Piloting Considerations for Terminal Area Operations of Civil Tiltwing and Tiltrotor Aircraft

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ABSTRACT

The existing body of research to investigate airworthiness, performance, handling, and operational requirements for STOL and V/STOL aircraft was reviewed for its applicability to the tiltrotor and tiltwing design concepts. The objective of this study was to help determine the needs for developing civil certification criteria for these aircraft concepts. Piloting tasks that were considered included configuration and thrust vector management, glidepath control, deceleration to hover, and engine failure procedures. Flight control and cockpit display systems that have been found necessary to exploit the low-speed operating characteristics of these aircraft are described, and beneficial future developments are proposed.

NOMENCLATURE

CTOL	Conventional Takeoff and Landing
IMC	Instrument Meteorological Conditions
SAS	Stability Augmentation System
STOL	Short Takeoff and Landing
V	Airspeed
V/STOL	Vertical/Short Takeoff and Landing
γ	Flightpath angle
θ	Pitch angle

INTRODUCTION

After many years of research and testing of numerous and diverse V/STOL concepts, the possibility is now emerging that tiltrotor and tiltwing aircraft might enter civil operations during the next decade (Refs. 1, 2). Indeed, the V-22 Osprey tiltrotor aircraft, a military prototype currently undergoing acceptance testing, is paving the way for possible civil applications.

During the past several years, various piloted simulations have been conducted of both of these design concepts (Refs. 3 - 5). The objectives of these simulations have included concept evaluation, detailed systems development, and the investigation of airworthiness and certification issues associated with the operation of these aircraft in instrument meteorological conditions (IMC) in the terminal area.

At the same time, many research efforts conducted over the past three decades have examined the stability and control, handling, and performance requirements for both powered-lift STOL transport-category aircraft and military jet V/STOL aircraft. References 6-11 and their associated bibliographies provide a comprehensive summary of this research. More recently, the introduction of digital flight control technologies has stimulated research in integrated flight/propulsion control for V/STOL aircraft, partly with the objective of providing a consistent control mechanization for the pilot over the high-speed and low-speed flight envelopes where thrust vector orientation differs markedly (Refs. 12, 13). Even though the tiltrotor and tiltwing design concepts received scant mention in the evolution of these V/STOL design requirements, much of this background research is relevant to these aircraft. Consequently, it is one objective of this paper to associate some of the airworthiness and piloting issues for these two aircraft design concepts with some of the general criteria contained in these references.

Considerable research has also been conducted over the past two decades to investigate operational procedures, flight control, and cockpit display systems needed to support terminal area operations by powered-lift STOL, V/STOL, and rotary wing aircraft in IMC. In addition to exploiting the short or vertical landing capabilities of these aircraft, the expectations implicit in this research have been to take advantage of their potential to operate in airspace not easily used by higher speed conventional

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aircraft and hence increase the throughput of the air traffic control environment. The low-speed kinematics associated with these operations dominate many of the piloting issues, such as the initial deceleration procedure, the determination of the scheduled glidepath angle, the corresponding selection of the aircraft approach configuration, the attendant safety margins, and the influence of winds and turbulence. Hence, much of this research is also generally applicable to tiltrotor and tiltwing operations (Refs.14-17).

In addition, investigations focusing on IMC terminal area operations specific to the tiltrotor and tiltwing design concepts have been conducted. A large moving-base simulator was used to evaluate three candidate conversion procedures for tiltrotor aircraft executing 6 degree instrument approaches (Ref. 3). A subsequent simulation evaluated various levels of control integration and flight director sophistication during both constant speed and decelerating approaches on glidepaths as steep as 25 degrees (Ref. 4). For the tiltwing concept, flight tests in simulated IMC using a programmable electronic display system for approach guidance were conducted (Refs. 18-20). The research reported in Ref. 21, although conducted in "visual" conditions, represents a recent ground-based simulation of the tiltwing concept that included investigations of decelerating and descending approaches to hover.

This paper seeks to distill from this body of prior research those piloting considerations deemed important in the operation of civil tiltrotor and tiltwing aircraft. In the presentation which follows, the distinguishing characteristics of each design that impact pilot control are discussed briefly. Basic procedural philosophy from transport category CTOL operations is reviewed to establish a desirable guideline for civil V/STOL operations. Next, configuration management issues associated with thrust vectoring and conversion from cruise to powered-lift flight are discussed, including recommendations specific to both tiltrotor and tiltwing concepts. Glidepath tracking considerations are reviewed, including comments concerning the execution of curved, decelerating, and descending approaches. Throughout, there is discussion of flight control and cockpit display systems that must be provided to ease the piloting task. Finally, some of the piloting considerations that would be involved in the event of engine failure during the steep approach (or go-around) are reviewed.

PRINCIPAL FEATURES OF TILTROTOR AND TILTWING

The tiltrotor and tiltwing design concepts have significant differences that have long presented the opportunity for interesting technical discussion (Ref. 22) . Although it is not the objective of this paper to promote the relative merits of each design concept, some of their unique characteristics are worthy of emphasis because they lead to differing piloting considerations for the operation of these vehicles in instrument conditions in the terminal area.

Throughout this paper there is little discussion of basic dynamic response criteria, particularly for the angular degrees-of-freedom that are important for the inner control loops. This is not to de-emphasize the importance of these handling qualities to the pilot, but rather is recognition of their already thorough treatment, exemplified in Refs. 7, 8, 10, and 11. Following the approach taken in Ref. 7, for example, it is assumed that good attitude stabilization is provided so that handling qualities in the pitch axis particularly are not a consideration.

Two aircraft, the XV-15 Tiltrotor (Ref. 23) and the CL-84 Tiltwing (Ref. 24) are used to illustrate the principal features of each concept. The helicopter-like characteristics of the XV-15 (Fig. 1) are embodied in two features, the significantly lower disc loading (Table 1), and the use of longitudinal cyclic pitch. Low disc loading results in good low-speed operating efficiencies, lower noise, lower downwash impingement effects, and good vertical axis damping in hover and during low-speed steep approaches.

The use of cyclic pitch control introduces a rotor flapping degree-of-freedom not usually found in tiltwing designs. Not only does this feature eliminate the need for a separate moment-generating device for pitch control at low airspeeds when the nacelles are rotated, it also alleviates some of the sustained pitch attitude changes that otherwise would be required to orient the thrust vector.

Table 1. Disc loading (lb/ft^2)

Titltwing CL-84-1[a]	Titlrotor XV-15[b]	Helicopter S-76B[b]
41	13	7.7

[a] At design max hover weight

[b] At design gross weight

For the CL-84 Tiltwing (Fig.2), the higher disc loading and the fully immersed wing are mainly responsible for its unique characteristics. Much higher propulsive efficiencies make the tiltwing more suitable for missions that emphasize cruise performance, while at low speed, downwash velocities are high and vertical damping is low. Furthermore, the high drag associated with the fully immersed and tilted wing, and the absence of any propeller

