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Simulation Evaluation of Pilot Inputs for Real Time Modeling During Commercial Flight Operations

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SIMULATION EVALUATION OF PILOT INPUTS FOR REAL TIME MODELING DURING COMMERCIAL FLIGHT OPERATIONS

Final Report

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ABSTRACT

Aircraft dynamics characteristics can only be identified from flight data when the aircraft dynamics are excited sufficiently. A preliminary study was conducted into what types and levels of manual piloted control excitation would be required for accurate Real-Time Parameter IDentification (RTPID) results by commercial airline pilots. This includes assessing the practicality for the pilot to provide this excitation when cued, and to further understand if pilot inputs during various phases of flight provide sufficient excitation naturally. An operationally representative task was evaluated by 5 commercial airline pilots using the NASA Ice Contamination Effects Flight Training Device (ICEFTD). Results showed that it is practical to use manual pilot inputs only as a means of achieving good RTPID in all phases of flight and in flight turbulence conditions. All pilots were effective in satisfying excitation requirements when cued. Much of the time, cueing was not even necessary, as just performing the required task provided enough excitation for accurate RTPID estimation. Pilot opinion surveys reported that the additional control inputs required when prompted by the excitation cueing were easy to make, quickly mastered, and required minimal training.

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INTRODUCTION:

A team comprised of personnel from The University of Tennessee Space Institute (UTSI), Tullahoma, TN, Bihrle Applied Research Inc. (BAR), Hampton, VA, NASA Glenn Research Center, Cleveland, OH, and NASA Langley Research Center, Hampton, VA, has successfully developed a prototype Ice Contamination Envelope Protection system (ICEPro). This work was funded under a grant by NASA's Research Opportunities in Aeronautics program (ROA-2006), to mitigate the environmental hazard of aircraft icing. The ICEPro system facilitates flight envelope protection by making continuous real time vehicle stability and control characteristics assessments, which are synthesized into flyable pilot cueing along with visual and aural alerts during in-flight icing conditions. Detection of degraded aircraft stability and control and performance due to icing is carried out by a Dynamic Inversion Control Evaluation System (D-ICES) that compares expected aircraft behavior from *a-priori* knowledge base with current measures of those behaviors. When differences reach defined thresholds, Real-Time Parameter IDentification (RTPID)[1-3] methods are invoked to estimate current stability and control characteristics, which continuously provide envelope protection pilot cueing and alerts. The development effort included simulation-based design, testing, and verification with simulated airframe icing. A pilot in-the-loop study was then conducted to gather pilot performance data and opinions of factors such as situation awareness, system integration, and workload, which allowed researchers to assess the utility of ICEPro. Results of the study indicated that the system performed as expected and pilot performance benefited from the envelope protection cues. An additional study was conducted to determine the ability of RTPID and D-ICES to handle atmospheric turbulence. Results of that study indicated that the system performed as expected if the stability and control characteristics were corrected for measurement errors associated with atmospheric turbulence[4].

The remaining technical issue for RTPID is its ability to handle low data information content. Aircraft dynamics characteristics can only be identified from flight data when the aircraft dynamics are excited sufficiently. In the absence of an automated onboard excitation system (OBES) (which was used for ICEPro up to now), it is necessary to do a preliminary study of what types and levels of piloted control excitation would be required for accurate RTPID results. This includes assessing the practicality for the pilot to provide this excitation when cued, and to further understand if commercial airline pilot inputs during various phases of flight provide sufficient excitation naturally. In this study, the effect of not having an OBES on D-ICES was not evaluated because it is of secondary importance to RTPID.

The research questions investigated in this study are:
When an aircraft is manually being flown by a commercial airline pilot, what phases of flight do not involve enough control activity to provide high confidence real time stability and control estimation, and is it feasible to cue the pilot to perform additional control activity in addition to that required to perform the flight task at hand?

The purpose of this study is three-fold:
1.) Understand the effectiveness of normal manual pilot control inputs in maneuvering and non-maneuvering phases of flight for providing the required level of aircraft dynamic mode excitation needed for high confidence real time aircraft stability and control estimation.
2.) Identify the phase(s) of flight and environmental conditions under which the pilot must be cued to provide additional control activity to achieve high confidence stability and control estimates.

3.) Develop a sense for the operational viability of requiring additional pilot manual control inputs with respect to workload related issues such as task performance, attention, and situational awareness of atmospheric turbulence and icing.

The objectives of this study are:

1) Using a small sample of five commercial airline pilots in a fixed-base nonlinear aircraft simulation, evaluate time histories of real time stability and control parameters with normal manual pilot inputs alone for making high-confidence stability and control estimates (less than 20 percent error) as the pilots perform typical non-maneuvering and maneuvering flight tasks in icing conditions with varying levels of atmospheric turbulence.
    a. Determine the portion or portions of the maneuvers which do not provide sufficient data information content relative to the aircraft short period, Dutch roll, and roll subsidence modes, and thereby do not support the achievement of high confidence parameter estimates for the ICEPro system.
    b. When stability and control estimates are poor, cue the pilot to make additional control inputs via flight displays and evaluate the pilot's ability to correctly make the required inputs during the given flight task.
    c. Evaluate RTPID stability and control parameter estimates when manual pilot inputs are being made. This study will focus on the evaluation of RTPID without the use of an OBES.

2) Obtain subjective pilot opinion data on the usefulness of the flight displays, attention issues regarding the cueing, and workload when having to provide additional control activity in addition to that required for task performance.

UTSI, BAR, and Rich Ranaudo (Consultant) worked together in a Joint and Cooperative Agreement NNX13AH29A. The technical monitor for this work was Dr. Eugene Morelli from the NASA Langley Research Center. The agreement forms the basis for the assignment of tasks and the commitment of resources that each organization provides to the research effort. During the study, all parties met on a regular basis to resolve technical issues.

DESIGN OF EXPERIMENT:

Due to the small sample of commercial airline pilots used in this experiment, the data were analyzed descriptively. Quantitative data such as the number of times aileron, elevator, and rudder cues were displayed to each pilot versus the phase of flight and level of atmospheric turbulence were recorded, along with the effectiveness of their manual inputs for satisfying the criteria to remove the cues. Pilot opinion surveys were also conducted to assess the effectiveness of their pre-test training, the impact of cueing on their situational awareness and prioritization of flight control use, and their assessment of cueing on workload and attention when performing a specific flight task. Procedurally, each pilot was required to fly a precision instrument approach procedure (Figure 1), where non-maneuvering tasks such as a straight and level segment, and maneuvering tasks, such as making turns, descents, flying a precision instrument approach, and finally executing a missed approach procedure were required. The RTPID algorithm was the primary mechanism for turning the manual control alerts on and off, and this bit was recorded during each phase. Pilot opinion data was extracted from the responses to the survey questions, and summarized in bar charts.

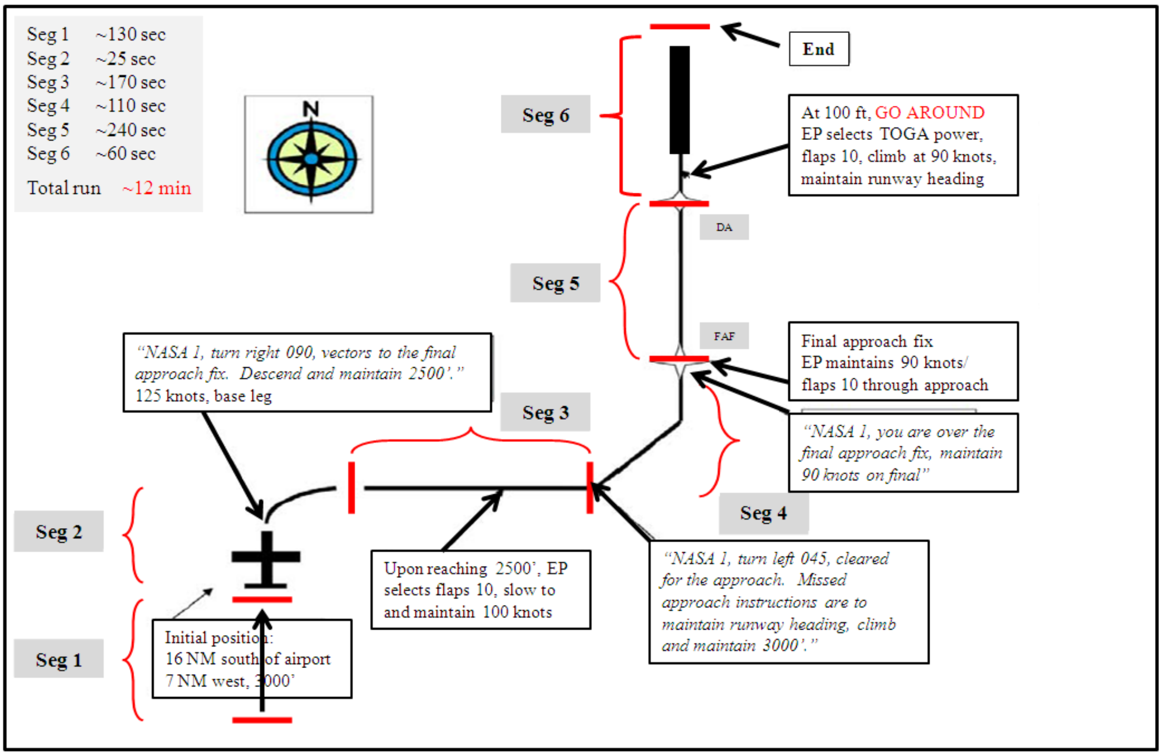


Figure 1: Modified approach and landing task

Atmospheric turbulence was tested as calm, light, and moderate. Severe turbulence was not tested because the de Havilland Twin Otter aircraft is unable to maintain approach speeds in severe turbulence without encountering wing stalls. Atmospheric turbulence implementation and levels were defined per MIL-F-8785C and were based on the Dryden Turbulence Spectrum. According to MIL-F-8785C, the probability of exceeding light atmospheric turbulence levels is between 10^{-1} and 10^{-2}, for moderate turbulence, the probability is approximately 10^{-3}, and for severe turbulence it is approximately 10^{-5}, as shown in Figure 2[5] derived from MIL-F-8785C. Therefore, severe turbulence levels are not very likely to be encountered. The RMS turbulence wind speed values are also shown in Figure 2 as a function of altitude. The turbulence velocity components were generated randomly within the guidelines of the Dryden spectrum and added to the aircraft velocity components to generate the total velocity components. A random number was used to generate the velocity components from the turbulence spectrum resulting in unique sequences of random numbers from test to test. The three velocity components from the turbulence calculations were added to their appropriate body frame velocity components (u, v, w) that were generated from the aircraft dynamics so that the velocity components used for the vehicle motion calculations included the components from the atmospheric turbulence model.

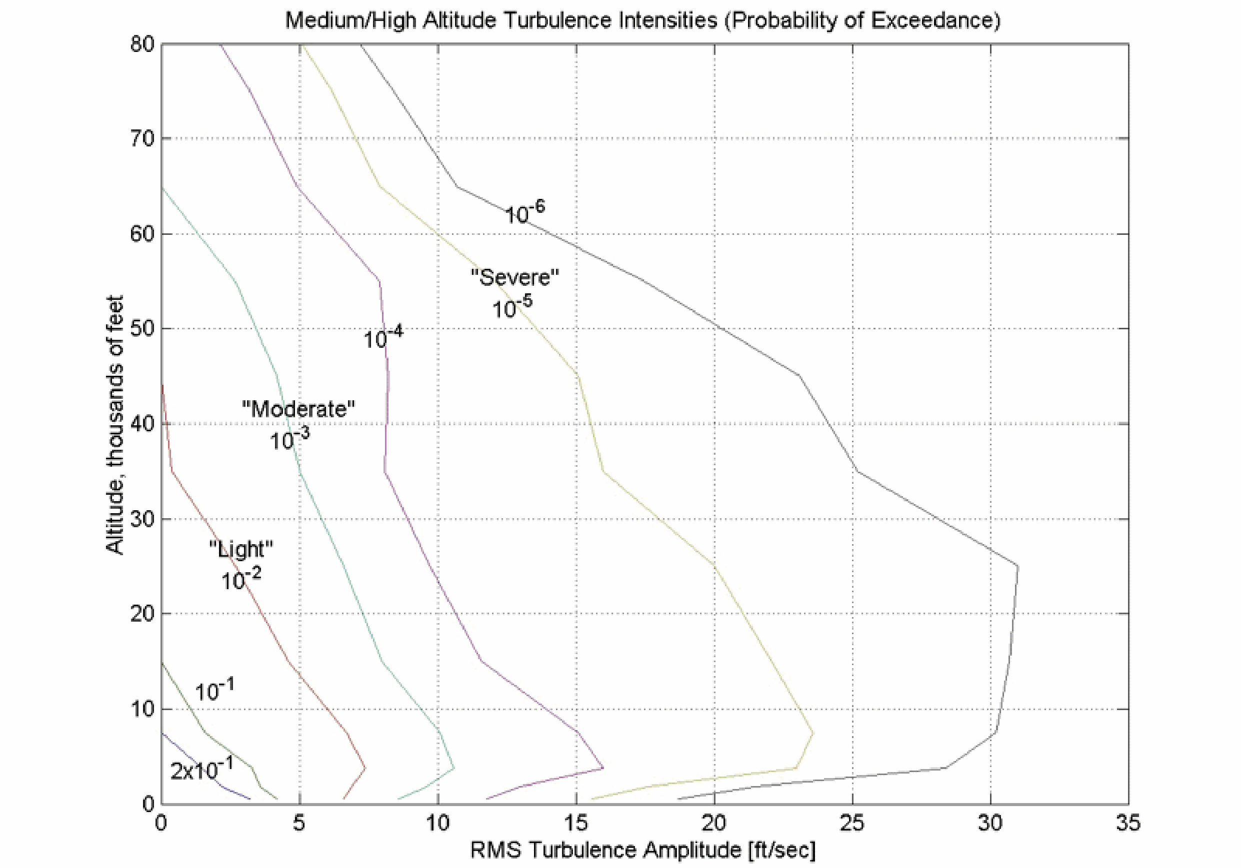


Figure 2: Atmospheric Turbulence Definition

For local modeling over a short time period, the force and moment coefficients can be modeled using linear expansions in the aircraft states and controls:

$$C_L = C_{L\alpha}\Delta\alpha + C_{L_q}\frac{\Delta q\bar{c}}{2V_0} + C_{L\delta}\Delta\delta + C_{L_0} \tag{1a}$$

$$C_D = C_{D\alpha}\Delta\alpha + C_{D_q}\frac{\Delta q\bar{c}}{2V_0} + C_{D\delta}\Delta\delta + C_{D_0} \tag{1b}$$

$$C_Y = C_{Y\beta}\Delta\beta + C_{Y_p}\frac{\Delta pb}{2V_0} + C_{Y_r}\frac{\Delta rb}{2V_0} + C_{Y\delta}\Delta\delta + C_{Y_0} \tag{1c}$$

$$C_m = C_{m\alpha}\Delta\alpha + C_{m_q}\frac{\Delta q\bar{c}}{2V_0} + C_{m\delta}\Delta\delta + C_{m_0} \tag{2a}$$

$$C_l = C_{l\beta}\Delta\beta + C_{l_p}\frac{\Delta pb}{2V_0} + C_{l_r}\frac{\Delta rb}{2V_0} + C_{l\delta}\Delta\delta + C_{l_0} \tag{2b}$$

$$C_n = C_{n\beta}\Delta\beta + C_{n_p}\frac{\Delta pb}{2V_0} + C_{n_r}\frac{\Delta rb}{2V_0} + C_{n\delta}\Delta\delta + C_{n_0} \tag{2c}$$

The Δ notation indicates a small perturbation from a reference condition. In each expansion, a single term is shown to represent all relevant and similar control terms, to simplify the expressions. For example, in Eq. (2b), the term $C_{l\delta}\Delta\delta$ represents all the control terms for C_l, e.g. $C_{l\delta}\Delta\delta = C_{l\delta_a}\Delta\delta_a + C_{l\delta_r}\Delta\delta_r$. In Eq. (2b), C_{l_o} represents the non-dimensional rolling moment at a reference condition, and similarly for the other expansions.

