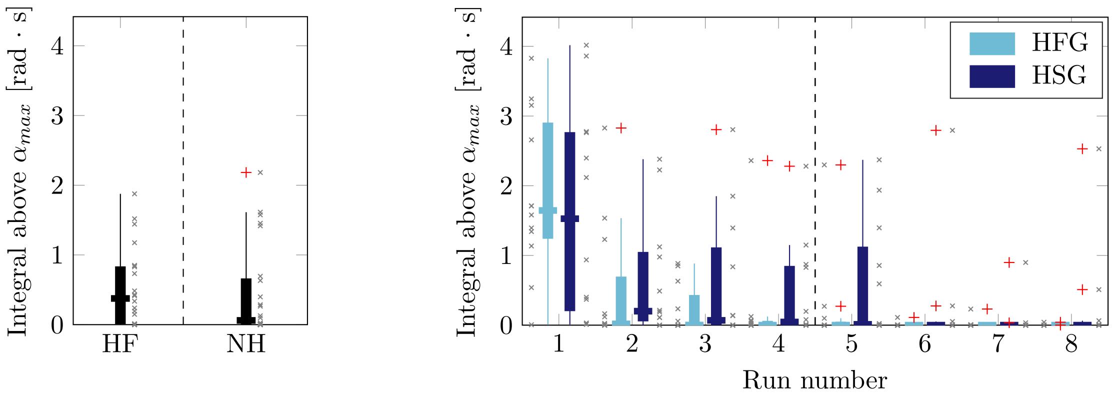
(a) Initial analysis **(b) Individual runs**

Fig. 17 Time with angle of attack above maximum value during windshear recovery

feedback.

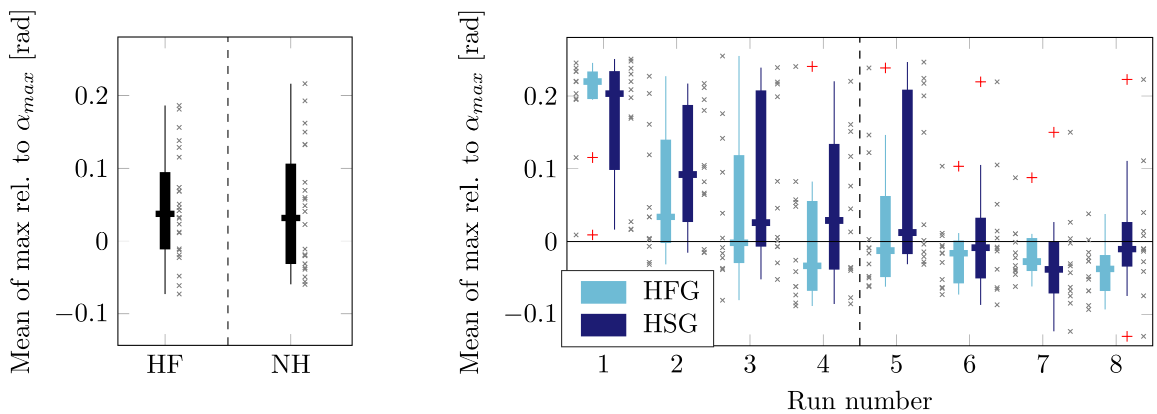
To find out why no effect of the haptic feedback was found, the windshear performance is plotted for each individual run in Fig. 16b. This shows that, irrespective of whether haptic feedback is supplied or not, a strong learning effect is present during the first runs, resulting in unchanged means, as shown in Fig. 16a. Additionally, it shows that the median of the haptic first group (HFG) reduces faster compared to the haptic second group (HSG). To investigate this learning effect present, statistical analysis is performed to compare Runs 1 and 4, indicating a statistical difference for the HFG ($\chi^2 = 8.33$, $p < 0.01$) and near statistical significance for the HSG ($\chi^2 = 3$, $p = 0.08$). Using a Wilcoxon Rank Sum, no statistical significance at Run 4 is found between both groups ($W = 42$, $p = 0.09$), although although the plot show a small difference in median. Friedman analysis on Runs 4 and 8 did not show a significant difference in means for both groups. In other words, there seems to be no further improvement in performance in the final four runs.

Pilots were instructed to stay within the FE limits at all times. Although time spent outside the FE should ideally be zero, the means for both blocks shown on Fig. 17a indicates that this was not always the case. Similar to the performance in terms of altitude lost during the recovery, this performance metric does not have a visual or statistical difference when providing haptic feedback. As also seen with that previous metric, this metric shows a quicker improvement of the performance metric in terms of each run as shown on Fig. 17b. There again is a visual and statistical difference between Runs 1 and 4 for both groups (HFG: $\chi^2 = 12$, $p < 0.001$, HSG: $\chi^2 = 8.33$, $p < 0.005$). Although visually the HSG appears to spend more time above the maximum angle of attack, no statistical significance using the Wilcoxon Rank Sum was found between the results of Run 4 for both groups, possibly due to the fact that numerous data-points are at zero. Nevertheless, the median of the HFG approaches zero from Run 2, whereas the median of the HSG has a median clearly above zero even at Run 4. Statistical analysis showed no difference between Runs 4 and 8 for the HFG, yet the HSG has a 'near' statistically significant difference ($\chi^2 = 3.57$, $p = 0.059$).



(a) Initial analysis **(b) Individual runs**

Fig. 18 Integral of angle of attack above maximum value during windshear recovery

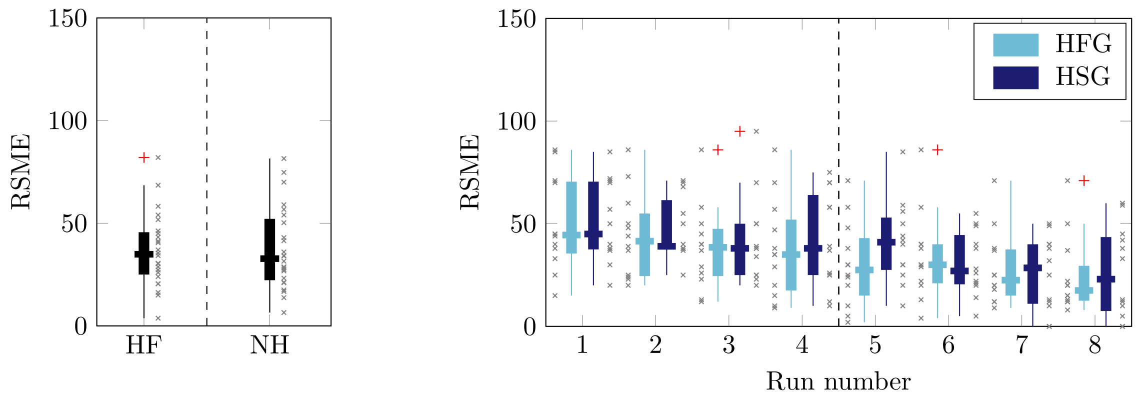


(a) Initial analysis **(b) Individual runs**

Fig. 19 Highest angle of attack obtained during the windshear recovery, relative to the maximum angle of attack (positive values result in a stall warning).

