Ground-Simulation Investigation of VTOL Airworthiness Criteria for Terminal Area Operations

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A two-part ground simulation investigation of variables that affect VTOL terminal area operations was conducted. The baseline vehicle selected was a generalized tilt-rotor aircraft. Experimental variables included the manner in which conversion from airborne to thrust-borne flight is effected, the coupling between conversion and aircraft pitch and heave control, and the allowable range of airspeeds at given thrust inclination angles. Four pilots conducted over 200 piloted evaluations of combinations of these variables for representative VTOL terminal area tasks. Among the results shown are that, for visual approaches, the conversion profile had minimal influence on the aircraft's acceptability but, for instrument approaches, desired performance could be achieved only if all of the conversion was performed prior to acquiring the glide slope, or if additional automation and display assistance was provided.

Introduction

THE possible advent of a civil version of the military JVX tilt-rotor aircraft has renewed interest in the definition of suitable airworthiness criteria for this class of aircraft. For example, research concerning powered-lift STOL[1] has recently been incorporated into an updated version of the Part XX Airworthiness Standards being proposed for adoption.[2] Unfortunately, most of the suggested criteria are based on data for configurations significantly different than the tilt rotor, which rotates relatively large thrust devices at relatively low disk loadings to achieve the VTOL capability. Accordingly, a joint program has been instituted to investigate airworthiness concerns that are generic to the tilt-rotor class of vehicle.

This paper discusses the results of an initial two-phase ground-simulation experiment conducted under this joint program. The emphasis in these initial investigations was on terminal-area (approach and landing) operations since that is the portion of the flight envelope in which the vehicle is converted from the airplane configuration to the helicopter configuration. In general, it is expected that existing airworthiness standards will cover either the airplane or the helicopter modes but that no standards exist that adequately cover conversion and partially converted configurations.

The following section of the paper expands on the selection and design of the experimental variables. Following this description is a summary of the experimental equipment and procedures and then a review of the results.

Design of the Experiment

Mathematical Model

The mathematical model used for this experiment was a generalized version of the XV-15 tilt-rotor configuration-specific model described in Ref. 3. This model includes the rotor dynamics in a quasistatic sense only (no tip-path plane dynamics) but contains complex aerodynamic interaction representations for this tilt-rotor class of vehicle, as well as detailed descriptions of XV-15-specific characteristics (e.g., engine governor). For the experiment, the model was generalized to incorporate a full-state feedback and full-control interconnect stability and control augmentation system (SCAS) similar to one used in a generic simulation for helicopters described in Ref. 4, and to allow addition of arbitrary overall forces or moments as a function of velocity or nacelle angle.

For the baseline configuration, the weight, inertia, and aerodynamic parameters were held at the XV-15 values. Representative stability and control characteristics at three flight conditions for this configuration are given in Table 1. These characteristics are based on a quasistatic representation of the governor dynamics, and the velocity/nacelle-angle combinations are those that correspond to the conversion profile variations examined in the experiment.

Conversion Procedure Variations

A major variable in this experiment was the manner in which the conversion from the airplane mode to the helicopter mode was conducted in the terminal area. For the class of vehicle under consideration, the aircraft enters the terminal area so configured that the thrust vector is horizontal. As a result, it is important, from both an airworthiness and an operational point of view, to determine the best manner in which to effect the change to the final approach configuration in which the thrust vector is vertical. For this experiment, three different procedures were considered, all based to some extent on XV-15 operating conditions. In all cases, the aircraft was assumed to be entering the terminal area at 150 knots with the thrust vector horizontal (nacelle angle zero), and with flaps set at 20 deg. As shown in Fig. 1, this flight condition is near the center of the conversion corridor for the baseline XV-15 in level flight. In the XV15, the flaps must be reset to 40 deg for nacelle angles above 60 deg; in the conversion corridor, this nacelle angle corresponds to an airspeed of about 110 knots. Accordingly, a midconversion condition (nacelle-angle/airspeed) of 60 deg/110 knots was selected as an intermediate flight condition. The final approach condition was picked to be 60 knots, with the nacelles vertical (90 deg). In the XV-15, a preferable combination would be roughly 80 deg/80 knots because of the

Submitted June 26, 1984; presented as Paper 84-2105 at the AIAA 11th Atmospheric Flight Mechanics Conference, Seattle, WA, Aug. 21-23, 1984; revision received Jan. 2, 1985. This paper is declared a work of the U.S. Government and therefore is in the public domain.

