HANDLING QUALITIES INFLUENCES ON CIVIL TILTROTOR TERMINAL OPERATING PROCEDURE DEVELOPMENT

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EXTENDED ABSTRACT

BACKGROUND

The potential for tiltrotor aircraft as civil transports has been well recognized (ref. 1). Realization of that potential requires development of operating procedures tailored to take advantage of the tiltrotor's capabilities, including thrust vectoring independent of body pitch attitude and good low-speed control. While the tiltrotor shares flight characteristics with both fixed wing airplanes and helicopters, it must convert between those flight modes, typically within the context of precise terminal operations.

A series of piloted simulation experiments has been conducted on the NASA Ames Research Center Vertical Motion Simulator (VMS) to investigate the influence of tiltrotor cockpit design features on developing certification and operating criteria for civil tiltrotor transports. Handling qualities evaluations have shaped cockpit design guidelines and operating procedure development for a civil tiltrotor. In particular, four topics demonstrate the interplay of handling qualities and operations profile in the development of terminal operating procedures and cockpit or control equipment for a civil tiltrotor: conversion (airplane to helicopter mode), final approach path angle, operating profile speeds and speed changes (particularly under instrument conditions), and one engine inoperative operational considerations.

EXPERIMENT DESIGN AND CONDUCT

Civil tiltrotor transports are expected to be designed to an all-weather standard, in common with most commercial, scheduled airline aviation. Thus, evaluation task performance standards were derived from Airline Transport Rating standards. Evaluation atmospheric conditions included clear or cloudy and calm or turbulent conditions. Simulation evaluations were conducted with a 40,000 pound gross weight tiltrotor transport model. Most evaluations used an attitude command control system.

- EXPERIMENTAL VARIABLES

Conversion from airplane mode to helicopter mode must be accomplished within tight altitude tolerances. Cockpit displays and control features have been developed to assist task performance during conversion and to improve handling qualities ratings. Figure 1 summarizes handling qualities ratings results for four cockpit and control variations involving flap schedules, nacelle position control and cockpit guidance and control display format.

- CONFIGURATION CONTROL

Flap schedule # 1 features an abrupt flap deployment with specific airspeed and nacelle angle gates. Although an automatic flap schedule, its function is similar to manual, discrete position, flap control. Flap schedule # 2 features more general use of airspeed and nacelle angle schedules. Flap schedule # 3 was created to minimize trim pitch attitude changes during conversion. It also features a simple automated schedule dependent upon airspeed and nacelle position, with airspeed used only above 80 knots and only nacelle angle input in slow speed configurations.

Nacelle control variations include a basic "beep" nacelle movement control, "beep" control with a set of fixed nacelle angle stops, and a piloted-initiated, semi-automatic system. Using the basic nacelle "beep" control, the pilot must continuously move nacelle position using a momentary control switch. The nacelle detent system adds a set of fixed stops for the conversion, allowing a pilot to continuously move the nacelles without actively monitoring their position. Some action, either depressing a switch or waiting a fixed length of time, is required to release the stop, permitting further aft nacelle movement. The semi-automatic nacelle movement system provides an alternative to the "beep" control (although the latter is retained for operational flexibility and emergency conditions). The semi-automatic nacelle system uses both fixed position stops and fixed nacelle movement rates between those stops. A pilot controls the nacelle-position conversion by simply depressing a switch once to initiate movement to the next position stop.

- DISPLAY VARIATIONS

Cockpit display variations evaluated have included a basic set of instruments with only the "raw data" glide slope and localizer error added to the basic instrument set, the addition of a four-cue (pitch, roll, power, and nacelle position) flight director, and a developmental flight path vector display format.

- EFFECTS OF CONTROL AND DISPLAY VARIATIONS

As shown in figure 1, a basically equipped aircraft with abrupt flap movement, "beep nacelle control and "raw " guidance data yielded only adequate handling qualities for a level flight conversion task. Further, the range of handling qualities ratings (which reflect task performance) includes significant "inadequate" evaluations. In general, pilots found altitude control difficult, especially in instrument meteorological conditions (IMC) or with winds and turbulence. The addition of a nacelle detent system had almost no effect on the handling qualities ratings, although pilot commentary indicated some improvement. Provision of a less abrupt automatic flap schedule ("flaps # 2"), semi-automatic nacelle movement system and additional control and guidance display yielded border-line satisfactory handling qualities ratings for the conversion. All handling qualities ratings were at least adequate with similar improvements in task performance. As documented in reference 2, both the cross-pointer flight director and the developmental flight path vector display formats provided similar handling qualities ratings. Further development of a flap schedule explicitly developed to minimize trim pitch attitude changes during the conversion ("flaps # 3") plus further development of both the semi-automatic nacelle movement control and the flight path vector display provide solidly satisfactory handling qualities ratings. Although the ratings range is the same for this cockpit equipage and the previous one (flight director, etc.), the bulk of the ratings are now solidly in the satisfactory range.

