Evaluation of the Rotational Throttle Interface for Converting Aircraft Utilizing the NASA Ames Vertical Motion Simulator

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ABSTRACT

An experiment was conducted to compare a conventional helicopter Thrust Control Lever (TCL) to the Rotational Throttle Interface (RTI) for tiltrotor aircraft. The RTI is designed to adjust its orientation to match the angle of the tiltrotor's nacelles. The underlying principle behind the design is to increase pilot awareness of the vehicle's configuration state (i.e. nacelle angle). Four test pilots flew multiple runs on seven different experimental courses. Three predominant effects were discovered in the testing of the RTI: 1. Unintentional binding along the control axis resulted in difficulties with precision power setting, 2. Confusion in which way to move the throttle grip was present during RTI transition modes, and 3. Pilots were not able to distinguish small angle differences during RTI transition. In this experiment the pilots were able to successfully perform all of the required tasks with both inceptors although the handling qualities ratings were slightly worse for the RTI partly due to unforeseen deficiencies in the design. Pilots did however report improved understanding of nacelle movement during transitions with the RTI.

INTRODUCTION

There are currently two tiltrotor aircraft flying; the Bell-Boeing V-22 and the Bell-Agusta 609 (not currently certified). These two tiltrotor aircraft have the ability to vector their thrust through nacelle position changes over a range of ~97.5 degrees (0 degrees defined as the thrust vector being horizontal, and 90 being vertically up). Research has been conducted over the last 50 years since the advent of the Bell XV-3 as to which power inceptor design is the most appropriate. In all transport category FAA certified aircraft, the power control design mimics both the magnitude and direction of thrust of the vehicle (Refs. 1 & 2). In other words, the inceptor's movement is a correlated representation of the vehicles intended response. Because tiltrotor aircraft vary their thrust vector over a wide range, neither a fixed-wing nor rotary-wing inceptor provides this same representation throughout all flight envelopes.

Currently the thrust/power control inceptors found in the V-22 and BA609 (respectively) differ in that the V-22 Thrust Control Lever (TCL) is similar to an airplane style throttle inceptor (forward to increase thrust) while the BA609's Power Lever (PL) is similar to a helicopter collective control inceptor (up to increase power). Due to this dichotomy, and the fixed nature of the power control axis, the movement of the TCL or PL does not always correspond to the intended response of the vehicle.

Since the development of the Bell XV-3, a variety of power control inceptors have been developed and tested for tilt wing/rotor aircraft. One goal of this prior work was to find the most appropriate inceptor design for this category of aircraft. In this pursuit, many factors come into play in assessing the power inceptor's effectiveness: Pilot background, role (e.g. transport, tactical, cargo, etc), and size of vehicle.

Tiltrotor/Wing Power Inceptor History

In the late 1960's the Ling-Temco-Vought (LTV) XC-142 was under development (Fig. 1). Classified as a tiltwing, the XC-142 also had a variable thrust vector. In this aircraft both pilots were provided with fixed-wing style throttles while the captain (right seat) was also provided with a helicopter-style collective inceptor (Fig. 2). Because the collective and throttle were not a single interface, the captain was required to remove their hand and reposition it on the other controller during nacelle/wing transition. It is believed the system was deemed inadequate due to this requirement to change hand positions during transition, a critical phase of flight.

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Figure 1. Ling-Temco-Vought (LTV) XC-142

Figure 2. LTV XC-142 Flight Deck with Throttle and Collectives (depicted in circles)

Following the XC-142, Jim Cheatham of Magnum T/R Inc. proposed a 9-passenger tiltrotor concept that included a new throttle inceptor (Fig. 3). This new inceptor also called the Magnum, rotated aft as the nacelles rotated forward in order to map the linear movement of the power axis to the vehicle’s response in helicopter and airplane modes. The main deficiency of the Magnum was that it also required the pilot to remove their hand during transition and the system was not adopted.