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configuration-specific flying qualities, but the 90-deg/60-knot condition was considered to be more typical, and this approach speed corresponds to that used in a previously conducted investigation of helicopter terminal-area operations.[5]

On this basis, the three conversion procedures, designated profiles A-C, were selected. In profile A, the entire conversion to a 60-knot speed with the thrust vector vertical (90 deg) was made before acquiring the glide slope. This profile in effect forces the VTOL aircraft to perform the final approach as if it were a helicopter. In profile B, a partial conversion to the 60-deg/110-knot flight condition was performed before the glide slope was acquired, with the remainder of the conversion to 90 deg/60 knots being performed while descending on the glide slope. The intent with this profile was to treat the nacelle setting in a manner somewhat analogous to flap settings for a fixed-wing aircraft; that is, to have one or two "approach" settings that are selected at different points on the approach. Finally, profile C required the entire conversion to be performed after the glide slope had been acquired at 150 knots. Profile C, assumed to be the most demanding in terms of aircraft capability, is similar to the tasks reported in Ref. 6.

Conversion Corridor

VTOL aircraft typically have a range of airspeeds and rates of climb permissible for each possible value of thrust inclination; the envelopes of this range over all thrust inclinations define the conversion corridor. These limits may be caused by several factors, depending on the type of aircraft under consideration. For the XV-15, the low-speed side of the corridor is limited by angle of attack because of buffet, the high-speed side by blade-bending moments. The corridor for this aircraft is quite large, with ±25 knots available in level flight (Fig. 1).

To modify the low-speed end of the corridor, the wing area was reduced from 181 to 133 ft^2; the result of this change in wing loading was an increase of about 10 knots in the speed required for the same angle of attack at the 110-knot flight condition. To modify the high-speed side of the corridor, it was assumed that the blade-bending moment could be approximated as being proportional to blade loading (specifically angle of attack of the blades), and so blade chord was reduced from 1.17 to 0.95 ft. In level flight, an equivalent blade angle of attack was therefore reached at an airspeed that was about 10 knots lower for the 110-knot condition. These modifications had only a minor effect on the stability and control characteristics. The reduced conversion corridor is also shown in Fig. 1. Aural warnings for both the lower and upper limits were included in the sound simulation for this experiment.

Pitch/Heave Coupling from Conversion or Power

Because of the importance of precise pitch control to the control of speed and rate of descent during the approach, coupling inputs either from configuration changes during conversion or from power changes during the approach have a significant influence on the suitability of the aircraft for terminal-area operations. For example, the XV-15 exhibits a nose-up pitch moment with nacelle rotations toward 90 deg; this characteristic, in combination with a significant heave input from conversion at nacelle angles near zero, creates glide-slope tracking difficulties during conversion. Although it was

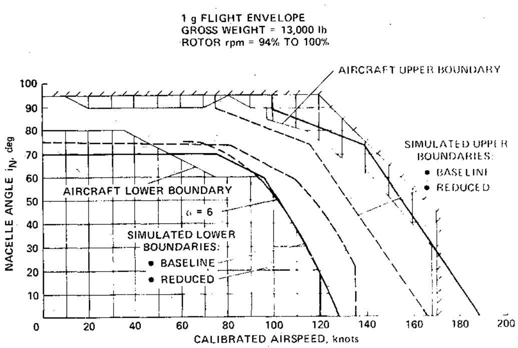

Fig. 1 Conversion corridors.

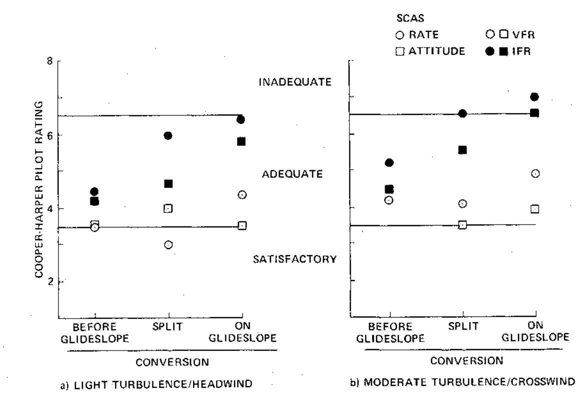

Fig. 2 Influence of conservation profile.