For this study, the moment control terms $C_{m\delta_e}, C_{l\delta_a}, and\ C_{n\delta_r}$ where the most important and only equation 2 was used for modeling. The primary flight display (PFD) was modified with three alert messages to the pilot "ELEV", "AIL", and "RUD" as shown in Figure 3. The messages are triggered by the results of RTPID. When the error bars exceed 20% of $C_{m\delta_e}, C_{l\delta_a}, and\ C_{n\delta_r}$ respectively the message(s) come on. In order to alert the pilot, the messages are amber in color and generate a single audio tone. The message will remain until the pilot sufficiently moves the controls in that axis to lower the error bars below the 20% threshold for 10 seconds.

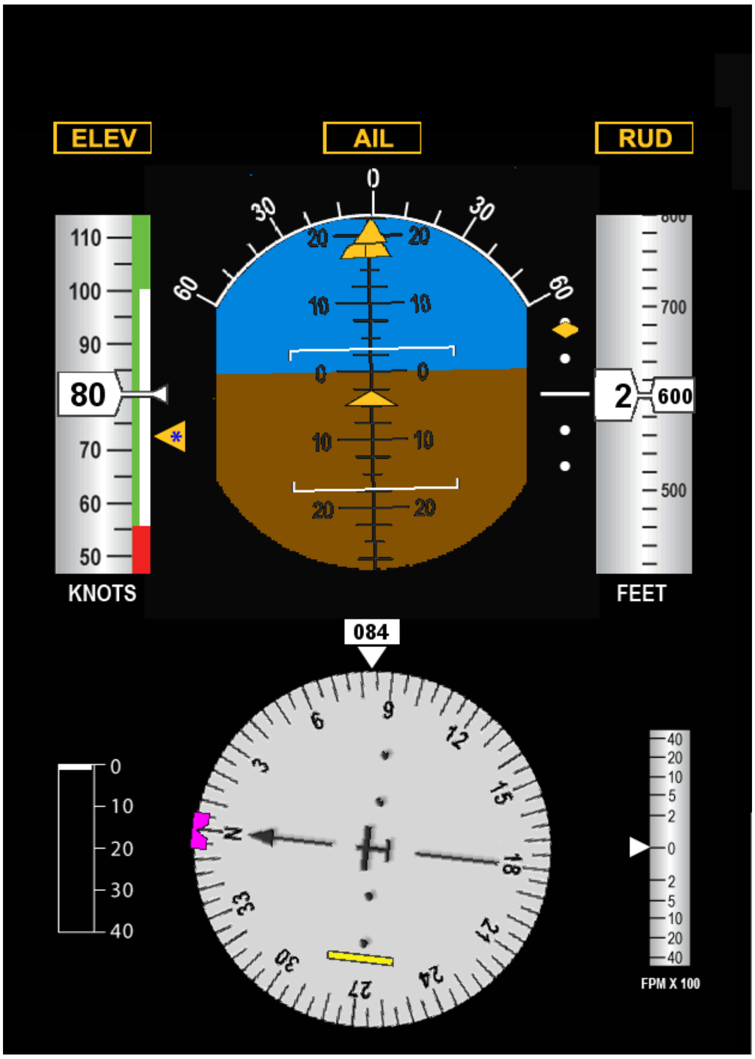


Figure 3: Primary Flight Display

In this study, the RTPID mechanization included a hard reset of the recursive Fourier transforms every 50 seconds. Every time the reset occurs, the algorithm "forgets everything."

In other words, the 50 second resets implement periodic total amnesia. A better implementation would be to use the data forgetting feature of RTPID. Data forgetting allows the algorithm to remember everything, but de-emphasizes older information. This modification was not implemented due to cost constraints. The effects of these 50 seconds resets are studied.

TEST METHOD:

A detailed breakdown of the precision instrument approach procedure is presented in Figure 1. Starting at a point 16 miles south and 7 miles west of the airport at 3000 feet, the pilot takes control of the aircraft and begins the approach in segment 1. Segment 1 is representative of straight and level cruise flight. After performing a right descending turn in segment 2, the aircraft is configured for the approach (flaps are lowered to 10 degrees) and directed to slow to 100 knots in segment 3. The pilot then turns left (segment 4) and flies from the final approach fix to the decision altitude in segment 5. Finally, when reaching 100 feet above ground level a go-around is called and the pilot climbs to 2000 feet ending segment 6. All approaches were conducted in the Ice 2 configuration in simulated instrument meteorological conditions and a cloud deck of 400 feet. The Ice 2 configuration represents wing and tail ice accretions caused by a de-icing boot failure of 22.5 minutes.

Two commercial airline pilots were scheduled to initially validate the general test technique, and an additional three commercial airline pilots were scheduled to conduct the full test. Pilots were labeled alphabetically from A to E in chronological order corresponding to when they flew their approaches. Pilot A had over 16,000 hours flying time with over 9,000 hours in the Boeing 737 airframe and was a current airline captain. Pilot B had 25,000 hours with over 18,000 in the Boeing 737 and had recently retired as a senior airline captain. Pilot C had over 17,000 hours flying time with experience in the A-4 and S-3 and was a current airline captain. Pilot D had over 6,500 hours of flying time primarily in the F-15 and QF-4 and was a current airline first officer. Pilot E had 14,000 hours of flight time in a variety of business jets and was a current Cessna Citation X captain for a fractional private jet ownership company. All five pilots flew all approaches within the Federal Aviation Administration (FAA) established Airline Transport Pilot (ATP) performance criteria for precision instrument approach procedures.

In order to facilitate data collection, both a test director and system operator operated the Ice Contamination Effects Flight Training Device (ICEFTD)[6] for each run. The ICEFTD will simply be referred to as "the simulator" for the remainder of this report. Figure 4 shows the ICEFTD in use.

Figure 4: NASA's Ice Contamination Effects Flight Training Device (ICEFTD)

During testing, the evaluation pilot wore a headset and was completely enclosed in the simulator by a system of curtains as shown in Figure 5 and Figure 6. This isolated the pilot from any outside disturbances or distractions, and enhanced the fidelity of the simulation environment. The test director stood behind the simulator cab and acted as an air traffic controller and provided the callouts listed in italics in Figure 1. The test director also operated a GoPro® video camera which was placed in the right rear of the simulator and allowed researchers to review pilot actions and audio after each run was conducted.

Figure 5: Air Traffic Control Station

The system operator started and stopped the simulation and was responsible for data collection following each run from a remote engineering station. Consequently, this person could not see the ICEFTD instrument panel. Therefore, a copy of the PFD displayed to the pilot was provided, as shown in Figure 6. During the evaluation runs, neither the test director nor the system operator spoke to the pilot while a run was conducted in order to maintain a sterile cockpit environment.

Figure 6: Engineering Station

DATA COLLECTION:

In order to adapt to trends visible during initial testing, two major changes were made between the runs flown by Pilot A and those flown by Pilot B – a summary of test runs are shown in Figures 7 and 8. The general outline for both pilots was one general practice session, two practice runs, followed by evaluation runs. For the first part of the test, pilot A flew three runs with ATP performance criteria, followed by three runs with “ATP/2” performance criteria. (For example, if a pilot was asked to maintain an airspeed tolerance of +/-10 knots for ATP performance criteria, “ATP/2” standards would require an airspeed tolerance of +/-5 knots.) The second part of the test was a repeat of the first in terms of standards, but for the first set of three runs light atmospheric turbulence was added and the final set of three runs moderate turbulence was added.

PILOT A			
Run #:	Test director:	System operator:	Brief description:
1	Martos	More'	First practice run, up and away, coached
2	Martos	More'	First full practice approach, heavily coached with airspeed cues, etc
3	Martos	More'	Second full practice approach, minimal coaching *(followed by a break)*
4	Ranaudo	More'	First approach for data
5	Ranaudo	More'	Second approach for data
6	Ranaudo	More'	Third approach for data *(followed by a break)*
7	Ranaudo	More'	First "ATP/2" data run
8	Martos	More'	Second "ATP/2" data run
9	Martos	More'	Second "ATP/2" data run *(followed by a lunch break)*
10	Ranaudo	Martos	"ATP/2" standards, first light turbulence data run
11	Ranaudo	Martos	"ATP/2" standards, second light turbulence data run
12	Ranaudo	Martos	"ATP/2" standards, third light turbulence data run *(followed by a break)*
13	Ranaudo	Martos	"ATP/2" standards, first moderate turbulence data run
14	Ranaudo	Martos	"ATP/2" standards, second moderate light turbulence data run
15	Ranaudo	Martos	"ATP/2" standards, third moderate turbulence data run

Figure 7: Summary of approaches for Pilot A

PILOT B			
Run #:	Test director:	System operator:	Brief description:
1	Martos	Ranaudo	First practice in sim, up and away, coached
2	Martos	Ranaudo	First full practice approach, coached with airspeed cues, etc
3	Martos	Ranaudo	Second full practice approach, minimal coaching *(followed by a break)*
4	Martos	Ranaudo	First approach for data
5	Martos	Ranaudo	Second approach for data *(followed by a break)*
6	Martos	Ranaudo	First "ATP/2" data run
7	Martos	Ranaudo	Second "ATP/2" data run *(followed by a break)*
8	Martos	Ranaudo	"ATP/2" standards, first light turbulence data run
9	Martos	Ranaudo	"ATP/2" standards, second light turbulence data run *(followed by a break)*
10	Martos	Ranaudo	"ATP/2" standards, first moderate turbulence data run
11	Martos	Ranaudo	"ATP/2" standards, second moderate light turbulence data run

Figure 8: Summary of approaches for Pilot B

Due to observable pilot fatigue and written feedback, the decision was made to limit the overall number of evaluative runs conducted by each pilot. As a result, Pilot B flew the same general approaches as Pilot A but conducted two runs per segment instead of three. The remaining pilots (C, D, and E) all followed the Pilot B procedure with two data runs per segment. Specific run data for Pilots C, D, and E are summarized in Figures 9-11, respectively. Due to time constraints, Pilot C flew a reduced number of runs in atmospheric conditions. The second major change made between Pilot A and Pilot B was to decrease the de-latch time for an aileron, elevator, or rudder excitation message from 10 seconds to 1 second. De-latch time is the amount of time a criteria must be satisfied for the message to extinguish. In this study, less than 20 percent parameter error for 10 seconds was required to extinguish the message. Pilot A demonstrated that a 10 second de-latch was a nuisance. Pilot A had to wait 10 seconds after applying an input to determine if the additional input was sufficient to clear the excitation cue. For all subsequent pilots the de-latch criteria was changed to 1 second. Latch time is the amount of time the criteria must be satisfied for the message to annunciate. In this study, more than 20 percent parameter error for 10 seconds was required to annunciate the message. All pilots flew with the 10 second latch criteria.

PILOT C			
Run #:	Test director:	System operator:	Brief description:
1	Martos	More'	First full (practice) approach, coached
2	Martos	More'	Second full (practice) approach, coached (followed by a break)
3	Martos	More'	First approach for data
4	Martos	More'	Second approach for data *(followed by a break)*
5	Martos	More'	First "ATP/2" data run
6	Martos	More'	"ATP/2" standards, first light turbulence data run

Figure 9: Summary of approaches for Pilot C

PILOT D			
Run #:	Test director:	System operator:	Brief description:
1	Martos	More'	First approach for data, ATP standards
2	Martos	More'	Second approach for data, ATP standards
3	Martos	More'	First "ATP/2" data run
4	Martos	More'	Second "ATP/2" data run *(followed by lunch)*
5	Ranaudo	More'	First light turbulence data run, ATP standards
6	Ranaudo	More'	Second light turbulence data run, ATP standards
7	Ranaudo	More'	First moderate turbulence data run, ATP standards
8	Ranaudo	More'	Second moderate turbulence data run, ATP standards

Figure 10: Summary of approaches for Pilot D

PILOT E			
Run #:	Test director:	System operator:	Brief description:
1	Martos	More'	Practice approach, coached by Borja
2	Martos	More'	First approach for data, ATP standards
3	Martos	More'	Second approach for data, ATP standards *(followed by a break)*
4	Martos	More'	First "ATP/2" data run
5	Martos	More'	Second "ATP/2" data run *(followed by lunch)*
6	Martos	More'	First light turbulence data run, ATP standards
7	Martos	More'	Second light turbulence data run, ATP standards
8	Martos	More'	First moderate turbulence data run, ATP standards
9	Martos	More'	Second moderate turbulence data run, ATP standards

Figure 11: Summary of approaches for Pilot E

DATA COLLECTION AND ANALYSIS:

Pilot flight performance data parameters, which were available through a flight data file that was resident in D-Six[7]®, were sampled at 50 Hz. MATLAB® routines were used to collect and reduce these data for further analysis. Quantitative data such as the number of times aileron, elevator, and rudder cues were displayed to each pilot versus the phase of flight and level of atmospheric turbulence were recorded, along with the effectiveness of their manual inputs for satisfying the criteria to remove the cues, indicating that the pilot had provided sufficient excitation for accurate stability and control parameter estimation in real time. These data were tabulated, grouped, averaged, and graphed for comparison. For each of the three control axes, a frequency domain analysis was conducted using Systems Technology Incorporated (STI) FREquency Domain Analysis (FREDA) MATLAB toolbox. FREDA was used to generate plots displaying the amplitude of different input frequencies versus time.

Thus, information was obtained regarding what input frequencies were used, their amplitude, and when they were used. This data was used to study the effectiveness of commercial airline pilot inputs for system identification using RTPID. In addition to these performance data, other parameters were recorded during each run to provide a more complete picture of the pilot's control strategy, which was useful in training and de-briefing the evaluation pilots. This included GoPro audio and video files for each run as well as training sessions.

The pilot performance data quantified how well the pilot flew the approach task, and the number and duration of excitation cues. In addition to pilot performance data a post-test survey analysis was used to obtain subjective pilot opinion data on the usefulness of the flight displays, attention issues regarding the cueing, and workload when having to provide control activity in addition to that required for task performance.

RESULTS AND DISCUSSION:

Simulation studies accomplished for this work showed that all pilots met the FAA ATP performance standards for a precision approach with different control input strategies, and were effective in making the excitation cues disappear without any test pilot control input training. It was found that all pilots flew with similar airspeed, altitude, heading, localizer, and glideslope performance and correlations between pilots, segment, and criteria could not be established. Rudder warnings occurred with the most frequency with few aileron and elevator excitation cues in all segments of flight. While less excitation cues occurred in latter approaches with simulated atmospheric turbulence, rudder cues still occurred at a higher rate regardless of atmospheric turbulence. This motivated an investigation into the hard coded 50 seconds RTPID resets.

Scalogram, power frequency, and cutoff frequency metrics were introduced and used to investigate which phases of flight and atmospheric turbulence conditions provided the most control activity and promoted system identification using RTPID. Segment 5 (precision instrument approach) provided the most control activity and hence provided the best environment for system identification. This result was expected because in this segment the pilot is tightly coupled with the aircraft as the pilot follows precise vertical and lateral guidance to the runway. Although other segments provided instances conducive to system identification, none were as consistent as segment 5. Pilot control activity in segments 1 and 2 were shown to not be conducive to system identification. Differences in piloting technique were studied in order to understand the effectiveness of pilot inputs for system identification. It was found that all pilots used a different control strategy in obtaining the same performance standards. This suggests that 5 pilot strategies were involved in the experiment.

Pilot opinion surveys were conducted immediately after all testing was completed in order to obtain subjective opinion data on the usefulness of the flight displays, attention issues regarding the cueing, and workload when having to provide control activity in addition to that required for task performance. Pilots reported that the excitation cueing (visual and oral) was effective in getting their attention and was well implemented. Pilots additionally reported that the additional control inputs required when prompted by the excitation cueing were easy to make, quickly mastered, and required minimal training. Lastly, pilots reported that although they did not mind making the inputs, they felt it interfered with the task and degraded their performance. However, analysis showed that all pilots flew within the required ATP performance standards.

EXCITATION CUE ANALYSIS:

Figure 12 is a tally of aileron excitation cues for all five pilots during segment 1 (cruise) and segment 5 (precision approach). The cruise segment resulted in the most aileron excitation cues while segments 4-6 resulted in zero aileron excitation cues. Results for segments 4 and 6 are not shown. This is expected since segment 5 starts at the final approach fix and ends at the decision altitude, and is considered a high gain task as pilots must work hard to maintain airspeed, localizer, and glideslope required by ATP performance standards. Segments 4 and 6 required significant aileron activity. Additionally, segment 2 (descending right turn) and segment 3 (flap transition) resulted in a 2-3 aileron excitation cues for Pilot A. The remaining pilots B-E did not record any aileron excitation cues in segments 2 and 3. Results for segments 2 and 3 are not shown. As a result, higher control activity lessened the number of excitation cues. In contrast, the cruise segment does not require the same level of aileron activity and resulted in more excitation cues.

