2015

Design and Evaluation of a Haptic Display for Flight Envelope Protection Systems

J. Ellerbroek

M.J.M. Rodriguez y Martin

M.M. van Paassen

M. Mulder

DESIGN AND EVALUATION OF A HAPTIC DISPLAY FOR FLIGHT ENVELOPE PROTECTION SYSTEMS

J. Ellerbroek, M. J. M. Rodriguez y Martin, M. M. van Paassen, M. Mulder
Faculty of Aerospace Engineering, Delft University of Technology,
Kluyverweg 1, 2629 HS, Delft, The Netherlands

This paper describes the design and initial evaluation of a haptic display that is aimed to complement a `hard' flight envelope protection system. The evaluation mainly focused on usability of the presented haptic cues, and on the handling qualities of the stick with active feedback. Results are presented for two evaluations, concerning stall protection feedback and load factor protection feedback respectively. They show that while subjects are positive about the added information cue, and are able to correctly identify limiting actions, they are not consistently able to identify changes in the aircraft's condition.

Modern fly-by-wire aircraft, such as the Boeing 777 and the Airbus A380 are equipped with Flight-Envelope Protection (FEP) systems, in order to ensure operation within a specific safe operating domain. These systems are designed to avoid commands that would result in unwanted situations such as 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, Lacaze, & Souyris, 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 flight envelope protection systems, the number of handling and control-related accidents has greatly reduced. On the other hand, extreme maneuvers that take the aircraft beyond the envelope limits 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 an accident such as the one avoided in the China Airlines incident can, in principle, be avoided with a soft envelope protection system in place, an important disadvantage is that in any situation, pilots have the ability 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 play an (even more) important role, especially in non-nominal situations.

The discussion about these two approaches to envelope protection therefore remains a valid and important one, where the optimal solution is likely to lie with a combination of both approaches, rather than one of the above extremes. This report describes an addition to the hard envelope protection system that addresses the problem of lack of Situation Awareness (SA) (with respect to flight envelope limits / limiting) that can occur. An advanced haptic feedback system is proposed, which addresses the communication of flight-envelope boundaries to the pilot, and how they relate to control inputs from the pilot. The haptic system uses force and stiffness feedback to communicate how manoeuvrability is affected by flight envelope boundaries.

Haptic communication of FEP boundaries

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, Mulder, & Boer, 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.

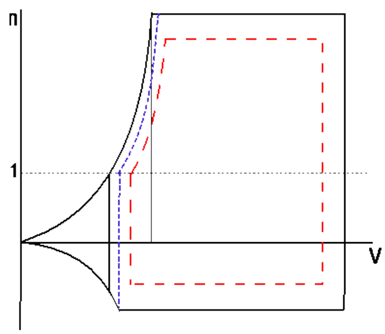

Figure 1. Flight envelope with areas where haptic feedback is active.

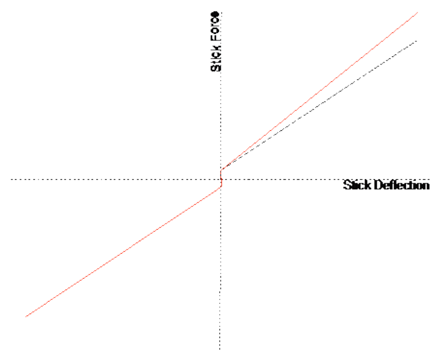

Figure 2. Increased stiffness near stall

Haptic feedback near stall

The haptic feedback provided in near-stall situations is divided into two categories, depending on the severity of the minimum speed incursion. Two areas are defined here, see Figure 1. The inner border (red dashed line) indicates the area beyond which proximity to the stall limit is communicated by increased stiffness on the stick, the effect of which is illustrated in Figure 2. When speed is reduced beyond the second border, (blue dashed line in Figure 1) a vibration (a.k.a. `stick shaker') is felt on the stick.

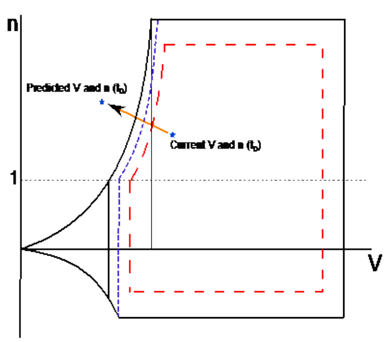

Figure 3. Predicted state outside the envelope.