Table 1 Longitudinal transfer functions for baseline tilt-rotor model

A: 90 deg/60 knots: $\Delta(s) = (0.88;1.00)(0.033;0.30)$
B: 60 deg/110 knots: $\Delta(s) = (0.45;1.75)(0.22;0.31)$
C: 0 deg/150 knots: $\Delta(s) = (0.44;2.13)(0.16;0.25)$

	A	B	C
$N^{u}_{\delta_{long}}$	1.065(0.57)(−0.41;329)	0.14(1.84)	−0.02(−377.5)(0.34;1.51)
$N^{H}{}_{\delta_{long}}$	−0.52(−0.029)(0.10;6.19)	−0.03(0.11)	1.30(−11.66)(8.94)(0.08)
$N^{\theta}_{\delta_{long}}$	−034(0.61)(0.058)	−0.44(0.15)(0.58)	−0.68(0.75)(0.12)
$N^{u}_{\delta_{throt}}$	−0.19(6.30)(−1.55)(0.23)	2.16(0.024)(0.39;1.85)	1.51(0.37)(0.53;2.11)
$N^{h}_{\delta_{throt}}$	5.72(1.39)(−0.33)	3.95(1.56)(−0.28;0.82)	−0.24(−0.09)(0.14;9.00)
$N^{\theta}_{\delta_{throt}}$	−0.060(0.23)(0.087)	−0.10(−0.39)(0.31)	−0.09(−0.056)(0.89)
$N^{u}_{i_n}$	−30.77(0.53)(0.36;1.13)	−7.80(0.59)(0.39;1.76)	−2.80(4.70)(0.71;1.81)
$N^{h}{}_{i_n}$	32.39(−0.071)(0.40;1.38)	21.38(−0.006)(0.28;1.98)	6.10(0.053)(0.21;6.15)
$N^{\theta}_{i_n}$	0.87(0.75)(−0.056)	0.24(1.68)(−0.10)	−0.99(0.90)(0.08)

Notes: 1) Characteristic equation $\Delta(s) = (\zeta;\omega)$; 2) N^{i}_{j} = numerator of the ith state to jth control $= K(s+\lambda)(s^2+2\zeta\omega s+\omega^2) = K(\lambda)(\zeta;\omega)$; 3) units: u in ft/s, $\dot{h}$ in ft/s, θ in rad, δ_{long} is longitudinal stick in inches, δ_{throt} is throttle command in inches, i_n is nacelle angle in rad.

beyond the scope of this experiment to examine a wide variation of these characteristics, a limited investigation was designed to provide some indication of their effects.

In particular, pitch and heave inputs from conversion and pitch inputs from power were obtained as control derivatives at 5-deg intervals of nacelle angle around a nominal transition combination of nacelle angle and speed that approximated the center of the conversion corridor. These perturbation forces and moments were then integrated as a function of nacelle angle for the range 0 to 90 deg, and the mathematical model of the XV-15 was modified to permit addition or subtraction of these resulting total forces and moments. By subtracting them, the conversion or power influences could be approximately eliminated; by adding them, the influences could be doubled. Table 2 gives the resulting control derivatives and trim control positions at three flight conditions.

Stability and Control Augmentation System (SCAS)

The type and level of stability augmentation incorporated in the aircraft has a significant effect of the ability to perform the terminal-area tasks, particularly to do so on instruments. In the helicopter instrument-flight-rules (IRF) airworthiness investigations summarized in Ref. 5, it was found that attitude augmentation in pitch and roll was necessary to achieve pilot ratings in the satisfactory category. At least this level of augmentation has also been found necessary for VTOL instrument approaches including a conversion.[6,7] The XV-15 tilt-rotor aircraft, however, like most prototype VTOL machines, incorporates an SCAS that effectively provides only rate damping plus shaping.

To verify the previously noted[6,7] requirement for attitude augmentation for this class of VTOL, two types of augmentation were considered in this experiment: the basic XV-15 rate-based system, and a generic attitude-command system. The generic attitude-command SCAS used rate and attitude feedbacks in pitch and roll with no shaping; fairly low gains were used to achieve attitude dynamics of approximately 1.5 rad/s.[8] In addition to the pitch and roll attitude augmentation, this SCAS incorporates sideslip and pseudosideslip rate directional augmentation above 30 knots to improve turn following, and yaw-rate plus heading directional augmentation below 30 knots to provide a heading-hold function.

Conversion Control Implementation

In addition to the primary variables described above, several additional variations were considered to a limited degree. The first was the manner in which the conversion was actually commanded. In the XV-15, nacelle rotation is accomplished with a rate "beeper" switch on the power lever, which rotates the nacelles at a rate of 7.5 deg/s. Three alternatives were examined. The first was a lower commanded rate (1.5 deg/s) to reduce the rate of conversion coupling and is still commanded with the beeper switch. The second provided a direct selection of three possible nacelle angles via a flap-selector lever; the available values were those used for the conversion profiles (0, 60, and 90 deg), and the flaps were programmed to move automatically to their correct setting as a function of nacelle angle.