Safety during the windshear recovery is further evaluated using the integral of the angle of attack above the maximum value allowed by the flight envelope, with the per block averaged results in Fig. 18a. As before, no difference is observed (visually or statistically), yet Fig. 18b shows a difference between Runs 1 and 4 (for both groups $\chi^2 = 12$, $p < 0.001$). Although no statistical difference is found between both groups at Run 4, a statistical significant difference is found between Runs 4 and 8 for the HFG ($\chi^2 = 5$, $p < 0.05$) as all participants have near zero metric, and near statistical difference for the HSG ($\chi^2 = 3.57$, $p = 0.059$) although the visual change appears to be quite large.

The second safety metric is the closest point to the maximum angle of attack, for which the per-block means are shown on Fig. 19a. These again show no difference. Focusing on the individual runs in Fig. 19b, Friedman tests show a significant difference between Runs 1 and 4 for both groups (HFG: $\chi^2 = 8.33$, $p < 0.01$, HSG: $\chi^2 = 12$, $p < 0.001$). While a Wilcoxon test comparing the results of both groups at Run 4 did not show statistical significance, one has to observe one critical difference: the mean of the HSG (hence without haptic feedback) is above zero, meaning that at least half of the participants reached angles of attack above the maximum. For the HFG, the median is below zero, indicating that at least half of the participants in the HFG did not exceed the maximum angle of attack. Looking at the evolution of the metrics after the break, the HFG seems to slightly improve yet this is not supported by statistical significance. On the other hand, the HSG does have a 'near' statistically significant difference from Runs 4 to 8 ($\chi^2 = 3$, $p = 0.083$). In addition, it is clear that the spread of all data reduces and the median approaches zero when providing haptic feedback.



(a) Initial analysis **(b) Individual runs**

Fig. 20 Rating Scale Mental Effort (subjective workload).

C. Subjective measures

The subjective measures are divided in metrics obtained after each run, and metrics obtained after a block of four runs with, or without, haptic feedback.

1. Subjective measures obtained after each run

After each run, participants are asked to fill in a Rating Scale Mental Effort (RSME) on a calibrated scale ranging from zero to 150, indicating how much mental load was required for the task. The results per block are shown in Fig. 20a, and similarly to the objective measures, have no difference (both visually and statistically). The results per run in Fig. 20b clearly show a learning effect: an improvement is present from the initial run towards the final run. Both groups show a similar trend, and no statistical differences between groups are observed within one run.

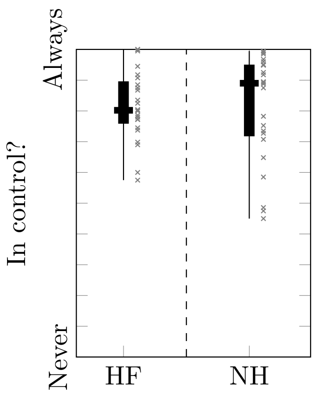
Situation awareness is subjectively measured by asking the pilot whether (s)he has the feeling of being control (Fig. 21) and the feeling of missing information (Fig. 22). Ideally, a pilot always has the feeling of being in control and is never missing information. Looking at the plot for block in Fig. 21a and Fig. 22a, no differences between conditions can be seen, confirmed by no statistical difference. When looking at the individual runs (Fig. 21b and Fig. 22b), no clear visual differences can be seen between groups in terms of trend or final value. Statistical analysis showed a significant difference for the HFG with the feeling of being in control of Run 4 compared to Run 8 ($\chi^2 = 2.78$, $p < 0.1$). An additional interesting point can be the transition from Run 4 to Run 5: going from receiving haptic feedback to no feedback (HFG) increases the feeling of missing information, and when enabling the haptic feedback reduces the feeling of being in control (HSG). Nevertheless, this is not supported by statistical significance using a Friedman test for both sub-scales.

2. Subjective measures obtained after a block

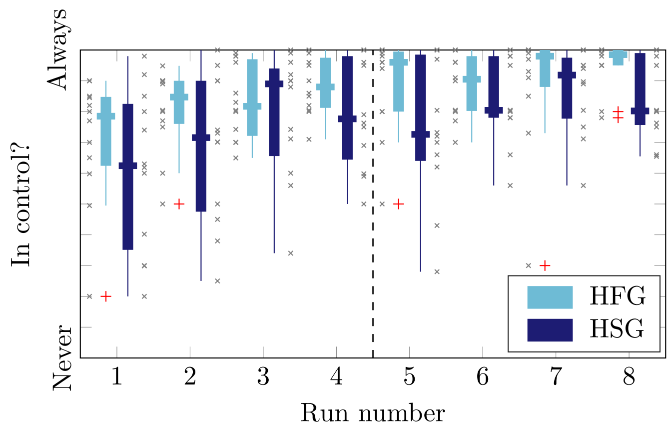
After a set of four runs with or without haptic feedback, a questionnaire queries the pilots for more high level feedback on the way of presenting the flight envelope limits. Two typical scales are used and shown here. First of all, a Modified Cooper-Harper rating scale is presented for which the results are shown in Fig. 23. Keep in mind that the scale ranges from ten to one, where one is the best score. Additionally, the horizontal lines on the figure indicate the tipping point for the questions on the decision tree. Both the figure and statistical tests did not show a difference between groups for either haptic feedback or no haptic feedback. Equally so, the figure and Friedman test did not show an in-between participant difference for the haptic feedback.

Secondly, a Van Der Laan-questionnaire asks nine questions to score the system on usefulness and satisfaction, keep in mind that due to the definition of the questionnaire, a perfectly useful and satisfying system would score minus two on both scales. Fig. 24 shows the results for the analysis, Fig. 24a shows the raw scores for both groups and indicates that both with and without haptic feedback, the system is well received in terms of usefulness and satisfaction.