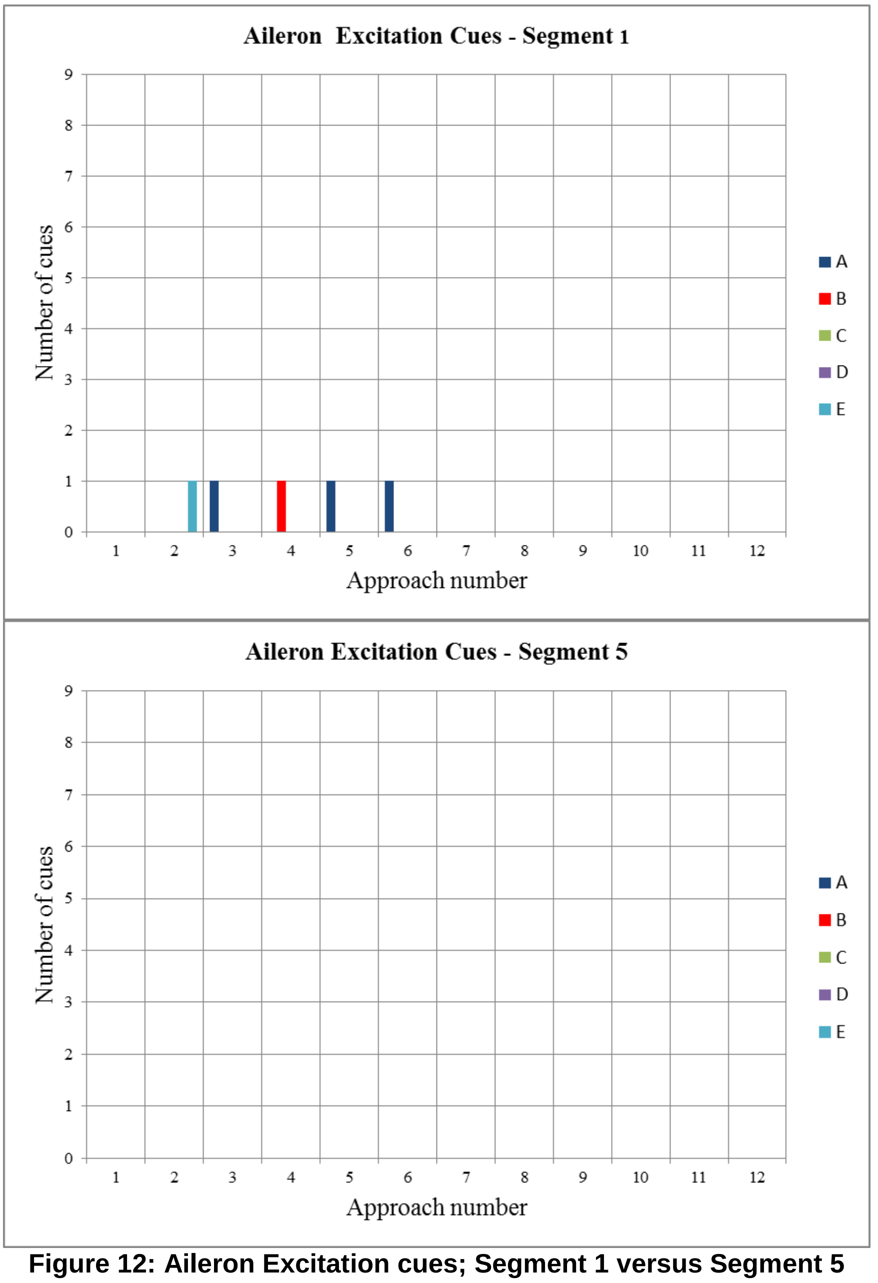
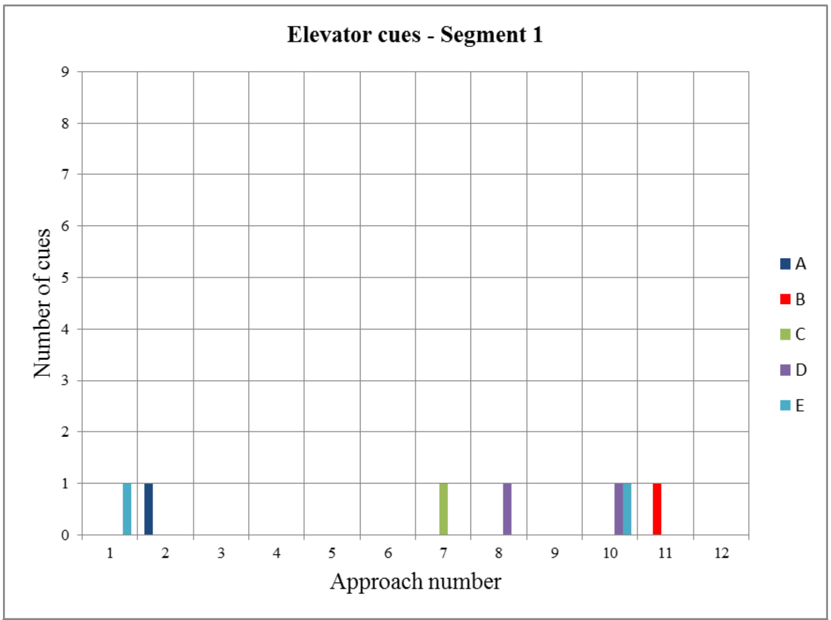


Figure 12: Aileron Excitation cues; Segment 1 versus Segment 5

Figure 13 is a tally of elevator excitation cues for all five pilots during the segment 1 and segment 5. The cruise segment resulted in the most elevator excitation cues while segments 5 and 6 resulted in the fewest excitation cues. Results for segment 6 are not shown. This is expected since the cruise segment does not require significant elevator control activity and segments 5 and 6 require extensive use of elevator control inputs. Additionally, segments 2-4 resulted in less elevator excitation cues than segment 1 and more excitation cues than segments 5 and 6. This is expected since segments 2-4 require elevator activity for a descending right turn (segment 2), flap transition (segment 3), and a left turn to the final approach course (segment 4). Results for segments 4-6 are not shown.



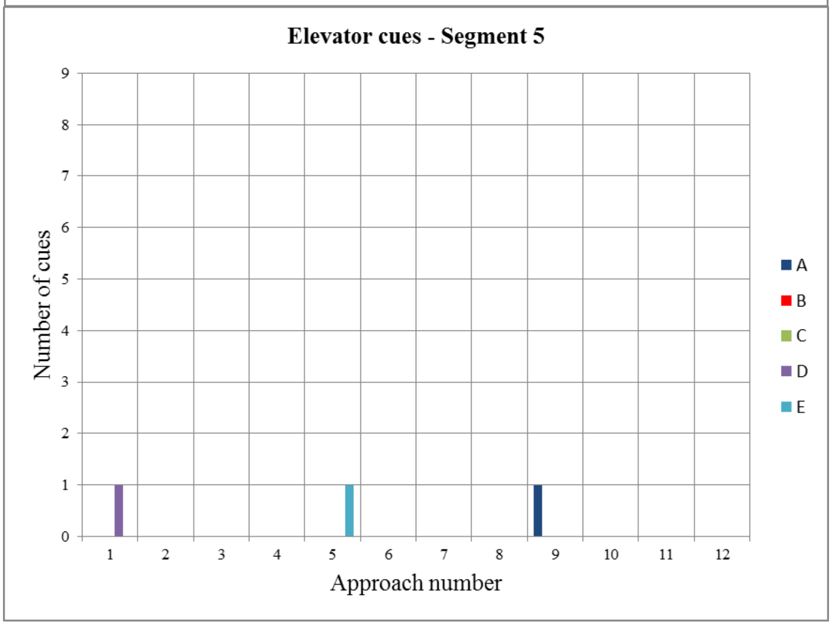


Figure 13: Elevator Excitation cues; Segment 1 versus Segment 5

Figure 14 is a tally of rudder excitation cues for all five pilots during the segment 1 and segment 5. With the exception of Pilot B, pilots had more rudder excitation cues in segment 5 than in any other segment. This seems counter-intuitive because segment 5 requires the greatest amount of consistent control activity. Video footage suggested that the remaining four pilots maximized their attention on the elevator and aileron in order to fly the precision approach (vertical and lateral guidance) cues and minimized their attention on rudder inputs. This division of attention was not expected but seems appropriate to the task.

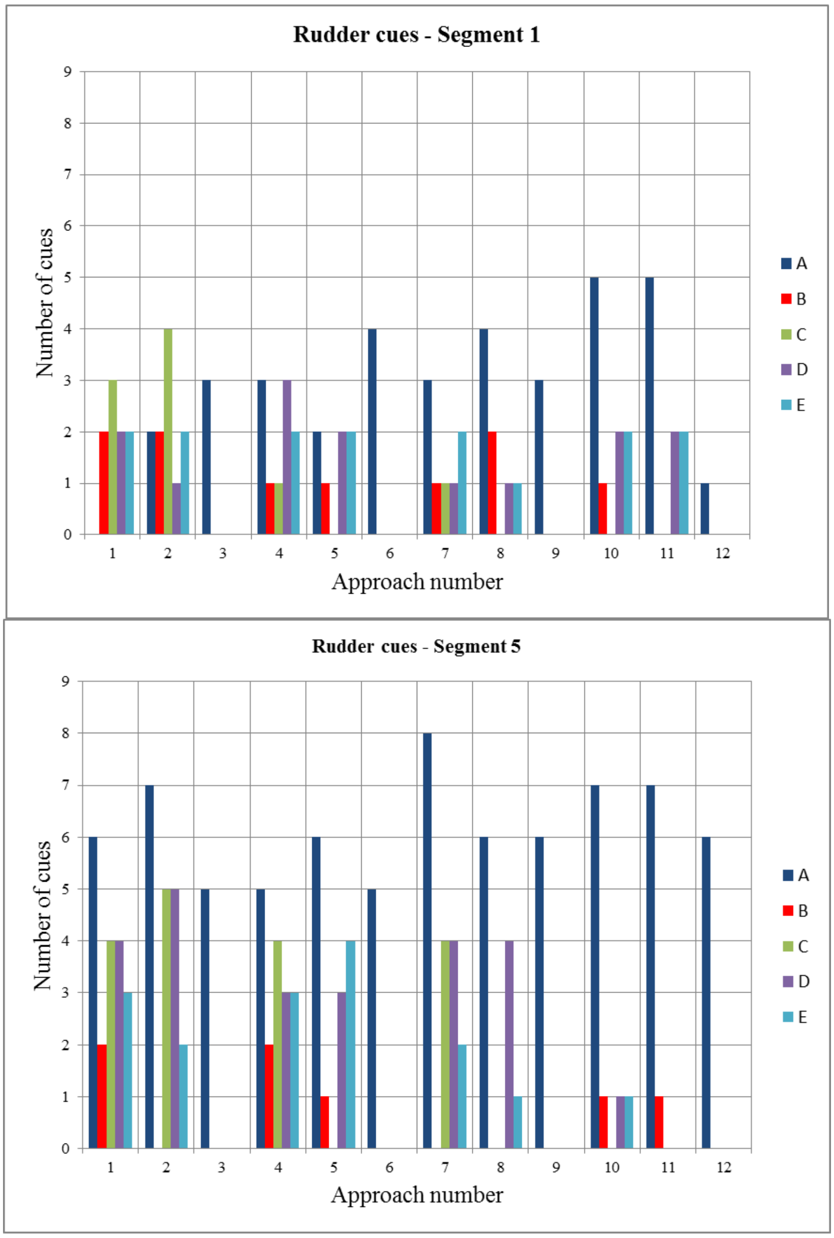


Figure 14: Rudder Excitation cues; Segment 1 versus Segment 5

The unusually high number of rudder excitation cues for all pilots prompted an investigation into the hard coded 50 seconds RTPID resets. The results of segment 5 during the first ATP/2 run for each pilot are shown in Figure 15.

Rudder Excitation Cues for Segment 5	DATA				
Pilot	A	B	C	D	E
Number of resets (50 sec RTPID)	5	5	5	6	6
Number of rudder excitation messages	5	2	4	3	3
Number of rudder excitation messages due to reset (50 sec RTPID)	5	1	4	3	3
Number of rudder excitation messages due to poor excitation	0	1	0	0	0
Number of resets (50 sec RTPID) that did not result in a message (good excitation)	0	3	1	3	3
Percent of rudder excitation messages that resulted from reset (50 sec RTPID)	100%	50%	100%	100%	100%

Figure 15: 50 SECOND RTPID RESET

The results in Figure 15 show that for 4 out of 5 pilots 100% of the messages were caused by the hard coded 50 seconds RTPID resets. In almost all cases there were more resets than there were rudder excitation messages. This is expected because during some of the resets the pilots were moving the rudder pedals in order to complete the task and provided enough natural excitation that the 20% error criteria was satisfied even after a reset. However, there were times when there wasn't enough excitation and it resulted in a rudder excitation message. The results for the remaining segments are not shown. The results for the remaining runs are similar and are not shown.

The elevator and aileron excitation messages were not affected by the 50 seconds RTPID reset because the elevator and aileron were continuously used throughout the instrument approach task.

The effect of hard coded 50 seconds RTPID resets make it difficult to draw any conclusions on the rudder excitation messages. However, when excitation cues were examined side by side for all pilots, an interesting trend emerged between Pilot A and Pilot B. Both Pilot A and Pilot B recorded similarly low numbers of aileron and elevator excitation cues, but a dramatically different number of rudder excitation cues. Pilot B consistently had more rudder excitation cues than Pilot A, indicative of a lack of rudder activity. Pilot A recorded a greater number of rudder excitation cues in segment 5 – sometimes as many as 8 per approach – compared to Pilot B. The rudder excitation cue trends for Pilot A are directly attributable to pilot technique and 50 seconds RTPID resets. After examining video and audio footage collected during Pilot A approaches, it became clear that coordinating turns was not a priority. As a result rudder excitation cue occurred more frequently and only upon receiving an excitation cue would Pilot A provide rudder input. It was repeatedly observed that most pilots had a tendency to fly with their feet on the floor and not on the rudder pedals.

A better implementation is to use RTPID's data forgetting feature. Data forgetting allows the algorithm to remember everything, but de-emphasizes older information. This work is recommended for a future study.

This experiment was designed so that an increase in atmospheric turbulence would cause greater control activity and less excitation cues. In general, pilots had less excitation cues in all axes in light atmospheric turbulence versus a calm atmosphere. However, with the exception of Pilot B, pilots had more excitation cues in moderate atmospheric turbulence. This seems counter-intuitive because greater atmospheric turbulence should require a greater amount of control activity. Video footage suggests that although pilots may be able and willing to correct course deviations in moderate atmospheric turbulence, the increase in atmospheric turbulence could induce the pilot to forego attempts at course correction rather than make excessively large and frequent inputs.

Since all approaches were conducted within the minimally acceptable FAA ATP performance standards for a precision approach, it was possible to examine pilot performance side-by-side and examine the data for trends. As an example, Figures 16-18 show aileron, elevator, and rudder data during segment 5 of each pilot's first approach flown to the 'ATP/2' standards. Red arrows are used to emphasize rudder pedal time histories. The simulator used in this research had control loading in the pitch axis, with simple springs connected to the rudder pedals and ailerons. The effect of not having control loading on the aileron and rudder on the results is unknown. This is recommend for a future study.