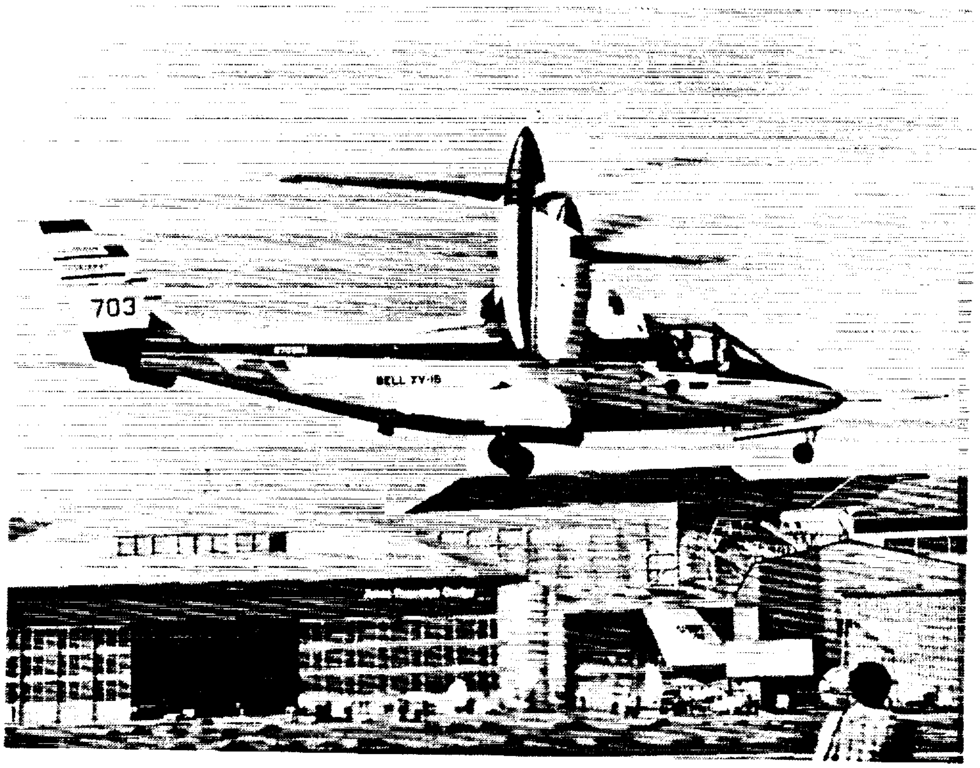

Figure 1. XV-15 Tiltrotor

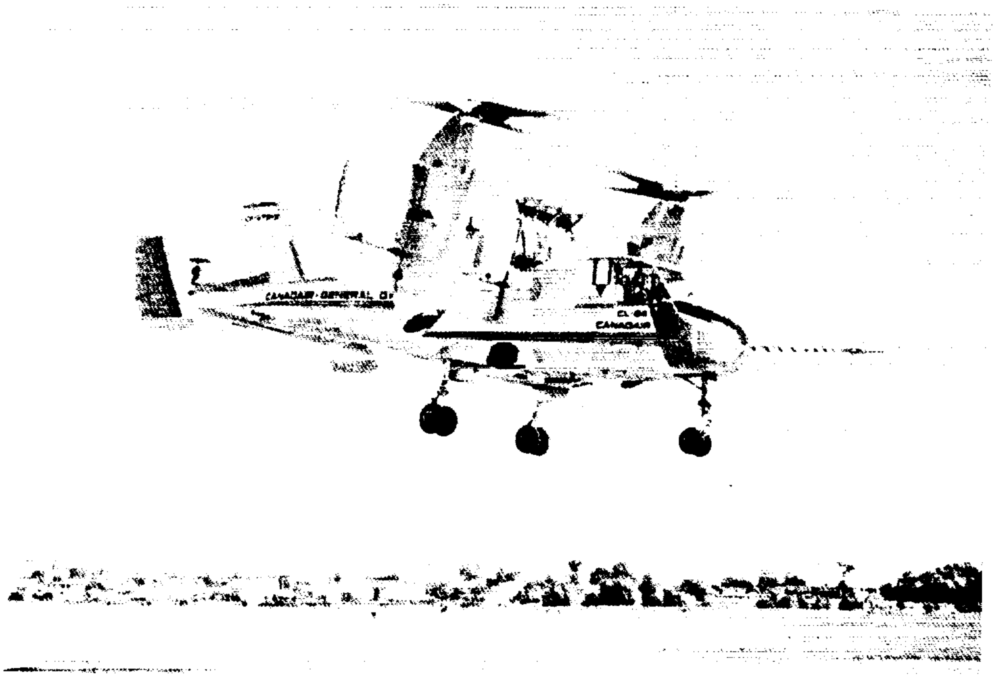

Figure 2. CL-84 Tiltwing

flapping degree of freedom both serve to make pitch attitude an unusually ineffective control at low speed for accomplishing speed or flightpath control. In the tiltwing, an auxiliary effector is used in the absence of propeller cyclic for pitch attitude control at low speed.

One of the major differences in the two designs is reflected in their level flight "conversion corridors", depicted in Fig. 3. Figure 3(a) shows the relatively wide range of airspeeds available to the XV-15 pilot in level flight at nacelle angles above zero (Ref. 23). In contrast, Fig. 3(b) shows that the CL-84 pilot had available only a very narrow range of airspeeds at each intermediate wing angle when constraints on comfortable pitch attitudes are taken into account (Ref. 24). To be discussed subsequently, these characteristics are the source of important procedural, workload, and handling qualities considerations for the pilot in his configuration management of the aircraft during terminal area entry, approach, and landing.

Further information concerning the pilot control requirements during the conversion to powered-lift is revealed in the level-flight power-required curves for the XV-15 and CL-84 shown in Fig. 4 (Refs. 25, 24). The progression of operating points from the frontside of the power-required curve during initial maneuvering, to the minimum drag point (typically) during steep low-speed descent, and then fully onto the backside for deceleration to hover is of significance. Especially for the tiltwing, a large increase in power is required as hover is approached. Associated with this change in operating points for both concepts, and corresponding to the change in orientation of the thrust vector angle from horizontal to vertical, is a change in pilot technique for managing airspeed and flightpath angle. Some of the pilot control and cockpit display issues involved in transitioning from a conventional "frontside" technique to a "backside" control technique during precision instrument approaches are described in Refs. 4, 8, 13, 15, and 26.

The flightpath angle-airspeed (γ-V) trim maps described in Ref. 8 portray best the piloting technique, aircraft performance, and safety margin considerations associated with the low-speed steep approach configurations. The γ-V map for the simulated tiltrotor aircraft of Ref. 4 in the approach configuration with nacelle angle 80 is shown in Fig. 5(a). The vertical slopes of the constant attitude lines indicate that flightpath control about the scheduled 6 degree path, D in Fig. 5(a), can be achieved with minimum crosscoupling into speed using power adjustments alone while maintaining constant attitude. The locally horizontal segments of the constant power lines indicate that airspeed control about the scheduled operating point can be achieved with minimum crosscoupling into flightpath by using attitude adjustments while maintaining constant power. The

