Pilot Preferences on Displayed Aircraft Control Variables

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Abstract. The experiments described here explored how pilots want available maneuver authority information transmitted and how this information affects pilots before and after an aircraft failure. The aircraft dynamic variables relative to flight performance were narrowed to energy management variables. A survey was conducted to determine what these variables should be. Survey results indicated that bank angle, vertical velocity, and airspeed were the preferred variables. Based on this, two displays were designed to inform the pilot of available maneuver envelope expressed as bank angle, vertical velocity, and airspeed. These displays were used in an experiment involving control surface failures. Results indicate the displayed limitations in bank angle, vertical velocity, and airspeed were helpful to the pilots during aircraft surface failures. However, the additional information did lead to a slight increase in workload, a small decrease in perceived aircraft flying qualities, and no effect on aircraft situation awareness.

Keywords: Bank Angle, Pitch Angle, Vertical Velocity, Aircraft Speed, Workload, Cooper-Harper Controllability Rating

1 Introduction

Adaptive control in flight applications has a long and rich history dating back to the 1950s. Currently, adaptive control is considered for highly uncertain, and potentially unpredictable, flight dynamics characteristic of adverse conditions, such as upsets, stall, post-stall high angle-of-attack or damage, induced on transport or high-performance aircraft. Some recent flight experiences of pilot-in-the-loop with an adaptive controller have exhibited unpredicted interactions [1, 2]. In retrospect, this is not surprising once it is realized that there are now two adaptive systems interacting, the adaptive flight control system and the pilot. The pilot controls the attitude of the vehicle and the method of control may change due to varying system parameters. The experiments, described in the paper, explored how pilots want information about available control authority transmitted and how this information affects pilots before, during, and after an aircraft failure.

The aircraft dynamic variables that pilots want to know relative to flight performance were initially narrowed to energy management variables. Further down select

adfa, p. 1, 2011.

of variables to translational velocity, rotations around longitudinal and lateral axes, was informed by 5 loss-of-control envelopes proposed in [3]. Because these variables included 0^{th}, 1^{st}, and 2^{nd} order derivatives, a survey was conducted in order to pare the relevant variables down to single parameters in the longitudinal and lateral axes rotations, and for translational velocity related information.

From the survey results, two stand-alone displays were designed to indicate the available maneuverability envelope dependent on the health of the aircraft. During normal aircraft operations, the displays showed full control-authority maneuverability envelope. After a control surface failure, the displays indicated how much maneuver authority was available to the pilot based on the newly calculated safe flight envelope.

The two experiments described in this paper looked at how pilots want information about available maneuver authority transmitted and how this information affects pilots before and after an aircraft control surface failure. Recommendations to improve the displays, based on pilot comments, will be discussed in the Conclusions.

2 Parameter Survey Experiment Procedure

In order to narrow the aircraft attitude parameters related to the flight envelope displayed to the pilot, an initial survey was designed and conducted to acquire in-house pilot preferences. In particular, respondents were asked their opinions about the usefulness of, difficulty in understanding, acceptability of, and the amount of time spent referencing the displayed parameter.

Each respondent indicated his ratings on the displayed parameter. The parameters were bank angle (a scalar), turn rate (a velocity), and turn load limit (an acceleration) for lateral control. For longitudinal control, the parameters were pitch angle, vertical velocity, and vertical acceleration. Finally, for translational velocity, speed and acceleration preferences were the considered parameters. Respondents also provided comments about each parameter.

The displayed parameters indicated how close the aircraft was to the limit where the controller could give near normal control responses. Furthermore, the respondents were told that the aircraft was at top of descent but that the flight envelope had changed due to a control surface failure. An example of the displays respondents were asked to rate is shown in Figure 1.

Three respondents filled out the survey and two test pilots were asked their opinions on the same questions regarding what flight envelope information they thought would be the most beneficial. The survey respondents were an average of 51 years old and had an average of 1517 flight hours and 19 years of flight experience. The two test pilots were an average of 53 years old and had an average of 5850 flight hours and 30 years of flight experience.