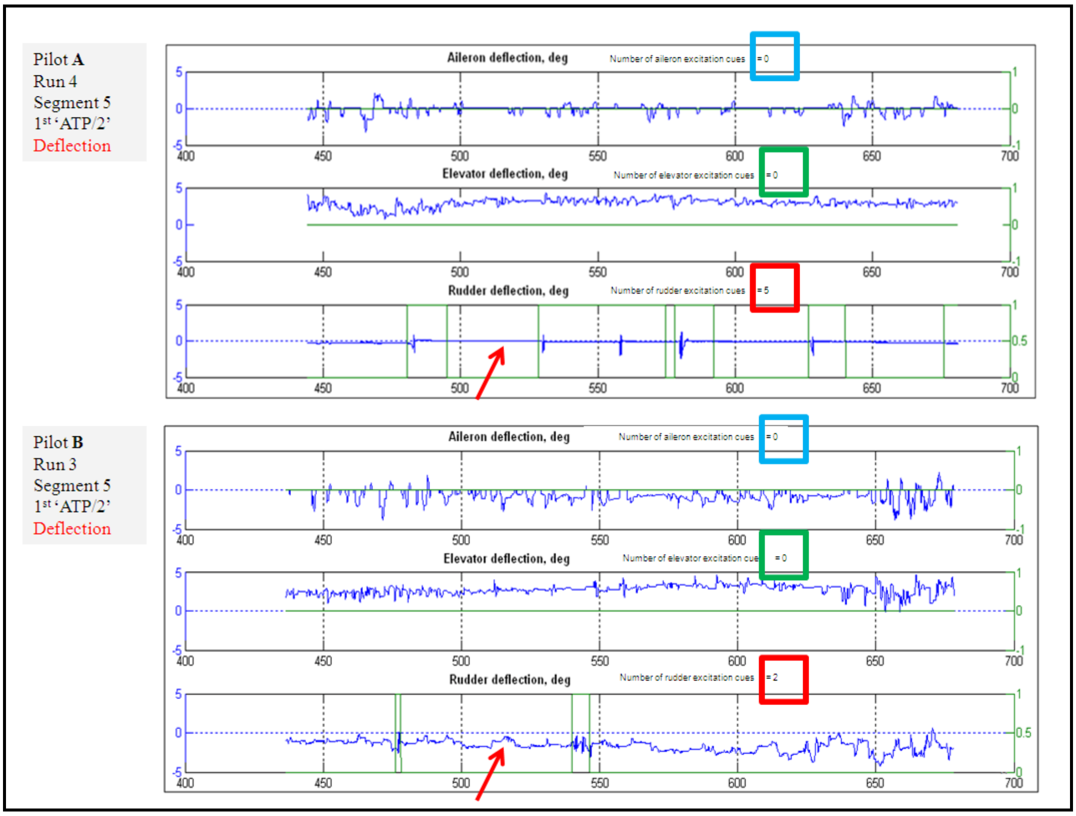


Figure 16: Aileron, elevator, and rudder deflections; run 4/3, Segment 5, Pilots A and B

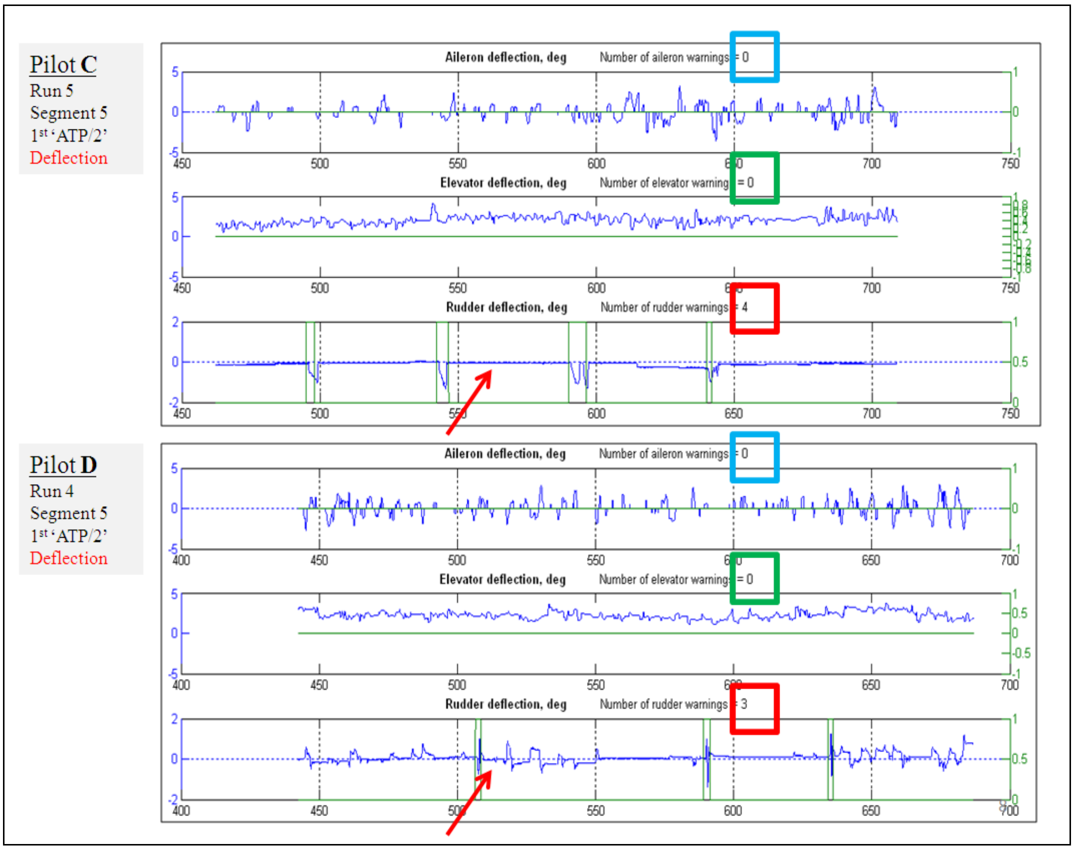


Figure 17: Aileron, elevator, and rudder deflections; run 5/4, Segment 5, pilots C and D

Pilots A and C had large regions in all approaches where minimal rudder activity was recorded. In direct contrast, Pilots B, D, and E consistently applied coordinating rudder inputs. This is an important observation, as differing control strategies between pilots help explain the difference in the number of excitation cues between pilots. Similar trends in the data were repeatedly observed for each pilot indicating that the number of excitation cues was driven by pilot technique and not a flaw or external bias present in the experiment.

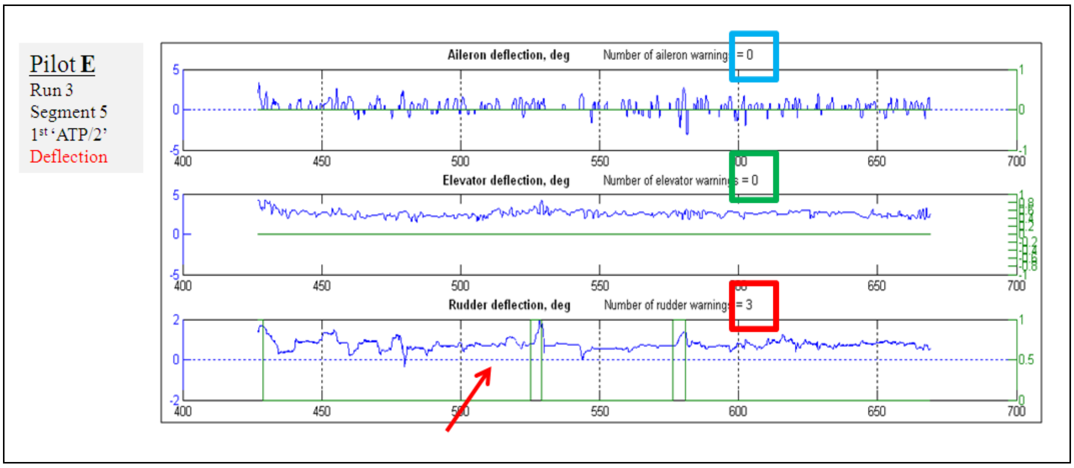


Figure 18: Aileron, elevator, and rudder deflections; run 3, Segment 5, pilot E

Figures 19-21 provide insight into the amount of time that the various excitation cues were illuminated during segment 5 of the approach. First, a distinct difference is present when comparing Pilot A and Pilot B because the RTPID logic for de-latching of excitation cues was modified from 10 seconds to 1 second between Pilot A and Pilot B. The de-latching 1 second logic was not changed for Pilots B-E. Although Pilot A's excitation warnings illuminated for a longer of period of time than Pilot B's, this was not due to pilot activity or inactivity, but instead due to a change in the RTPID display logic.

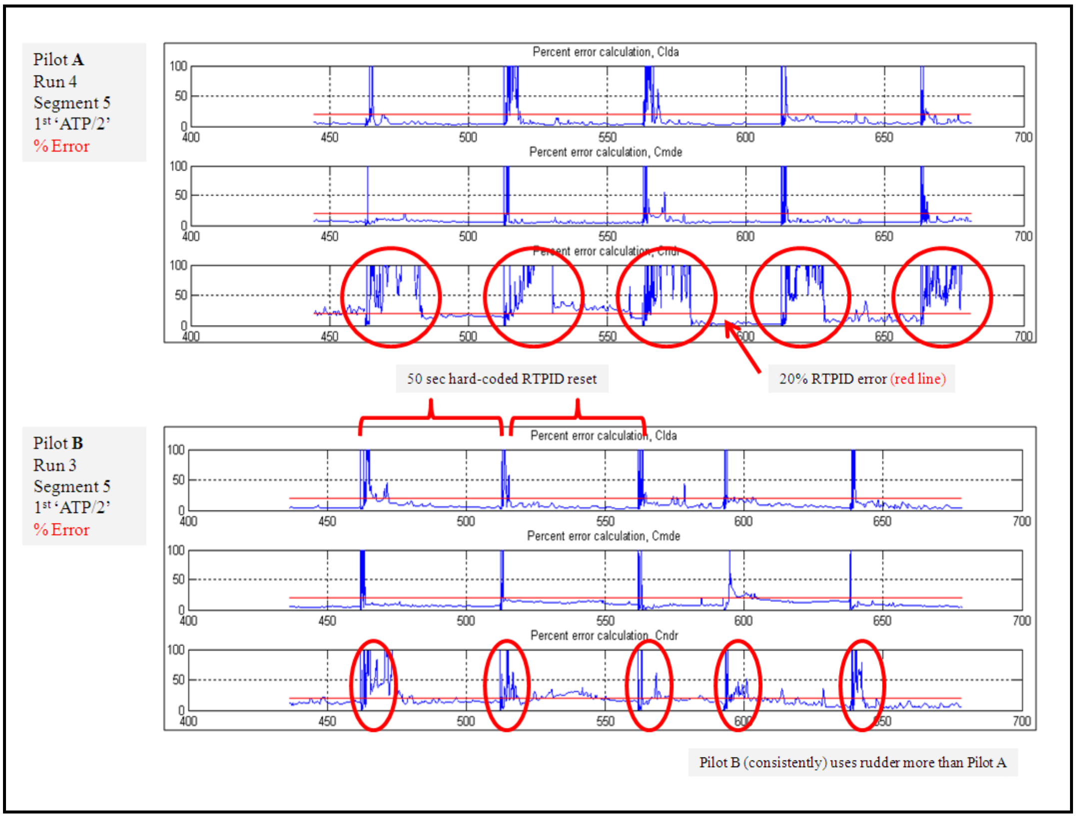


Figure 19: Percent error calculations; run 4/3, Segment 5, pilots A and B

In addition, the red line at the bottom of each subplot denotes the 20% RTPID error target, so values which rise above the 20% line for 10 seconds will trigger the excitation cue logic. In general, achieving a 20 percent error or less in large parameters is easier than in small parameters. This study studied on-axis control derivatives which are considered to be larger parameters typically unaffected by this sensitivity. Otherwise, the use of an absolute error metric is a better solution. When comparing Pilot A and Pilot B, the five corresponding red circles for rudder percent error calculations denote the major difference in measured pilot control strategies. While the 50 second RTPID resets occurred for all pilots, the percent error values were consistently higher for Pilot A due to the lack of rudder activity.

The five major data spikes in all aileron, elevator, and rudder time histories are due to the 50 seconds hard-coded RTPID resets (data forgetting scheme) and are undesirable. This study found that data forgetting schemes originally designed for an OBES in ICEPro can provide false, ambiguous, or nuisance alerting cues to the pilot. Data forgetting is a critical aspect of RTPID to prevent real time stability and control estimates from being biased by old data[4].

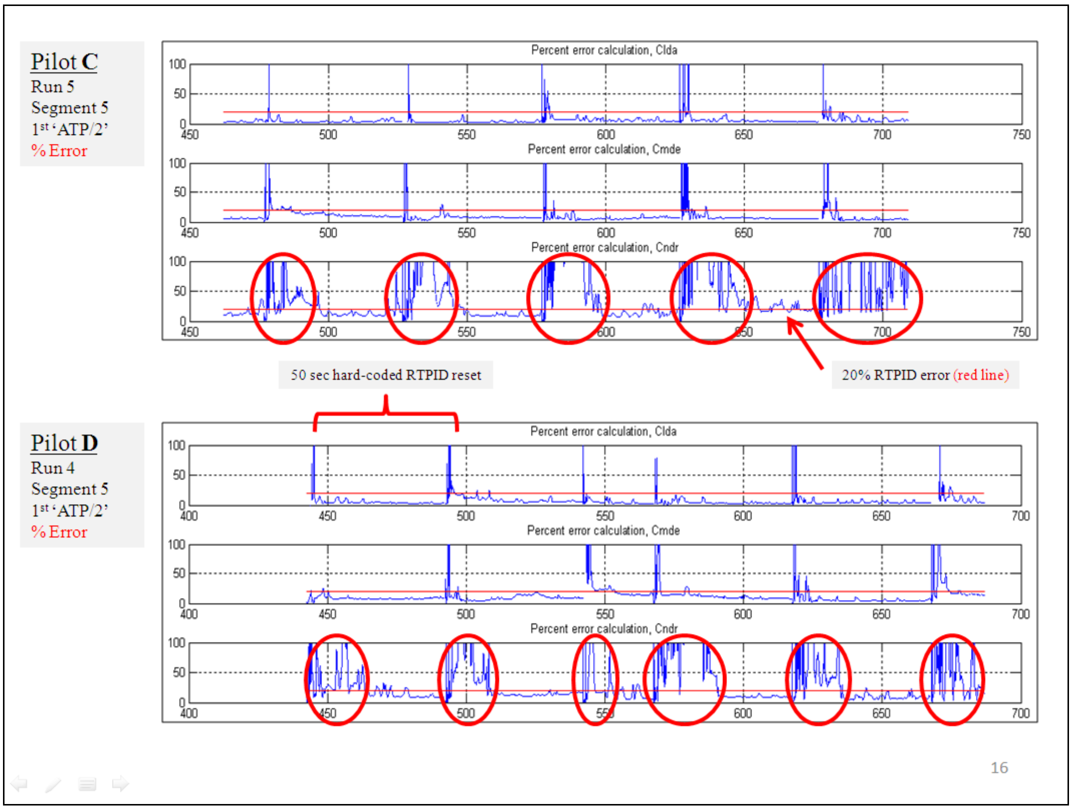


Figure 20: Percent error calculations; run 5/4, Segment 5, pilots C and D

For Pilots B-E, aileron and elevator excitation cues occurred infrequently because continuous control inputs occurred in both axes. As a result, the percent error time histories for $C_{L\delta a}$ and $C_{M\delta e}$ show excellent identification results for the entire segment. However, for Pilots A, C, D, and E, the percent error for $C_{N\delta r}$ was consistently greater than 20 percent. The lack of rudder activity resulted in poor system identification results. However, when the rudder excitation cue was active, all pilots extinguish the cue quickly. This trend is shown in the percent error $C_{N\delta r}$ time histories for all pilots.