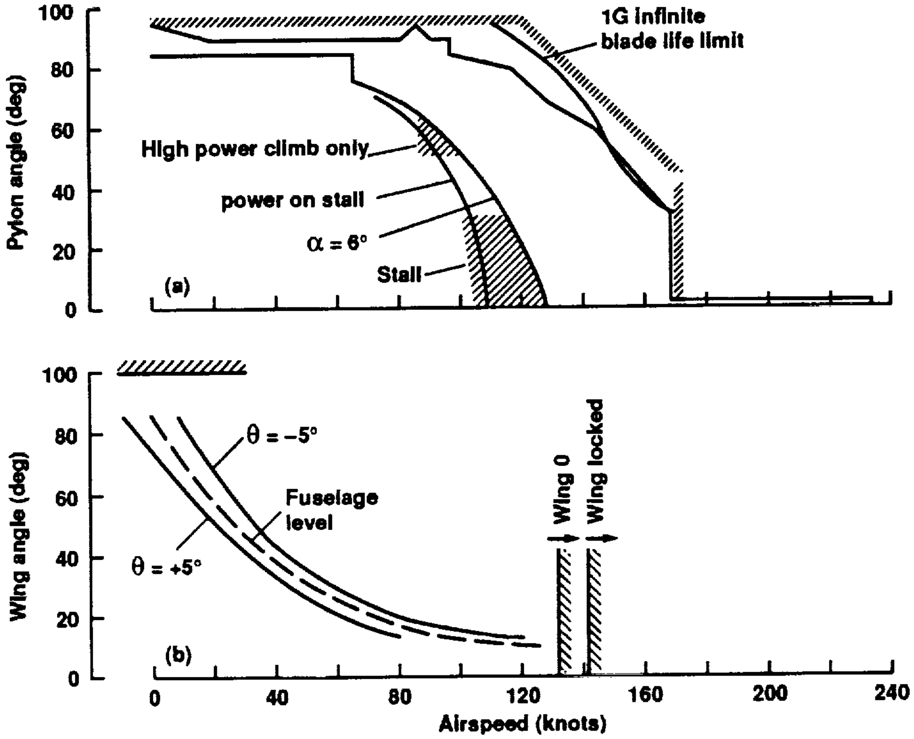

Figure 3. Level-flight conversion corridors. (a) XV-15; (b) CL-84

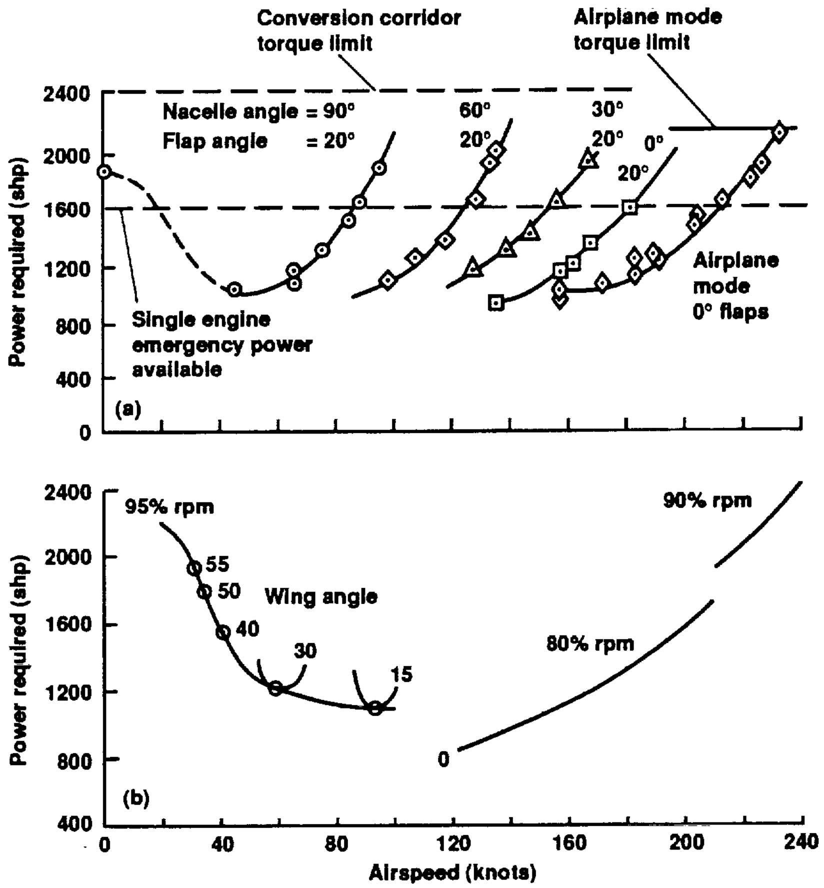

Figure 4. Level-flight power required. (a) XV-15; (b) CL-84

relatively shallow gradient between the constant attitude lines indicates that pitch attitude changes would be moderately effective in controlling airspeed with a sensitivity of about 6 kt/deg. Yet the speed-attitude stability of the tiltrotor is strong enough that the piloting technique of maintaining a specific pitch attitude reference during approach (within 0.5 degrees for example on an expanded-scale attitude indicator) would be effective in maintaining the approach airspeed within a narrow range. A good pitch-attitude-hold stability augmentation system (SAS) would greatly facilitate this aspect of the pilot's control task.

In comparison, the tiltwing is characterized by such excessive speed stability that the use of pitch attitude is considered impractical as a mechanism for speed control because excessively large attitude changes would be required. This consideration becomes of particular concern for civil operations, where pitch attitude usage for both trim and control should be kept within about 5 degrees of fuselage level. Figure 5(b) shows a γ-V map representative of a tiltwing with wing angle 40. Flight-test data from Ref. 24 were used to plot the strikingly steep gradient between the constant attitude lines, only 1.2 kt/deg. Changes in the component of gravity along the aircraft longitudinal body axis brought about by pitching are offset by the large changes in drag that result from only very small speed changes.

Pitch attitude thus cannot be used effectively as an active method for setting or even for regulating airspeed in the tiltwing. Rather, airspeed is so strongly determined by wing angle that pitch attitude should be considered simply as a configuration setting, controlled most effectively by a good attitude-hold SAS. In the final analysis, speed regulation at the intermediate and higher wing angles is of little importance anyway, since it has little influence on aerodynamic safety margins, or on trajectory. Instead, wing angle and power setting strongly dominate these considerations.

Finally, the buffet that is characteristic of the tiltwing in the low-speed descent configuration poses significant design, piloting, and operational considerations, since it presents a significant limitation on feasible descent and deceleration profiles. Figure 6 from Ref. 27, to which

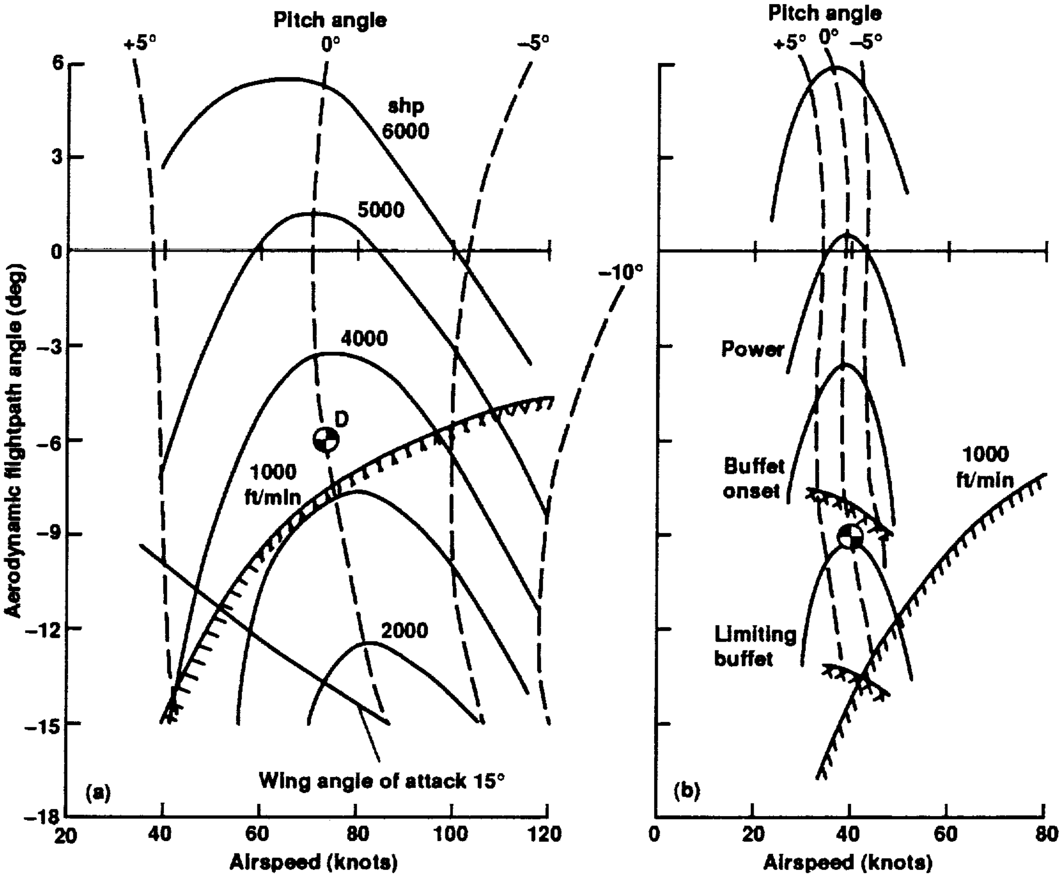

Figure 5. Trim conditions during steep descent. (a) Tiltrotor, nacelle 80 deg; (b) Tiltwing, wing 40 deg

flight-test data provided in Refs. 24 and 28 have been added, depicts the buffet boundaries for the CL-84 prototype and a subsequent model, the CL-84-1 aircraft. The buffet occurs when operating near the maximum lifting conditions for the wing, and is thought to be influenced by the basic wing chord/propeller diameter ratio, the details of the wing leading edge and trailing edge flap schedules, the fuselage incidence angle as reflected by the trim pitch angles used for approach (nosedown attitudes were alleviating), and details in local wing contours and surface condition. The reasons for the differences in the buffet characteristics between the two models were not well understood even by the aerodynamic designers (Ref. 27). Indeed, the published data appear to be somewhat inconsistent, suggesting that efforts were constantly underway to improve the aerodynamics associated with the problem.

Reference 28 describes a buffet encounter in the CL-84-1 in the wing 40 configuration that represented a limiting flight condition: "Although the power was held constant for the next 7 to 8 seconds, the indicated rate of descent did not stabilize and continued to increase (above 850 fpm) until buffeting and nose and wing drop occurred." Relatively small low frequency pitching oscillations frequently preceded nose-drop. Although progressively deeper penetration into buffet represented a significant disruption to the flight condition, recovery of the aircraft was easily effected by adding power.