3 Parameter Survey Experiment Results

In general, respondents indicated that they wanted bank angle and vehicle speed information (Figure 2). For lateral control, respondents commented that bank angle was

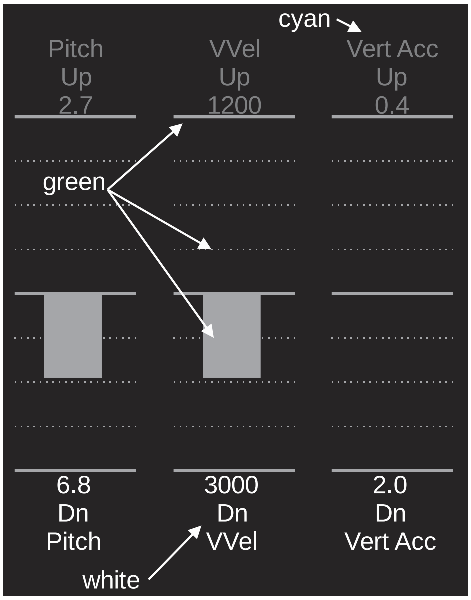

Fig. 1. Longitudinal Parameters and Their Associated Displays for the Survey

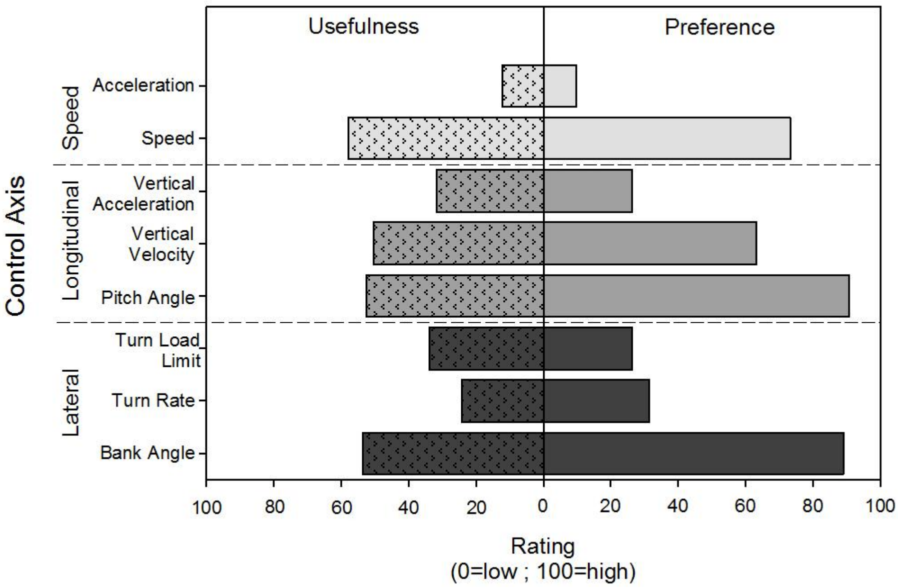

Fig. 2. Survey Control Information Usefulness and Preference

the "most helpful" although "knowing the turn load limit might be useful in windy conditions." This sentiment is reflected in the Usefulness and Preference Lateral ratings in Figure 2. The difference of usefulness between bank angle and turn load ratings in Figure 2. The difference of usefulness between bank angle and turn load limit is smaller than the difference of preference between these two parameters. Hence, turn load limit might be useful during high loading conditions. However, the load factor is a function of bank angle so bank angle was chosen as the preferred lateral control parameter to display for information related to the flight envelope.

For translational velocity, all respondents indicated that Speed was the “most useful and critical to controlling the aircraft.”

As for longitudinal control, respondents were fairly evenly divided, especially for usefulness, between pitch angle and vertical velocity as indicated in the Longitudinal ratings in Figure 2. Several respondents said that pitch angle is “important for go-arounds.” Others indicated that vertical velocity is “extremely useful, especially when establishing ascent or descent profiles.” Thus, vertical velocity was chosen to be displayed rather than pitch angle because the longitudinal-related comments from the survey respondents slightly favored vertical velocity and conversations with the two test pilots indicated that vertical velocity was more useful for controlling aircraft in a steady-state climb or a descent.