Fig. 24b shows the differences of the system with haptic feedback, relative to the no haptic feedback case. Looking at the mean of all participants, only a small improvement in usefulness is obtained. More intriguing is the mean of each

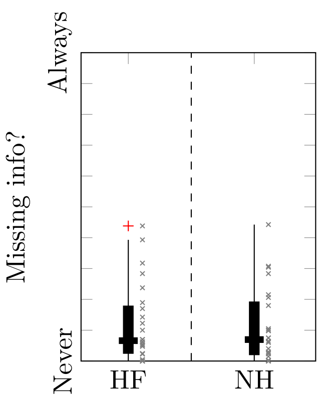


(a) Initial analysis

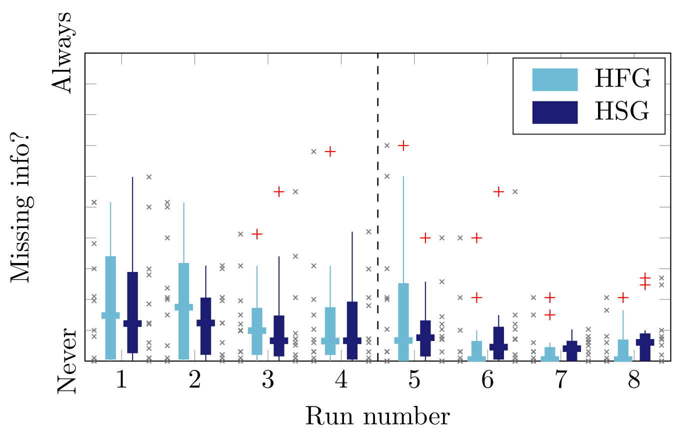


(b) Individual runs

Fig. 21 Did the pilot have the feeling of being in control?



(a) Initial analysis



(b) Individual runs

Fig. 22 Did the pilot have the feeling (s)he was missing information?

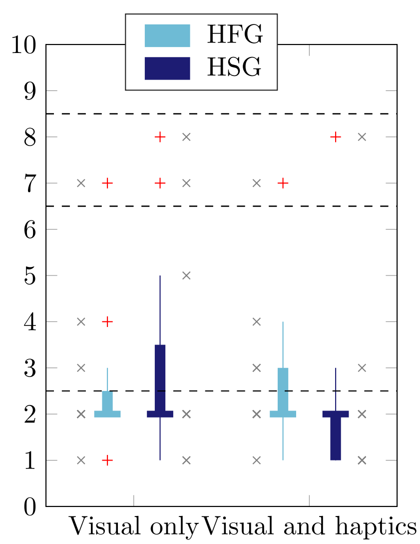
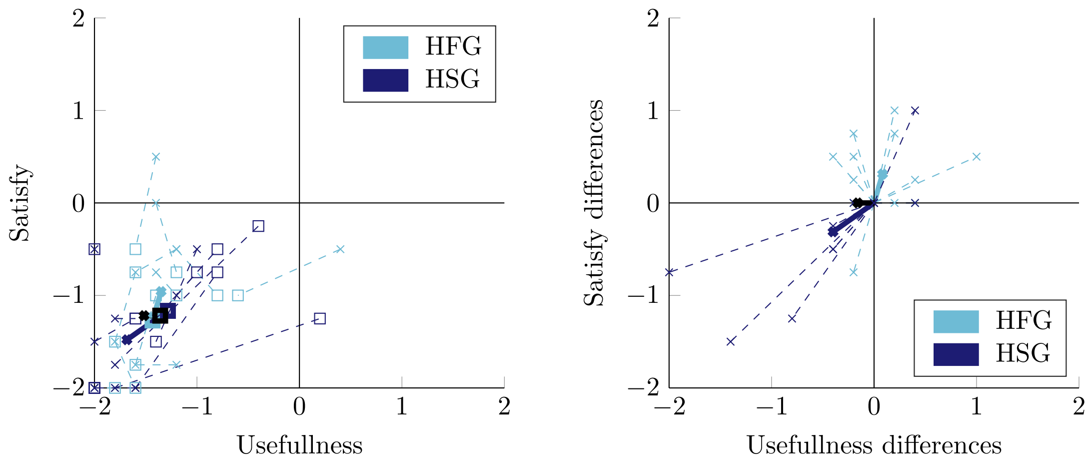


Fig. 23 Modified Cooper-Harper rating



(a) Raw data

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

Fig. 24 Van Der Laan-ratings. Black bold indicates population mean, coloured bold indicate group means. Squares represent the score after a block without haptic feedback, crosses with haptic feedback.

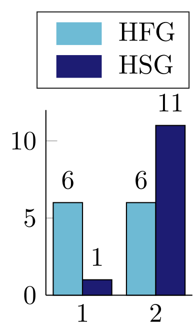


Fig. 25 Which feedback system is preferred by the pilots?

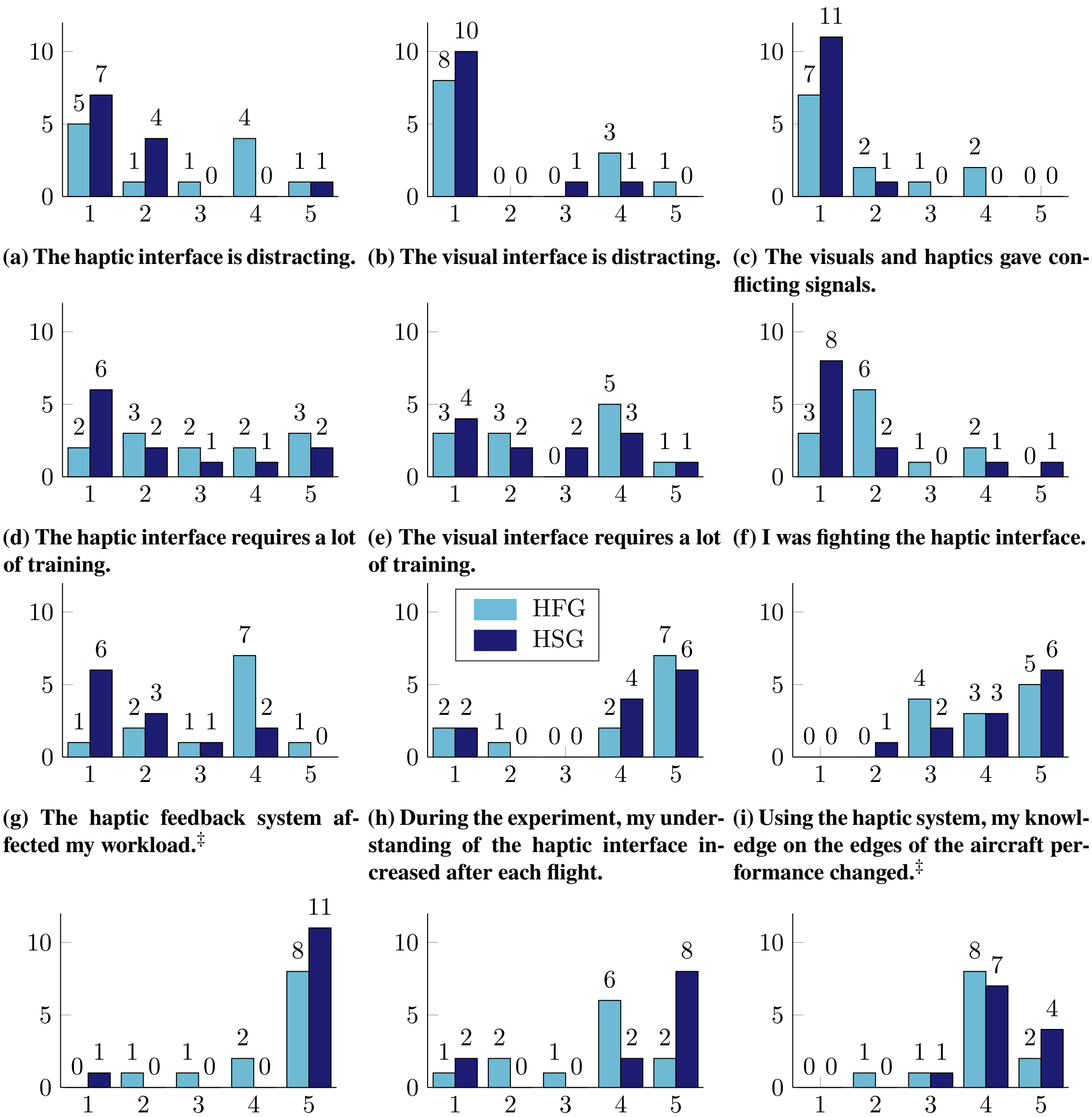
group separately indicated with the bold lines. This indicates that the participants who started without haptic feedback experience the system with haptic feedback to be more useful and more satisfying. On the contrary, participants who started with haptic feedback experienced the conditions without haptic feedback as more useful and satisfying. As such, an order effect of presenting the haptic feedback is present.