Figure 3. Magnum in 0°, 45°, and 90° position

Rotational Throttle Interface

To address the issue of combining a collective and throttle and providing a suitable inceptor that both mapped nacelle position congruently and did not require the pilot to remove their hand, the Rotational Throttle Interface (RTI) (Fig. 4) (Ref. 3) was developed. The goal of the RTI was to map the inceptor control axis input to the vehicles thrust axis response in thrust vectoring aircraft. The design principle behind the RTI was to create an intuitive system in which the pilot could always push or pull in the intended direction of vehicle response through a single fluid inceptor.

Figure 4. Rotational Throttle Interface (RTI)

METHODS

In order to test the RTI, simulated flight trials were conducted at the NASA Ames Vertical Motion Simulator (VMS). NASA’s CTR-4/95 full envelope tiltrotor flight model (Ref. 4) was used in conjunction with a Moffett Field visual scene and an ADS-33E evaluation task course. Modifications were made to the ADS-33E maneuvers to accommodate the differences in tiltrotor operations versus helicopter operations. The flight control system response type was Rate Command Attitude Hold (RCAH) for all testing. Both NASA’s TCL (Fig. 5) and the RTI prototype were tested against each other representing the baseline and experimental configurations respectively.

Figure 5. NASA Ames Thrust Control Lever

Simulator Flight Deck Configuration

The NASA Ames VMS T-Cab (Transport-Cab) was utilized for the experiment. The cab was configured with a single set of controls for the right pilot's seat consisting of a center stick, rudder pedals, and a power inceptor (TCL or RTI) mounted to the left of the pilot. The center stick and pedals were back-driven to set the inceptor trim positions at the start of each data run via NASA modified McFadden control loaders.

Seven independent collimated visual displays consisting of a left and right 90^o lateral view (2), a left and right 45^o quartering view (2), a left and right 0^o view (2), and a chin window view (1) positioned on the right side of the flight deck for the flying pilot (all angles are referenced from flight deck centerline) (Fig. 6).

Figure 6. NASA VMS T-Cab

Pilots were provided three reconfigurable displays (Fig. 7) consisting of the NASA Ames CTR PFD (Fig. 8), the NASA Ames VMS emulation of the CAAS Horizontal Hover Display Page (Fig. 9), and a standard top-down navigation plan view display. In addition, all three displays where emulated on the left side non-flying pilot's station. A center display was also provided for ADS-33E maneuver criteria measures for in-between trial review.