4 Maneuver Authority Display Experiment Procedure

The maneuver authority display (MAD) experiment looked at whether an adaptive controller helps pilots during control surface failures and whether an additional display indicating how close the vehicle is to reaching the limit of safe maneuver authority was helpful during and after control surface failures. The variables shown on the new display, which informed the subject of the available maneuverability envelope, were the ones identified by the survey and flight-test pilots: bank angle, vertical velocity, and aircraft speed. These new displays were then used in a human-in-the-loop experiment to look at their effects on pilot performance in the presence of aircraft control surface failures, specifically in the cruise phase of flight while initiating a climb, a descent, or a heading change maneuver. These maneuvers were indicated on the primary flight display (PFD) via the flight director.

The physical setup of the simulator incorporated an out-the-window view in the upper center 30-inch diagonal screen and four 20-inch touchscreens below the out-the-widow screen. The middle-left touchscreen depicted the PFD and the middle-right touchscreen depicted the engine indication display (EID). The far-left touchscreen contained the available maneuverability envelope display, when present, and the far-right touchscreen displayed the after run questions. Subjects flew the aircraft with a right-handed joystick.

The two displays tested were the dial display (Figure 3) and the circle display (Figure 4). In both displays, the information shown was the same but the format was different. In each display, a green wedge filled in from zero the percentage of available safe flight envelope used in the maneuver. For example, for vertical velocity (VVel) in Figure 3, the aircraft is descending at about 80% of 3000 feet per minute. When the available control authority changed due to a control surface failure, the displayed number went from white to cyan in color and the value changed to the new

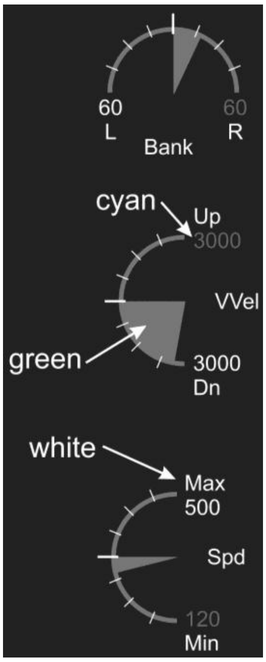

Fig. 3. Dial Display

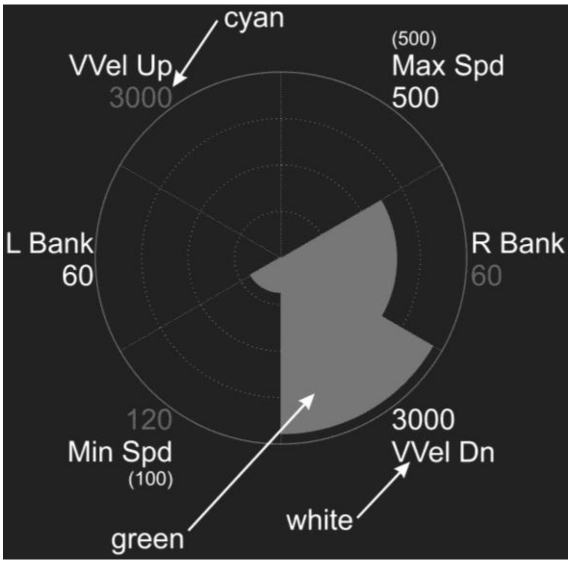

Fig. 4. Circle Display

limit indicating available maneuver authority. For example, for minimum speed (Min Spd) in Figure 4, the aircraft's safe minimum speed is now 120 knots as indicated by the cyan number. For this experiment, the available safe maneuver envelope was predefined for each scenario rather than calculated in real time during the subjects' simulation data runs.

