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Design and evaluation of a Flight Envelope Protection haptic feedback system

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Abstract: This paper describes the design and evaluation of a shared control, haptic feedback system to communicate Flight Envelope Protection System intent. The concept uses a combination of stiffness feedback and vibration to communicate proximity of the aircraft state to flight envelope boundaries. In addition, a stick center shift can be applied by the envelope protection system to cooperatively perform corrective actions in case of severe excursions of the envelope margins. Results from the evaluation experiment show improved performance with haptic feedback in both scenarios. Workload ratings were unaffected. Pilot opinion was unanimously positive, especially with regard to the combination of stiffness feedback and vibration cues. *Copyright ©2016 IFAC*

Keywords: shared control, haptics, flight envelope protection

1. INTRODUCTION

Modern fly-by-wire aircraft, such as the Boeing 777 and the Airbus A380 are equipped with Flight-Envelope Protection (FEP) systems that should ensure operation within a specific safe operating domain. The protection in these systems essentially ignores or modifies pilot inputs that would result in unwanted situations like stall, over-speed, or excessive load factors. A distinction can be made between so called ‘soft’ protection, where the crew can override the protection system by applying excess force on the controls, and ‘hard’ limits that cannot be overridden (Traverse et al. (2004)).

On the one hand, the arguments for ‘hard’ envelope protection are clear: excursion of the aircraft beyond these limits leads to unsafe situations that potentially result in structural damage of the aircraft, and can ultimately lead to unrecoverable loss of control. Indeed, with these FEP systems, the number of handling and control-related accidents has greatly reduced. On the other hand, extreme maneuvers can sometimes be necessary as a last resort, where the only alternative is the certainty of a crash. In the China Airlines B747 incident in 1985, for instance, pilots were required to overstress the horizontal tail surfaces to recover from a roll and near-vertical dive (NTSB (1986)). This recovery would have been impossible had a hard envelope protection system been in place.

Similarly, also ‘soft’ envelope limits have their benefits and drawbacks. While accidents as described above might be avoided with a soft FEP in place, a disadvantage is that pilots are free to control the aircraft into dangerous situations. This means that pilots have to be fully aware of the limitations of their aircraft, and experience will be essential, especially in non-nominal situations.

A generic problem with envelope protection systems is that the contribution of the automation to the control of the aircraft may

not be clear to the pilot; excessive responsiveness, or a lack of responsiveness of the aircraft to pilot inputs may indicate structural changes in the aircraft or its control surfaces, be the consequence of actions of the protection system, or, in case where the pilot’s and co-pilot’s controls are not mechanically linked, be inputs from the other crew member. This introduces the potential for a lack of Situation Awareness (SA) that may occur at critical states near the edge of the flight envelope.

The discussion about these two approaches to envelope protection therefore remains important, with the optimal solution likely to lie in a combination of both approaches, rather than one of the extremes. This paper describes an addition to a hard FEP system that addresses the lack of situation awareness that may occur with respect to the flight envelope. A haptic feedback system is proposed, which addresses the communication of flight-envelope boundaries to the pilot, and how these relate to control inputs from the pilot. The haptic system uses stiffness and vibration cues to communicate how manoeuvrability is affected by flight envelope boundaries.

2. HAPTIC CONCEPT

In line with Billings’ concept of human-centered automation (Billings (1996)), haptic feedback is seen as a way to flexibly share information and control between the human operator and the automation on a physical level (Abbink et al. (2012)). To address the lack of SA with respect to flight envelope limiting, and more generally to the flight control system state, a haptic display is therefore proposed, that complements the existing ‘hard’ FEP system. The current concept considers longitudinal limits; lateral limits will be added in future iterations.