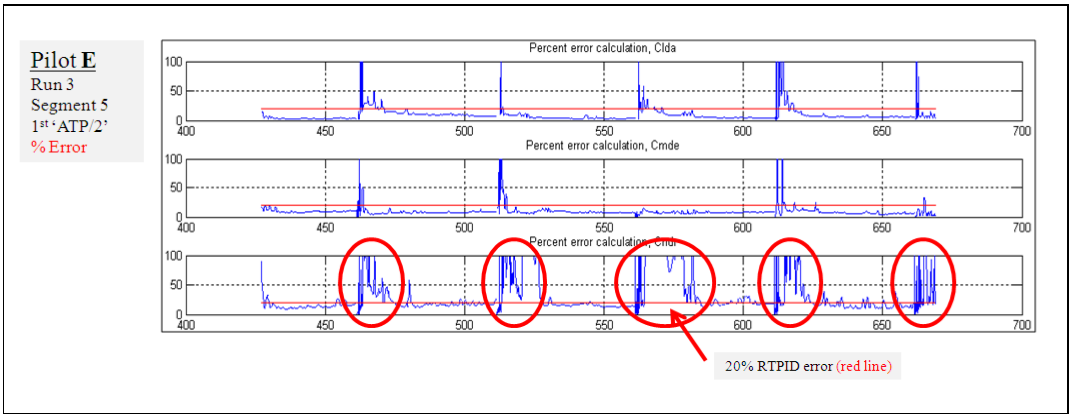


Figure 21: Percent error calculations; run 3, Segment 5, pilot E

Very few aileron and elevator excitation cues occurred in all six segments of flight. Rudder warnings occurred with the most frequency, and Pilot A had the most rudder warnings of any pilot by an order of magnitude. While less excitation cues did occur in latter approaches with simulated atmospheric turbulence, rudder cues still occurred at a higher rate regardless of atmospheric turbulence. This trend is attributable to pilot technique as evidenced by video and by the 50 seconds RTPID resets, and is likely reinforced by pilot experience in wide body passenger aircraft with yaw dampers. It was repeatedly observed that pilots had a tendency to fly with their feet on the floor and not on the rudder pedals. In general, all pilots met the performance criteria with different control input strategies, and were effective in making the excitation cues disappear without any test pilot control input training.

PILOT CONTROL ANALYSIS:

For each of the three control axes, scalogram plots[9, 10] were computed using a Morlet Wavelet in STI's FREDA MATLAB toolbox. FREDA was used to generate scalograms displaying the amplitude of different input frequencies versus time. Thus, information was obtained regarding what input frequencies were used, their amplitude, and when they were used. For example, Figure 22 shows an aileron input scalogram for segment 5 of Pilot B's first ATP/2 standard approach in a calm atmosphere. The scalogram shows a large jump in elevator input (magnitude scale) at a low frequency (frequency scale) towards the end of the segment (time scale) due to the increased sensitivity of the precision approach guidance. Most of the input energy is below 3 rad/sec or 0.48 Hertz (Twin Otter short period natural frequency is 0.5 Hertz) and is marked with a dashed green line on Figure 22. However, there are several areas when the input energy is on both sides of 3 rad/sec. This is expected because pilots inherently provide inputs near the natural frequency in order to maneuver the aircraft. Similar patterns were observed for all pilots, and in calm and moderate atmospheric turbulence conditions, although the results are not shown.

Scalogram data was used to calculate the cutoff and power frequencies[8]. Cutoff and power frequencies were used to estimate the pilot's operating frequency and the intensity of the inputs at that frequency. These were useful diagnosis tools in order to determine which phases of flight inherently produced significant control activity. Although control activity in itself is not sufficient for RTPID (RTPID requires control inputs with sufficient magnitude at the right frequencies) it aided the study for each segment of the approach.

Cutoff frequency at a particular instant in time is calculated by examining a time slice of the scalogram. The Cutoff frequency is defined such that the integral of the input energy for the time slice from zero to the cutoff frequency is half the value of the integral from zero to infinity.

$$\frac{\Psi_1^2(t)}{\Psi_{total}^2(t)} = \frac{\frac{1}{2\pi}\int_0^{\omega_1(t)} G_{\delta\delta}(t)\,d\omega}{\frac{1}{2\pi}\int_0^{\infty} G_{\delta\delta}(t)\,d\omega} = 0.5$$

However, in this process, information regarding the amplitude of an input is lost, and it is easy to see that a task requiring very small inputs could produce cutoff frequencies similar to those of a task requiring large inputs. The power frequency reintroduces this information by multiplying the cutoff frequency by the maximum input energy amplitude found on the time slice.

$$\omega_G(t) = \omega_{cutoff}(t)\max G_{\delta\delta}(t)$$

Figure 23 shows the time varying cutoff and power frequencies obtained from the scalogram in Figure 22. The cutoff values in Figure 23 from 525 to 575 seconds are not used for analysis because the power frequency is below the cutoff frequency. Cutoff values for the remainder of the run are used for analysis because the power frequency is above the cutoff frequency. As a rule of thumb, the cutoff frequency is only used when the power frequency is greater than the cutoff frequency. From Figure 23, average and maximum values were obtained for cutoff and power frequencies. These values are then used for the subsequent analysis.

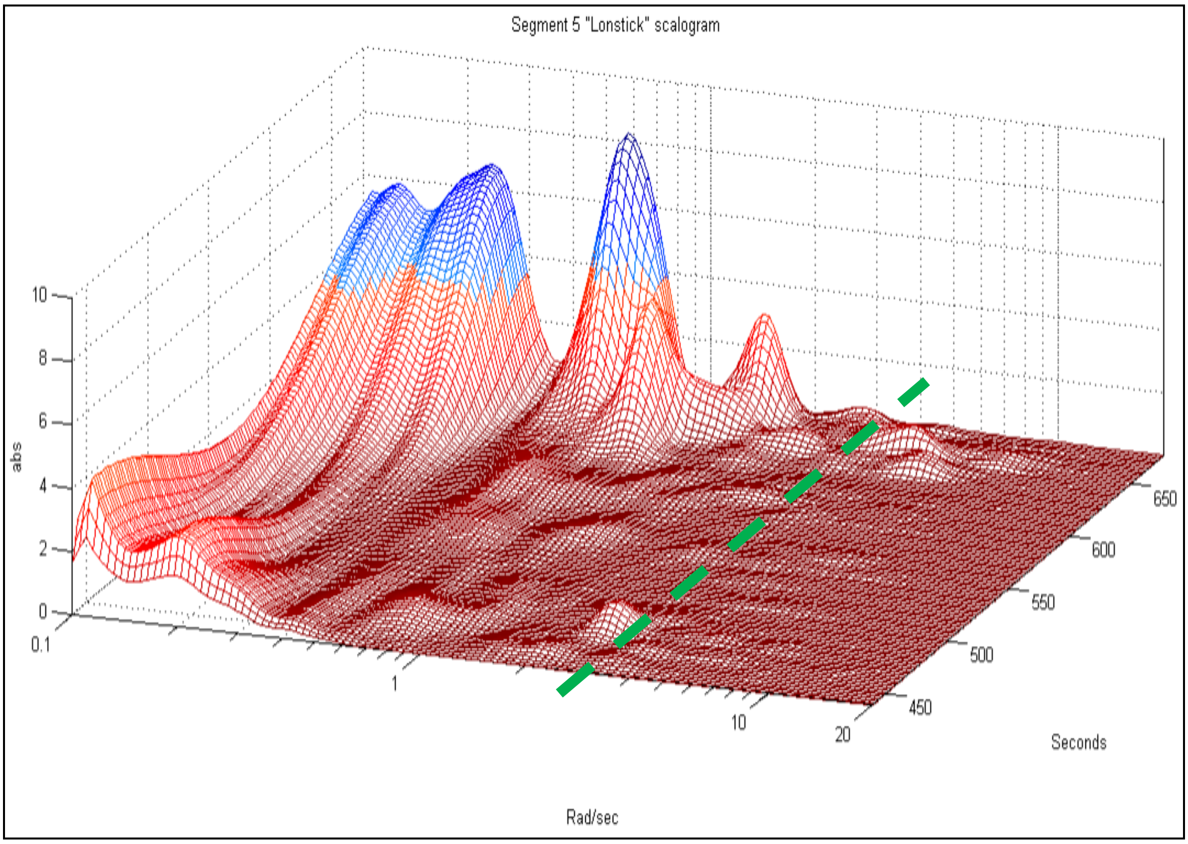


Figure 22: Pilot B Lonstick (elevator) input scalogram, Segment 5, first ATP/2 approach

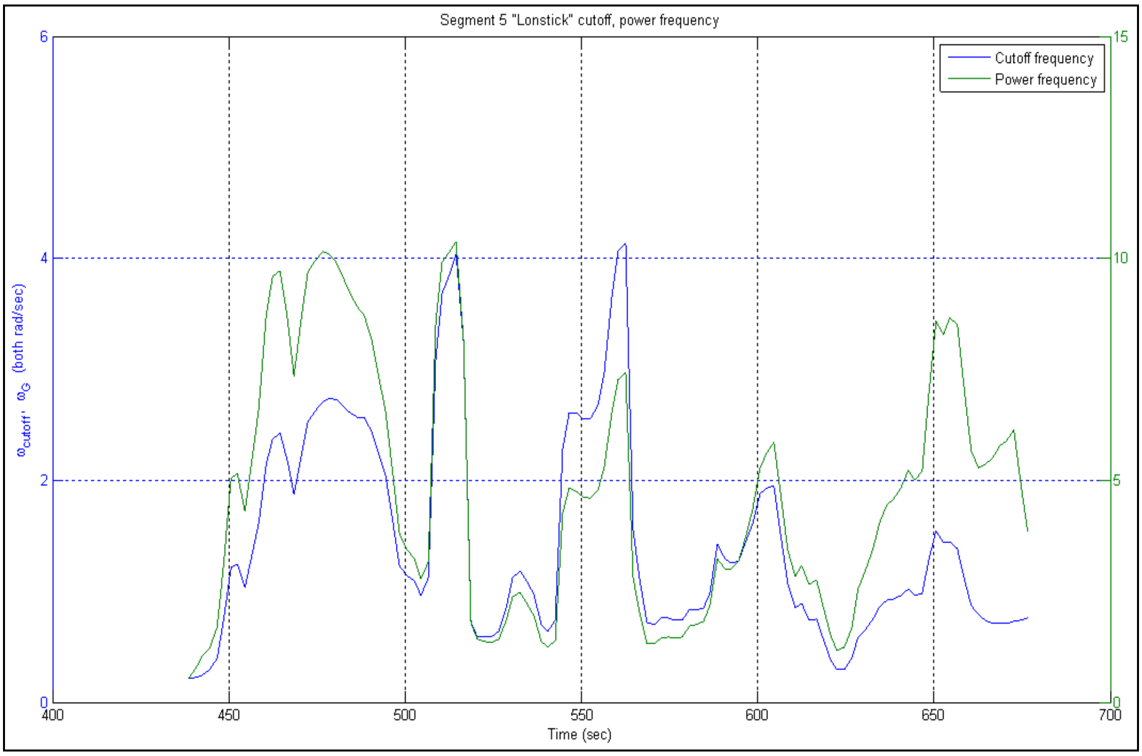


Figure 23: Lonstick (elevator) Cutoff and Power Frequencies for Pilot B, Segment 5, first ATP/2 standards approach

The power frequency was used to further investigate which phases of flight and atmospheric turbulence conditions provided the most control activity and promote system identification using RTPID. Segments 1 (cruise task) and segment 5 (precision instrument approach) were chosen to represent the two extremes of pilot control activity. Figure 24 shows the power frequencies for all control axes (aileron, rudder, and elevator) averaged across all pilots for all six segments of the first light atmospheric turbulence run.

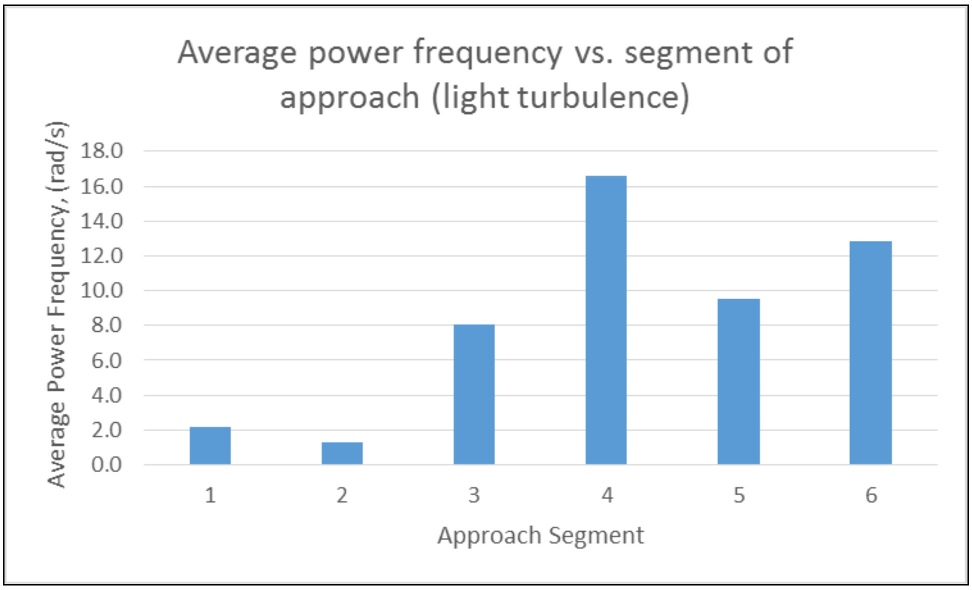


Figure 24: Power Frequency versus approach segment averaged across pilots and input type

Power frequencies for segment 5 are substantially greater than those for segment 1. This indicates that overall, pilots had to make larger and/or more frequent inputs in segment 5, which is indicative of higher workload. It is also indicative of the reduced number of elevator and aileron excitation cues in segment 5 and the increased number in segment 1. This suggests than segment 5 promotes the most pilot activity and in turn the best system identification conditions. Segment 2 (a basic turn) is frequently seen in flight but does not promote system identification because of the lack of control activity. Segment 3 (flap transition) promotes system identification because of the required configuration change and resulting control effort. Unfortunately flap transitions are singular events in a flight profile. Segments 4 and 6 have higher average values as the result of one unusually large input to make a turn and join the precision approach guidance (segment 4) or raise the nose during the go around procedure (segment 6). These singular events promote system identification conditions but are not as consistent as segment 5. Similar patterns were observed with calm and moderate atmospheric turbulence conditions, although the results are not shown.

Figure 24 showed power frequencies averaged across all pilots and control axes. In order to investigate the variation of input intensity in greater detail, power frequencies between pilots, control inputs, performance standards, and atmospheric conditions were studied.

Figures 25-27 show average power frequencies for each pilot across control inputs, performance standards, and atmospheric conditions. The average power frequency was first calculated relative to time in each run and then averaged across the number of runs for each approach type. Power frequencies for Pilot C are not included in these figures since Pilot C completed a disproportionally low number of approaches in atmospheric turbulence conditions due to time constraints and, as a result, had power frequencies that were not comparable to those of the other pilots when averaged across approaches. Power frequencies have been taken from segment 5, which had greater and hence more representative control activity. In general, Pilot A consistently had the lowest average power frequencies across control inputs, performance standards, and atmospheric conditions, while Pilot B consistently had the highest. This indicates that Pilot A tended to use relatively small and infrequent control inputs, while Pilot B used very large and frequent inputs in comparison. This was previously confirmed by examining the number of excitation cues per pilot.

Figure 25 shows that the variation of aileron input was small. Although Pilot A does have the lowest aileron input power frequency, and Pilot B has the highest, their power frequencies differ by only a factor of 1.3.

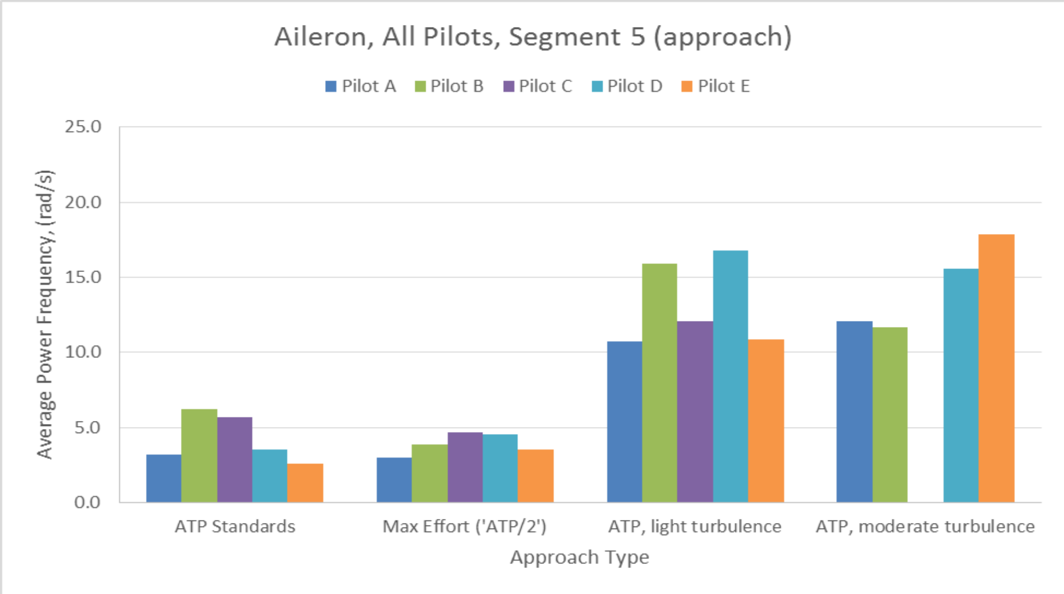


Figure 25: Aileron Power Frequency versus Approach Type

In Figures 25-27, power frequency tends to increase as the tolerances tighten or atmospheric turbulence increases. All pilots increased their inputs intensities when atmospheric turbulence was introduced. However, in some cases, average power frequencies seem to stagnate. For example, the strictness of the standards (ATP versus ATP/2) and the relative intensity of atmospheric turbulence (light versus moderate) have a small effect on aileron and elevator Power Frequencies. This suggests that the design of experiments could be modified to only include ATP standards and light atmospheric turbulence. This is important because commercial airline pilots are accustomed to flying ATP standards and because operationally light atmospheric turbulence has the highest probability of occurrence.