Each subject performed several runs without the new displays (none), then several runs with a display (randomly either the circle or dial display), and finally several runs with the remaining display. During each data run, flight technical data were recorded in addition to a NASA-TLX workload rating ([4, 5]), Cooper-Harper (CH) handling qualities rating ([6-8]), and situation awareness questions. After all the data runs, subjects filled out a final questionnaire asking them about their preferences on the information in the new displays showing how close the vehicle is to reaching the limit of safe maneuver authority and the new displays themselves.

The seventeen subjects in the MAD experiment were an average of 48±10 years old with the youngest 29 years old and the oldest 61 years old. All of them were airline transport rated pilots with an average of 26±11 years of flight experience (minimum flight experience = 7 years and maximum flight experience = 45 years) and an average of 10,706±7164 hours of flight experience (minimum flight hours = 2,100 and maximum flight hours = 23,400).

5 Maneuver Authority Display Experiment Results

Overall, the MAD experiment results for new experimental display preferences mimicked the parameter survey results. Unless noted otherwise, display in the following sections refers to the new experimental display indicating how close the vehicle is to reaching the limit of safe maneuver authority and mentioned parameters are associated with the new experimental display.

5.1 Practicality

The vast majority of the subjects thought that the experimental display was practical. In fact, 13 subjects said the display was practical compared to 4 subjects who reported that the display was impractical. Five of the 17 subjects commented that the display provided "relevant additional information" although one subject did mention that the information was "not relevant during normal conditions" and another said that it was "not enough information during a failure."

5.2 Preferred Content

Subjects in the MAD experiment indicated that they preferred to have pitch angle, vertical velocity and vehicle speed flight envelope information available to them on the experimental display (Figure 5). Once again for longitudinal control, subjects slightly preferred vertical velocity over pitch angle. Subjects also said that the additional roll flight envelope information (10 subjects) was the most desirable over pitch (5 subjects) and yaw (1 subject) flight envelope information.

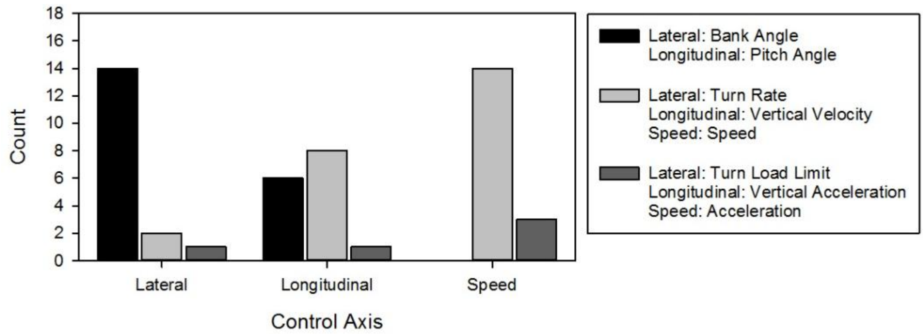

Fig. 5. Maneuver Information Preferences for the MAD Experiment

For lateral control, subjects commented that bank angle was "useful" (5 subjects) on the experimental display and a "well-known and understood measure" (5 subjects). A couple of subjects stated the bank angle was "useful for preventing upsets" but two other subjects said that turn rate information could be "useful for upset prevention."

Subject comments for longitudinal control on the display were split between pitch angle and turn rate. Three subjects mentioned that pitch angle was "useful" while one subject mentioned that vertical velocity was "useful." For how "well known and understood" a measure was, two subjects said this was true for pitch angle and three subjects indicated that this was true for vertical velocity. Also, regarding "upset prevention," two subjects said that pitch angle was good for this while three subjects said vertical velocity was good for upset prevention. Other comments regarding vertical velocity indicated that it was "required knowledge for safe flight" and it typically is used during "normal operations and for approaches."

As for translational velocity, subjects overwhelmingly preferred speed over acceleration on the experimental display. Five subjects mentioned that it is a "well-known and understood measure" and four subjects said it was "useful." Also, two subjects stated that speed was "useful for upset prevention." As for acceleration, two subjects said they did not need this displayed because "you can feel changes in acceleration."

5.3 Situation Awareness

In general, the added displays did not adversely affect a subject's situation awareness of the status of the aircraft with respect to airspeed, altitude, heading, and the aircraft system status. Hence, subjects were able to maintain their general situation awareness about the aircraft even with the additional displays present.