2.1 Haptic feedback near stall

The haptic feedback provided near stall is divided into two categories, depending on the severity of the minimum speed

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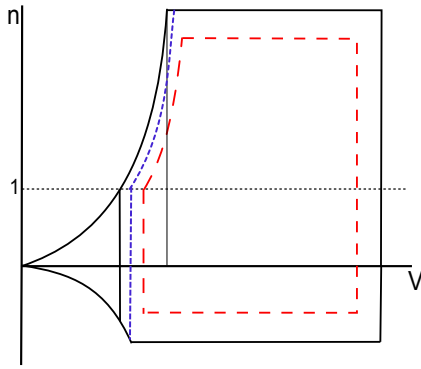


Fig. 1. Flight envelope with haptic feedback areas.

incursion. Two areas are defined here, see Fig. 1. The inner border (red dashed line) indicates the area beyond which proximity to the stall limit is communicated by increased stiffness of the stick. When speed is reduced beyond the second border, (blue dashed line in Fig. 1) a vibration (a.k.a. ‘stick shaker’) is felt on the stick, adding a discrete warning sign.

To translate perceived feedback into a desired action, it is required that the pilot receives the force feedback with sufficient anticipation. If for example the aircraft experiences a sudden increase in load factor while its velocity is rapidly decreasing, the stall speed might be reached very quickly. Examples of situations where this might happen are a sustained pull up or a steep turn. In these situations it is important to take pilot reaction time into account. To this end, predictions are made of load factor and speed. When the predicted values exceed the envelope limits, the haptic feedback boundaries are shifted to match the aircraft’s current velocity.

In case of a near-stall situation, recovery maneuvers can require a simultaneous load factor reduction and a speed increase. While a change in load factor can be achieved rapidly, maintaining a certain load factor and increasing the thrust to gain velocity is a much slower process, and might even be impossible when thrust is at maximum or in case of engine failure. Whether a load factor reduction is sufficient, or whether an increase in speed is required to return to a safe state depends on the location of the unwanted state within the envelope, see Fig. 2. Here, case 1 illustrates a situation where a reduction in load factor is sufficient to return to the safe envelope. For case 2 it can be seen that reducing stick output to neutral (the 1g line in Fig. 2) isn’t enough to return to the safe envelope. In addition, a speed increase is required, which can be obtained by a pitch-down command. This is communicated haptically by shifting the neutral point of the stick stiffness curve to the desired deflection.

2.2 High load factor protection

In high load factor situations, an increased stiffness profile is applied which is proportional to the relative proximity of the aircraft state with respect to the applicable load factor limit. The stiffness varies between the nominal stiffness at the highest considered commanded load factor where no additional feedback is given, and twice the nominal stiffness when the load factor is equal to either the maximum or minimum allowed load factor. The resulting stiffness profile is similar to the increased stiffness in certain near-stall situations.

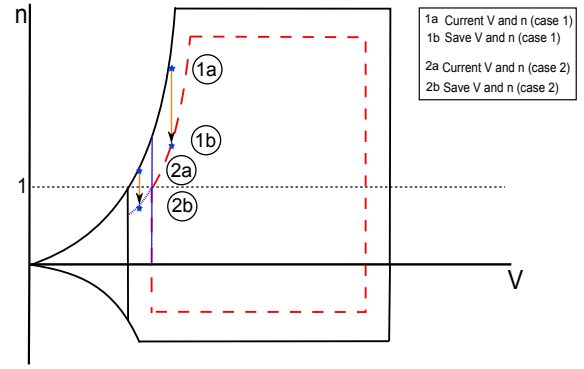


Fig. 2. Effect of load factor reduction.

2.3 Other protections

In addition to stall and load factor, Airbus flight-envelope protection systems also implement limitations in near-overspeed situations, and in extreme attitude situations. Both these envelope limitations are implemented in the haptic system using increased stiffness profiles, similar to the near stall stiffness adaptation. Should the evaluation of the haptic system identify confusion issues due to the similarity of the feedback cues, a future design iteration will investigate possible alternative feedback methods.

3. EXPERIMENT

A part-task evaluation was performed to evaluate the proposed haptic feedback system. The evaluation consisted of two scenarios; one considering the aircraft encountering a windshear situation, and a landing scenario with heavy lateral gusts and ice formation on the wings.