The significantly different characteristics of these two aircraft designs, and their clear differences from CTOL aircraft argue undeniably for special operating procedures. Yet it is important to recognize that there remain aspects of their operation that can be patterned beneficially on CTOL experience.

CTOL OPERATING GUIDELINES

It might be said that there are at least two fundamental differences between CTOL and V/STOL operations. The first arises from the operating environment. To facilitate the integration of V/STOL aircraft in the confined noise-sensitive route structures of busy terminal areas and to exploit the operating potential of these aircraft, curved and steep flightpaths to vertiports or to designated sections of existing airports will be required. The unusual low-speed kinematics and the correspondingly greater effect of winds at the surface and along the approach path impact both the

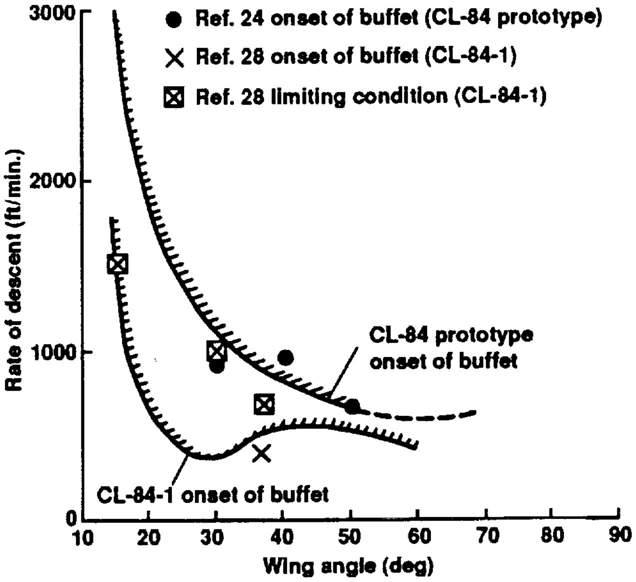

Figure 6. CL-84 Tiltwing buffet boundaries

geometry of terminal area flightpaths and the descent and climb performance of the aircraft in its low-speed high-drag configuration.

The second fundamental difference is associated with the requirement to orient the thrust vector from a general horizontal direction to a vertical direction in order to gain access to the low-speed portion of the flight envelope. This creates unique configuration management and aircraft control problems for the pilot, and for the designer who seeks to alleviate some of the lift, thrust, drag, and pitching moment effects on the pilot's behalf through various sophistications in flight/propulsion control integration.

These differences notwithstanding, there is a clear need and good justification to strive for close similarity with the operational procedures and flight control characteristics that have evolved over decades of operating CTOL aircraft in the civil environment. These procedures and characteristics, broadly reflecting simplicity and conservatism and motivated largely by achieving maximum possible safety, are often substantially different than ones that may be appropriate for the military missions with which V/STOL aircraft typically have been associated. Hence, it may be important to emphasize within the V/STOL community the sometimes differing character of civil operations as civil V/STOL designs are developed. Those operational procedures and flight control considerations that follow CTOL experience and which are relevant to the theme of this paper are discussed below.

1. On arrival in the terminal area, a reasonable maneuvering speed is established that is consistent with air traffic control requirements. This typically involves an initial flap setting and a speed in the vicinity of 200 kt. For V/STOL aircraft, there would also be preparation for initial thrust vectoring (such as wing or pylon unlock).

2. At a well delineated point just prior to beginning descent, the approach configuration is established while in level flight. For a CTOL aircraft, this often involves several progressive flap selections, each accomplished by a single pilot or co-pilot action. Specific guidelines are used to determine when it is appropriate to effect the next configuration change, such as known distance from the final approach fix, approaching glideslope intercept, or crossing the outer marker. Configuration changes are designed or indeed required to be benign to the pilot's control task and to the quality of the passengers' ride. For V/STOL aircraft, these configuration changes would involve thrust vectoring. The final action just prior to beginning descent (such as undercarriage selection) is often one that yields the drag and thrust settings appropriate to the scheduled descent angle.

3. During descent, the pilot is actively manipulating at most two longitudinal controls, one to maintain or adjust the flight reference (usually airspeed) and the other to maintain the flightpath. Prior to landing, there may be at most one more single-action configuration change, such as the selection of final landing flaps. The lateral flightpath is maintained by actively manipulating the same pilot control inceptor used for active control in the longitudinal axis. In normal circumstances pedal control is not required.

4. Should an engine failure occur at any point on the

approach, there is at most one single-action configuration change needed to continue to land, or to achieve a positive climb rate if the pilot elects to go around.

These important guidelines are reflected in the proposed airworthiness standards for civil powered-lift aircraft contained in Ref. 8. The remainder of this paper discusses the terminal area operation of civil tiltrotor and tilwing aircraft in the context of these well-established general procedures.

CONFIGURATION MANAGEMENT DURING INITIAL CONVERSION

Findings from Previous Tests

In V/STOL aircraft, decelerating transitions to hover have typically been more difficult to perform than accelerating departures. Even so, the management of aircraft configuration through conversion from cruise to hover did not emerge as a significant problem area until flight in instrument conditions was investigated (Refs. 18, 29). Reference 20 describes some of the piloting difficulties encountered in the CL-84 tiltwing aircraft during hooded partial conversions from wing 0 to wing 12, and subsequently, through wing 45 to hover. In that aircraft, the wing was tilted using a beep switch mounted on the top of the power lever. At wing 0, the wing-up tilt rate was 2 deg/sec, increasing linearly from wing 0 to wing 45 where it was maintained at 6 deg/sec. (The wing-down tilt rate was 12 deg/sec from wing 100 to wing 45, thereafter the rate decreased linearly to 3 deg/sec at wing 0.) Although these tilt rates at low wing angles seem modest, their nearly direct equivalence with angle of attack changes assured strong lift, drag, and pitching moment interactions. The effects of these interactions were the main causes for the slower wing tilt-rate scheduling. It is significant that these wing tilt-rates were developed for visual conversions conducted close to the ground where visual cues were good.

In simulated instrument conditions, the piloting difficulties encountered when converting from an initial wing 0, 120 kt configuration to the wing 12, 90 kt initial approach configuration consisted of a strong vertical response to initial wing incidence change, together with a strong nose-up pitching moment. The recommended technique for the CL-84 during this initial wing tilting was to reduce the power temporarily and to simultaneously adjust the fuselage attitude to level, a change of about 5 degrees. The CL-84 had a rather weak pitch SAS in this regime, so the pilot had little assistance in resisting the nose-up trim change and in coordinating the required nose-down pitch change. As the conversion progressed beyond wing 35, which corresponded to about 45 kt, the ballooning tendency decreased rapidly and power had to be added progressively. As described in Ref. 20, even though the correct coordination to maintain level flight during conversion was a demanding task, acceptable levels of performance could be achieved in visual conditions. However, when visual cues were limited to only those available from the CL-84 display symbology, the pilot workload became extremely high.

Similar piloting problems, described extensively in Refs. 3 and 29, were encountered during conversions in "visual" and IMC for simulated tiltrotor aircraft. Schedules ranging from full conversion in level flight to full conversion along the glidepath were investigated. It was determined that "instrument operations employing thrust vector conversion are going to have to provide some additional assistance to the pilot to achieve ratings in the 'satisfactory' category". In addition to the use of a three-cue flight director system, consideration was given to the use of discrete nacelle angle detents rather than the incremental nacelle-rate "beep" switch which was located on the power lever. This detent concept was implemented subsequently and evaluated briefly with favorable results (Ref. 4). Not surprisingly, good attitude stabilization was found beneficial in suppressing unwanted pitching upsets arising from aerodynamic crosscoupling effects when first tilting the nacelles.

Indeed, there seems to be little justification in a civil V/STOL design for the pilot to exercise continuous control over the full range of thrust vector angles, as traditionally provided in the past. Instead, there seems to be a good foundation for implementing several discrete, single-action configuration changes, each tailored to the inherent deceleration characteristics of the aircraft and for minimum crosscoupling. This tailoring would include an appropriate wing or nacelle actuation rate, as well as appropriate flap scheduling. If the pitching moments associated with initial vectoring are strong, an interconnect with the moment effector should be considered to absorp them. Alternatively, the authority and off-load features of the pitch-attitude stabilization system should be such that the moments can be contained. Consistent with existing CTOL procedures, it is preferred to implement these configuration changes as discrete selections in level flight, where the operational significance of flightpath disturbances due to configuration changes is minimized.