Figure 7. NASA Ames VMS T-Cab with TCL

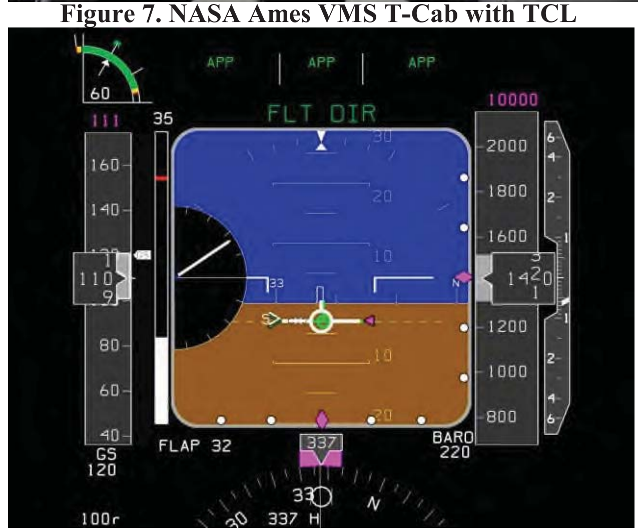

Figure 8. NASA Ames CTR PFD

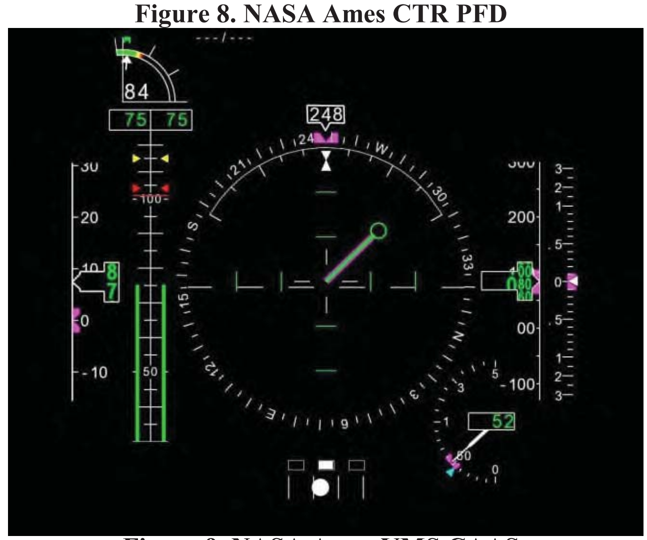

Figure 9. NASA Ames VMS CAAS

INCEPTOR DESIGN

Thrust Control Lever Description

Two inceptors were tested in this simulation; NASA's conventional helicopter-style TCL and the Rotational Throttle Interface. The NASA TCL is a single axis linear inceptor supported by an air bearing connected to McFadden force feedback control loader (Refs. 5 & 6). The inceptor travel is oriented slight aft of vertical with a total range of approximately seven inches.

Rotational Throttle Interface

The RTI had three Degrees of Freedom (DoF) and was comprised of a rotating arm (first DoF), a linear slide (second DoF), and a rotating grip (third DoF). The linear slide and rotating grip are contained within the rotating arm. The rotation range of the rotating arm is 0-97.5 degrees (Fig. 10) to allow for a 1:1 mapping of the V-22 and BA-609 nacelle rotation ranges.

Figure 10. RTI oriented at 95°, 90°, 45°, and 0°

Movement was actuated by an electro-mechanical system driven off of two independent stepper motors with a closed loop position feedback system. The angles of the rotating arm and rotating grip were controlled by the stepper motors and were not able to be back driven by the pilot. The linear (second DoF) slide position represented desired throttle level (six inches of total travel). RTI throttle friction was set via a pneumatic cylinder located within the rotating arm and was commanded by the pilot through a partial-turn rotary potentiometer. The potentiometer controlled an electronic pneumatic valve, which in turn scaled throttle friction appropriately via a pneumatic cylinder using a friction pressure device. Friction could be turned off instantaneously via a trigger on the grip much like a collective mag-brake found in larger helicopters.

SIMULATION EXPERIMENTAL DESIGN

Four test pilots evaluated the TCL and the RTI in seven different flight scenarios. Of the four pilots, three came from a rotary wing background while the remaining one came from a fixed-wing background with AV-8 Harrier (VTOL) flight experience. One of the test pilots had also flown tiltrotor aircraft prior. Only three of the four test pilots were able to accomplish all motion and fixed based trials using both the TCL and RTI. The TCL was tested entirely fixed-based while the RTI was tested fixed-base through the full set of flight scenarios and then with motion for four of the seven scenarios.

Seven test maneuvers were derived from existing ADS-33E tasks (Ref. 7), previous CTR simulations, and newly developed tasks to test the tiltrotor nacelle conversion corridor envelope with the RTI. The seven maneuvers consisted of hover, vertical maneuver, depart/abort, Nap-Of-the-Earth (NOE), brown-out landing, aborted VFR "normal" approach, and instrument guidance approach task. The hover, vertical maneuver, depart/abort, and instrument guidance approach task had objective performance goals the pilot needed to meet. Depending on the achieved performance, the task was assigned either a desired, adequate, or inadequate performance rating. For the NOE, brown-out landing, and aborted VFR "normal" approach, no objective performance metric was utilized though pilots did respond to the experiment questionnaire (Appendix) as in the previous four. The following section will describe each task maneuver.

Hover

The hover runs were accomplished by maneuvering the vehicle from a predetermined start location offset aft, laterally to the left, and at a fixed altitude above a target area. Guidance was provided via traffic cones, targets, and target boxes outside of the cockpit in front of and to the right of the pilot. An example of these out of the window targets can be seen at the right side of Figure 6.

Vertical Maneuver

The vertical maneuver was accomplished by executing a vertical climb, arresting at a specified altitude, and then a descent to the start position within a specified time while maintaining heading, longitudinal, and lateral position within specified desired and adequate limits. Guidance again was provided via simulated traffic cones, targets, and target boxes oriented in front of and laterally to the right of the pilot.