For the third alternative conversion control implementation, an automatic nacelle rotation schedule was designed for the terminal-area tasks under consideration. For each of the three possible conversion profiles described earlier, a commanded ground-speed profile as a function of range-to-go was defined assuming a constant 0.10-g deceleration during conversion. A nominal transition profile to fit roughly through the center of the baseline conversion corridor was then defined. These two commands in conjunction, therefore, define the required nacelle angle as a function of range to perform the appropriate conversion. This option was selected through a cockpit switch and was examined briefly both with and without the flight directors, which are described next.

Flight Director Displays

A very brief investigation of three-cue flight director displays was also undertaken for the instrument approaches. In general, the performance of decelerating approaches on instruments has been shown to require display information more complex than the conventional position-error data given by glide-slope and localizer needles, even for helicopters.[7,9] The simplest way to achieve this goal with electromechanical instruments is to incorporate the additional information as an integrated command set in flight directors. A variety of research and operational programs has been devoted to this problem for helicopters[7,10,11] and VTOL aircraft[6,12] and formed the general basis for the design of the three-cue flight directors examined in this experiment.

Guidance information was assumed to be provided by a microwave landing system providing distance measuring equipment (DME), azimuth, and elevation data. These data were processed to provide generalized velocity and position commands in a general rectangular coordinate system with origin at the touchdown point. These commands, as well as the actual velocities, were then resolved into an aircraft-heading-referenced vertical frame for presentation on the director needles.

The horizontal velocity commands are those mentioned earlier for the automatic nacelle rotation. Three commands, corresponding to the three ways of effecting the conversion, were implemented, with a deceleration of 0.1 g being commanded during the conversion. The vertical command consisted of a constant-altitude portion, rounded-off glide-slope intercept command, and a 6-deg glide-slope command to the landing point; this command was implemented as consistent altitude and altitude-rate commands based on horizontal distance from the decision height. Finally, the lateral (with respect to the approach centerline) velocity command was simply proportional to lateral displacement, thereby providing an exponential capture profile.

The general intent in designing flight directors is to provide the pilot with "steering" commands that are easy for him to control while still providing good pilot-aircraft closed-loop following of the commands. This task is complicated for the VTOL application because of the large variations in aircraft response characteristics that occur through a conversion; only limited success was achieved in this experiment. As in previous work,[6,9] the design was based on manual-control theory. The equations and gains used are given in Ref. 8.

Experimental Equipment and Procedures

Ames Research Center's Vertical Motion Simulator (VMS) ground-based simulation facility was used for this experiment. This facility includes a complex movable structure to provide

Table 2 Trim and moment-control effectiveness data

	Baseline	Reduced moments	Increased moments
Longitudinal trim position	5.22/6.41/5.16	5.22/6.86/6.90	5.22/5.95/3.41
Throttle trim position	4.44/5.12/4.67	4.44/5.07/4.71	4.44/5.95/4.67
Moment due to thrust, $M_{\delta_{throt}}$	−0.059/−0.100/−0.091	−0.059/−0.017/−0.002	−0.059/−0.182/−0.182
Moment due to inclination, M_{i_n}	0.867/0.239/0.987	0.544/0.031/0.363	1.19/0.438/1.60

Notes: 1) Values at 69/110/150 knots; 2) units for longitudinal stick and throttle in inches, inclination in rad.

six-degree-of-freedom motion, which is characterized by a large vertical travel capability (±30 ft) and hence good fidelity of vertical motion cues of up to 1 g incrementally. For these experiments, a large longitudinal travel (±20 ft) was also used, thereby enhancing the longitudinal acceleration cues experienced during the conversion maneuvers in this aircraft. The VMS also incorporates a four-window, colored, computer-generated display visual system, which is presented to the pilot through a collimating lens. For the first simulation phase, a conventional runway and airport area were simulated to allow run-on STOL landings. In the second phase, the operations were conducted to an offshore oil rig. In all cases, fog simulation was available to provide the reduced visibility environments used in the IMC runs, and a stereo sound system was used to provide aural cues.

The approaches were started about 4.5 n. mi. from the destination, at a heading simulating radar vector intercept of the localizer, and at an altitude of 1500 ft in the first phase and at 2000 ft during the second phase. A 6-deg glide slope was simulated for all runs. In the first phase, the landing task required a visual deceleration from 60 knots to about 30 knots, followed by a run-on STOL landing. Wind conditions encountered were either a 10-knot headwind with light turbulence (2-3 ft/s rms) or a 10-knot crosswind with moderate turbulence (4-5 ft/s rms). For the IMC approaches, the ceiling was 400 ft with 1-mile visibility, or 200 ft with 0.5-mile visibility. In the second phase of the experiment, the initial deceleration was performed on instruments, and then a final visual deceleration from about 25 knots to a hover and vertical landing on a simulated oil rig was conducted. For the visual approach, the pilot had a 10-knot crosswind on the approach, which became a headwind during the final turn on to the rig with moderate turbulence. For the instrument approach, it was a 10-knot headwind during the approach and a crosswind for the landing, with light turbulence. The ceiling was 400 ft with 1-mile visibility.