For elevator inputs (Figure 26), input intensities differ by a factor of roughly 2, indicating differences in piloting technique. Nevertheless, power frequencies are relatively high.

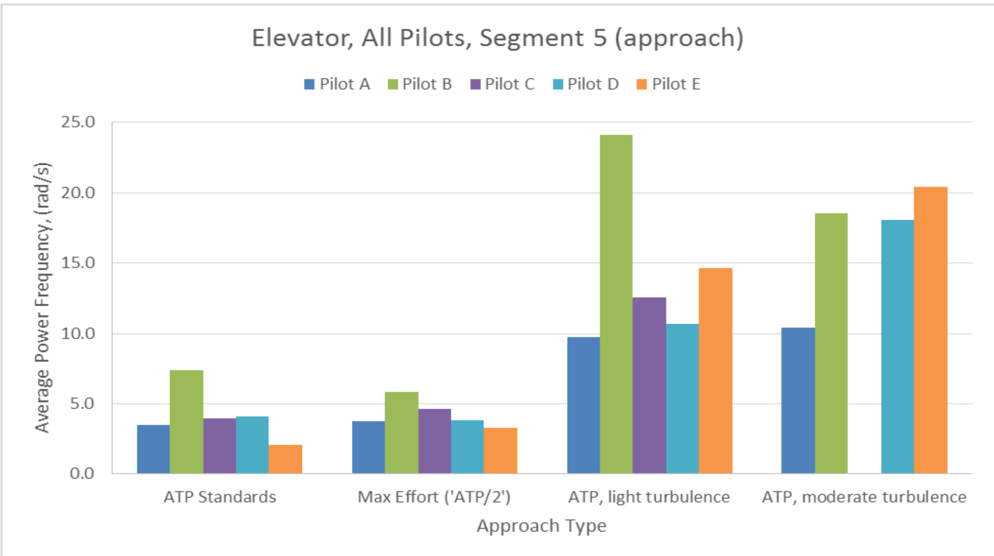


Figure 26: Elevator Power Frequency versus Approach Type

Pilot B and Pilot E depict two different trends. Pilot B's average aileron and elevator power frequencies decreased noticeably when approach performance standards were tightened or the severity of flight turbulence was increased. This phenomena was counter-intuitive because it was expected that additional inputs would be required to correct path deviations as performance standards tightened or as atmospheric turbulence became more severe; however, these results are attributable to piloting technique.

First, while heightened approach standards are likely to require more frequent corrections, those corrections will, at the same time, have to be smaller. Pilot B had a tendency to use relatively large control inputs, and had to greatly reduce the magnitude of these inputs upon encountering tighter restrictions on the flight path; however, a significant change was not necessary for the other pilots. As a result, power frequencies for the other pilots tended to remain constant or even increase slightly as the approach standards were tightened.

Additionally, the observed decrease between light and moderate turbulence is also attributable to piloting technique. While a pilot may be able and willing to correct course deviations in light turbulence, an increase in turbulence could induce the pilot to forego attempts at course correction rather than make excessively large/frequent inputs. Once again, the fact that Pilot B was already making very large inputs even in light atmospheric turbulence supports this analysis. Pilot B would have had to make extremely large inputs to maintain the same correction scheme used before. Thus, it is likely that Pilot B was unable to safely make larger inputs and sacrificed attempts to correct for atmospheric turbulence in order to maintain better control of the aircraft.

Pilot E had increasing power frequencies with increasing performance standards and atmospheric turbulence conditions. This trend was consistent for all control axes.

Figure 27 shows that the average rudder power frequencies differ by a factor of nearly 12 with aileron and elevator average power frequencies. However, Pilot B produced rudder power frequencies an order of magnitude above those of all the other pilots. All pilots had increasing power frequencies with increasing performance standards and atmospheric turbulence conditions.

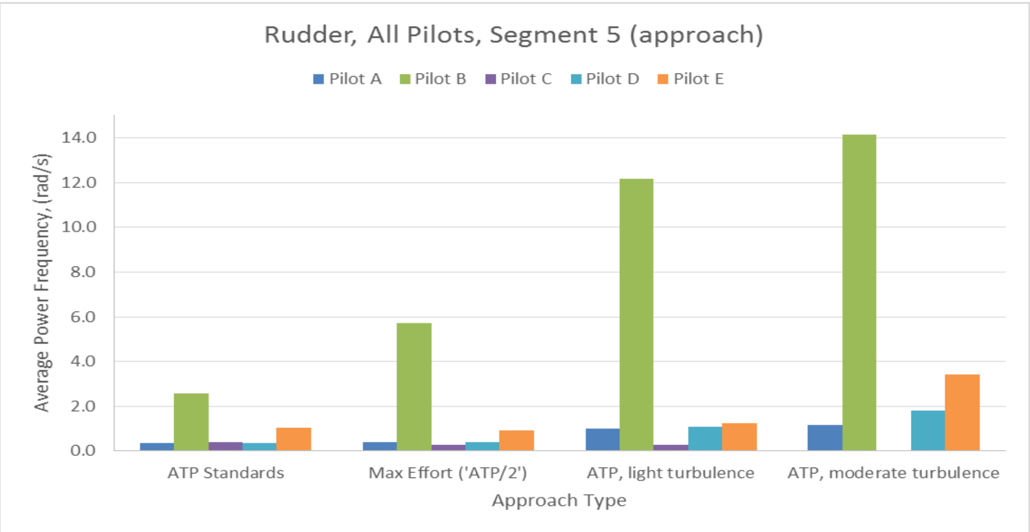


Figure 27: Rudder Power Frequency versus Approach Type

The cutoff frequency was used to further investigate power frequency behavior. Figure 28 shows the rudder cutoff frequencies for each pilot averaged across all approaches for segment 5.

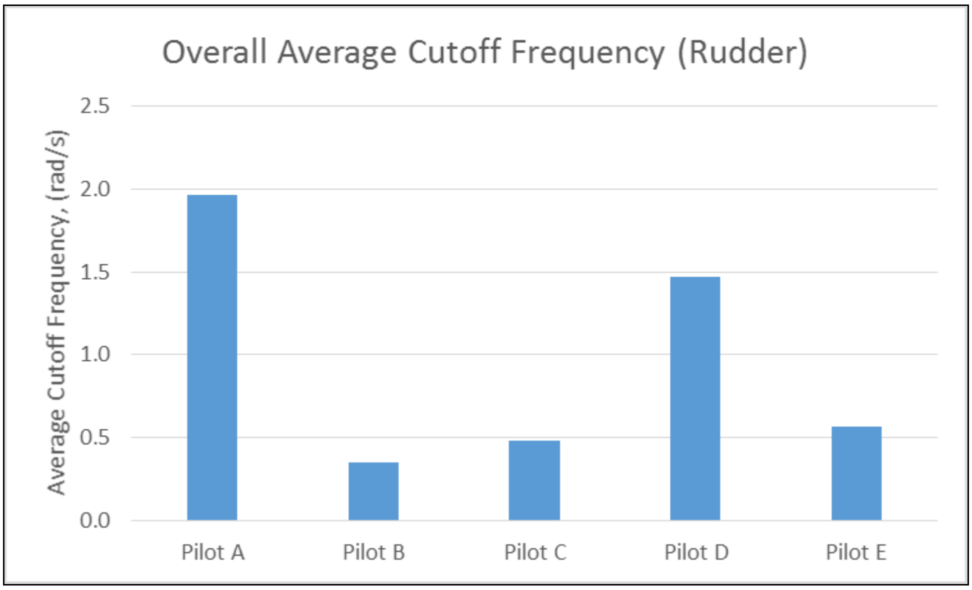


Figure 28: Average Cutoff Frequencies for Rudder Inputs

Pilots A and D had high rudder cutoff frequencies, indicating fast rudder inputs. The unusually high values are likely the result of faster rudder inputs than the other pilots when clearing excitation messages. The final point of interest in Figure 28 is that Pilot B has a very low rudder cutoff frequency. However, Pilot B had very large rudder power frequencies. Thus, it can be concluded that Pilot B made large but slow rudder motions.

The power frequency was used to investigate which phases of flight and atmospheric turbulence conditions provided the most control activity and promote system identification using RTPID. Segment 5 (precision instrument approach) provided the most control activity along with the least number of excitation cues, and therefore was most conducive to system identification. This result was expected because in this segment the pilot is tightly coupled with the aircraft as the pilot follows precise vertical and lateral guidance to the runway. Although other segments provided instances conducive to system identification, none were as consistent as segment 5. If pilots were provided similar lateral and vertical guidance, system identification could be carried out in any phase of flight with natural pilot control activity and minimal excitation cueing. However, as previously analyzed, all pilots were effective in making the excitation cues disappear without any test pilot control input training.

Differences in pilot technique were studied in order to understand the effectiveness of pilot inputs for system identification. Scalogram, power, and cutoff frequencies plots were used to determine that all pilots used a different control strategy in obtaining the same piloting performance standards. This suggests that 5 pilot strategies were involved in the experiment. Pilots A and B represent the two extremes tested while pilots C-E were somewhere within those extremes.

The most effective way of changing the pilots control activity was to change the atmospheric conditions. Changing the atmospheric conditions (calm versus light/moderate) was more effective in increasing the pilots control activity than tightening the pilot’s performance standards (ATP vs ATP/2). This is important because commercial airline pilots are accustomed to flying ATP standards and because operationally light atmospheric turbulence has the highest probability of occurrence.

PILOT OPINION SURVEY RESULTS:

Pilot opinion surveys were conducted immediately after all testing was completed. The survey consisted of four parts. Except for questions relating to pilot experience and flight ratings, questions were written in a Likert question-statement format, which asked the pilot for level of agreement, or frequency of occurrence. Pilot responses to these questions provided information which helped understand factors that either motivated their control strategy, or explained how their background and training influenced their attention skills and perception of workload.

Part I – <u>Demographics and Flight Operations</u> –In addition to the demographic data collected in this section, questions were asked to determine the phases of flight that the pilots preferred to fly manually, or if and when company standard operations procedures required them to use an autopilot. The purpose for these operational questions was to gain some sense for which phases of flight manual pilot control was most likely based upon pilot preferences and company standards. The list of questions follows and Figure 29 provides a summary of the pilots' responses. A discussion and analysis of the results follows.

1. I estimate that I manually fly the aircraft most during the ________ phase of flight?
   Climb Cruise Descent Approach

2. My airline SOP encourages or requires use of the autopilot for most operations.
   Strongly Disagree Disagree Undecided Agree Strongly Agree

3. I prefer to use the autopilot to fly the airplane in turbulence.
   Strongly Disagree Disagree Undecided Agree Strongly Agree

4. I use the autopilot most often when flying instrument approach procedures.
   Strongly Disagree Disagree Undecided Agree Strongly Agree

5. I generally fly most visual approaches manually.
   Strongly Disagree Disagree Undecided Agree Strongly Agree

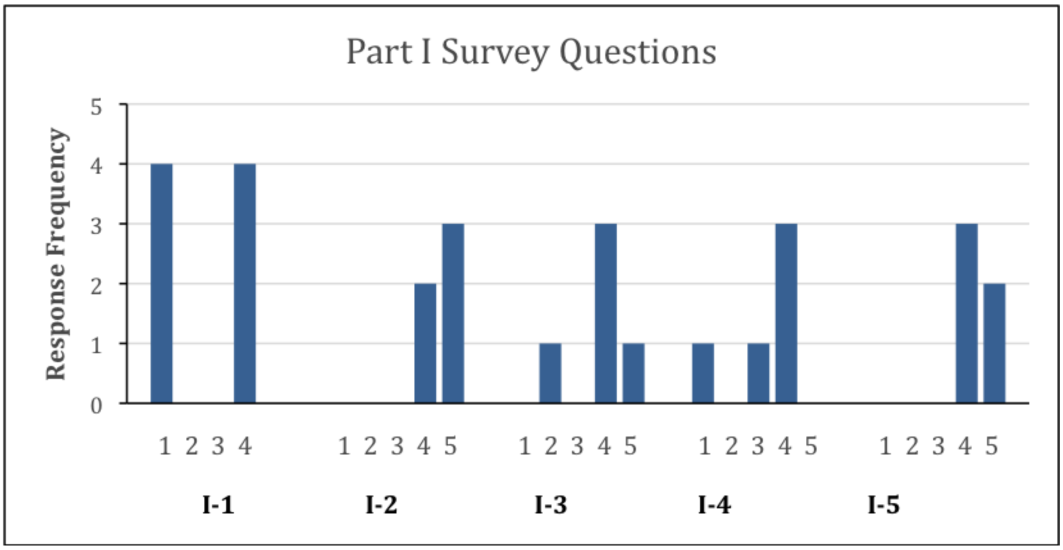


Figure 29: Responses to Flight Operations Survey Questions

Part I Discussion

Question one asked for the phase of flight the pilot felt they manually flew the aircraft most. This was the only fill – in question in the survey, where the authors were expecting just one of the choices to be selected. Three of the pilots however, selected two responses, which is the reason for the eight total responses as shown in Figure 29 instead of five. Regardless, the responses were equally split between the climb phase and the approach phase, which is not surprising since these two phases are the ones with the greatest requirement for maneuvering. From a proficiency standpoint, pilots need to maintain their "stick and rudder" skills and these phases provide the necessary opportunity for meeting that requirement.

In question two, pilots were asked if company standard operating procedures encourage or require use of autopilot for most operations. Two pilots agreed and three strongly agreed with the question. However, all the pilots did indicate that it was really their choice to decide when they would use manual or autopilot operation based on the operational factors existing at the time. For example, most airlines train pilots to connect the autopilot when dealing with an inflight emergency or abnormal condition. This allows them to work better as a team to resolve the issue at hand. However, it is the pilot's prerogative to decide whether or not to follow this policy.

Question three asked pilots if they preferred to use auto pilot in turbulent conditions. Three pilots agreed and one pilot strongly agreed with the statement regarding use the autopilot in turbulence. One pilot disagreed. Operationally, most airlines encourage autopilot use in turbulence because it generally gives the passengers a better ride while greatly reducing the pilot's workload when performing a flight task.

Question four asked what phase of flight they would use the autopilot most. Three of the pilots agreed that they use the autopilot most often when flying instrument approach procedures, one was neutral and one disagreed. The agreeing pilots qualified their answers during debriefing by clarifying that they do not exclusively use the autopilot for approach procedures, only that it is a phase of flight where they are more likely to use it.

Question five asked if pilots manually controlled the aircraft on visual approaches and all pilots agreed or strongly agreed that they fly visual approaches manually. In general, when weather permits, air traffic facilities offer visual approaches as they greatly expedite departures and arrivals.

Part II. Pre-Test Training – The next set of questions were related to the pilot's opinion of how difficult it was for them to master the control technique that would provide the necessary excitation for satisfying the manual control alert cue. This question relates to the practicality of training operational pilots to perform this control task and how well they can master the skills needed to produce good stability and control parameter estimates. The list of questions and a discussion of the results follow. The responses to the questions are shown in Figure 30.

1. The control input concept for updating the aircraft state was easy for me to understand.

   Strongly Disagree Disagree Undecided Agree Strongly Agree

2. Even after much practice, I felt that I initially made either too little or too much control input when a control input cue alert came on.