Tiltrotor

Shown in Fig. 7 is a possible level-flight conversion sequence for the 40,000 pound tiltrotor aircraft simulated in Ref. 4. Associated with the nacelle angle changes is the automatic flap schedule tabulated in the figure. A

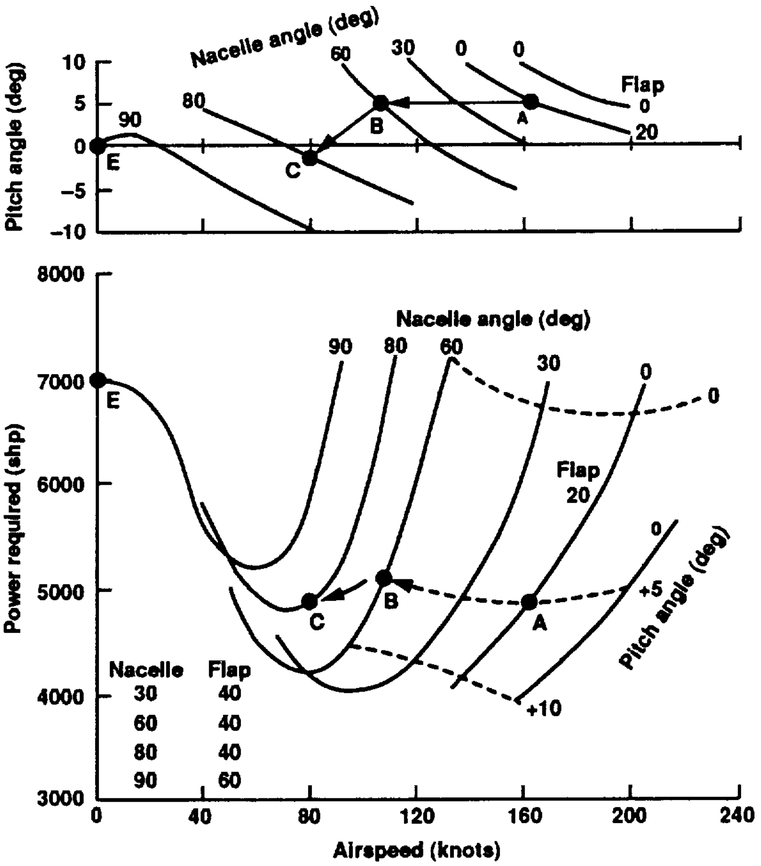

Figure 7. Tiltrotor level-flight trim conditions

manual flap setting of 20 degrees is first selected by the pilot to facilitate initial maneuvering and to reduce the trim pitch angle at lower airspeeds. Point C in Fig. 7 represents the nacelle angle 80 configuration that will be used for descent. Point D in Fig. 5(a) represents the trim conditions on the 6 degree glidepath chosen for this example. To arrive at this approach configuration in level flight with minimal power changes and with the most predictable and repeatable adjustments in pitch attitude, the sequential attainment of points A, B, and C might be recommended. Alternatively, it may be elected to bypass C, and transition directly from B to D upon glideslope intercept. In either case, the management of pitch attitude during this sequence and during the subsequent descent includes regulation about significantly different trim values, emphasizing the importance of pitch axis stability augmentation. In Ref. 4, an attitude-command system with the capability to "beep" the reference attitude to the desired reference value was used. A three-cue flight director was also found necessary to assist the pilot in maintaining the ± 100 ft standard for altitude performance during the level-flight conversion sequence (Ref. 30). The use of attitude-command stability augmentation and flight director guidance is consistent with the findings of Ref. 17, which reviewed many prior investigations of systems requirements for IMC approaches in both helicopters and V/STOL aircraft.

This depiction of the conversion trajectory as a succession of quasi-steady trim conditions is an idealization, since power will still have to be retarded and pitch angle reduced to counter ballooning. Nevertheless, the proposed trajectory represents a useful goal in determining programmed flap and nacelle angles to be achieved in response to each single action configuration change. A final smaller (single-action) configuration change to nacelle angle 90, and a final deceleration would be accomplished late in the approach in order to adjust the trim pitch angle to a range more appropriate for hover and subsequent vertical landing at E.

The data of Fig. 7 were used to plot the conversion corridor shown in Fig. 8, bounded by trim pitch angles deemed in a comfortable range for civil operations. The higher speed portion of the corridor is further limited by torque available at the lower nacelle angles. In the presence of these practical constraints the conversion corridor for the simulated tiltrotor aircraft of Ref. 4 is seen

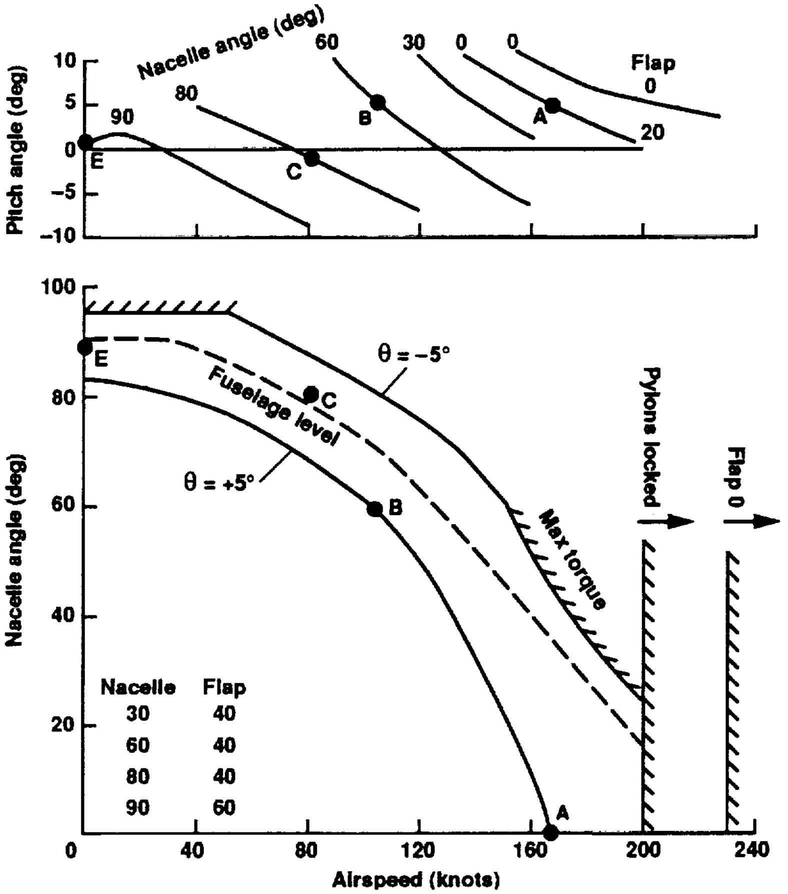

Figure 8. Tiltrotor conversion corridor with attitude limits

to be significantly narrower than first implied by the XV-15 corridor that was presented in Fig. 3(a).

Tiltwing

It should be emphasized that the extreme narrowness of the tiltwing conversion corridor shown in Fig. 3(b) does not imply any difficulty for the pilot in remaining within it. Rather, it reflects an unusually constrained relationship between aircraft configuration and airspeed over which the pilot has little control other than by adjusting wing angle. The utilization of wing angle during the approach and landing, and the influence of this on height control requirements dominate the pilot's task.