3.1 Apparatus and aircraft model

The TU Delft SIMONA simulator was used to evaluate the haptic feedback concept. The SIMONA is a full motion, six degree of freedom research-simulator. It features an electric active side stick system, which has been used to implement the haptic flight envelope protection feedback system. The aircraft model that was used during the experiment was a proprietary nonlinear six-degree of freedom Airbus A320 model, developed by DLR. This model is able to imitate icing conditions by adapting several aerodynamic coefficients in the model. In response, the fault-tolerant controller included in the model is able to re-estimate the flight envelope online, and use this information to adapt the flight envelope protection system. Wind and turbulence were simulated, varying with scenario.

3.2 Independent variables

The experiment was designed to test the haptic feedback system in two different scenarios; a windshear and a high-workload approach with icing scenario. The haptic feedback system was tested against a baseline system with only passive stick characteristics. Hence, haptic feedback was a factor with two levels: An active haptic feedback system for flight envelope protection could be either present or absent. The haptic feedback system was tested for different control laws, i.e., different levels of automatic envelope protection. Hence, control law was a factor with two levels: the aircraft could be either in normal law or in alternate law. In the latter case, stall protection is not present.

3.3 Experiment design and procedure

The experiment design can be considered as a within-subjects, repeated measures. The experiment was set-up as a part-task evaluation, mainly focused on the manual control task. Subjects were assisted by a co-pilot, who managed flap selection and communications. After a briefing on the experiment and the functioning of the haptic display and the adaptive protection system, subjects performed several training runs. The training session was ended based on observed performance, in agreement with the subject. Separate training scenarios were used. All runs were randomized using a Latin-square design.

3.4 Dependent measures

Objective measures of safety, performance, and workload were derived from time histories of aircraft state data. In the windshear scenario, the margin between measured and maximum angle of attack, and the margin between measured and target pitch angle were used as measures of performance. In the second scenario, the turn to final overshoot was used for this, together with the average margin to the maximum bank angle. The alpha margin was used as a measure of safety. Stick deflection and rate were used as objective measures of workload.

Because the haptic flight envelope protection system aims to improve pilot situation awareness and reduce workload, subjective measures also play an important role in the evaluation. The evaluation therefore included subjective assessments of situation awareness and workload (NASA TLX, Hart and Staveland (1988)), and a general questionnaire covering pilot preference, opinion, and comments.

3.5 Subjects

Seven Airbus A330 pilots (6 male, 1 female) participated in the experiment. Only Airbus pilots were selected as test subjects as the experiment required knowledge and experience regarding flight control law reconfiguration and the associated procedures. Six subjects had prior experience with windshear conditions, and two subjects had previously experienced a degraded flight control law.

3.6 Hypotheses

The experiment considered the following hypotheses:

- H1** Haptic feedback will lead to **improved flight control performance** near the edges of the flight envelope. Hence, compared to the condition with only visual and aural cues, the pilot should be capable of determining when, and how fast the performance limitations of the aircraft are reached.
- H2** The haptic display will **improve pilot awareness** of the aircraft critical flight state under high workload, compared to the baseline condition where the pilot can only rely on visual and aural warning cues.
- H3** Haptic feedback will be **equally effective** when an envelope limit moves towards the current aircraft state, compared to when the pilot manoeuvres the aircraft state towards an envelope limit.
- H4** The haptic display will lead to **reduced workload**, compared to the baseline with a passive stick.

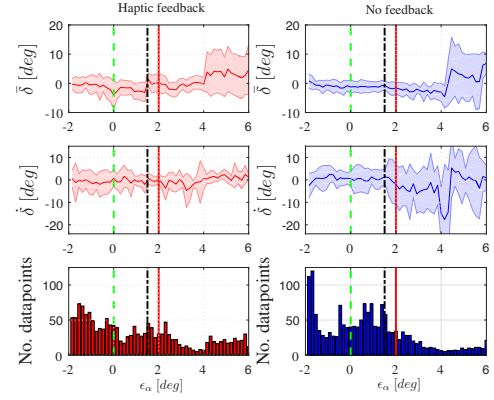


Fig. 3. Stick activity in normal law, windshear scenario.