The primary source of data for both simulation experiments was the pilot comments. Each evaluation consisted of at least one approach, with repeats if the pilot requested. At the conclusion of each approach, a Cooper-Harper rating was assigned, and comments were made with reference to a comment card. The pilots were instructed that "desired" performance would be generally within one dot for tracking, and "adequate" performance would be within two dots.

Pilot Rating Results

Cooper-Harper pilot ratings and associated pilot comments form the basis for the assessment of the effect that experimental variations considered in this study had on the suitability of the modeled characteristics for the tasks evaluated; these data are given in Table 3 and in the figures. Although separate ratings for landing were obtained during the second phase of the experiment, only the ratings having to do with the conversion itself will be discussed.

The influences of conversion profile and stability/control augmentation in terms of average Cooper-Harper ratings are shown in Fig. 2. Consider initially the data for the conditions in which there was a headwind and light turbulence. In visual conditions, the rate-based SCAS received ratings in the satisfactory category for the profiles (A and B) in which all or part of the conversion was accomplished before glide-slope acquisition. Pilot comments indicated that fairly substantial nose-down trim changes were required through the conversion, particularly for nacelle angles from 60 to 90 deg, and that during the conversion, significant ballooning above the desired flight path occurred; the trim rate was considered to be poorly matched to the trimming requirements occasioned by these conversion influences. With these two profiles, however, the pitching inputs and uncommanded altitude excursions occurred either before the descent was begun or early in the descent and, hence, were not considered to degrade performance below the desired level. When all the conversion was performed while descending (profile C), the ballooning above the desired flight path occurred later in the approach. This degradation in precise flight path control, coupled with the additional work load involved in getting the entire conversion completed in time to be properly set up for the final flare, was noted in the pilot comments as the reason for the drop in the average rating to the adequate category; however, desired performance was still generally considered attainable.

With the attitude-command SCAS, the pilots noted a significant improvement in longitudinal predictability. Although it was still evident that large trim changes were required throughout the conversion and that airspeed control still required compensation, the comments indicated that the ballooning in conversion could be quite easily counteracted with pitch attitude and that power could be set and left alone more easily. As a result, the ratings showed that desired performance was achievable for all three profiles.

In general, therefore, the conversion profile had only a minor influence on system suitability for visual approaches, regardless of SCAS type, in headwind conditions with light turbulence. In the crosswind conditions, performance with the rate SCAS degraded, particularly in the lateral-directional axes, and desired performance could not be attained when all the conversion was performed while descending. In these conditions, the attitude SCAS did provide a more noticeable improvement in both longitudinal and lateral tracking, so that desired performance was again attainable for all three profiles.

For the instrument approaches, the pitch control and conversion-induced coupling problems were strongly influenced by the profile. Considering initially the headwind/light-turbulence data, the pilot comments emphasized that the attitude changes through conversion and the coupling from con-

Table 3 Pilot rating data for baseline configuration

Wind	Flight condition	SCAS	Profile A	Profile B	Profile C
Headwind/ light turbulence	VMC	Rate			4
			4	4	5
			3	2	4
		Attitude	4		
			4	4	4
			3		3
	IMC	Rate	4	6 5	7 6
			4.5	6 7	6 7
			4.5	7	5.5 6
			5		7.5 6
		Attitude	3	5	5
			4	5	7 7
			5.5	4	4.5 4.5
					7
Crosswind/ moderate turbulence	VMC	Rate	4.5	5	4
			4	3	4
			4	4.5	4.5
			4.5	4	7
		Attitude		4	4
				3	4
					3.5
					4
	IMC	Rate	4.5	6	7
			6	7	
		Attitude			7
			4.5	5.5	6

version seemed more extensive. If all the conversion was performed before the glide slope was attained (profile A), the ratings generally indicated that desired performance was still achievable, albeit at the expense of considerable pilot compensation. This was because the glide slope was tracked at constant configuration. This result is in fact consistent with the helicopter IFR results discussed in Ref. 5; as with the helicopter experiments, the addition of an attitude-augmented SCAS provided enhanced speed control and reduced excitations from other inputs, so that the ratings moved more toward the satisfactory region. With the 60- to 90-deg nacelle-angle part of the conversion performed on the glide slope (profile B), the ratings with the rate SCAS degraded considerably to the point where adequate performance was just attainable. The ballooning in glide slope during conversion from 60 to 90 deg led to getting high and being unable to return quickly enough; on instruments, this ballooning did cause a degradation in performance that was not evident in visual conditions. Pilot comments also indicated that it was very difficult to watch the nacelle-angle gage while converting on instruments, and that the lateral-directional tracking deteriorated significantly. For this profile, the attitude SCAS was of significant benefit for instrument approaches. The ratings now became 4 or 5, and the comments point to the fact that much less attention to attitude control was required; as a result, the pilot could attempt to perform the conversion at constant attitude.