5.4 Workload

Mental demand did increase significantly ($F_{(2, 764)} = 3.5$; $p \leq 0.03$). This may have been an artifact of display design rather that information content because only the circle display was significantly different from the none case. The overall workload of subjects increased slightly, but not statistically significantly, with the additional display (Figure 6). Hence, maneuver envelope information of bank angle, vertical velocity, and vehicle speed did not appreciably increase workload. This may indicate that either the information was the right information on the display or that the display was not attended to by the subjects.

5.5 Cooper-Harper Controllability Rating

Subjects also reported a slight increase in CH ratings with the maneuver envelope information although this increase was not statistically significant (Figure 7). As with workload, this information did not significantly hinder the subjects' ability to control the aircraft. It does appear that the displays did worsen handling qualities slightly as seen by the shift of the number of CH ratings at 1 and 2 for no display to a CH rating of 3 for both the circle and dial displays. This shift may be due to additional information that must be attended to and understood while maintaining control of the aircraft.

5.6 Pitch and Roll Error

Pitch and roll error were calculated by taking the difference between the actual air-

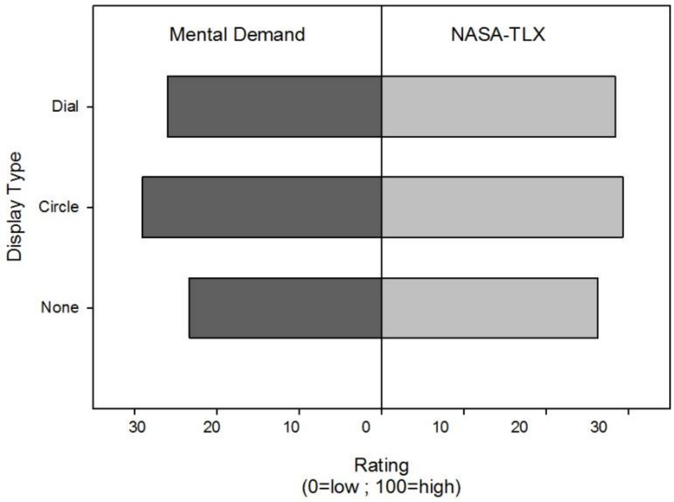

Fig. 6. Mental Demand and Overall Workload Ratings for the CAD Experiment Displays

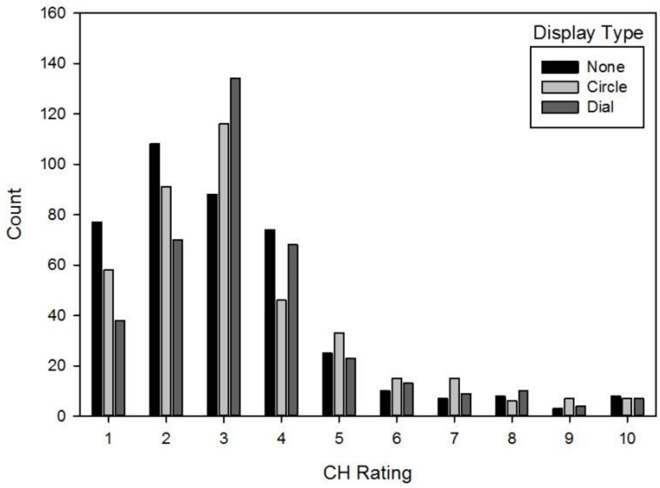

Fig. 7. Count of Cooper-Harper Controllability Ratings by Display Type

craft pitch and roll angle and the commanded pitch and roll angle. This was further broken down by the error before and after a control surface failure.