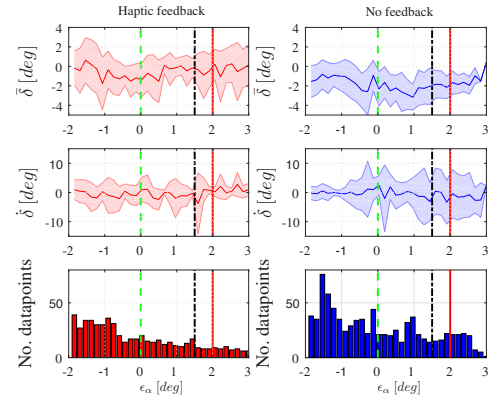


Fig. 4. Stick activity in alternate law, windshear scenario.

4. OBJECTIVE RESULTS

4.1 Windshear: Stick deflection and stick rate

Fig. 3 and Fig. 4 show the control activity in terms of stick deflection and stick rate, with and without haptic feedback in normal and alternate law, respectively. Here, control activity is distributed by the alpha margin ϵ_α :

$$\epsilon_\alpha = \alpha - \alpha_{prot} \quad (1)$$

The relative occurrence of each value of ϵ_α is plotted in a histogram together with the control activity. In these figures, three relevant values of ϵ_α are marked: $\epsilon_\alpha = 0^\circ$, $\epsilon_\alpha = 1.5^\circ$, and $\epsilon_\alpha = 2.0^\circ$, which correspond, respectively, to α_{prot} , stick shaker onset, and α_{max} . Compared to the no feedback conditions, it can be seen that stick deflection is more negative (pull-up) for $0 < \epsilon_\alpha < 2$ in normal and alternate control laws when haptic feedback is present. In other words, subjects were more inclined to increase the angle of attack (AoA) when haptic feedback was present, instead of giving way to the increased force on the stick. When comparing Fig. 3 to Fig. 4 a difference in control behavior can also be observed between control laws, where stick deflection is more moderate in normal law. This can be explained by the fact that for $\epsilon_\alpha > 0^\circ$, side-stick deflections become proportional to the angle of attack in normal law. Therefore, smaller longitudinal side-stick deflections are required to maintain a high AoA configuration when compared to the alternate law case in which longitudinal side-stick deflections result in load factor commands.

4.2 Windshear: Alpha margin

The alpha margin is expressed by ϵ_α defined above. Fig. 5 shows the average alpha margin (and the 95% confidence intervals, for $\epsilon_\alpha > 0^\circ$) for each of the four configurations. The green and red horizontal dashed lines indicate the stick shaker onset and α_{max} , respectively. ANOVA shows that significant ($p < 0.01$) differences exist between configurations; pairwise Bonferroni tests show that differences between all configurations are significant ($p < 0.01$). The figure clearly shows that with haptic feedback (the left graphs of Fig. 5) the average alpha margin is smaller and also much closer to the required AoA. Haptic feedback considerably helped pilots to maneuver close to the prescribed stall limit, especially in alternate law.

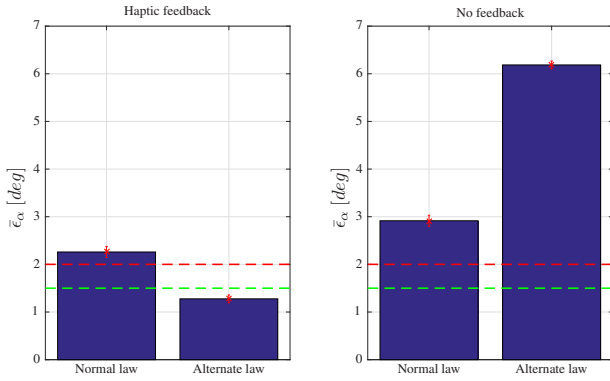


Fig. 5. Alpha margin, windshear scenario.