For the tiltwing aircraft entering the terminal area, initial procedures would involve a manual flap selection to facilitate maneuvering down to an airspeed in the vicinity of 120 kt, as well as preparation for wing tilting. This would include unlocking the wing, engaging the drive mechanism for the tail-mounted propeller used for low-speed pitch control, and selecting the higher propeller rpm needed for V/STOL operation. For the tiltwing aircraft represented by the conversion characteristics shown in Fig. 3(b), the very strong pitch-heave coupling associated with the first 10-15 degrees of wing angle change, combined with the recommended procedure of simultaneously adjusting fuselage angle to level, both argue strongly for a slowly programmed initial configuration change to about wing 15. Other aerodynamic surfaces such as leading and trailing edges flaps would be scheduled automatically. Selection of this configuration change should be accomplished by a single pilot action, not through the incremental or sustained operation of a wing-tilt rate switch. Control over pitch attitude during this period might be achieved most effectively with an attitude-command system for which the pilot "beeps" the reference attitude down to level. A tailored pitch command implemented within the flight director display would probably be helpful. Additional single-action selections to wing angles 25 and 40, for example, would provide flexibility to the pilot in dealing with strong headwinds during approach while also configuring the aircraft beyond the range where ballooning is most problematic. Although these sequential configuration changes would position the aircraft for the steep descent portion of the approach, continuous control of higher wing angles must somehow be provided in order to achieve hover.

STEEP DESCENT

Tiltrotor

Having established the desired approach configuration, represented by C in Fig. 7, and just prior to capturing descent guidance, the tiltrotor pilot reduces power and lowers the undercarriage with the objective of arriving at the scheduled descent condition represented by point D in Fig 5(a). Many of the pilot control considerations during the steep low-speed descent are evident from this figure. The 6 degree descent condition selected corresponds to a still air descent rate of 785 fpm, a suitable margin from the maximum value of 1000 fpm recommended in Refs. 6 and 8, and close to the nominal 500 fpm recommended for low-speed aircraft in Ref. 28. The 15 degree angle-of-attack line shown in Fig. 5(a) does not necessarily represent any limiting aerodynamic phenomenom, but in general, any aerodynamic limits along with the minimum and maximum power limits would be represented on this diagram. The nearly vertical constant attitude lines and the locally horizontal segments of the constant power lines at the scheduled operating point reflect little coupling between power and speed as long as attitude is held constant. This permits the pilot to track the glidepath easily using power alone, while simply maintaining a level fuselage angle. A good attitude-retention SAS would facilitate this task, especially in the presence of any transient pitching moments caused by power changes, or by atmospheric turbulence (Ref. 17).

As concluded in Ref. 4, also corroborated by research reviewed in Ref. 17, a three-cue flight director is essential to assuring satisfactory handling qualities and performance during steep approaches, even when conducted at constant speed. Further, the restriction of control in the longitudinal plane to the active manipulation of at most two inceptors, offers the potential identified in Ref. 15 for flying precision curved approach profiles in IMC. As identified in Refs. 15 and 31, the additional aid needed in these circumstances is an adequate means (such as a moving-map electronic display) to assure situational awareness during the approach procedure.

Consistent with other recommendations set forth in Ref. 8 for civil powered-lift operations and easily seen from the γ-V map of Fig. 5(a), (1) there are available at least four degrees of aerodynamic flightpath angle margin above and below the scheduled path with which to accomplish corrections, (2) level flight is easily achievable without any configuration change, and (3) ample safety margins exist surrounding the scheduled operating point to account for gusts and normal tracking errors. In addition, as required by Ref. 8, only two controls are being actively manipulated to track the flightpath and maintain the speed reference.

Tiltwing

As readily seen from the comparitive γ-V trim maps in Fig. 5, the situation during low-speed steep descent is very different for the tiltwing. The useful speed range is dramatically smaller, and the occurrence of buffet even at moderate descent angles severely limits the envelope available. An approach wing angle of 40 degrees and an airspeed of about 40 kt is used as the basis for this discussion, since characteristics of the CL-84 in this configuration are amply described in the literature.

The wing 40 configuration was selected for the CL-84 flight investigations of Refs. 18-20, whose emphasis was on IMC recovery of V/STOL aircraft to small ships. The approach profiles consisted of initial descents on 9 or 12 degree approach paths followed by level decelerations to hover at 100 feet. The wing 40 configuration was chosen as the best overall compromise towards minimizing handling difficulties during final stages of the approach to hover. In strong headwind conditions, a lesser wing angle was used with the objective of maintaining approach groundspeed in the vicinity of 40 kt. Although height rate damping was poor at these low speeds, necessitating display or flight director compensation, the control effectiveness was more consistent and there was less crosscoupling than at lower wing angles. The attitude stabilization system was reasonably effective in assisting the pilot in maintaining the fuselage attitude a few degrees negative during descent, a technique found effective to reduce buffet. However, the crosscoupling from power or wing angle changes to the pitch axis was still considered significant and a source of difficulty (Ref. 20).

The buffet characteristics of the CL-84 were not reported in Refs. 19 and 20 as presenting limitations or causing particular difficulties during the simulated IMC approaches. This implication of relatively benign characteristics is offset by the potential for the much more significant limitations that were described earlier. This characteristic of the tiltwing, barring its complete resolution in future designs, poses the difficulty that the pilot and passengers will likely encounter buffet routinely during descent, if not on the nominal path then during downward corrections to it. Most importantly, it represents a limiting angle-of-attack condition from which protection must be assured.

The methodology developed in Ref. 8 for this type of limiting flight condition recognizes that angle-of-attack excursions away from the scheduled approach condition are a result of piloting actions such as corrections to glidepath, aircraft or system variabilities such as gust sensitivity or the standards of guidance provided to the pilot, and exposure to vertical gusts. Corrections to glidepath are accommodated by requiring that the scheduled approach path be at least 4 degrees above the prohibited angle-of-attack boundary (which could be drawn on the γ-V map of Fig. 5(b)). The location of the prohibited angle-of-attack boundary is determined by applying the required vertical gust protection, or angle-of-attack margin, to the limiting angle-of-attack (buffet) condition. As seen in the example of Fig. 5(b), there is virtually no angle-of-attack margin available, since the limiting condition is already coincident with the 4 degree maneuvering requirement.

The angle-of-attack margin that is proposed in Ref. 8 provides protection from a 20 kt vertical gust, giving the same level of protection for powered-lift aircraft that is enjoyed by conventional transports. The 30 degree margin (at the 40 kt approach speed) required by this "equivalent safety" standard seems conservative, especially for the tiltwing with its high slipstream velocities. However, it serves to emphasize the improvements that are required in tiltwing buffet characteristics. Equally important, it points to the need to gain operating experience with this class of aircraft to provide a sound basis for the development of sensible airworthiness criteria.

DECELERATION TO HOVER

Operations to designated areas of existing airports might adequately require only short landings from approach conditions like those just described. However, operations to vertiports will require the capability for final deceleration to hover in poor visibility conditions. This final phase was investigated for the tiltrotor during the simulations reported in Ref. 4, and for the tiltwing during the flight-tests reported in Refs. 18-20.

Tiltrotor

Programmed decelerations along the glideslope to a ten foot hover were carried out on 9, 15, and 25 degree descent paths from initial speeds of 55, 35, and 20 kt respectively. The aircraft was first established in the final hover configuration with nacelle angle 90 degrees prior to glideslope intercept, and three-cue flight director guidance was used. The programmed deceleration rate to a 10 ft hover over the pad was 0.025g, or slightly less than 0.5 kt/sec. Breakout altitude was 200 ft, after which the remaining deceleration was accomplished using a combination of flight director guidance and visual references. On the 9 and 15 degree glideslopes, fully satisfactory pilot ratings were obtained for operations in calm air, and borderline satisfactory ratings were achieved in moderate turbulence. (The very steep 25 degree approaches involved high pilot workload, suggesting that such profiles would have to be strongly justified on the basis of vertiport siting requirements to receive continued consideration.) These results are consistent with the CTOL operating guidelines; no final configuration change was required after acquiring the glideslope, and only two longitudinal controls required active manipulation.

A six degree approach initially at 80 kt and nacelle angle at 80 degrees was also investigated. Programmed deceleration was again 0.025g and a 200 ft breakout altitude was used. A fourth flight director cue was incorporated to prompt the pilot when he should begin beeping the nacelle angle to 90 degrees. Satisfactory pilot ratings were achieved, even in moderate turbulence. Similar to the 9 and 12 degree approaches, glideslope tracking performance was approximately 0.2 degree standard deviation. Pilot rating and tracking performance data for the decelerating approaches of Ref. 4 are shown in Fig. 9. Since the power trim data shown in Fig. 7 for the nacelle 80 and 90 configurations indicate only small differences, it can be inferred that the small pitch attitude adjustment associated with selecting nacelle 90 could be accommodated easily within a final single-action selection. This would be comparable to the final flap selection in a CTOL aircraft.