D. Debriefing questionnaires

In order to have a structured debriefing session when all runs are completed, a questionnaire involving 19 questions was presented to the pilots. The first and foremost question presented pilots a simple choice: do you prefer to fly with or without haptic feedback? Results to this first question are shown in Fig. 25, which follows the order effect stated before with the Van Der Laan-questionnaires: the vast majority of the HSG prefers the haptic feedback, the participants in the other group are divided: half of them prefer the haptic feedback. Most other debriefing questions used a five point Likert-scale for which questions and results are shown in Fig. 26.

Pilots indicate that the haptic and visual display are not distracting (respectively Fig. 26a and Fig. 26b), yet are indecisive on whether a lot of training is needed (Fig. 26d and Fig. 26e). Shown on Fig. 26c, they do indicate that the combination of visual and haptic feedback did not give conflicting signals (as they were designed for in Ref. [22]).

Focusing on the haptic feedback, most pilots felt that they were not fighting the haptic feedback (Fig. 26f), nevertheless they are indecisive on whether the workload was changed (Fig. 26g). For this latter question, note the order effect: the HFG mostly indicates a marginal increase in workload, whereas the HSG indicates a decrease in workload. The majority of the pilots indicate that there is a learning effect present over the run (Fig. 26h), and they agree that their knowledge on



(a) The haptic interface is distracting. **(b) The visual interface is distracting.** **(c) The visuals and haptics gave conflicting signals.**

(d) The haptic interface requires a lot of training. **(e) The visual interface requires a lot of training.** **(f) I was fighting the haptic interface.**

(g) The haptic feedback system affected my workload.‡ **(h) During the experiment, my understanding of the haptic interface increased after each flight.** **(i) Using the haptic system, my knowledge on the edges of the aircraft performance changed.‡**

(j) The haptic interface helps in preventing critical situations. **(k) If a critical situation occurs, the haptics helps in resolving it.** **(l) When implementing this system on an aircraft, what would be the effect on safety?§**

Fig. 26 Debriefing Likert-scale questions. Possible answers (unless specified otherwise) were: 1) Disagree 2) Slightly disagree 3) Disagree nor agree 4) Slightly agree 5) Agree

‡ Possible answers: 1) Decreased 2) Marginal decrease 3) Did not change 4) Marginal increase 5) Increased

§ Possible answers: 1) Much unsafer 2) Unsafer 3) Safer nor unsafer 4) Safer 5) Much safer the edges of the FE did increase using the haptic feedback (Fig. 26i).

As mentioned in the Introduction section, upset prevention is one of the major fields to improve in aviation, and our participating pilots agree that this haptic feedback system can help to achieve this (Fig. 26j). When in an upset condition, the majority of our participants think the haptic feedback system might help, yet their answer is not as convincing (Fig. 26k). The final Likert-type question asked the pilot for the effect when implementing this haptic feedback on an aircraft, Fig. 26l shows that a clear majority of the pilots believe that implementing this system can improve safety.

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

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

V. Discussion

Five hypotheses were formulated, all related to the comparison between the conditions with (HF) and without (NH) haptic feedback. First, risk homeostasis was expected to be present in the form of improving performance metrics while objective safety metrics decreased. Results showed no difference between the haptic enabled/disabled conditions for both metrics, hence this hypothesis is not supported by the data. Second, workload was expected to decrease which did not show in both the RSME or the debriefing questionnaire, again not supporting the hypothesis. Third, enabling haptic feedback should improve situation awareness which is not supported by the two situation awareness-related questions proposed to the pilots after every run. Pilots did indicate in the debriefing, however, that the haptic feedback increased their knowledge of the flight envelope, and that it should help to prevent critical situations, as well as to resolve them. So even though this hypothesis is not supported by the data, there are subjective indicators of improved situation awareness as a result of haptic feedback. Fourth, although handling qualities as observed with a Modified Cooper-Harper rating were expected to improve, the results obtained do not support this hypothesis. Finally, Van Der Laan-questionnaires indicate an overall positive acceptance of the system both with and without the haptic feedback. When enabling haptic feedback, the acceptance rating when averaged over all participants improves as expected in the hypothesis, hence supporting this last hypothesis. In summary, all hypotheses except the last one are not supported by the data.