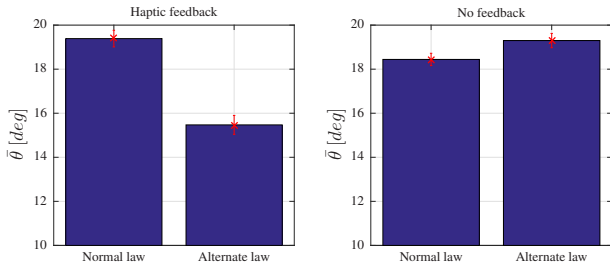


Fig. 6. Pitch margin, windshear scenario.

4.3 Windshear: Pitch margin

The average pitch angle (with 95% confidence intervals) is shown in Fig. 6. As expected pitch angles are high on average, ranging between 15 and 20 degrees. ANOVA shows that significant differences exist between the four conditions ($p < 0.01$). Note, that when following procedure, a pitch angle of 17.5 degrees should be maintained (see Fig. 3). Only the *alternate law/haptic feedback* condition average was lower than this threshold. Tentatively speaking, without haptic feedback the control objective of the subjects could have been to more strictly maintain a fixed pitch angle, and pay less attention to AoA excesses which are represented on the Primary Flight Display (PFD) as velocity indications below the protection speed.

4.4 Icing: Flight tracks and turn overshoot

For the ease of the visual approach and to compensate for the low visual resolution, the experiment scenario was flown near dusk when the runway was easily visible due to its lighting.

From the recorded flight tracks it could be concluded that pilots were aware of their position with respect to runway 27, as all flight tracks were alike. One flight, with subject 5, experienced a crash during the left turn to final 27 as the aircraft entered a stall, that was not successfully recovered. An ANOVA test on turn overshoot did not reveal a significant effect of haptic feedback ($F(3,14) = 0.81, p > 0.05$).

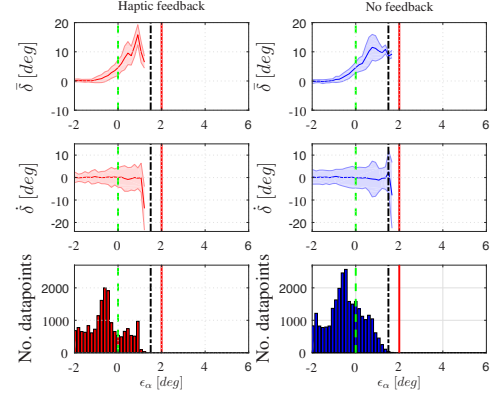


Fig. 7. Stick activity in normal law, icing scenario.

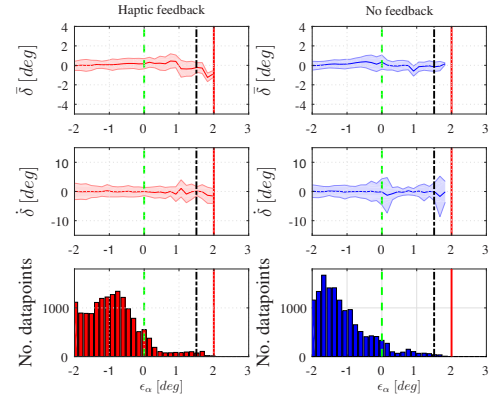


Fig. 8. Stick activity in alternate law, icing scenario.

4.5 Icing: Stick deflection and stick rate

Similar to the windshear results, the control activity is shown as a function of the alpha margin ϵ_α . Fig. 7 and Fig. 8 show the control activity for the normal law (haptics on and off) and alternate law (also haptics on and off), respectively. Please note that as α_{prot} varies according to the flap configuration and the icing severity, α_{prot} was again subtracted from the measured AoA for the sake of a fair comparison of the conditions. For both normal as well as alternate law, no noticeable differences in control activity can be observed as a consequence of haptic feedback. Nevertheless, if the stick deflection is compared for normal and alternate law, one can observe that when operating in normal law the stick deflection increases when α_{prot} increases, which is not seen when operating in alternate law.