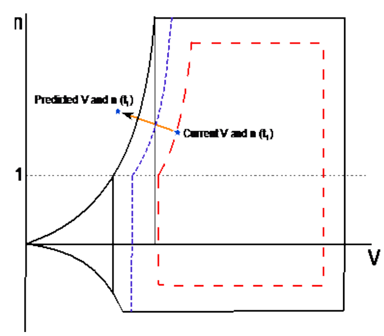

Figure 4. Adapted haptic boundaries.

To be able 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 such maneuvers are a sustained pull up or a high bank angle coordinated turn. Due to the rapid increase of the stall speed caused by the fast rise in load factor, it is necessary to take into account the time the pilot needs to understand and react to the haptic feedback. To this end, predictions are made of load factor and speed (see Figure 3) taking into account a certain cognition time. When predictions exceed the envelope limits, the haptic boundaries are shifted to match the aircraft's current velocity, see Figure 4.

In case of a near-stall situation, recovery maneuvers can consist of both reducing load factor and increasing velocity. A change in load factor can be achieved rapidly, by reducing the commanded load factor with the stick. 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 Figure 5. 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 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, see Figure 6.

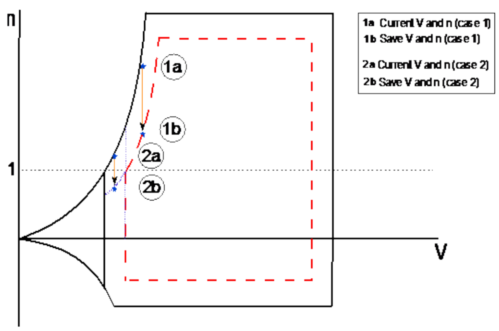

Figure 5. Situations where a load factor reduction is or isn't sufficient.

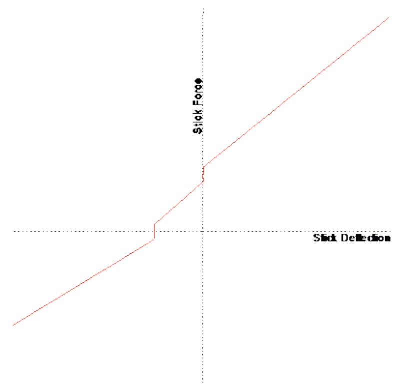

Figure 6. Neutral point shift

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 one times the nominal stiffness at the highest considered commanded load factor where no additional feedback is given, and two times 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, illustrated in Figure 6.

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 illustrated in Figure 2. 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.

Experiment

The experiment has been set-up as a part-task evaluation, a co-pilot was not present during the experiment. To focus analysis on the effects of the haptic feedback system, otherwise present visual and aural warnings regarding the FEP system were absent during the experiment.

In the stall protection evaluation, subjects were requested to perform a wings-level, maximum thrust climb (such as in a go-around). In nominal conditions, the task here is to maintain a constant velocity, controlling the aircraft's pitch angle. Some time after the pilot has reached a stable climb, the stall speed is slowly increased by simulating icing conditions. With (adaptive) envelope protection enabled, the response of the aircraft is to push down its nose.

In the load factor protection evaluation, subjects were requested to find the roll angle that corresponded to the applied load factor limit. Because the current haptic display implementation uses stiffness feedback (i.e., feedback is only felt for non-zero stick deflections), the automatic pitch control during banking was circumvented by applying an additional load factor command.

Two subjects participated in this preliminary experiment, both male, both active A330 captains. Subjects are aged 55 and 49, with an average flight experience of 10,000 hours.

Results

Stall protection evaluation

After establishing a steady, maximum thrust climb, stall speed was increased gradually due to the worsening of aerodynamic properties caused by icing. This increase in stall speed caused the adaptive alpha protection to act, providing a pitch down input (see Figure 7), which both test pilots tried to counter in order to maintain the same pitch attitude, see Figure 8. In other words, neither pilot was able to correctly identify the change in flight envelope. This behavior was consistent between pilots, and between support system conditions. From the questionnaire it became clear that both subjects assumed that the nose down behavior was the result of a reduced elevator authority.