Depart/Abort Maneuver

The depart/abort maneuver began with the aircraft in a hover at a predetermined fixed location. Using the nacelle rotation, the pilot accelerated to 40 knots. At 40 knots, using nacelle control, the pilot decelerated to stop at a hover within a predetermined area. The time to complete the maneuver, stopping position, and vehicle attitude were used as performance measures/metrics.

Nap-Of-the-Earth

Performance of the inceptors in low level flight was evaluated using a simulated Nap-Of-the-Earth (NOE) task through the NASA Ames campus. Speed was controlled via nacelle rotation and throttle position. Speeds ranged from 0 to 85 knots. Figure 11 depicts the simulated NOE course.

Figure 11. Simulated Nap-Of-the-Earth course

Brown-Out

The brown-out landing was a straight in visual approach. At 35-50 ft above the runway and at speeds slower than effective translational lift, a brown-out condition would be simulated by occluding all visual references except for the view out of the pilot's lower right chin window. The pilot was instructed to continue the descent to a full touchdown.

Aborted VFR "normal" approach

The aborted VFR "normal" approach was identical to the brown-out maneuver except that instead of a brown-out condition being presented, the pilot was instructed to execute a go-around at the 200ft agl decision height. The task was complete once the aircraft was converted to full airplane mode with the vehicle in a climbing ascent at 200 knots or more. No objective performance metric was utilized for this task.

Instrument Guidance Approach

The instrument guidance approach task was the longest of the seven maneuvers and was a full visual approach to land with the pilot beginning on a 45^{o} entry to left downwind for Moffett field. The pilot was required to convert the aircraft from airplane to helicopter mode and execute a landing at the runway number markings. No objective performance metric was utilized for this task.

Of the seven test maneuvers, hover, vertical maneuver, and depart/abort were classified as low speed/minimal conversion tasks, while the remaining four where full envelope/full conversion tasks. The goal of the tasks was to provide an environment to test both inceptors through their full operational range. The four low speed conversion maneuvers were also tested with full motion.

Pilots were given a minimum of three training runs with the option to continue with further runs until they felt proficient at the desired task. Once comfortable, pilots executed a minimum of three evaluation runs. The latter three were recorded for objective data and the pilots were also asked to provide comments and Handling Quality Rating (HQR) utilizing the Cooper-Harper rating scale. To assist in the acquisition of pilot comments, a questionnaire (Appendix) was provided.

RESULTS

From a flight perspective, control was possible throughout helicopter, fixed-wing, and transition modes with both the baseline TCL and experimental RTI. However subjective data illustrated some deficiencies with the RTI that were reflected in the pilot's comments and HQR ratings. Pilots reported three predominant concerns with the thrust control using the RTI:

1. The rotation of the RTI with nacelle angle during transition created some confusion in which way to move the grip to control the throttle.
2. Pilots were not able to distinguish between fine changes in the RTI's housing angle making interpretation of exact nacelle position difficult. While this did not have an effect on overall task performance, it was an unexpected finding.
3. Precise throttle control with the RTI was difficult due to an unanticipated binding of the system along the throttle axis.

These concerns are more fully discussed in the following sections.

HQR Results

In total there were three experimental test pilots that completed the experiment with both the TCL and RTI configurations in fixed-base simulation (RTI-F), and the RTI in motion-base (RTI-M) as well. The fourth pilot was not able to complete all tasks on motion and fixed-base.

Table 1 shows the handling qualities ratings results for the Mission Task Elements (MTEs) for which handling qualities ratings were collected. The TCL results shown in this table were collected with the VMS cab on a fixed platform (no motion). The RTI results were collected both with the cab fixed and with motion. 'RTI-F' refers to the results with the cab on a fixed-platform, and 'RTI-M' refers to the results with motion.

Table 1. Handling Quality Rating Results.

		Hover	Vertical	Depart/Abort	IFR
	TCL	4.5	5	4	4
Pilot 1	RTI-F	5	3	4	4
	RTI-M	4	3	4.5	4
	TCL	7	7	7	3
Pilot 2	RTI-F	7	7	7	4
	RTI-M	7	7	7	4.5
	TCL	4	3	3	3
Pilot 3	RTI-F	4	4	4	4
	RTI-M	4	4	4	4

It is important to note that Pilot 2 was a fixed wing pilot with harrier experience not accustomed to helicopter flight and collective control systems for hover and low speed tasks, specifically the rate command attitude hold. The HQ ratings of 7 could be explained by the pilot's training and inexperience with helicopters.