The pitch and roll errors were not significant except for the pitch error before a failure by display type ($F_{2, 1166} = 3.2$; $p \leq 0.04$). As can be seen in Figure 8, the pitch error typically decreased after the failure for all display types with the biggest decrease for the circle display although the circle display's error was the highest overall for the displays. For the roll error, the error increased after the failure although the increase was the least for the circle display. Therefore, the vertical velocity information for pitch control helps after the control surface failure but the bank angle in-

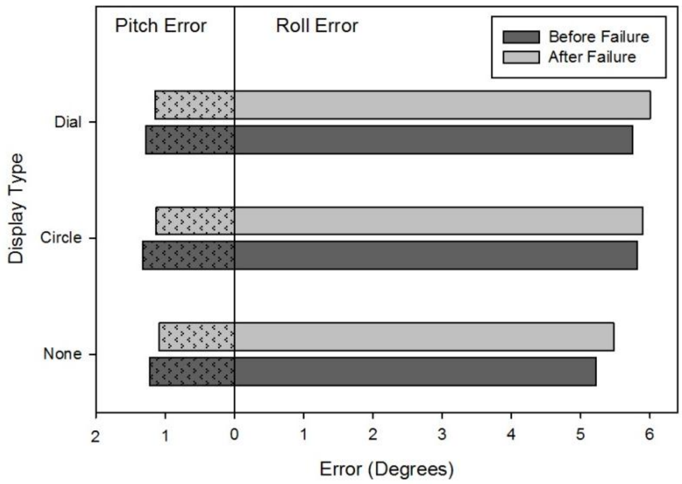

Fig. 8. Pitch and Roll Error by Display Type Before and After the Control Surface Failure

formation after the control surface failure for roll control does not.

The result indicating decreasing pitch error after a failure may be fortuitous because three of the five loss-of-control envelopes include the longitudinal axis [3] so attending to maneuvering safely within the flight envelope in the longitudinal direction may aid the most in preventing upsets. Finally, the circle display had the largest decrease in pitch error and the smallest increase in roll error indicating that the integrated display showing large wedges was easier to process than the dial display.

6 Conclusions

To maintain control of an aircraft before, during, and after control failures, pilots want to know the limits of the aircraft's new maneuver envelope. The two experiments described above began to look at what maneuver envelope information pilots need in order to safely control the aircraft after a control surface failure.

The survey results indicated the pilots would want to know available safe bank angle, vehicle speed, and either pitch angle or vertical velocity during and after a control surface failure. For lateral and translation velocity control, respondents commented that bank angle for the former and speed for the latter were the most helpful. As for longitudinal control, respondents were fairly evenly divided between pitch angle and vertical velocity. Several respondents said that pitch angle is important for go-arounds. However, vertical velocity was used because others indicated that vertical velocity is extremely useful, especially when establishing ascent or descent profile and the survey respondents slightly favored vertical velocity.

From the survey results, the MAD experiment looked at two new displays showing how close the aircraft was to reaching the limit of safe control of bank angle, vertical velocity, and aircraft speed. The results from this experiment indicated that pilots did in fact want this information. Specifically, pilots said that they did want to know bank angle, vertical velocity, and aircraft speed maneuver envelope information. Furthermore, this additional information did not appreciably increase workload, adversely affect situation awareness, or affect vehicle controllability negatively. The CH handling qualities ratings may have increased slightly, however, due to either wrong information provided or because pilots had another display to look at during a failure. Lastly, the new additional display did not negatively affect the ability of the pilots to control the aircraft before or after a control surface failure.

Therefore, bank angle, vertical velocity, and aircraft speed are acceptable maneuver envelope information to display to pilots especially after a control surface failure which may alter the safe maneuver envelope. Exactly how to show this information is being further investigated. Several subjects commented that they wanted the information integrated into the primary flight display; in particular, into the horizon display for bank angle information, the vertical speed indicator for vertical velocity, and the speed tape for the speed envelope information. Other subjects indicated that they preferred the separate display because it was easier to see changes when they occurred although some subjects said they only wanted the display present when a failure occurred. Lastly, with regards to the display of the information, a few subjects did suggest changing vertical velocity to pitch angle during takeoffs and go-arounds. Whether this information switching would increase the chance of "mode" confusion should be fully investigated before incorporating this into a future display indicating available maneuver envelope of the aircraft.

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