4.6 Icing: Alpha margin

During the approach, subjects were instructed to maintain (on their discretion) the lowest possible velocity, following an Air Traffic Control (ATC) message: ‘due to traffic maintain minimum velocity’. Most pilots did not select a velocity lower

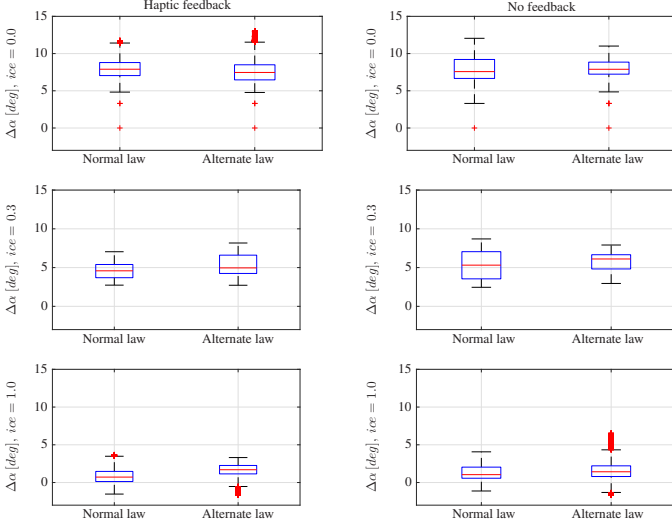


Fig. 9. Alpha margin in the icing scenario.

than the lowest selectable speed (VLS), which was set at 130 kts. Moreover, due to the atmospheric turbulence, which led to significant IAS fluctuations, pilots clearly took VLS as the minimum selectable velocity. After the compliance with this instruction, icing conditions were triggered by the experimenter. The stall speed increase due to icing could in all conditions be visually monitored on the speed tape of the PFD. As a result of the stall speed increase, pilots positively readjusted the selected speed to a higher value, as the current indicated speed would approach V_{prot} . For the icing scenario, the alpha margin is defined as:

$$\Delta\alpha = \alpha_{prot} - \alpha \quad (2)$$

Note that this definition is reversed, compared to the definition of ϵ_α . Hence, a positive alpha margin implies that $\alpha < \alpha_{prot}$. A Kolmogorov-Smirnov test revealed that the alpha margin data were not normally distributed. Therefore the KruskalWallis test was employed for statistical evaluation, and results are shown using box plots. Fig. 9 shows the resulting alpha margin, classified in three icing stages: no icing (0%), 30% icing, and full icing (100%). A significant difference between conditions was found at 0% icing ($\chi^2 = 699.48, p < 0.01$), 30% icing ($\chi^2 = 922.21, p < 0.01$), and 100% icing ($\chi^2 = 8696.75, p < 0.01$). Post-hoc Bonferroni tests revealed that all conditions were significantly different, except at 30% icing. Despite these significant differences, no clear patterns can be discerned.

4.7 Icing: Bank margin

Fig. 10 shows the average bank angle margin, i.e., the average margin between the bank angle limit and the actual bank angle of the aircraft. The red whiskers show the 95% confidence interval. The results show a minimal trend both as a result of control law and haptic feedback, where the average bank margin was smaller in normal law, and when haptic feedback was present. These differences are, however, not significant ($F(3, 14) = 2.51, p = 0.101$).