When all of the conversion was performed on the glide slope, the ratings and comments demonstrate that for the rate SCAS the aircraft was marginally inadequate for the task, with ratings of 6 and 7 being given. Hurrying the conversion meant that the ballooning problems during the 60-to-90-deg portion were exacerbated, and the glide-slope tracking got away from the pilot. In addition, bank-angle control deteriorated because of the increased attention required longitudinally, and monitoring the nacelle-angle gage was considered very distracting. Similar comments were made about the aircraft with the attitude SCAS, although the improved lateral-directional predictability did assist somewhat, and several of the pilot ratings improved to around 5. As would be expected, turbulence and the crosswind had a deleterious effect for approaches on instruments for all the profiles, most noticeably with the rate SCAS. Pilot comments emphasized in particular the additional difficulty in bank-angle control and more difficulty in maintaining pitch attitude. The ratings for the profile with all conversion on the glide slope now fell into the inadequate category. It is worth pointing out that this profile with a raw data display is operationally very difficult and that some of the flight characteristic variations were beginning to be washed out by this degree of difficulty.

On the basis of these results, therefore, the general influences of the conversion profile are as follows. Performing all the conversion before glide-slope acquisition (profile A) led to nearly desired performance when an attitude SCAS was implemented and to a clearly adequate capability with a rate SCAS; this profile forces the VTOL to perform the glide-slope tracking in a fixed configuration like a helicopter, and these results are generally consistent with results for helicopters. Performing part of the conversion before acquiring the glide slope and part after acquiring it (profile B) led to a reduced level of adequacy for instrument approaches, particularly with the rate SCAS. This reduction was due primarily to conversion-induced pitch and heave inputs caused by the baseline aircraft characteristics. The advantage of performing only part of the conversion on the glide slope was that it could be performed early in the approach, allowing some time at fixed configuration to get stabilized before breakout. Finally, performing all conversion while descending on the glide slope (profile C) was considered adequate in visual flight but marginally inadequate on instruments; there was little benefit from the attitude SCAS for instrument approaches. To some extent, this result is an operational problem and indicates the need for additional assistance in augmentation or display sophistication or both for a task in which the aircraft configuration is continually varying during the crucial periods; this result is consistent with previous research in instrument decelerating approaches.[6,7,9-12]

Figure 3 presents data concerning the influence of the conversion corridor width for the approach profile with partial conversion on the glide slope (profile B). Recall that the low-speed boundary was modified by approximately 10 knots by reducing the wing area and that the high-speed boundary was artificially constrained after the blade chord was reduced; aural warnings were sounded when these boundaries were exceeded. With the reduced wing area only, the pilot noted that the aircraft had to be pitched nose down as power was reduced to avoid the low-speed boundary; he considered this a small constraint. With the reduced high-speed margin, it was necessary to make the conversion more slowly in order to keep the aircraft off the high speed warning, and the aircraft had to be allowed to baloon off the glide slope in order to decelerate; hence, the IFR performance degraded to marginally adequate ($PR = 6$). With both ends of the speed corridor constrained, the rating went to the inadequate category ($PR = 7$). The comments were that the constrained corridor required power and speed to be monitored very closely, with pitch attitude being used to stay within the corridor; hence, tracking exceeded ± 2 dots, and the pilot felt that flight-path control capabilities during conversion were too limited for certification.

In Fig. 4 are shown data related to the influence of basic aircraft coupling from conversion and power changes. Recall that for the baseline aircraft, a nacelle tilt toward 90 deg produces a nose-up moment for all nacelle angles and that power increases produce a nose-down moment approximately constant with nacelle angle (Table 2). Consider initially the profile B results. The influence of increasing both the moments was noted in the comments as a requirement for high forces and displacements and, for the instrument approach, the conversion performance deteriorated sufficiently that both high- and

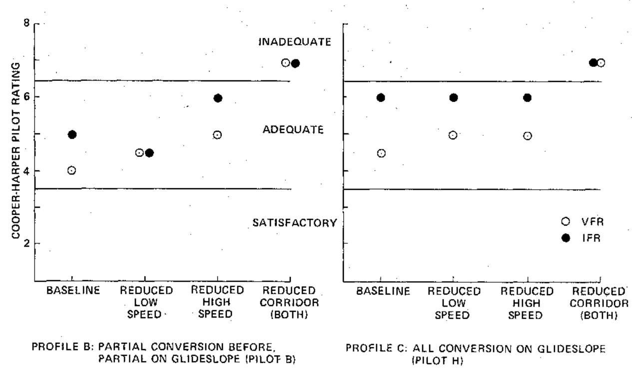

Fig. 3 Influence of conservation corridor.