The hover and vertical maneuver task results shown in table 1 did not require any nacelle angle change and therefore did not include any effects of RTI transition. The results for these two tasks show a slight degradation in the handling qualities ratings with the RTI when compared with the TCL. This degradation is also reflected in the pilot comments to the questions listed in the appendix. The differences in ratings were not a result of RTI transition as it did not rotate during the hover and vertical maneuvers. The differences however can be explained by the following:

1. The physical positioning of the RTI is a compromise between a collective and throttle due to its combination of the two and its transformation via rotation. Pilots commented that the RTI did not feel as natural as a standard collective, throttle, or TCL.
2. All pilots noted some binding or stiction of the RTI making it difficult to precisely set and adjust the throttle grip position. Pilots were asked to comment on the binding, but to try to limit its effects on the handling qualities ratings. It is still suspected that some of the degradation in HQ ratings with the RTI is still due to the binding.
3. A third possible reason was that the orientation of the grip and amount of travel available between the TCL and RTI grip were different. The TCL motion axis is also angled slightly aft of vertical, while the RTI motion axis is slightly forward to match the trim pitch attitude of 86 degrees for this aircraft.

For the depart/abort and instrument guidance approach tasks that involved nacelle angle changes and corresponding rotation of the RTI, HQ ratings were generally worse with the RTI than with the TCL. One factor to keep in mind when considering these results is the influence of the binding or stiction that was seen with the RTI. As previously mentioned, pilots were asked try to limit the effect of binding on their handling qualities ratings, or essentially to provide a handling qualities rating for the RTI if binding had not been present. Even with this instruction, it is still believed that the binding issue accounts for some of the degradation with the RTI HQRs and is reflected heavily in the comments.

Another important factor in the degradation of the handling qualities ratings with the RTI is that pilots experienced some confusion as to which direction to move the grip to add and remove power during nacelle transition as the flight condition and nacelle angle changed. This will be discussed in more detail later in this section.

In order to more fully assess the effects of the RTI, it is important to consider the pilot comments in the evaluation. Typically pilot comments provide a much richer set of data than just the handling qualities ratings alone. With respect to the binding, the predominant effect was that it was more difficult to make fine power adjustments along the throttle axis. Subjective pilot comments further indicated that the magnitude of this effect was tightly coupled to the aggressiveness of the maneuver. One pilot reported in the brownout maneuver for the 2nd question inquiry *"Not an aggressive maneuver but able to be as aggressive as wanted to be, precision for RTI was fine"*. In contrast, in a similarly aggressive maneuver, another pilot indicated *"just following the guidance, aggressive to follow the guidance… with RTI tended to put in too big an input which was a function of the binding"*. Unfortunately, correction of the binding issue was not possible during this test, however it was resolved after and is not considered to be a technical hurdle of the system. While pilots were asked to try to disregard the binding in the system, it still effected HQR ratings and comments throughout the entire evaluation.

For the depart/abort and instrument guidance approach tasks, the RTI vibrated slightly while the inceptor was converting due to a slight misalignment of the internal gear mechanisms that controlled the rotation. This was not intended, but did give a positive outcome where the pilots received a haptic indication that the nacelles were actually moving via the inceptor vibration, this was noted particularly by the pilots who had no prior tiltrotor flight. The single pilot with tiltrotor experience was more familiar with the response of other cues in the cockpit (e.g. outside visuals, motion, and cockpit cues) as to whether the nacelles were moving. For pilots that are unfamiliar with these vestibular/visual cues, the only indication of nacelle angle and movement is from an indicator on the PFD; an example of this symbology can be found in the upper left corner of the displays in figures 8 and 9.

Pilots commented that neither the rotational position of the RTI nor the RTI grip provided a precise reading of the nacelle position. Pilots were able to distinguish between gross position changes and major orientations such as vertical or horizontal, however, they were not able to sense RTI position with greater than ~20 degrees of accuracy.