- TERMINAL AREA PROCEDURES

Steep final approach flight path angles have been suggested as a means of minimizing noise footprints or reducing required land-use control around a vertiport. Such operations are limited, though, by generic aircraft characteristics and specific handling qualities considerations, all of which contribute to the handling qualities ratings shown in figure 2.

As noted in references 3-5, a general operating consideration limits the descent rate for routine terminal operations to less than one thousand feet per minute when below one thousand feet altitude. Using this rule of thumb, nominal final approach speeds can be calculated based on the flight path angle. Table 1 lists nominal approach conditions (airspeed and nacelle angle) for a transport tiltrotor based on this consideration. The low approach speeds on final approach prompt two aircraft-specific operating profile planning considerations: low speed handling qualities and one engine inoperative (OEI) flight performance margins. OEI safety margins will be discussed later.

- LOW-SPEED HANDLING QUALITIES

Low speed handling qualities concerns include both aircraft dynamic response and the influence of winds and turbulence on low speed flight. The CTR-simulations have not yet addressed aircraft dynamic response. The attitude stabilization of the modeled tiltrotor transport has been sufficient for the task. Winds, particularly cross-winds, and turbulence do prompt a general aircraft low speed handling qualities issue. At slow speeds, a cross wind component can have a significant effect. Crabbing the aircraft heading into the relative wind can produce dramatic off course heading yaw angles. Dynamic yaw variations approaching ninety degrees have been observed with very steep and slow approaches. As shown in figure 2, winds and turbulence ('Turb") degrade handling qualities ratings for glide slope tracking. Steeper glide slope angles require slower approach speeds which results in a widening handling qualities split between calm and wind/turbulence for steeper approaches.

Added to the effects of wind and general low speed dynamic response is the shift of aircraft response from "front-side" to "back-side" control wherein the thrust control becomes the primary vertical flight path control and pitch attitude becomes the velocity control. Accentuated when flying in instrument meteorological conditions, the shift to "back-side" control requires more than basic instruments (attitude, altitude and airspeed) for satisfactory handling qualities. Also illustrated in figure 2 is a comparison between use of "raw data" and a flight director. A flight director or other advanced display helps the pilot to transition to and use a "back-side" control technique as required by the aircraft flight mechanics.

Another general consideration for the final approach is to maintain a clear view of the intended approach (and landing) aim point throughout an approach in visual meteorological conditions (VMC). For commercial flight operations, one might impose a limit on negative pitch attitude such that one could impose a flight operation limit on approach path angle based on the field of view over the nose of the aircraft. For a typical transport layout, pilot commentary during civil tiltrotor handling qualities evaluations suggests a limit around 15 degrees approach angle. Handling qualities ratings for the 15 degree glide slope shown in figure 2 bear some impact of field of view concerns as revealed in pilot commentary. Although the task evaluated was flown to an IFR standard, clear conditions were part of the evaluation matrix. Some pilots were more concerned than others with occasional obscuring of the approach aim point. On a 25 degree glide slope, the approach aim point always was obscured and was reflected in most handling qualities ratings. The combination of obscured approach aim point and high susceptibility to cross wind control problems at the slow approach speeds make a 25 degree approach extremely difficult for manual control.

Approach operations profile development necessarily involves decelerating flight. Considerations of efficient aircraft operation and air traffic control in a complex urban traffic area suggest a need to maintain airplane mode flight speeds until close-in to the vertiport. Conversely, instrument flight operations are generally best served by gradual flight condition changes, allowing a pilot to make required trim condition changes, such as with airspeed or configuration. Configuration change concerns led to the selection of a slow nacelle conversion rate as discussed previously. Trim changes with airspeed, even with a fixed configuration, led to selection of a very small deceleration for IMC-segment operations. The flight director used in the CTR simulation experiments has received generally good evaluations, but its command profile for airspeed had to be tailored for decelerating operations. A pause at an intermediate configuration was found useful to allow the aircraft to decelerate and stabilize on a known trim point. A peak deceleration of 0.125 g is achieved during an initial conversion from airplane mode at 180 knots to 60 degrees nacelle angle at 120 knots, even with a slow nacelle conversion rate of 2 degrees per second. This level flight deceleration has proven acceptable in pilot commentary. A peak deceleration of 0.10 g, recorded during conversion from 60 to 80 degree nacelle angle and deceleration to 70-80 knots, has not been as well received. In the current approach flight profile, this conversion and deceleration is followed quickly by glide slope capture. The combination of deceleration and flight path angle change results in active retrimming with both pitch attitude and thrust-power controls.