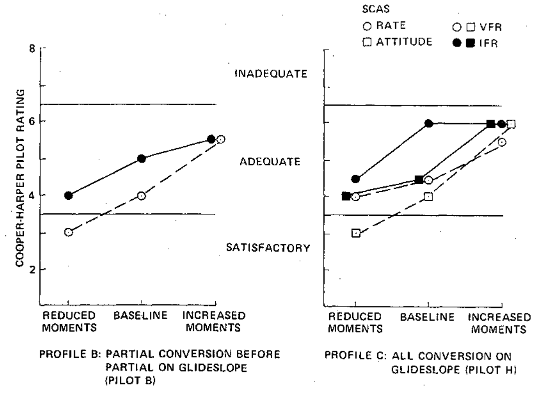

Fig. 4 Influence of aircraft coupling moments.

low-speed warnings were actuated. The change in pilot rating, however, was only about one unit for the instrument approaches, with adequate performance still being considered attainable. Reducing both the moments did not elicit any specific comments about the conversion from the two pilots who flew this profile, although their ratings did improve by about one unit; apparently, the improved conversion capability permitted more attention to be paid to getting set up for the deceleration at breakout.

For profile C, the moment variations were examined with both levels of SCAS. With the rate SCAS, increasing the moments led to a significant degradation in visual conditions; the instrument capability was already marginal, as was discussed earlier, and so the increased moments did not affect the rating. Decreasing the moments led to a significant improvement for the IFR approach, with the comments indicating that although trimmability seemed poor, the nacelles could be beeped continuously without an adverse influence on accurate flight. With the attitude SCAS, the increased moments again led to a marginally adequate capability. The comments noted that 1) the low-level attitude augmentation employed was not sufficient to eliminate the influences of collective-to-pitch coupling, 2) the forces seemed high, and 3) the conversion performance was poor enough to reach the speed boundaries. With the reduced moments and the attitude SCAS, trim was still considered a problem, but there were no difficulties staying within the corridor or performing the approach task, and desired performance could be achieved in both VMC and IMC.

On the basis of these data, it is clear that the inherent coupling moments have a significant influence on the terminal-area capability for this class of aircraft, but it is not clear what a limiting value would be. Reference 13 discussed the influence of the pitch-from-power coupling on the achievable closed-loop path-control bandwidth; "adverse" coupling would be given by negative values of this derivative, and this coupling was hypothesized to limit the path-control capabilities of the aircraft. In this experiment, both the baseline and the doubled-moments configurations exhibited adverse coupling, and it is apparent that the increased-moment case at least is marginally adequate. The specific numbers suggested in Ref. 13 appear unrealistically small, however, and additional work in this area is indicated.

The examination of the alternate conversion control implementations and flight director displays was conducted using only the most difficult conversion profile (profile C). The data related to the influences of these variables are shown in Fig. 5. Using a conversion rate of 1.5 deg/s instead of the baseline 7.5-deg/s rate resulted in a fairly significant improvement in rating from one pilot (from 6 to 4.5, indicating desired

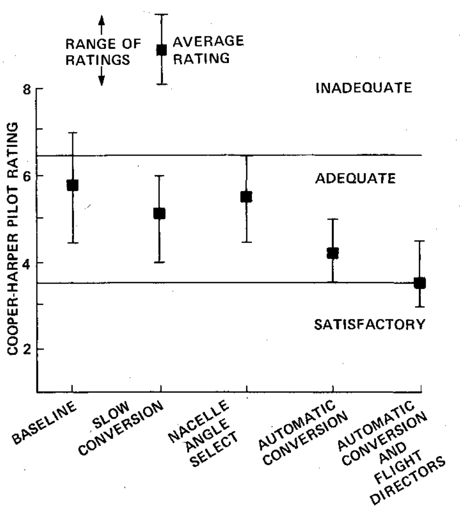

Fig. 5 Influence of conversion procedure and displays.

performance achievable) but no improvement for two pilots. The one pilot commented that the slower rate appreciably reduced the coupling caused by the conversion and, in fact, made the process somewhat easier because of the slower movement of the nacelle-angle gage. For the other pilots, the conversion still required excessive attention to power changes, particularly at the end; it may have been that the slow rate did not leave them sufficient time to get settled before breakout, although the comments do not so state.