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

A reason for the non-effect on the hypotheses can be found in the design of the experiment: participants are divided in two groups where one group received haptic feedback for the first block of four runs (HFG) and the other groups received haptic feedback in the second block (HSG). The intended goal of this division was to perform a balanced comparison where the order effect due to unfamiliarity and training is eliminated. Nevertheless, the results of the individual runs already show that although all participants received a basic explanation of the interfaces (visual/haptic/aural) and a basic training with the model, the subsequent task and procedure used in the measurement runs was of such difficulty that all participants showed a major learning effect. This is also confirmed by some of the comments made by the participants after the experiment: they indicate that it was a lot to process from the start. As a result, a large order effect is present which cannot be compensated by the balanced experiment design, hence making a comparison of the per block averaged metrics useless. Additionally, the flight path presented on the outside visual is a challenging profile and is not a realistic profile which can be flow in the real aircraft with passengers (within six minutes the load factor varied between $0.45g$ and $1.6g$). The goal of this profile is to ensure that the initial condition for the windshear is always equal, which was achieved, yet probably induced more artefacts because of a training effect.

Despite this unexpected learning effect among all participants, the resulting metrics per run do show an interesting behaviour: when supplying the participants with haptic feedback from the start, the initial learning effect appears to be stronger. This is visible in all performance and safety metrics, as well as the subjective situation awareness (specifically the feeling of being in control), indicating that the haptic feedback might help in more quickly developing a proper strategy to handle the windshear recovery procedure. In addition, the first run without haptic feedback for the HFG does not show any regression, which indicates that there is no reliance on the haptic feedback for the developed strategy. Participants in the HSG, hence those who do not receive haptic feedback from the start, improve their performance over the first runs. Nevertheless, the spread of the metrics only matches the HFG after one run with haptic feedback. This suggests that the haptic feedback can help to improve an already developed strategy further.

The last remarks are based on the analysis performed and observations made in this paper. Further analysis should be performed to investigate the learning effect by fitting learning curves through the data of each participant and comparing their characteristic properties. [34] Furthermore, a re-design of the experiment setup is required to match a transfer-of-training experiment which involves a training phase (comparable to the first block in this experiment), followed by a test phase where the (haptic feedback) support is removed (comparable to the first run without haptic feedback for HFG), and a generalization run where the participants are performing a different, but comparable task, to investigate whether either a skill was learned or participants relied on a pure feedforward technique. [35]

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

VI. Conclusion

This paper presents a new iteration of a haptic feedback system, which uses force feedback through the control device to inform pilots on the Flight Envelope limits and protections of modern fly-by-wire aircraft. The new design uses forcing functions which are *asymmetric in both time and amplitude*, to inform pilots of an approaching limit *as well* as of the direction of the corrective action. The system is evaluated by 24 PPL/LAPL pilots who flew a flight trajectory shown on the outside visual and encountered a windshear during each run. To counter-balance the learning effect, the participants are divided in two groups: one group performed a block of four flights with haptic feedback, followed by a block of four flights without, the other groups vice versa. It was expected that the data would show that enabling haptic feedback during this windshear recovery allowed the pilots to have an increased performance while having a reduced (objective) safety margin, i.e., risk homeostasis, and that pilot acceptance and handling ratings of the system haptic feedback would increase when providing haptic feedback.

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

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

Acknowledgments

We would like to thank all 25 pilots who freed-up three hours in their schedule (excluding travel) to participate in this experiment.

References

[1] EASA, "EASA Annual Safety Review," Tech. rep., European Union Aviation Safety Agency, 2019. URL https://www.skybrary.aero/index.php/Annual_Safety_Review_-_EASA.

[2] IATA, "IATA Safety Report 2017," Tech. rep., International Air Transport Association, 2018. URL https://aviation-safety.net/airlinesafety/industry/reports/IATA-safety-report-2017.pdf.

[3] Ackerman, K. A., Talleur, D. A., Carbonari, R. S., Xargay, E., Seefeldt, B. D., Kirlik, A., Hovakimyan, N., and Trujillo, A. C., “Automation Situation Awareness Display for a Flight Envelope Protection System,” *Journal of Guidance, Control, and Dynamics*, Vol. 40, No. 4, 2017, pp. 964–980. doi:10.2514/1.G000338.

[4] Sherry, L., and Mauro, R., “Design of Cockpit displays to explicitly support flight crew intervention tasks,” *IEEE/AIAA 33rd Digital Avionics Systems Conference, Colorado Springs, (CO)*, 2014, p. 13. doi:10.1109/DASC.2014.6979425.

[5] Kramer, L. J., Etherington, T., Evans, E., Daniels, T., Young, S. D., Barnes, J., Schuet, S., Lombaerts, T. J. J., and Sherry, L., “Evaluation of Technology Concepts for Energy, Automation, and System State Awareness in Commercial Airline Flight Decks,” *Proceedings of the AIAA Modeling and Simulation Technologies Conference, San Diego (CA)*, 2019, p. 20. doi:10.2514/6.2019-0982, AIAA-2019-0982.

[6] Schuet, S., Lombaerts, T. J. J., Stepanyan, V., Kaneshige, J., Hardy, G., Shish, K. H., Robinson, P., Etherington, T., Kramer, L., Evans, E., Daniels, T., Young, S. D., and Rodzon, D., “Piloted Simulation Study Findings On Stall Recovery Guidance,” *Proceedings of the AIAA Modeling and Simulation Technologies Conference, San Diego (CA)*, 2019, p. 23. doi:10.2514/6.2019-0981, AIAA-2019-0981.

[7] de Stigter, S., Mulder, M., and van Paassen, M. M., “Design and Evaluation of a Haptic Flight Director,” *Journal of Guidance, Control, and Dynamics*, Vol. 30, No. 1, 2007, pp. 35–46. doi:10.2514/1.20593.

[8] Beeftink, D. G., Borst, C., Van Baelen, D., van Paassen, M. M., and Mulder, M., “Haptic Support for Aircraft Approaches with a Perspective Flight-path Display,” *IEEE International Conference on Systems, Man, and Cybernetics, Miyazaki*, 2018, pp. 3016 – 3021. doi:10.1109/SMC.2018.00512.

[9] Stepanyan, V., Krishnakumar, K., Dorais, G., Reardon, S., Barlow, J., Lampton, A., and Hardy, G., “Loss-of-Control Mitigation via Predictive Cuing,” *Journal of Guidance, Control, and Dynamics*, Vol. 40, No. 4, 2017, pp. 831–846. doi:10.2514/1.G001731.

[10] Van Baelen, D., Ellerbroek, J., van Paassen, M. M., and Mulder, M., “Design of a Haptic Feedback System for Flight Envelope Protection,” *Accepted for publication in Journal of Guidance, Control, and Dynamics*, 2019.