A commanded deceleration on glide slope may be assisted by appropriate display guidance. "Raw data" glide slope tracking evaluations shown in figure 2 were generally flown with a constant approach speed. The use of a flight director simultaneously provided for better handling qualities on steeper approaches and permitted a decelerating flight profile. Still, the acceptable level of deceleration with the flight director was limited by piloted handling qualities concerns. A deceleration of 0.025 g was selected for the flight director command profile for decelerations on glide slope. This required a very small pitch attitude increment for deceleration--important for field of view concerns. It also kept aircraft trim changes with airspeed at a manageable level for pilots.

- ONE ENGINE INOPERATIVE CONSIDERATIONS

Finally, the interplay of one engine inoperative flight performance, required for commercial transport operations, and handling qualities during the deceleration to hover for a vertical landing may drive the design of both aircraft and vertiport. In common with the XV-15, V-22 at design mission gross weight, and many rotorcraft, the modeled transport tiltrotor aircraft of the CTR simulations does not have enough power to hover with one engine inoperative. A landing decision point (LDP) for such an aircraft is defined by a requirement to be able perform an OEI go-around until the landing commitment is made. Tolerances for critical aircraft sensors, such as airspeed, and flight technical error, which must allow for up to a 10 knot airspeed error for airline transport operations, lead to selection of a nominal airspeed at decision with a comfortable margin above the minimum airspeed for OEI level flight. Both considerations led to selection of a 50 knot decision speed for the modeled transport. On a 9 degree glide slope, 50 knots provides an 800 fpm descent rate. For an LDP at 200 feet altitude, typical of Category 1 IFR operations, this provides a slim 15 seconds before impact if nothing is done to flare and land. A tiltrotor can use nacelle angle movement instead of pitch attitude to perform the required flare maneuver, but repeatable aircraft response, such as with a semi-automatic nacelle position system, becomes very important. Similar handling qualities rating were recorded for this final "nacelle flare" type of landing and for a landing procedure with a guided constant deceleration to a hover prior to landing. Both achieved border-line satisfactory-adequate handling qualities ratings under all weather conditions evaluated.

CONCLUDING REMARKS

In conclusion, piloted handling qualities interact with basic safety, aircraft flight mechanics, obstruction clearance concerns, and, potentially, noise footprint size to shape terminal operating procedure development. Handling qualities evaluations help define achievable, routine, operations for a given set of aircraft control and cockpit features. The paper will present the handling qualities and pilot-vehicle performance results of the most recent piloted simulator evaluations conducted on the NASA Ames Vertical Motion Simulator to develop both terminal area procedures and cockpit system requirements for civil tiltrotor transports.

References

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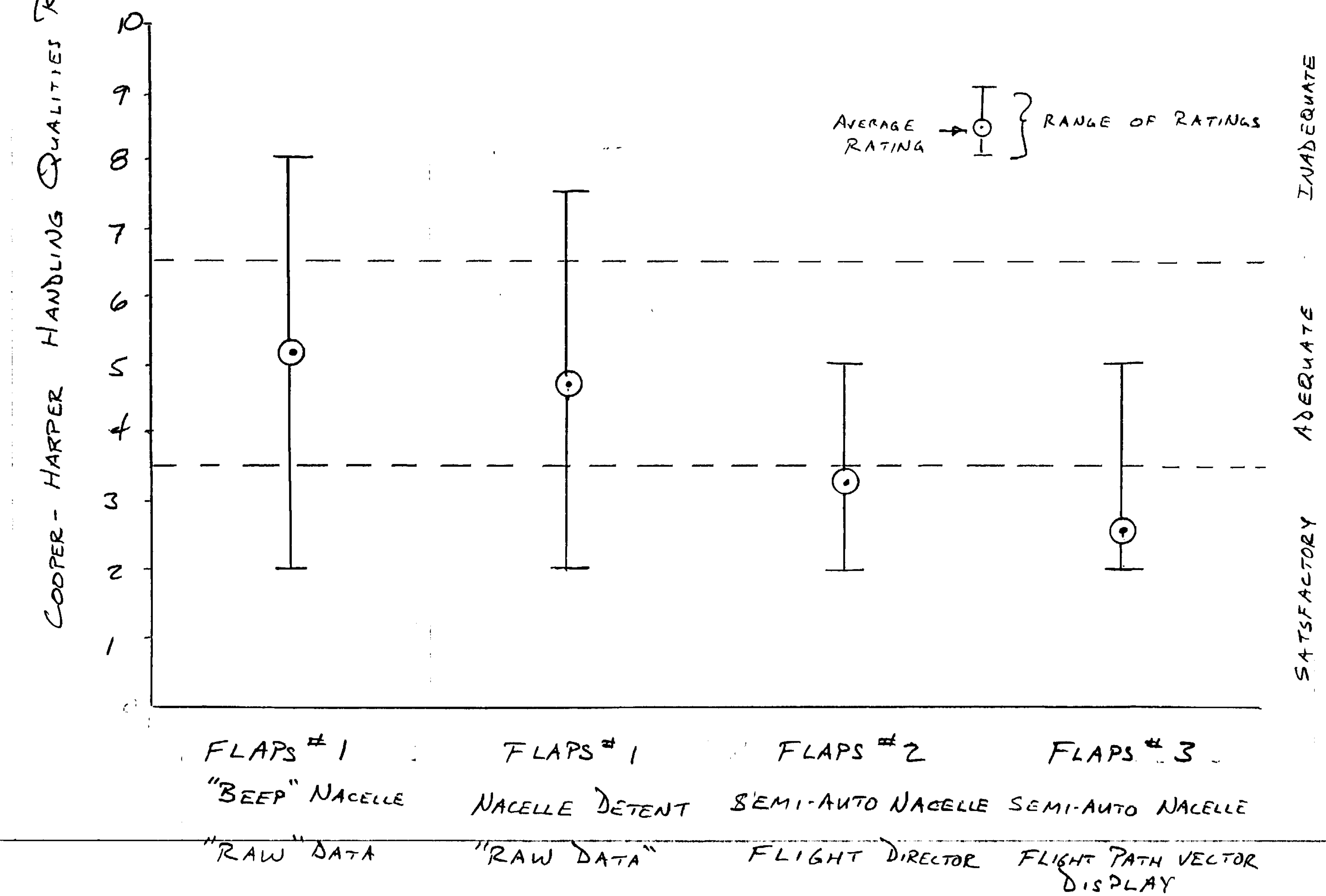
FIGURE 1: AIRPLANE MODE TO HELICOPTER CONVERSION HANDLING QUALITIES RATINGS