Using an interconnect to command a specific nacelle angle with a selector level did not provide the expected benefits although, again, fairly substantial differences among the pilots were exhibited. The comments indicated that not having to watch the nacelle-angle gage was a benefit but that the portion of the conversion from 60 to 90 deg was still very demanding because of the high coupling; in this regard, it was noted that when the beeper switch was used, this final portion of the conversion was performed in two or three beeps to help reduce the influence of the coupling, whereas the interconnect forced it all to be done at the 7.5-deg/s rate with no pauses. It is likely that the interconnect with a less rapid conversion rate between commanded angles would have provided more definitive improvements.

The automatic conversion made a significant improvement in general. For two of the pilots, the automation meant that additional concentration on the required power and attitude control was possible, with desired performance therefore becoming achievable. Another pilot, however, commented that the conversion-induced upsets were still a problem because he did not know exactly when the nacelles would rotate, and hence could not apply appropriate power or attitude cross feeds. Finally, adding the three-cue flight director display resulted in ratings generally within the satisfactory category. The pilot comments noted that the deceleration performance felt far better than with the raw displays, and that the pitch and power commands were of substantial assistance. It should be noted that, as has been discussed elsewhere (e.g., Ref. 9), results with flight directors are very sensitive to the director design logic. In this experiment, for example, changing the collective director logic slightly to provide less needle movement at high frequencies with collective inputs changed one pilot's rating from a 4.5 to a 3.0 for the conversion task. The importance of both the displayed information and a proper level of automation/augmentation that these results show (change in rating from 6 with no automation or director display to ratings around 3) is consistent with previous investigations of decelerating instrument approaches.

Concluding Remarks

A ground-simulation experiment to investigate airworthiness and operational aspects of tilt-rotor VTOL aircraft in the terminal area has been described. Variations in conversion procedure, conversion corridor, and conversion coupling to other axes were examined in both simulated visual and instrument conditions for representative terminal-area tasks. The simulated test configurations were evaluated for decelerating conversions from 150 to 60 knots, with tasks including subsequent fixed-configuration decelerations to either 30 knots or hover.

Based on the characteristics of the VTOL aircraft as simulated and the design and implementation of the variations that were considered, the following conclusions may be drawn from the results and interpretations of this experiment.

1) In visual conditions with a headwind and only light turbulence, performing part of all of the conversion while descending could be accomplished with about the same level of pilot acceptance as performing all the conversion before descent, given conversion and power coupling characteristics less than or equal to those of the baseline aircraft considered in this experiment. This result was not particularly influenced by the type of stability/control augmentation implemented.

2) In instrument conditions, the conversion procedure had a major influence on the degree of pilot acceptability. With raw-data displays and a manual conversion controlled by a thrust-angle tilt-rate switch, and again considering conversion and power coupling characteristics of the baseline aircraft, desired performance could be achieved with attitude augmentation only if all the conversion was accomplished before initiating the descent; the rate-damping augmentation provided a clearly adequate capability for this conversion procedure. Performing all the conversion while tracking the glide slope led to a marginally adequate to inadequate capability, essentially irrespective of the augmentation system. Crosswinds and a higher level of turbulence had a significant degrading effect.

3) Reducing the width of the conversion corridor from about ±25-knots to ±12 knots in level flight had a significant and deleterious effect. Since the ±25-knot limits of the baseline machine were rarely a problem until conversion coupling became high, it is likely that there is a marginally acceptable value between the two extremes considered here. For the limited corridor, the only terminal-area procedure possible would be to perform all the conversion before descending.

4) For instrument approaches with all the conversion performed while descending and tracking the glide slope in light turbulence, a marginally adequate capability is provided by raw-data displays and manual rate-commanded conversions with either a rate- or an attitude-control system. With the attitude-control system, the capability can be increased to the marginally satisfactory level by the addition of an automated conversion in conjunction with a three-cue flight director display.

5) The VTOL class of vehicle amplifies the interaction between the aircraft's airworthiness characteristics and the required operational situation for civil operations. For operations similar to those of helicopters, in which no conversion while descending is required, less air-frame capability is required than for operations that exploit the VTOL capability to convert from airplane to helicopter modes late in the approach phase.

Acknowledgments

This experiment was conducted as part of a joint program between the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA). The authors wish to express their appreciation to Mr. R. McFarland and, in particular, to Ms. M. Eshow for their exemplary efforts in performing the extensive computer programming required for this experiment. In addition, we are very grateful to the following individuals for their highly motivated and professional participation as evaluation pilots: P. Harper, Civil Aviation Authority, United Kingdom: P. Balfe and J. Arnold, FAA Southwest Region; R. Gerdes, NASA.

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