Strongly Disagree Disagree Undecided Agree Strongly Agree

3. I quickly mastered elevator, aileron, and rudder inputs when cued.

Strongly Disagree Disagree Undecided Agree Strongly Agree

4. I felt that the training I underwent adequately prepared me for the testing I performed.

Strongly Disagree Disagree Undecided Agree Strongly Agree

5. I had difficulty understanding how to adjust my control inputs for different airspeeds and wing flap configurations.

Strongly Disagree Disagree Undecided Agree Strongly Agree

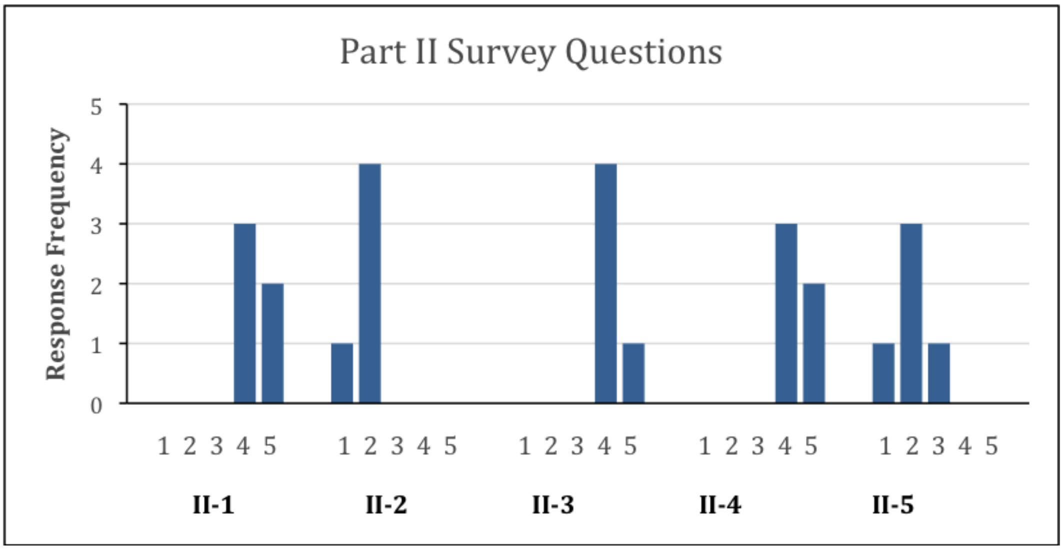


Figure 30: Response frequencies for Part II

<u>Part II Discussion</u>

Question one asked if was easy for the pilots to understand the control input concept for updating the aircraft state. Three agreed and two strongly agreed with the statement. The test conductors found that it took very little time, perhaps no more than five to ten minutes of explanation for the pilots to understand the basic concept behind RTPID, and why the manual input task was required.

The second question asked if the pilots felt that it took considerable practice to master a control technique necessary to satisfy the alerting requirements. Four of the pilots disagreed and one pilot strongly disagreed with this statement. During initial vetting of the test plan, the test conductors found that by simply asking the pilots to move the nose back and forth along the flight path in the appropriate control axis that was just enough to excite a small response but one that passengers would barely notice was all that was required.

Question three asked if pilots felt they quickly mastered the required control inputs when cued. Four pilots agreed, and one strongly agreed. The control input task took only a few minutes to master, but some of the pilots did comment on the fact that the feedback they received as to the effectiveness of their inputs was delayed and there was no tactile feedback from the fixed based simulator to help them assess the results of their control inputs. One pilot in particular indicated that he thought he could have done a better job of making the inputs if he had this feedback. In future research, it would be beneficial to conduct this study in an actual aircraft with all of the corresponding sensory feedback.

The fourth question was directed at the adequacy of pre-test training. All pilots received the same training consisting of briefings and practice before beginning the data collection runs, and all of them agreed or strongly agreed that the training was adequate.

In question five, the pilots were asked if it was difficult for them to tailor their control inputs to different conditions and configurations of flight. At high speed cruise for example, required input amplitude to provide the necessary excitation is relatively small, but at lower speeds the amplitude must be larger to account for the reduced control effectiveness. One pilot strongly disagreed with the statement, three disagreed, and one was neutral. This was not a surprising result as human pilots can generally adapt their control strategy to anticipated flight characteristics after some practice. The pilots in this test had practiced the approach procedure a few times before data collection and quickly learned how to anticipate and adapt their control input strategies to changes in flight condition and speed.

<u>Part III. Situation Awareness and Flight Control Priority</u> – In this section, pilots were asked questions that would provide some insight as to how they would respond to alerting cues if the aircraft was handling abnormally or if they thought that making additional inputs had a negative effect on any flight task they happened to be performing at the time. Additionally, the questions sought information on the effectiveness of the alerting cues in capturing the pilots' attention if alerted while performing a flight task, i.e., were the alerts seen to be distracting or not. The list of questions for this section and a discussion of the results follow. A summary of the pilots' responses to the questions are provided in Figure 31.

1. If I sensed aircraft handling problems I would hesitate to aggravate the situation with additional control inputs if alerted to do so.

Strongly Disagree Disagree Undecided Agree Strongly Agree

2. If the airplane was handling normally, and I was alerted to make additional control inputs, I would probably ignore the alerts or cancel them if I could.

Never Rarely Sometimes Very often Always

3. I became immediately aware of the manual control input alert when it was posted on the flight display.

Strongly Disagree Disagree Undecided Agree Strongly Agree

4. I thought the control input alerting cues distracted me from the task I was performing at the time.

Strongly Disagree Disagree Undecided Agree Strongly Agree

5. Having to respond to control input cues affected my task performance.

Strongly Disagree Disagree Undecided Agree Strongly Agree

6. I tended to make small control inputs initially when cued, and then make larger ones if the alert lights did not go out when they should have.

Never Rarely Sometimes Very often Always

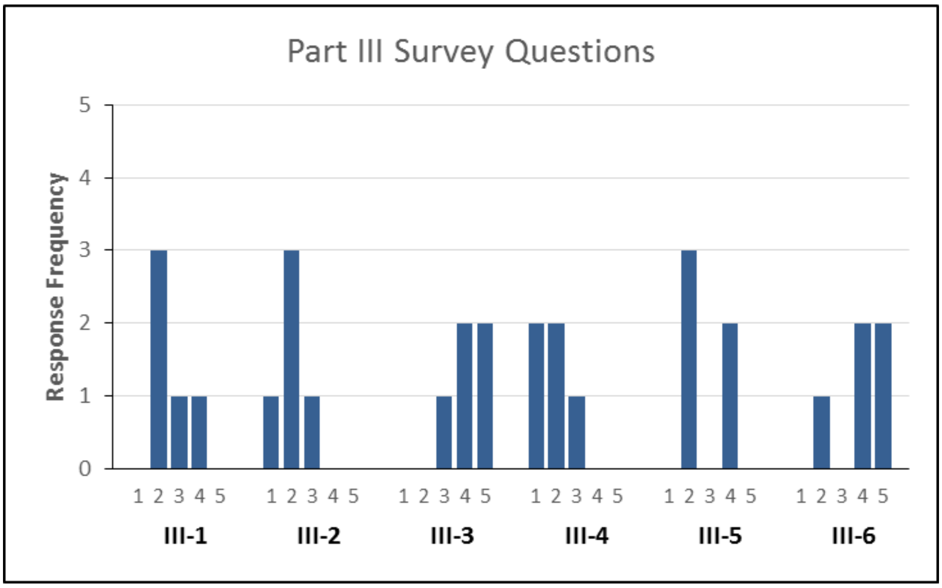


Figure 31: Response frequencies for Part III

<u>Part III Discussion</u>

The first question asked for agreement with the statement that the pilot would be reluctant to aggravate an apparent aircraft handling situation by making additional control inputs when cued. Three pilots disagreed one was neutral and one agreed. The issue here is that if a pilot is experiencing a handling abnormality, would the pilot be reluctant to make any additional control inputs that would aggravate the situation further. In this simulation, there were no perceptible handling issues so the pilots' responses were to a hypothetical situation, and perhaps influenced by their prior experience. In future research, it would be beneficial to ask this question again in a situation where the pilot is struggling with a real handling problem.

The second question asked for agreement with the statement that pilots would ignore or cancel control input alerts if the aircraft was handling normally. Three pilots disagreed with the statement, one strongly disagreed, and one pilot was neutral. Although this was a desirable result, the test profile was a relatively short event, on the order of 10 minutes. Future research should assess pilot opinion on a much longer flight that typifies an entire trip segment of two hours or more, where having to respond to repeated control alerting may be viewed differently.

The third question was asked to determine if the pilots felt they had immediate awareness of control input alerting when it was posted on the PFD. The purpose for the question was to verify that any delayed responses to a control input alert were not due to an integration issue. This specifically refers to how the excitation cues were integrated visually and orally on the PFD. As can be seen from the responses, two pilots agreed with the statement, two strongly agreed, and one was neutral. Since the PFD is the primary reference used by pilots for controlling the aircraft, the results of this question indicate that eventual integration of this system in an operational context should consider the PFD as the location to display control alerting cues.

The fourth question was asked to address a concern that alerting cues could distract the pilot when performing an operational control task such as an approach or departure procedure. Two pilots disagreed and two pilots strongly disagreed that alerting cues were distracting while one pilot was neutral. Test conductors observed each of the pilots during each test run and especially when flying the precision approach. It appeared that all of them remained focused on the flight task at hand, while maintaining the ATP performance standards that were required.

The fifth question asked the pilots if having to make manual control inputs when cued interfered with the performance of a flight task. The test profile consisted of several maneuvering sequences before beginning precision approach procedure. Two pilots (A, E) agreed that making control inputs interfered with the performance of a flight task, and three pilots, (B, C, and D) disagreed. The term “interference” in this question was used in a general sense because there can be many reasons for control alerts interfering with a flight task. Interference can be simply the annoyance of having to respond to several alerts throughout a flight; or, having to make additional control movements not associated with the flight task at hand; or, having to continually divide attention between flight guidance displays and alerting displays. Regarding number of alerts, Figure 32 shows the averaged cues for each of the pilots during the precision approach segment. Pilot A had the most alerts, 6.3 per run, which would support the notion that the sheer number of control alerts affected his task performance. Pilots B, C, and D had about half as many alerts, which seem to support the notion that fewer cues would have a lesser impact on perceived task performance. But pilot E, who had approximately 1/3 as many alerts as Pilot A, agreed that task performance was impacted by control alerting. Figures 25-27, which provide the averaged Power Frequency of each pilot’s control inputs, are a good indication of pilot control activity. Pilot A, the agreeing pilot, had the lowest control activity and thus the most alerts, as previously explained. Pilots B, C, and D, who disagreed that the cues affected their task performance, had high levels of control activity, and fewer alerts, as previously explained. But Pilot E, who with Pilot A felt that the alerting cues interfered with the performance of a task, also had high levels of control activity, but alerting was less because control activity was high. During the de-briefing, Pilot E felt that the additional control inputs did not support the task being performed. Nonetheless, all pilots performed the approach task well within ATP standards, regardless of their opinion of whether or not the control alerts interfered with their performance. Pilot opinion of “interference” is an important consideration as it relates to operational viability for eventual flight system certification, especially in high workload, real world situations.

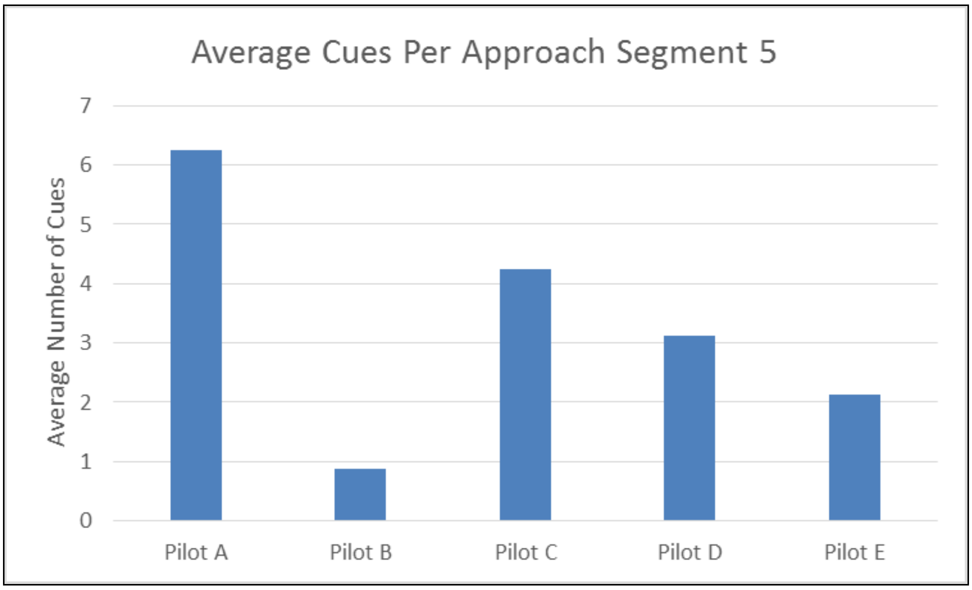


Figure 32: Averaged Alerting Cues for Precision Approach

Question six was asked to assess the control strategy pilots employed when responding to control alerts. During pre-test training, the test director emphasized that the inputs should only be large enough to satisfy the alerting cue and this is what they practiced until proficient before data collection began. The question was therefore worded to determine if pilots tended to make very small inputs first to see if they were adequate before making larger inputs. Two pilots agreed, two pilots strongly agreed, and one pilot disagreed with the statement. The only disagreeing pilot was Pilot A, who flew the first test profile with a *ten second* cue de-latch time before he could determine if his inputs were effective. (This de-latch time was later corrected to one second for pilots B, C, D, and E). Pilot A was aware of the ten second delay, and consciously waited for the de-latch time to expire to assess if more control inputs were needed. In retrospect, it was not often that pilots had to repeat their inputs to satisfy the alerting cue, but it was apparent that pilots wanted immediate annunciation of the effectiveness of their control inputs so they could in fact determine if additional inputs were required. It stands to reason that a pilot would make larger inputs if the first attempts were not successful, but delays in the annunciation of current alerting information could cause either unnecessary control inputs or excessive inputs to satisfy the alert.

<u>Part IV. Attention and Workload</u> – In this last section of the survey, questions were asked to assess the effects on the pilots' attention and workload when having to respond to manual control alerts while performing operational flight tasks. In an operational situation, pilots are characteristically goal oriented; they try to maintain good situation awareness and prioritize their actions so they can multi-task efficiently. For example, when performing an approach procedure, there are a series of tasks that a pilot must perform sequentially or in parallel, which include reviewing the procedure, accomplishing checklists, directing the flight crews' actions, maneuvering to execute the procedure, and communicating with air traffic control. It is a very busy time and accomplishing all these tasks efficiently presents large demands on their attention resources. If hazardous weather or an emergency situation is present at the time, the demands are even higher. The added requirement to respond appropriately to additional control input alerts beyond those required to perform the current flight task competes for these resources. It was therefore the objective of this survey part to develop only a basic understanding of how the added control input requirement impacted attention

and workload. A listing of the ten questions and discussion of results follow. The responses to the questions are provided in Figures 33 and 34.