Pilots also commented that they often found themselves trying to move the throttle grip in the wrong direction to increase and decrease thrust against the direction of travel, particularly during conversion. Pilots commented that they were often trying to push the grip in the wrong direction. One possible reason for this issue could be attributed by the method in which rotary-wing pilots manipulate power settings verses fixed-wing pilots. In a conventional helicopter, the pilot adds power by pulling with their fingertips, while in an airplane, power is added by the pilot pushing with their palm. Because the RTI combines both of these inceptors into a single device, the confusion may lie in that midway through, the control strategy itself reverses.

One pilot commented that it may be better if the pilot was able to manually control the conversion of the RTI between helicopter and airplane mode rather than having it automatically tied to the nacelle angle. This way the pilot would be able to control when the inceptor transitioned from vertical (helicopter) and horizontal (airplane) modes. This may eliminate the confusion in which way to move the inceptor in the intermediate (transition) positions.

CONCLUSIONS

An experiment was performed to evaluate the utility of the Rotational Throttle Interface that rotates with nacelle angle for thrust control of tiltrotor aircraft. Pilots indicated some deficiencies in the RTI partly due to an unintended binding issue along the throttle axis. Non-linear binding along the throttle axis causes significant detriment to the pilot's ability to accurately set power control. The conclusions gained from this study were valuable in understanding the critical components of the design, construction, execution, and testing of the RTI. The main lessons learned were:

1. Pilots were able to perform all of the tasks with the RTI throughout helicopter, airplane, and transition flight modes.
2. The 1:1 mapping of the inceptor angle to the nacelle angle did cause some confusion during nacelle rotation as to which direction to move the RTI grip to control power.
3. Fine angular sensitivity was not possible in the RTI beyond 20 degrees resolution.
4. Haptic feedback from the RTI during nacelle rotation provided an additional beneficial cue of nacelle movement.
5. Physical placement of the RTI was difficult due to a compromise in fixed-wing throttle and rotary-wing collective positioning differences.

Future studies plan to gain better understanding in the utility of the RTI system while specifically addressing the shortcomings of the current RTI's binding and control confusion issues.

APPENDIX

Pilot Questionnaire

Task Performance

1. Describe ability to meet DESIRED / ADEQUATE performance standards.

2. Describe aggressiveness / precision with which task is performed.

3. If trying for DESIRED performance resulted in unacceptable oscillations, did decreasing your goal to ADEQUATE performance alleviate the problem?

Aircraft Characteristics

4. Describe any objectionable controller force or motion characteristics, particularly with the Thrust Controller (TCL).

5. Describe predictability of initial aircraft response and ability to precisely control thrust.

6. Describe any objectionable oscillations or tendency to overshoot.

7. Describe any non-linearity of TCL response.

Demands on the Pilot

8. Describe overall TCL control strategy in performing the task (cues used, scan, etc.).

9. Describe any control compensation you had to make to account for deficiencies in the aircraft or TCL.

10. Describe any modifications you had to make to what you would consider "normal" Thrust control technique in order to make the aircraft behave the way you wanted.

Miscellaneous

11. How natural were the TCL inceptor motions required to perform the task?

12. Were there any undesirable characteristics of the Thrust Controller?

13. (RTI only) Did the rotation of the RTI with nacelle angle make it easier or harder to accomplish the maneuver?

14. (RTI only) Comment on the suitability of using position of the RTI arm and grip as a cue of nacelle position.

15. Comment on anything else related to the TCL.

Assign HANDLING QUALITIES RATING for overall task.

16. Using the Cooper-Harper rating scale, please highlight your decision-making process and adjectives that are best suited in the context of the task. If assigned HQR is Level 2, briefly summarize any deficiencies that make this configuration unsuitable for normal accomplishment of this task, i.e., justify why the procuring activity should reject this configuration as a means to accomplish this task.

17. What was the critical sub-phase of the task (e.g., entry, steady-state, exit) or major determining factor in the overall Handling Quality Rating (HQR) – with respect to the Thrust Controller?

18. Did the Thrust Controller have a significant impact on the assigned HQR?

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