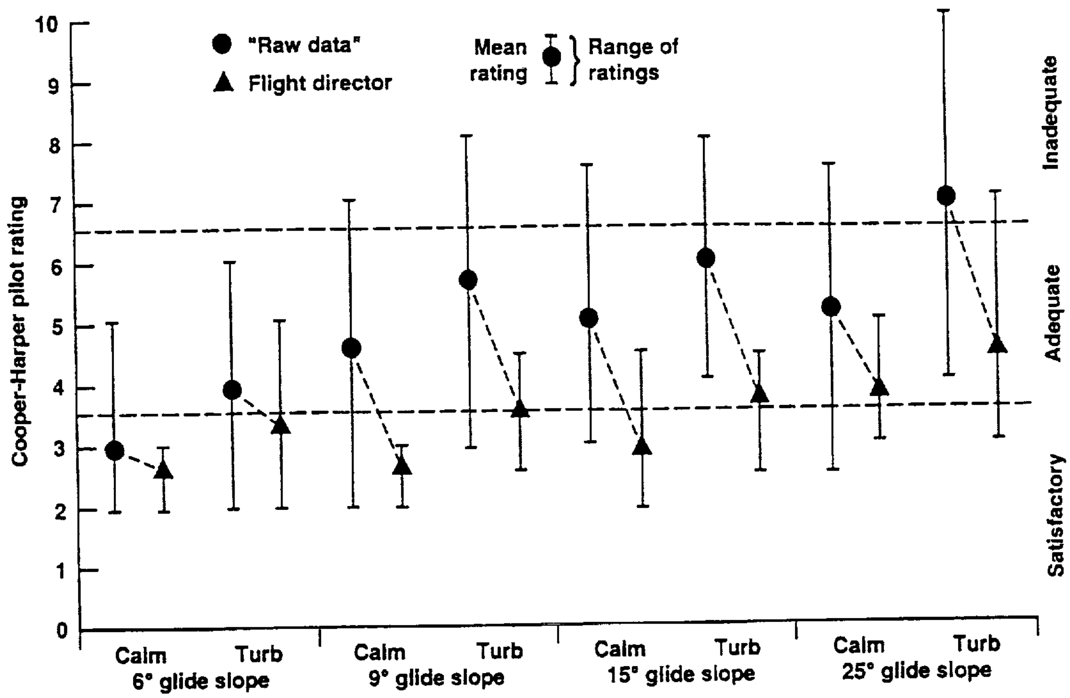


Figure 2. Glide slope tracking handling qualities ratings for various glide slopes and weather conditions using "raw data" cockpit instrumentation versus a flight director.

Table 1. Nominal Approach Conditions

Glide slope (degrees)	Airspeed (knots)	Nacelle angle (degrees)
6	80	80
9	55	85
12	40	90
15	35	90
20	25	90
25	20	90