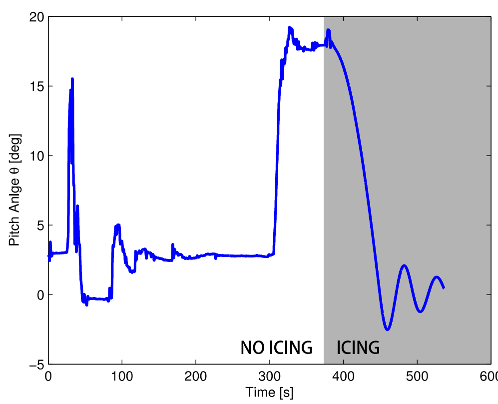

Figure 7. Example of pitch angle before and after icing.

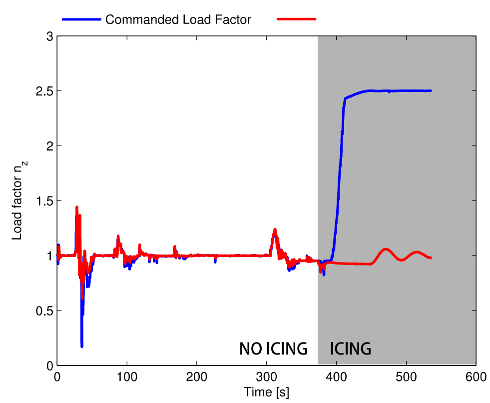

Figure 8. Example of commanded and measured load factor.

The commanded load factor in Figure 8 shows that after the envelope protection system has pushed the nose down, pilots invariably reacted by fully deflecting the side stick contrary to the nose-down command, and maintaining that input. The force-displacement relation for this behavior can be seen in Figure 9, and Figure 10, for the baseline condition and the haptic feedback condition, respectively.

What is clear from these graphs is that the force with which the aft deflection is applied more than saturates the forces applied by both the passive and the active side stick stiffness profiles. This means that any information that is supposed to be communicated through stiffness alterations cannot be detected by the pilot, because he/she is pulling harder than that against the end stop of the side stick.

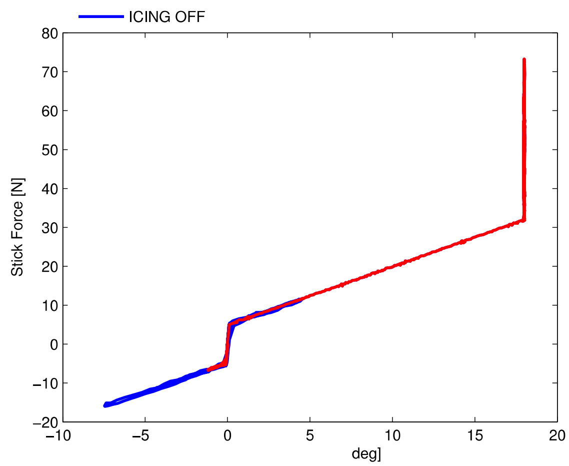

Figure 9. Force-displacement diagram in baseline condition.

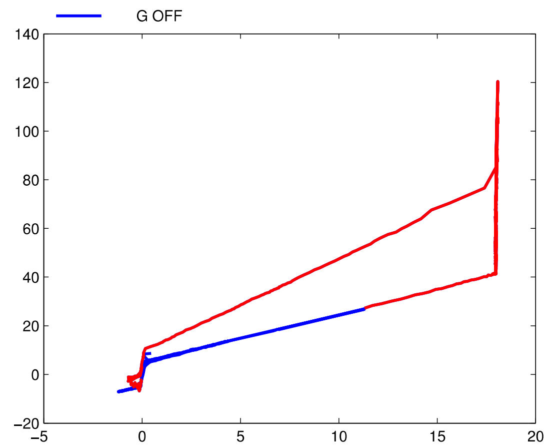

Figure 10. Force-displacement diagram in haptic feedback condition.

Load factor protection evaluation

Load factor limitation evaluation was established by means of a roll angle capture task. The goal in each run was to roll the aircraft, and stabilize at the roll angle where the load factor limitation feedback becomes active. Because this type of evaluation inherently requires some kind of feedback to be present, no baseline condition could be evaluated. The following results therefore only consider the haptic feedback ON condition.