[11] Van Baelen, D., Ellerbroek, J., van Paassen, M. M., and Mulder, M., “Evaluation of a Haptic Feedback System for Flight Envelope Protection,” *Proceedings of the AIAA Guidance, Navigation, and Control Conference, San Diego (CA)*, 2019, p. 25. doi:10.2514/6.2019-0367, AIAA-2019-0367.

[12] Chatrenet, D., “Les qualités de Vol des Avions de Transport Civil à Commandes de Vol Électriques,” *Active Control Technology: Applications and Lesson Learned*, AGARD, Neuilly-Sur-Seine, France, 1995, p. 5.

[13] Favre, C., “Fly-by-wire for Commercial Aircraft: the Airbus Experience,” *International Journal of Control*, Vol. 59, No. 1, 1994, pp. 139–157. doi:10.1080/00207179408923072.

[14] Niedermeier, D., and Lambregts, A. A., “Fly-By-Wire Augmented Manual Control - Basic Design Considerations,” *28th International Congress of the Aeronautical Sciences, Brisbane*, Vol. 100, 2012, pp. 1 – 14.

[15] Airbus, “A319/A320/A321 Flight Crew Operating Manual,” Tech. Rep. 36, Airbus, 2003.

[16] Bureau d’Enquêtes et d’Analyses pour la sécurité de l’aviation Civile, “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 (English courtesy translation),” Tech. Rep. June 2009, Bureau d’Enquêtes et d’Analyses pour la sécurité de l’aviation Civile, 2012.

[17] Boeing, “777 Flight Crew Training Manual,” Tech. rep., Boeing, 2008.

[18] Tappeiner, H. W., Klatzky, R. L., Unger, B., and Hollis, R., “Good Vibrations: Asymmetric Vibrations for Directional Haptic Cues,” *3rd Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Salt Lake City (UT)*, 2009, pp. 285 – 289. doi:10.1109/WHC.2009.4810863.

[19] Navarro, J., Mars, F., Forzy, J. F., El-Jaafari, M., and Hoc, J. M., “Objective and Subjective Evaluation of Motor Priming and Warning Systems Applied to Lateral Control Assistance,” *Accident Analysis and Prevention*, Vol. 42, No. 3, 2010, pp. 904–912. doi:10.1016/j.aap.2009.07.008.

[20] Huang, Z., Wu, Y., and Liu, J., “Research on effects of pattern, amplitude and frequency of pulse steering torque warnings for lane departure,” *Transportation Research Part F*, Vol. 31, 2015, pp. 67–76. doi:10.1016/j.trf.2015.03.008.

[21] Van Baelen, D., Ellerbroek, J., van Paassen, M. M., Abbink, D. A., and Mulder, M., “Just Feeling the Force: Just Noticeable Difference for Asymmetric Vibrations,” *Submitted to Proceedings of the 2020 IEEE International Conference on Human-Machine Systems, Rome (Italy)*, 2020, p. 6.

[22] de Rooij, G., Van Baelen, D., Borst, C., van Paassen, M. M., and Mulder, M., "Supplementing Haptic Feedback through the Visual Display of Flight Envelope Boundaries," *Proceedings of the AIAA Guidance, Navigation, and Control Conference, Orlando (FL)*, 2020, p. 25.

[23] 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.

[24] Lombaerts, T. J. J., Looye, G., Seefried, A., Neves, M., and Bellmann, T., "Development and Concept Demonstration of a Physics Based Adaptive Flight Envelope Protection Algorithm," *International Federation of Automatic Control*, Vol. 49, No. 5, 2016, pp. 248 – 253. doi:10.1016/j.ifacol.2016.07.121.

[25] FAA, "Windshear Training Aid - Volume 1," Tech. rep., Federal Aviation Administration, 1990.

[26] Netherlands AIP, "AD 2.EHM-ADC Aerodrome Chart," Online, Feb. 2018.

[27] Zijlstra, F. R. H., "Efficiency in Work Behavior," , 1993. Doctoral Dissertation.

[28] Wertheim, A. H., Bos, J. E., and Bles, W., "Contributions of roll and pitch to sea sickness," *Brain Research Bulletin*, Vol. 47, No. 5, 1998, pp. 517–524. doi:10.1016/S0361-9230(98)00098-7.

[29] Roscoe, A. H., and Ellis, G. A., "A subjective rating scale for assessing pilot workload in flight: a decade of practical use," Tech. Rep. 900019, Royal Aerospace Establishment, 1990.

[30] 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, No. 1, 1997, pp. 1–10. doi:10.1016/S0968-090X(96)00025-3.

[31] 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.

[32] Melman, T., de Winter, J. C. F., and Abbink, D. A., "Does haptic steering guidance instigate speeding? A driving simulator study into causes and remedies," *Accident Analysis and Prevention*, Vol. 98, No. January, 2017, pp. 372–387. doi:10.1016/j.aap.2016.10.016.

[33] R Core Team, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria, 2017. URL `https://www.R-project.org/`.

[34] Pool, D. M., Harder, G. A., and van Paassen, M. M., "Effects of Simulator Motion Feedback on Training of Skill-Based Control Behavior," *Journal of Guidance, Control, and Dynamics*, Vol. 39, No. 4, 2016, pp. 889–902. doi:10.2514/1.G001603.

[35] Deldycke, P., Van Baelen, D., Pool, D. M., van Paassen, M. M., and Mulder, M., "Design and Evaluation of a Haptic Aid for Training of the Manual Flare Manoeuvre," *Proceedings of the AIAA Modeling and Simulation Technologies Conference, Kissimmee (FL)*, 2018, p. 21. doi:10.2514/6.2018-0113, AIAA-2018-0113.

Appendix A. Full experiment data

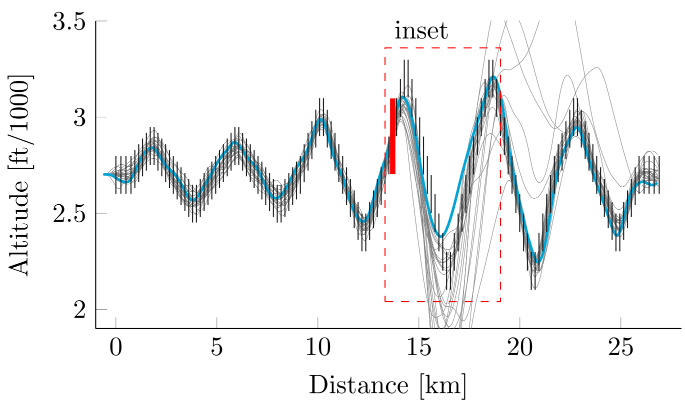
This appendix contains the flights of all participants, grouped per realization of the random-ordered flight paths. For each realization, Fig. 27 shows both the entire flight of each pilot and a zoomed inset which focuses on the start of the windshear recovery procedure. The metrics used in the paper are calculated on this specific part of the flights.