5. SUBJECTIVE RESULTS

5.1 TLX workload

Fig. 11 shows the Task Load index (TLX) ratings for the windshear and icing scenario. Irrespective of haptic feedback,

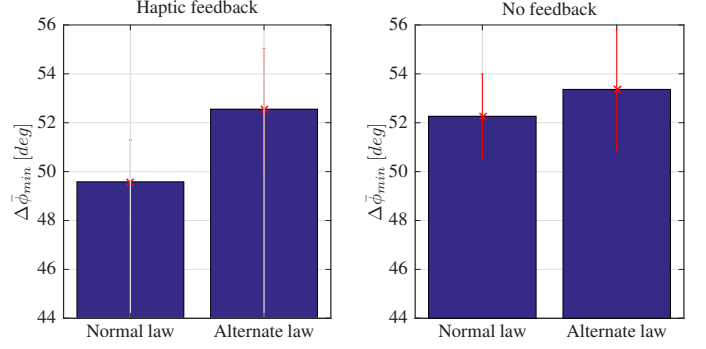


Fig. 10. Bank margin in the icing scenario.

or control law, the TLX weights for Mental Demand, Performance, and Effort were high, and those for Temporal Demand and Frustration Level low, in both scenarios. Haptic feedback did not lower the overall workload when working in normal law, which was unexpected, but did considerably decrease overall workload in alternate law. Due to the low number of data samples, all workload ratings and weightings were analysed using Kruskal-Wallis tests, which revealed no significant effects in either of the scenarios.

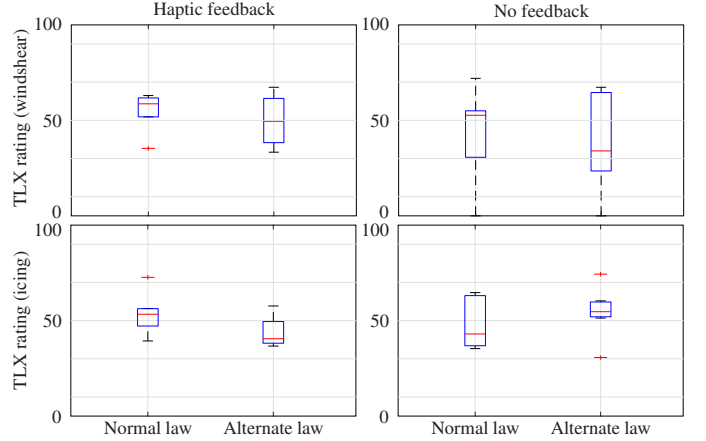


Fig. 11. TLX ratings for both scenarios.

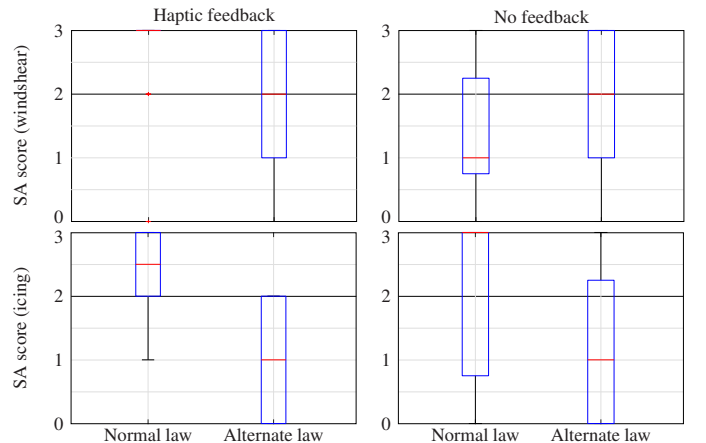


Fig. 12. SA scores for both scenarios.

5.2 Situation awareness

SA was evaluated by posing a set of questions after each experiment run. Following Hunt's method of measuring knowledge

Hunt (2003), the subject's certainty of his answer was used to rank the answers. Fig. 12 shows the SA scores for the windshear and icing scenarios. Correct answers (score ≥ 2) are situated above the black line. For the windshear scenario, a Kruskal-Wallis test revealed a significant difference between conditions ($\chi^2 = 9.36$, $p = 0.025$). A post-hoc test revealed a significant difference between haptic feedback on and off in normal law. For the icing scenario no significant differences were found ($\chi^2 = 6.37$, $p = 0.095$). Tentatively speaking, based on these results, a small benefit of haptic feedback on SA can be observed.