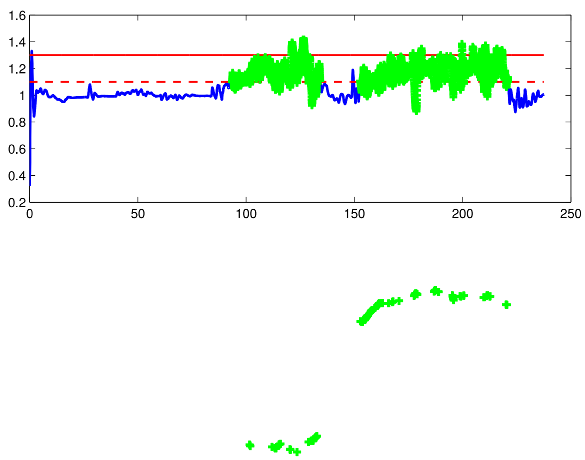

Figure 11. Example of a roll angle capture.

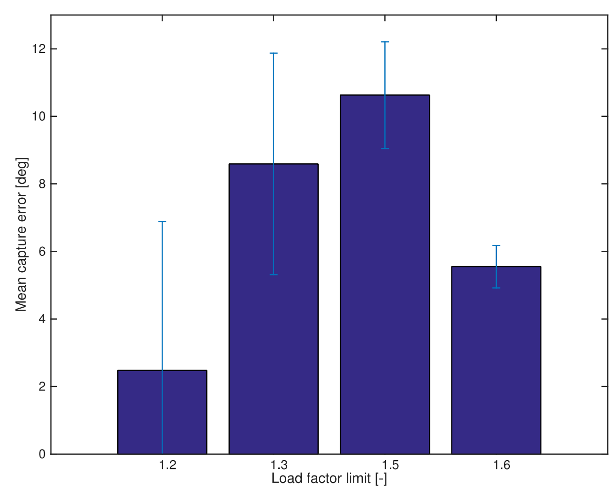

Figure 12. Average capture error.

Figure 11 shows time histories of load factor (top graph) and roll angle (bottom graph), in an example of a roll angle capture task. In this case, a load factor limit of n = 1.3 needed to be identified, corresponding to a maximum roll angle of φ = 40°, and a protection limit of φ = 25°. The green sections of the time histories indicate the ranges where the subject has identified the load factor limit feedback. This task has been performed for maximum load factors n = 1.2, n = 1.3, n = 1.5, and n = 1.6 (these correspond approximately with logical roll angles).

Figure 12 shows how well the subjects were able to identify the corresponding roll angles for each of the four load factor limits. From the deviation of the capture error it can be noticed that the subjects managed to perform the task more consistently with higher load factors.

Discussion and conclusions

At first sight, the experiment results seem to suggest that haptic feedback has the potential to improve the pilot's awareness during critical flight conditions. To be able to test this without similar systems confounding the results, this was tested with aural and stall visual warning cues unavailable. The haptic stall protection was tested by means of increasing the stall speed as caused by ice formation. While the haptic cues did work as a good attention catcher to make the pilot aware of the fact that the envelope protection system was acting, subjects could not successfully use this information to identify exactly what was going on. This was amplified by the fact that both subjects saturated the inputs, making it impossible to provide information through stiffness feedback only. A possible addition to combat this would be to look at the combination of stiffness feedback and a discrete force cue, such as a stick shaker. This will be considered in a next iteration of the concept. In the second evaluation experiment, subjects were capable of identifying maximum load factors, by means of levelling at corresponding roll attitudes. In all experiment runs, pilots were able to properly and accurately identify the roll angle corresponding to the maximum load factor.

Finally, both during the experiment, as well as in the post-experiment questionnaire, both subjects indicated that, despite initial scepticism, they were positive about the proposed system, which they considered as having the potential to be a useful addition. A further iteration of the haptic display concept, with an accompanying larger evaluation, are therefore planned to investigate this potential way forward.

Acknowledgements

This research was performed as part of the ACROSS project. This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under FP7-TRANSPORT, grant number 314501.

References

Abbink, D. A., Mulder, M., & Boer, E. R. (2012). Haptic shared control: smoothly shifting control authority? *Cognition, Technology & Work*. doi:10.1007/s10111-011-0192-5

Billings, C. E. (1996). *Aviation Automation: The Search for a Human-Centered Approach* (1st ed.). CRC Press.

NTSB. (1986). *Aircraft Accident Report - China Airlines Boeing 747-SP, N4522V, 300 Nautical Miles Northwest of San Francisco, California, February 19, 1985*. Washington D.C.

Traverse, P., Lacaze, I., & Souyris, J. (2004). Airbus fly-by-wire: A total approach to dependability. In *Proceedings of the 18th IFIP World Computer Congress*. Toulouse, France.