Each plot includes a thicker blue line which represents the flights of one extra participant (male) who was not included in the results. This participant was an outlier in terms of experience: although the participant had a valid current PPL, he was a retired professional pilot with 18,000 flight hours logged in jet fighters and large commercial aircraft (Boeing 747/767/777). Nevertheless, this participants was still invited to verify the results of the (in terms of large aircraft) inexperienced PPL/LAPL pilots.

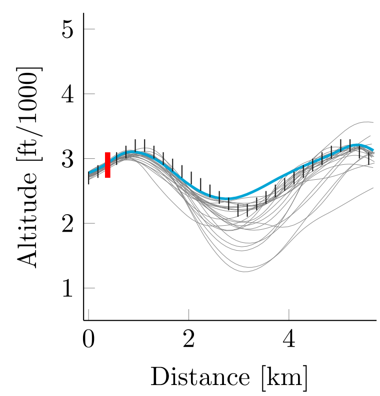
For now, the verification of the results is limited to comparing the flight paths of the experienced pilot with the other pilots. This shows that in nominal conditions, the behavior of all pilots is comparable: they all follow the flight path presented on the outside visual. As discussed in the paper, the flight path itself is rather challenging which is confirmed by the comments of the experienced pilot.

His first four flights (first block) were flown without haptic feedback, the final four flights (second block) are flown with haptic feedback. Flight paths are presented to the experienced pilot in the following order: five (Fig. 27j), four (Fig. 27h), eight (Fig. 27p), six (Fig. 27l), two (Fig. 27d), one (Fig. 27b), seven (Fig. 27n), and three (Fig. 27f). The figures show that the windshear performance (maximum altitude loss during recovery) is improving in that order. Furthermore, the initial performance on Fig. 27j is similar to all other pilots. Starting from his fourth flight (flight path realization 6, Fig. 27l), the experienced pilot is outperforming the other participants, even without haptic feedback.

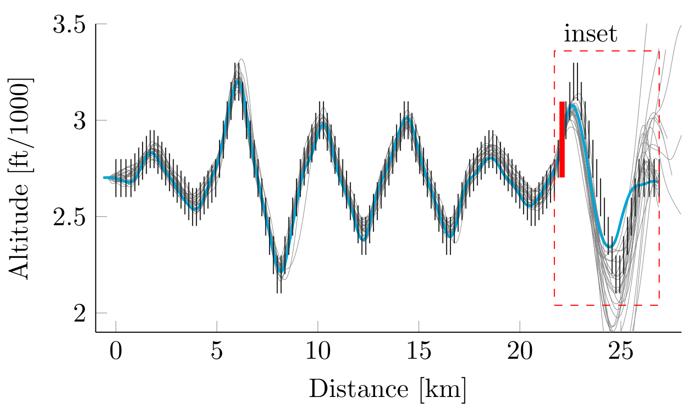
As there is similar behavior during nominal and emergency situations and although this is based on one comparison, we believe that the results obtained with the 24 pilots can be extrapolated to results obtained with professional pilots.



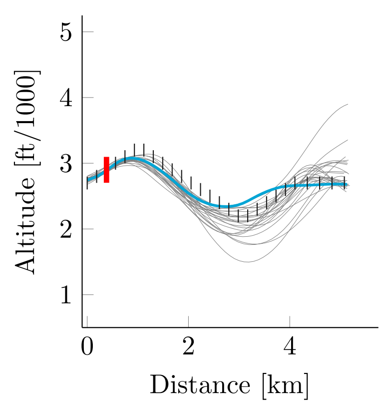
(a) Flight path realization one.



(b) Inset for realization one.

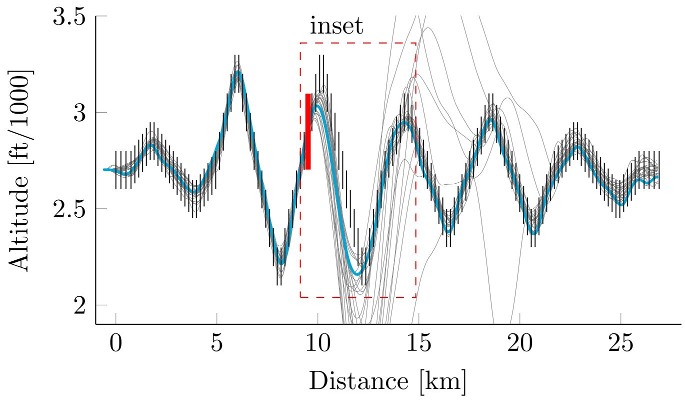


(c) Flight path realization two.

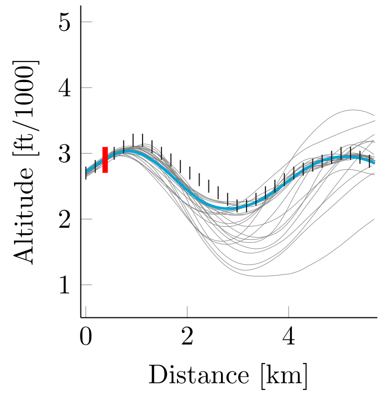


(d) Inset for realization two.

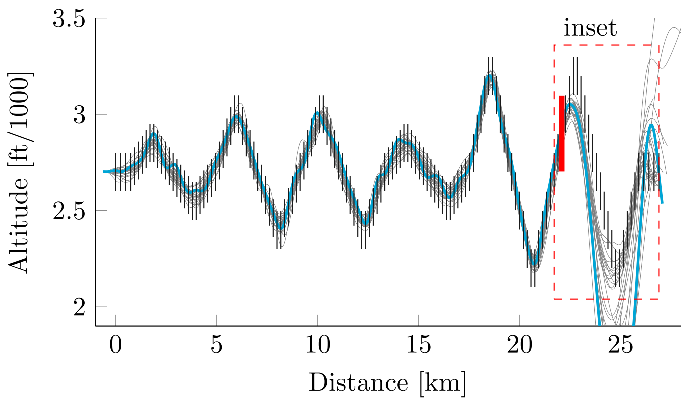
Fig. 27 All flown flight paths by all pilots, vertical lines indicate the gates on the outside visual, vertical thick red line indicates windshear trigger, thick blue line represents flight path of experienced participant.