6. DISCUSSION

The evaluation experiment considered the combination of a new adaptive envelope protection system and a haptic feedback system in a windshear and an icing scenario. In this experiment, several issues arose with regard to the fidelity of the simulation that might affect the results. First, several test subjects indicated a relatively high sensitivity of the pitch response of the aircraft model. This could be the result of poor tuning, but might also relate to the fact that their own flight experience is with larger aircraft. The windshear simulation was rated as good. It is therefore not expected that simulation-related issues affect the windshear results. The icing results, however, revealed that the poor post-stall behavior of the A320 model noticeably affected subjects' behavior. As a result, several runs were discarded.

The objective windshear experiment results demonstrate that pilots maintained stable control at the stick shaker onset with haptic feedback. This was not the case for the haptics off condition where the pilots abruptly returned the side-stick to its neutral position in order to avoid any further increase in angle of attack. In particular the alpha margin results showed a significant benefit of haptic feedback: they could more accurately determine how the aircraft states varied and when the stall limit was reached. Moreover, without haptic feedback, subjects showed more perseverance in keeping a fixed pitch angle and paying less attention for angle of attack excesses, which are translated on the PFD as velocity indications below V_{prot} . The windshear results therefore support the first hypothesis.

In the icing scenario, no clear effect of haptic feedback was found. Although significant differences were found between all conditions, in terms of alpha margin, these differences do not translate to noticeable trends. There are two possible influences: First, pilot behavior was very conservative regardless of condition, i.e., commanded speeds were never selected below VLS. Also the poor post-stall behavior of the A320 model might have contributed to the lack of visible results in terms of performance near the edges of the envelope. The other metrics show no significant effect of haptic feedback. The icing results therefore do not support the first hypothesis. Interestingly, subjects did indicate haptic feedback was most useful in the icing scenario.

In terms of objective measures, hypotheses 1 and 2 coincide. Additionally, the SA ratings show a (small) effect of haptic feedback. In the questionnaire, all subjects indicate that the haptic feedback improved their SA. They felt more able to determine the true edges of the actual flight envelope of the aircraft, and whether excess control inputs were given. Subjects also unanimously indicated that the presence of the haptic feedback system would help prevent critical events from occurring. On overall, haptic cue usefulness was rated high. Together, these results support the second hypothesis.

When comparing the control behaviour for the windshear scenario and the icing scenario, clear differences can be observed. During the ice formation when α_{prot} became smaller than the current angle of attack, haptic cues were not directly employed to maintain the angle of attack below the protection limit, as the side-stick deflections were not significantly altered. In contrast, the windshear results do show altered behaviour when α_{prot} is exceeded. In other words, pilots do not show the same control behaviour when the states approach the static envelope limits as compared to the case where the envelope limits approach the aircraft states. The third hypothesis is therefore rejected. Instead, pilots seem to have used the haptic cues as an indication to scan the speed tape of the primary flight display. This is supported by the questionnaire results.

Workload was assessed using the NASA TLX. For the windshear scenario a trend was found where haptic feedback lowered workload only in the alternate law conditions. In the icing scenario, this trend was visible in both normal law and alternate law, but was not significant. Hypothesis 4 is therefore not supported. In the questionnaire, however, subjects do indicate that the concepts will not have a detrimental effect on workload.

7. CONCLUSIONS

This paper presented a concept and initial evaluation for a haptic feedback system to bridge the gap between 'soft' and 'hard' envelope protection systems. By informing the pilot of the state of his aircraft relative to the flight envelope, and of the actions taken by the envelope protection automation, the aim of this haptic system is to improve operator awareness in critical situations. While results do show a positive effect of haptics on control behavior near the edges of the flight envelope, issues regarding the simulation of post-stall behavior, together with the small sample size, limit the validity of the results. A follow-up evaluation is planned that will focus on these aspects.

8. ACKNOWLEDGMENTS

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