An additional piloting consideration that was identified during the Ref. 4 simulations was the influence of pitch attitude during deceleration on the pilot's field of view. To allow adequate visual reference to the landing zone and vertiport environment, pitch angles within about 5 degrees of level were desired. Although this consideration depends on the particular cockpit environment, it is also considered reasonable for passenger comfort.

Tiltwing

Although piloting considerations in achieving the final hovering configuration are relatively minor for the tiltrotor, they dominate the tiltwing deceleration. In the CL-84, the task in Ref. 20 consisted of beeping the wing from 40 to about 86 degrees while maintaining pitch attitude with the centerstick. Power was slowly increased as wing angle increased, and was modulated to maintain altitude. Despite the pitch SAS that incorporated only a weak pitch attitude term, both power and wing angle changes coupled into the pitch axis, requiring the pilot to intervene to improve attitude-retention performance. The benefits of improved pitch-attitude-hold characteristics in these circumstances were confirmed recently during

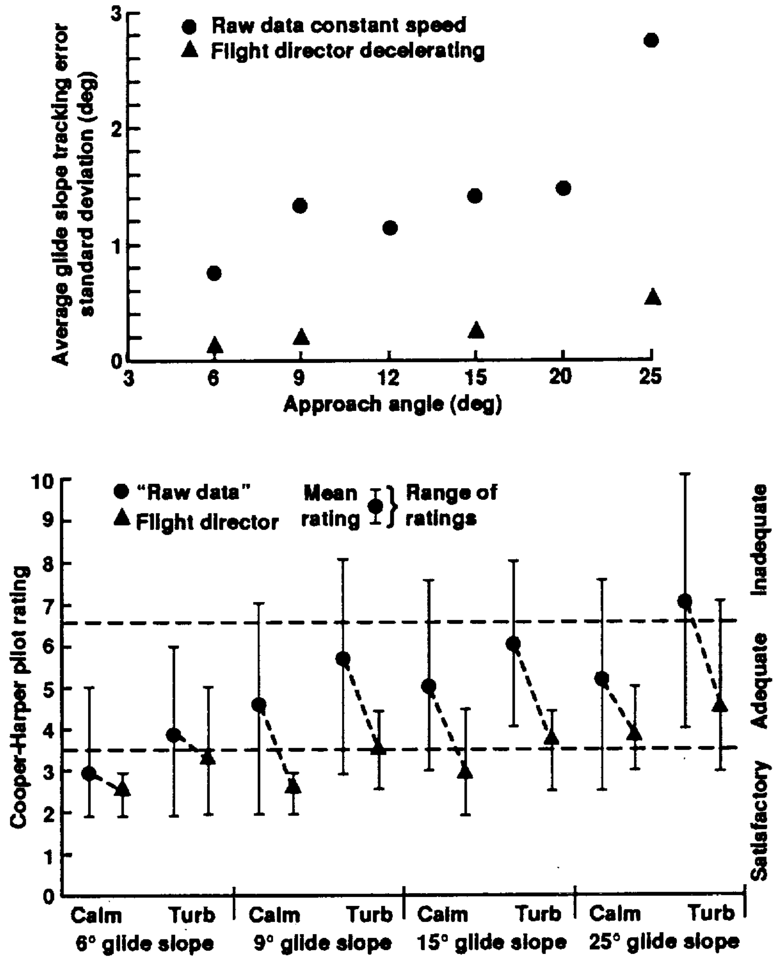

Figure 9. Performance and pilot ratings for steep descents in the simulated Tiltrotor of Ref. 4

investigations conducted in a large moving-base simulator (Ref. 21).

During the CL-84 IMC flight-tests and in the simulation, not only were three longitudinal controls involved in the deceleration, they were also inappropriately available to the pilot. The most traditional and effective control inceptor, the stick, was used only for stabilization, a task that could be accomplished wholly by an automatic system, while the two remaining active controls needed to manage the flightpath were concentrated in one inceptor, the throttle lever. Further, Ref. 32 pointed out the potential confusion in the operation of these power-lever controls in gusty conditions near hover.

Various alternatives have been proposed over the years to resolve these dilemma, such as driving the wing with the longitudinal stick once established in the powered-lift regime. However, the emerging technology of flight/propulsion control integration is perhaps the most effective means for resolution, since it offers the opportunity to optimize not only airframe and propulsion dynamics and aerodynamics, but also the pilot control interface with the vehicle. Various forerunners of this technology have been evaluated both in flight and in piloted simulations (Refs. 13, 33). The concept is illustrated in Fig. 10, taken from Ref. 12. Since it involves modern fly-by-wire architecture, this approach has the added advantage of dispensing with a complex mechanical mixing box and associated control runs.

The piloting difficulties encountered during the IMC decelerations reported in Refs. 19 and 20 were attributed to both control and display factors. Both of the display formats used were exclusively situational in nature, without the incorporation of dynamic compensation in any of the controlled symbology elements. While both display concepts were deemed effective for providing deceleration guidance, both were criticized as deficient in compensating for low vertical damping during approach. Since these early investigations, considerable improvements in display concepts for the shipboard

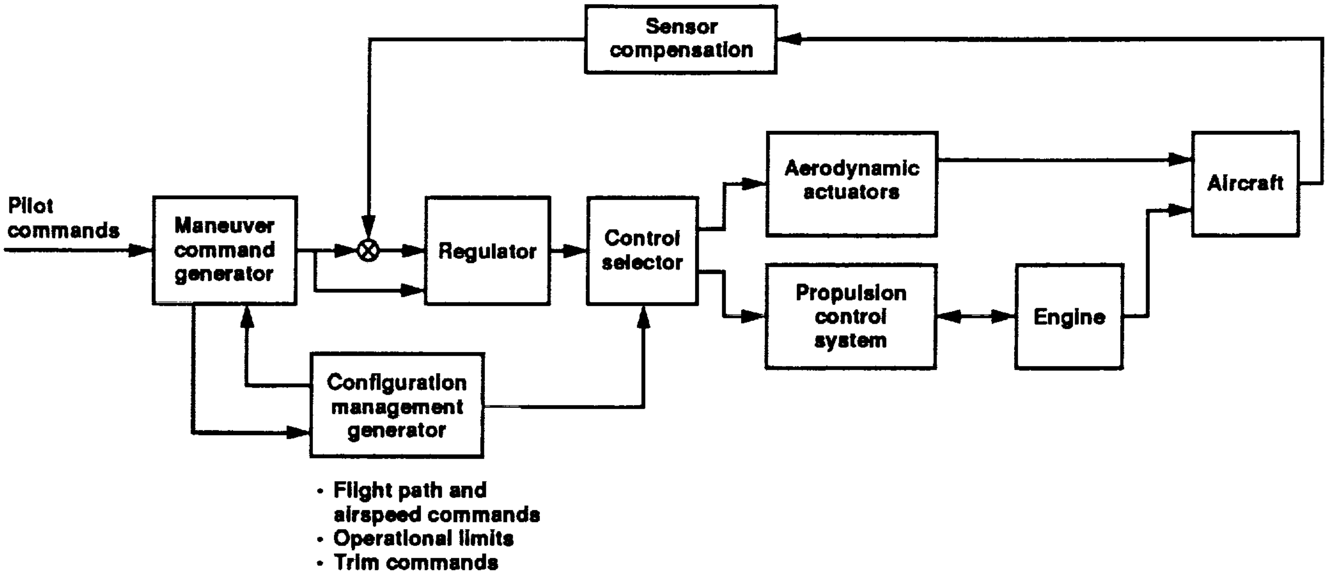

Figure 10. Integrated flight/propulsion control system structure (Ref. 12)

recovery task have been developed (Ref. 34).

The tiltrotor simulations and the tiltwing flight evaluations both confirm the general findings of Ref. 17 that an integrated display format incorporating directly or implicitly groundspeed and range guidance to the hover point is required for decelerating approaches. The display requirements may be reduced if higher levels of control sophistication, such as velocity or acceleration command systems are incorporated. (It is worth pointing out that the very high velocity-damping of the tiltwing results in characteristics that are essentially velocity-command and hold in response to wing tilting.) In any implementation, there is a clear need for symbology drive laws tailored to vehicle dynamics, using methods such as those described in Refs.15, 35, and 36.