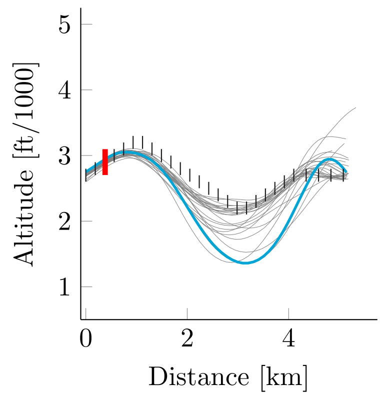
(e) Flight path realization three.



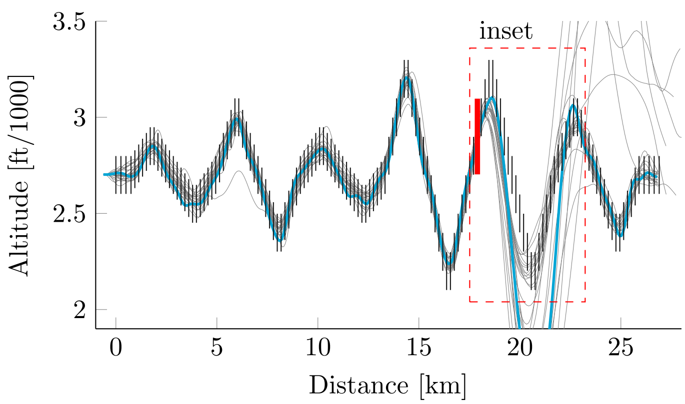
(f) Inset for realization three.



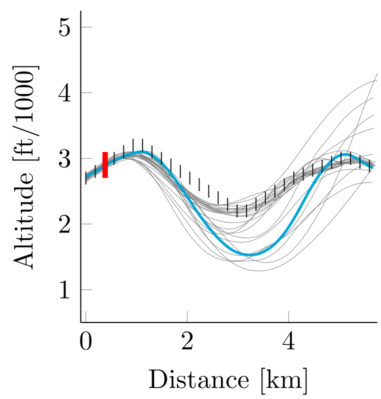
(g) Flight path realization four.



(h) Inset for realization four.

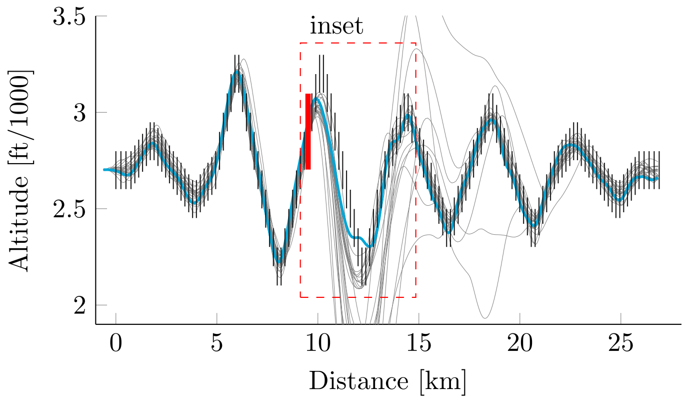


(i) Flight path realization five.

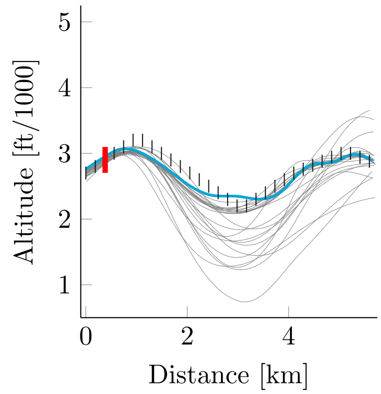


(j) Inset for realization five.

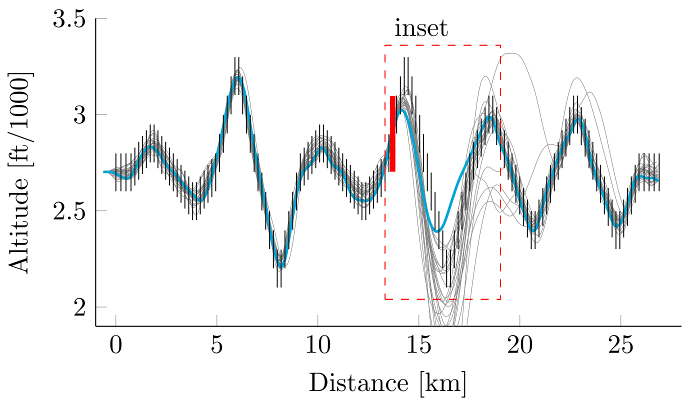
Fig. 27 (continued)



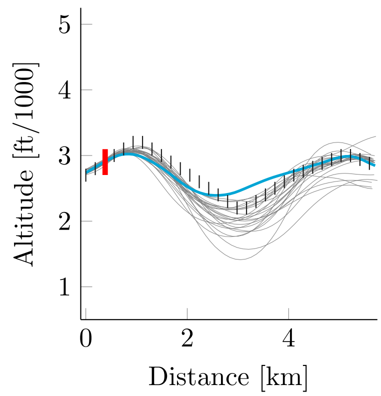
(k) Flight path realization six.



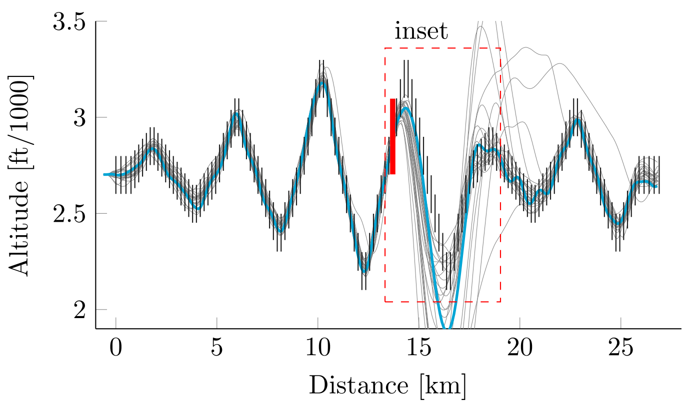
(l) Inset for realization six.



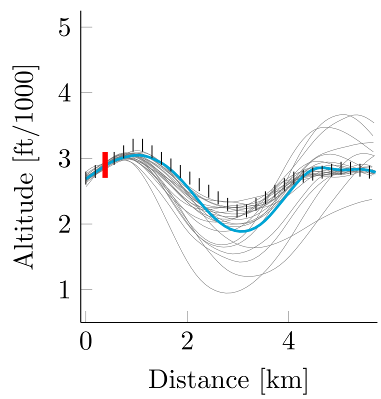
(m) Flight path realization seven.



(n) Inset for realization seven.



(o) Flight path realization eight.



(p) Inset for realization eight.

Fig. 27 (continued)