1. Aural alerts improved my reaction time to control input alerts.
Strongly Disagree Disagree Undecided Agree Strongly Agree

2. It was difficult to perform the proper manual control inputs in response to an alert.
Strongly Disagree Disagree Undecided Agree Strongly Agree

3. I believe that a control response to a control input alert should be at the pilot's discretion.
Strongly Disagree Disagree Undecided Agree Strongly Agree

4. It was annoying to have control input alerts going off when I was trying to fly an instrument approach to specific tolerances.
Strongly Disagree Disagree Undecided Agree Strongly Agree

5. I felt my accuracy when flying the precision approach was degraded by having to make additional control inputs during the task.
Strongly Disagree Disagree Undecided Agree Strongly Agree

6. Additional control input alerts should be inhibited when reaching approach minimums.
Strongly Disagree Disagree Undecided Agree Strongly Agree

7. I felt that having to maintain an awareness for control input alerts made it more difficult for me to monitor other aircraft systems during the instrument approach.
Never Infrequently Sometimes Very Often Always

8. The control input alerts were more difficult to integrate into my scan when maneuvering during descending turns or turns to headings flight.
Never Rarely Sometimes Very often Always

9. I thought the control input alerting cues were very salient and hard to miss.
Strongly Disagree Disagree Undecided Agree Strongly Agree

10. In turbulent conditions there were no control input alerts.
Strongly Disagree Disagree Undecided Agree Strongly Agree

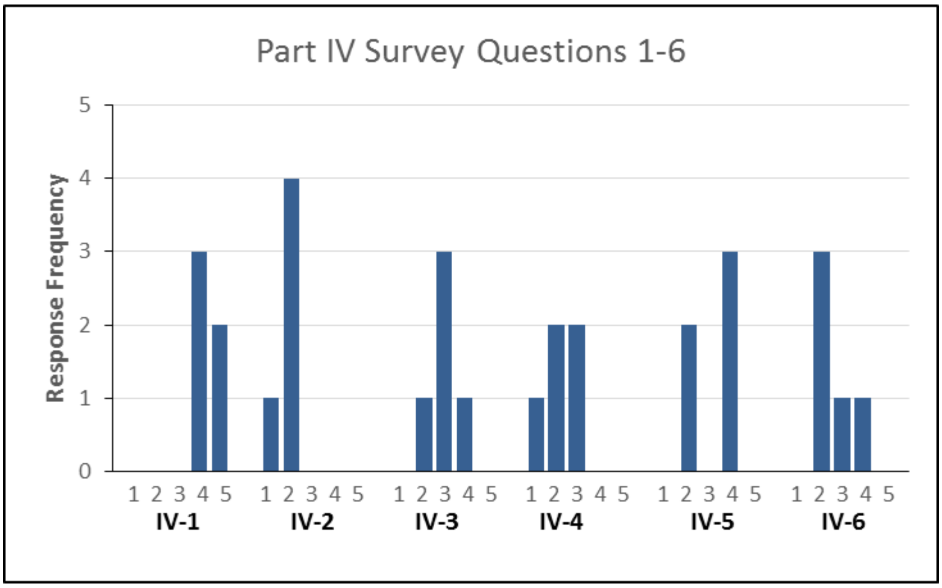


Figure 33: Response frequencies for Part IV; questions 1-6

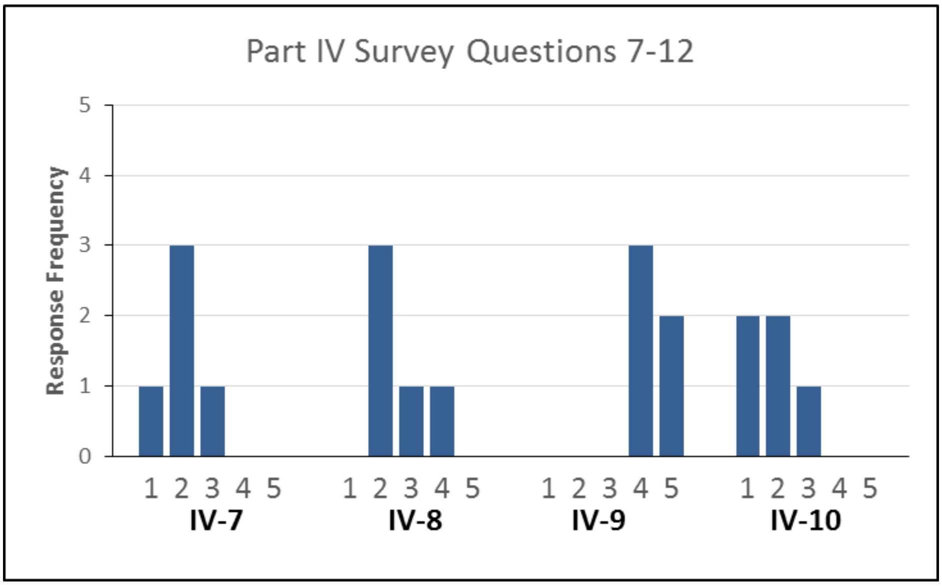


Figure 34: Response frequencies for Part IV; questions 7-12

<u>Part IV Discussion</u>

Question one asked for agreement on the benefit of using an aural alert to augment the visual alerting displays. This is a very common practice in modern flight systems, as human reaction to a recognized aural stimulus is quick and automatic. Three pilots agreed and two pilots strongly agreed that aural alerting improved their reaction time. In this research program, a chime was used to provide the aural cue and it appeared to be very effective. The control input alert was an amber message AIL, ELEV, RUD that was prominently displayed on the upper portion of the PFD. But correct design protocol requires that amber messages with corresponding aural alerts indicate a CAUTION condition, something that requires eventual pilot action due to a safety related issue. This may not be correct integration when there is no handling problem or safety issue with the aircraft. Therefore, integration of a manual control input alerting system involving both visual messaging and aural alerts is an integration issue that should be addressed in future research.

Question two asked for agreement with the statement that it was difficult to make the required control inputs. The issue of "difficulty" relates to workload, and the question was asked to assess only the task of making the inputs. Four pilots disagreed and one pilot strongly disagreed that making the required control inputs were difficult.

Question three asked for agreement with the statement that response to a control input alert should be at the discretion of the pilot. One pilot disagreed, one agreed, and three pilots were neutral. It would appear that since the data is tightly normalized around the neutral position, pilots are ambivalent on this issue and that they would be amenable to an integration that was either a mandatory or discretionary manual control input response. However, this test profile only focused on the control performance of the pilot when making manual inputs, and no messages of stability and control problems were shown to the pilot. Quite possibly, in a very high workload situation such as dealing with an inflight emergency or abnormal condition, a pilot's response to this question might be different, especially if there were no evidence of an aircraft handling problem and/or no stability and control alerting messages.

Question four was asked to assess whether or not the pilots felt that control input alerts were annoying when trying to fly an approach procedure to within specified tolerances. Performance tolerances were either ATP standards or ATP/2. In order to meet these performance standards, pilots had to focus their attention on minimizing course and glide slope errors, and it was of interest to assess if the added task of attending to control input alert cues were an annoying interference with this primary flight task. Two pilots disagreed that the alerts were annoying, one strongly disagreed, and two were neutral. The responses indicate that manual input control alerts did not seem to disturb the pilots when attempting to fly their very best instrument approach. The observation of the test conductors was that pilots immediately attended to any control alerts as soon as they were posted and that they were easily able to integrate them into their instrument scan.

Question five was asked to understand if the pilots felt that the additional control input requirement degraded their accuracy when flying a precision approach procedure. This question is a corollary to question five, Part III of the survey. A precision approach is perhaps the most tightly coupled pilot-in-the-loop task that is performed in flying operations, and this is where task-related pilot control is the most intense. It is therefore logical to expect that in a case where pilots may already be task saturated when flying an approach, having to make additional inputs could potentially affect task performance. Two pilots disagreed that their accuracy was affected, and three pilots agreed. The conditions under which the pilots flew the approach did not include any winds, but did include light and moderate turbulence conditions. Given the fact that there were no winds to contend with, it would appear from the pilots' responses that having to make additional control inputs while flying an approach procedure can affect approach task performance. Due to the disparity in the results, it would be appropriate to investigate this issue in future research programs.

Question six asked pilots if they agreed that manual control input alerts should be inhibited when reaching approach minimums (200 ft above ground). Modern flight systems generally inhibit certain non-critical alerts in phases of flight where they may distract the pilot and possibly result in an unsafe condition, such as during takeoff and landing. It was felt that since the configuration and flight condition of an aircraft is pretty well understood by the pilot when reaching approach minimums, that further alerting as they transition to landing would be unnecessary. Three pilots disagreed that alerts should be inhibited, one was neutral, and one agreed. In this simulation, pilots had to execute a missed approach at minimums, so they did not experience the "nuisance issue" that alerting during final landing flare and touchdown could present.

Question seven asked pilots how they *thought* the frequency of having to maintain awareness for control alerts would affect the difficulty of monitoring other aircraft systems during a precision approach procedure. This was another hypothetical question, since other than navigation; there were no other aircraft systems to monitor. One pilot responded *sometimes*, three pilots responded *infrequently*, and one pilot responded *never*. Pilot responses were likely colored by the number of times the alerts came on during the approach, and aileron and elevator alerts during this phase were few. Rudder alerts were more frequent, but that was because rudder control activity is typically sparse anyway. One may conclude that the pilots felt that maintaining awareness of manual control input alerts would have had minimal impact on the task of monitoring other aircraft systems. However, this is another area where future research should assess man-machine integration under more realistic flight conditions.

Question eight asked pilots how often they felt that integrating control alerts into their scan was difficult when maneuvering the aircraft. Three pilots said this occurred *rarely*, one pilot said *sometimes*, and one pilot said *very often*. This question addresses the issue relating to task prioritization and attention demands. When maneuvering, such as making turns to headings while in a climb or descent, the pilot's attention is focused on controlling pitch, roll, yaw, airspeed and planning for the altitude where transition back to level flight will be made. It is reasonable that a pilot will mostly scan those instruments that support the current flight task. If the requirement to respond to air traffic control, or manage other crew functions are also involved at the time, any non-task related monitoring will be more difficult to incorporate into the pilot's scan. Other than accomplishing the required flight maneuvers in the test profile, this simulation did not present any of these other demands.

Question nine asked for pilot agreement with the statement that the control input cues provided in the simulation were salient and hard to miss. Three pilots agreed and two pilots strongly agreed with the statement. Salience refers to characteristics such as loudness, frequency, brightness, etc., all of which immediately capture attention and improve reaction time. The cueing integration for this research program was effective and specifically designed to immediately capture the pilot's attention. However, an operational integration of alerting cues requires careful consideration, such as possibly providing a means for pilots to silence them if they are interfering with the performance of a more important task such as attending to an aircraft emergency condition, and there is no immediate need to update aircraft stability and control information.

Question ten asked pilots for agreement with the statement that there were no control alerts when flying in turbulence. The question was asked to help correlate the quantitative data with pilot opinion of the number of times they experienced a control alert in turbulent flight conditions with respect to attention and workload issues. Two pilots disagreed that there were no control alerts, two pilots strongly disagreed, and one pilot was undecided. Looking at the data from their runs in turbulence, there were continual rudder alerts in all maneuvering phases of the test profile, and that of course was because there was little rudder movement even in turbulence. On the other hand, there were very few elevator and aileron alerts for the pre-approach maneuvering sequences, and virtually none when flying the approach procedure. The pilots' responses indicate that they had no trouble incorporating the observation of control alerts into their instrument scans during all phases of flight, which is important from an attentional and workload standpoint. But taking these results further, one must consider that the rudder is primarily used by pilots to null a sideslip condition, or make a crosswind landing. Yet, because of its low use by pilots it produces so many alerts that rudder control inputs alerts could be seen as a nuisance by pilots. That can have an effect on operational viability and ultimately flight system certification.

Pilot opinion surveys were conducted immediately after all testing was completed in order to obtain subjective opinion data with respect to their perception of the usefulness of the flight displays, attention issues regarding the cueing, and workload when having to provide additional control activity in addition to that required for task performance.

Pilots reported that they typically fly the aircraft manually during the climb out and approach phases of flight. Both phases coincide with the segments where the greatest pilot control activity was measured along with the least number of excitation cues, and therefore are most conducive to system identification. Although most pilots favored the use of an autopilot in atmospheric turbulence, pilots reported that their airline standard operating procedures (SOPs) encouraged but did not require the use of an autopilot. This flexibility would allow pilots to manually fly in atmospheric turbulence and make use of the increased control inputs for system identification and require minimal excitation cueing.

Pilots additionally reported that the excitation cueing (visual and oral) was effective in getting their attention and well implemented. Pilots reported that the additional control inputs required when prompted by the excitation cueing were easy to make, were quickly mastered, and required minimal training. Pilots reported that although they did not mind making the inputs they felt it interfered with the task and degraded their performance. However, previous analyses have shown that all pilots flew within the required ATP performance standards.

CONCLUSIONS:

This study has shown that it is practical to use manual pilot inputs only as a means of achieving good RTPID in all phases of flight and in flight turbulence conditions. Simulation studies accomplished for this work showed that all pilots met the FAA performance criteria for a precision approach with different control input strategies, and were effective in satisfying excitation requirements when cued, without any formal test pilot control input training. Much of the time, cueing was not even necessary, as just performing the required task provided enough excitation for accurate RTPID estimation.

Very few aileron and elevator excitation cues occurred in all six segments of flight. Rudder warnings occurred with the most frequency primarily because of the 50 seconds RTPID resets. While fewer excitation cues occurred in latter approaches with simulated atmospheric turbulence, rudder cues still occurred at a higher rate regardless of atmospheric turbulence. This trend was found to be directly attributable to pilot technique as evidenced by video and to the 50 seconds RTPID resets. Pilot technique is likely reinforced by the subject pilots' experience in wide-body passenger aircraft with yaw dampers. It was repeatedly observed that pilots had a tendency to fly with their feet on the floor and not on the rudder pedals. Nevertheless, all pilots meet the performance criteria with different control input strategies, and were effective in making the excitation cues disappear without any test pilot control input training.

Scalogram, power frequency, and cutoff frequency metrics were introduced and used to investigate which phases of flight and atmospheric turbulence conditions provided the most control activity and promoted system identification using RTPID. Segment 5 (precision instrument approach) provided the most control activity along with the least number of excitation cues, and therefore was most conducive to system identification. This result was expected because in this segment the pilot is tightly coupled with the aircraft as the pilot follows precise vertical and lateral guidance to the runway. Although other segments provided instances conducive to system identification, none were as consistent as segment 5. It was found that segments 1 (cruise) and 2 (descending right turn) were not conducive to system identification. However, if pilots could be provided similar lateral and vertical guidance, system identification could be carried out in any phase of flight with natural pilot control activity and minimal excitation cueing.

Differences in pilot technique were studied in order to understand the effectiveness of pilot inputs for system identification. It was found that all pilots used a different control strategy in obtaining the same performance standards. This suggests that 5 pilot strategies were involved in the experiment. Pilots A and B represent the two extremes tested while pilots C-E represent intermediate cases.

It was found that the most effective way of changing the pilots control activity was to change the atmospheric conditions. Changing the atmospheric conditions (calm versus light/moderate) was more effective in increasing the pilots control activity than tightening the pilot’s performance standards (ATP versus ATP/2). In general, the higher workload tended to increase the pilot’s input intensity up to a point. Eventually, pilots were overloaded and stopped making additional inputs or even backed off slightly. This is important because line pilots are accustomed to flying ATP standards and operationally light atmospheric turbulence has the highest probability of occurrence.

Pilot opinion surveys were conducted immediately after all testing was completed in order to obtain subjective opinion data with respect to their perception of the usefulness of the flight displays, attention issues regarding the cueing, and workload when having to provide control activity in addition to that required for task performance.

Pilot’s reported that they typically fly the aircraft manually during the climb out and approach phases of flight. The climb out phase was not part of this study but the approach phase coincides with the segment where the greatest pilot control activity was measured. Although most pilots favored the use of an autopilot in atmospheric turbulence, pilots reported that their airline SOPs encouraged but did not require the use of an autopilot. This flexibility would allow pilots to manually fly in atmospheric turbulence and make use of the increased control inputs for system identification and require minimal excitation cueing.

Pilot’s additionally reported that the excitation cueing (visual and oral) was effective in getting their attention and was well implemented. Pilots reported that the additional control inputs required when prompted by the excitation cueing were easy to make, quickly mastered, and required minimal training. Pilots reported that although they did not mind making the inputs they felt it interfered with the task and degraded their performance. However, analysis showed that all pilots flew within the required ATP performance standards.

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14. ABSTRACT
Aircraft dynamics characteristics can only be identified from flight data when the aircraft dynamics are excited sufficiently. A preliminary study was conducted into what types and levels of manual piloted control excitation would be required for accurate Real-Time Parameter IDentification (RTPID) results by commercial airline pilots. This includes assessing the practicality for the pilot to provide this excitation when cued, and to further understand if pilot inputs during various phases of flight provide sufficient excitation naturally. An operationally representative task was evaluated by 5 commercial airline pilots using the NASA Ice Contamination Effects Flight Training Device (ICEFTD). Results showed that it is practical to use manual pilot inputs only as a means of achieving good RTPID in all phases of flight and in flight turbulence conditions. All pilots were effective in satisfying excitation requirements when cued. Much of the time, cueing was not even necessary, as just performing the required task provided enough excitation for accurate RTPID estimation. Pilot opinion surveys reported that the additional control inputs required when prompted by the excitation cueing were easy to make, quickly mastered, and required minimal training.

15. SUBJECT TERMS
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