Effect of Crosswinds

An important consideration for very low-speed and decelerating approaches is the effect of crosswind. For the pilot it represents perhaps the most significant accommodation that must be made between the air and ground reference frames, requiring the use of an additional control and creating additional display interpretation requirements. Both of these tasks can increase workload substantially in an IMC environment, especially when occurring simultaneously with deceleration.

A variable-stability helicopter was used to evaluate crab versus sideslip during steep decelerating approaches to 25 kt in crosswinds as high as 30 kt (Ref. 37). Only control considerations during simulated IMC were investigated; field-of-view and orientation issues at breakout were not addressed. Under these constraints, crabbed approaches were found satisfactory, as were sideslipped approaches up to a steady-state lateral acceleration level of approximately 0.07g. In the tiltrotor simulation reported in Ref. 4, the pilots evaluated lateral cyclic trim as an alternate means for generating the sideforce required for sideslipped approaches, finding that training in its use and the knowledge of current trim position were important requirements. An important additional control consideration is the availability of adequate authorities in both the yaw and lateral axes for steady-state trim, control, and disturbance-rejection purposes.

The display requirements in crosswind conditions require equally important consideration. Both head-up and head-down implementations are affected by large crab angles. Consistent with the findings of Ref. 17, and based on a review of recent electronic display concepts (eg. Refs. 34, 35), the display feature employed most frequently at very low speed appears to be a horizontal situation format with velocity-vector and landing-pad representation. Other display concepts, such as the flightpath oriented concept evaluated in Ref. 38, together with new head-mounted display technologies warrant further research.

ENGINE FAILURE

Aircraft control, propulsion system management, and aircraft performance are the primary considerations following engine failure. The cross-shafting that is incorporated in both the tiltrotor and tiltwing designs assures that roll and yaw moments are suppressed more than was typically the case for the powered-lift configurations considered in the development of Ref. 8. Consequently, the tiltrotor or tiltwing pilot, like the helicopter pilot, does not have to deal with lateral-directional control transients and can instead concentrate on the longitudinal control task, particularly propulsion system and flightpath management.

Propulsion system management following engine failure, however, is different than in helicopters and more similar to that required in the powered-lift aircraft considered in Ref. 8. Because of the blade-angle governing system that is typically used on tiltrotor and tiltwing aircraft, the pilot (or an automatic power compensation system) must effectively advance the power-demand lever in order to make available additional power from the remaining engine(s). The reaction time in restoring approach power or in establishing go-around power can be a critical factor in minimizing altitude loss immediately following engine failure. A limited amount of research in this area for powered-lift STOL aircraft has been conducted (Refs. 39-41). One method for assuring that all of the remaining power is easily and immediately available to the pilot without the requirement for an immediate action is with the flight/propulsion control integration concept described in Ref. 12. An integrated flight/propulsion control system with these characteristics was developed and tested in a powered-lift STOL aircraft (Ref. 13). The automatic engine failure compensation feature incorporated in the V-22 Tiltrotor represents a direct approach to solving this problem (Ref. 42).

Tiltrotor and tiltwing aircraft which have been flown to date exhibit engine out performance that is similar to twin-engine helicopters. The operating gross weight is usually such that level flight cannot be sustained below some airspeed in the vicinity of 30 to 40 kt, even at maximum contingency power, or without exceeding transmission limits. As an example, the engine-out climb performance for the simulated tiltrotor aircraft of Ref. 4 is shown in Fig. 11.

If operating at low altitude and at an airspeed lower than about 40 kt at the time of engine failure, the aircraft is committed to land, or if at sufficient altitude, it can be accelerated to a higher airspeed to achieve sustained level flight or climb. In the tiltrotor, the pilot may use either a temporary reduction in pitch attitude or a forward nacelle tilt to achieve, if necessary, the required speed and thence the sustained climb. In the tiltwing, the pilot may have to establish a specific nose-up pitch attitude and the wing angle may have to be reduced simultaneously to achieve the necessary steady climb gradient. Either maneuver is severely challenging for the pilot. As indicated in Fig. 11, the pitch attitudes needed to maximize single-engine climb performance may vary significantly among configurations, pointing to potential benefits that may be gained from specially-programmed engine-out flight director guidance.

Reference 8 includes extensive discussion of both continued approach and go-around for low-speed powered-lift aircraft with one engine inoperative. Performance requirements as well as permitted pilot actions for

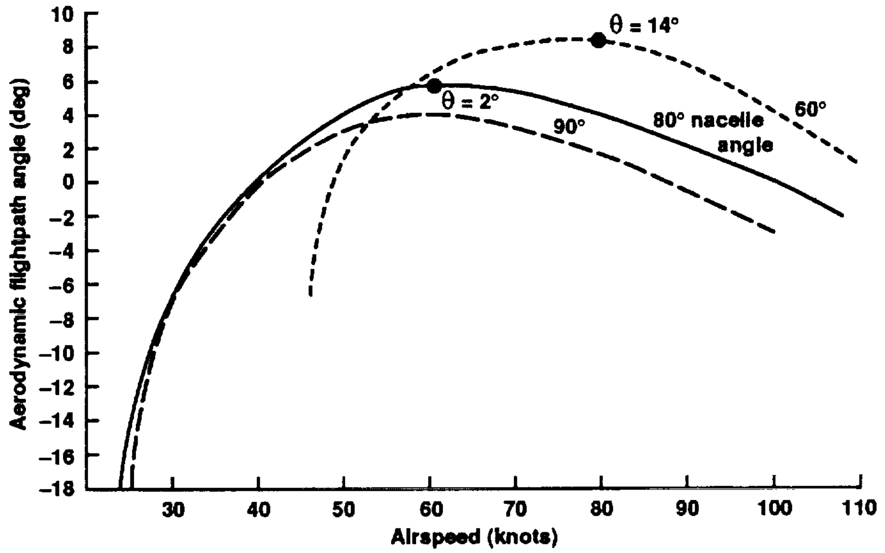

Figure 11. One-engine-inoperative climb performance for the simulated Tiltrotor of Ref. 4

reconfiguration are proposed. Pilot or system delays in initiating the proper go-around action, the environmental conditions, and the obstacle field of the particular landing and take-off zone will all influence critical decision heights and required climb gradients. The recommendations offered in Ref. 8 and the experience to be gained in future V-22 operations can provide important guidelines for developing engine failure criteria for V/STOL aircraft decelerating to hover.

CONCLUSION

Piloting considerations in the operation of tiltrotor and tiltwing aircraft during instrument approach to hover have been discussed on the basis of prior flight-test and simulation investigations, and in the context of general research that has been conducted over the decades on powered-lift aircraft. Operational procedures that have been discussed were patterned on CTOL precepts. Where appropriate, previously developed airworthiness proposals for powered-lift STOL aircraft have been applied to tiltrotor and tilwing V/STOL aircraft. Principal conclusions that can be drawn from this review suggest that (1) single-action discrete configuration changes are preferred that do not require continuous attention from the pilot, (2) attitude stabilization, probably attitude-command in pitch, is desired to reduce workload, and (3) a three-cue flight director are all required to achieve fully satisfactory pilot ratings for the conversion, steep approach, and deceleration. The use of deceleration guidance, including special cuing for setting configurations also appears to be required.

For the tiltwing, there are additional requirements. Low heave damping at the higher wing angles demands compensating dynamics in the flight director or in the vertical axis of the flight control system. The available descent envelope may be limited by airframe buffet. Finally, effective pilot control over wing tilt from initial conversion to hover may require advanced flight/propulsion control integration.

For both concepts, there is the need to investigate the potential of modern digital flight/propulsion control integration concepts to permit curved, decelerating, and descending approaches in constrained airspace. While the V-22 Tiltrotor is equipped with a redundant digital architecture, the pilot interface with the flight control system remains relatively conventional. At the same time, the thrust and power management systems in the V-22 are highly flexible and represent major advances, but they have not yet been integrated fully with the pilot's controls. These systems provide the means for fully integrated flight/propulsion control, optimizing the mechanization of the pilot's controls and simplifying the pilot's control task. Reductions in pilot workload to be accomplished in this manner can then lead to the benefits long expected from V/STOL aircraft, exploiting time and fuel operating efficiencies, and improving the throughput of the integrated air traffic control system.

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