JOURNAL OF AIRCRAFT
Vol. 30, No. 3, May–June 1993

Optimal Takeoff Procedures for a Transport Category Tiltrotor

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Abstract

TILTROTOR aircraft are capable of performing running takeoffs similar to an airplane, whereas they use vertical and short takeoffs when operating as a helicopter. A method is presented to determine optimal takeoff procedures according to the available field length such that the takeoff weight is maximized while also complying with the transport category regulations.

Contents

Commercial tiltrotors are expected to be certificated in the powered-lift transport category,[1] one which requires that the aircraft can continue takeoff in one-engine-inoperative (OEI) conditions once the critical decision point (CDP) has been passed (continued takeoff, CTO), and also be safely landed when power failure occurs during takeoff before reaching the CDP (rejected takeoff, RTO). These requirements impose a significant limitation on the takeoff weight, and accordingly, research has been directed at investigating optimal takeoff procedures to realize efficient tiltrotor operation.[2,3]

Our previous work developed a method to analyze helicopter takeoff procedures for transport category operations by applying nonlinear optimal control theory to a theoretical helicopter model.[4] This led to the present article which extends this method to include a tiltrotor configuration. The following state variables are considered: forward speed u, rate of descent w, pitch rate q, pitch attitude Θ, rotor rotational speed Ω, nacell angle i_n, height above the takeoff surface h, and flight distance from the takeoff point x, while the column and collective lever positions and nacelle angle rate are the control variables.

Vertical Takeoff Optimization

The maximum weight W for a vertical takeoff was determined under the condition that the touchdown speed factor (a sum of the squares of nondimensionalized forward speed and rate of descent at touchdown) is within the safety limit during an RTO. The performance index and the terminal conditions were given by

$$I = \min_{h(0)} \max W \tag{1}$$

$$[u(t_f)/u_{\max}]^2 + [w(t_f)/w_{\max}]^2 \leq 1, \quad h(t_f) = 0, x(t_f) = 0 \tag{2}$$

where $u_{\max}$ and $w_{\max}$ respectively denote the horizontal and vertical touchdown speed limitations. The engine failure height $h(0)$ was determined to be most critical to achieve a safe landing; thereby making this a minimax problem.

The critical decision height, i.e., minimum height to continue takeoff, was determined in this maximum weight condition while complying with the following terminal conditions[1]: a 35-ft clearance above the takeoff surface, a positive rate of climb, and attainment of the takeoff safety speed V_2, where

$$I = \min h(0) \tag{3}$$

$$h(t_f) \geq 35 \text{ ft}, \quad w(t_f) \leq 0, \quad u(t_f) \geq V_2 \tag{4}$$

Figure 1a shows calculated results for a typical tiltrotor configuration having the characteristics of the XV-15 research aircraft. It can be seen that the critical decision height obtained from Eq. (3) is much higher than the most critical height for a safe landing using Eq. (1). The RTO path from the critical decision height was determined to minimize the touchdown speed factor, with

$$I = \min\{[u(t_f)/u_{\max}]^2 + [w(t_f)/w_{max}]^2\} \tag{5}$$

$$h(t_f) = 0, \quad x(t_f) = 0 \tag{6}$$

Oblique Takeoff Optimization

The maximum weight for a short (oblique) takeoff is usually limited by the in-ground-effect hover ceiling provided both the CTO and RTO from the CDP can be accomplished within the available field length. The oblique takeoff was therefore

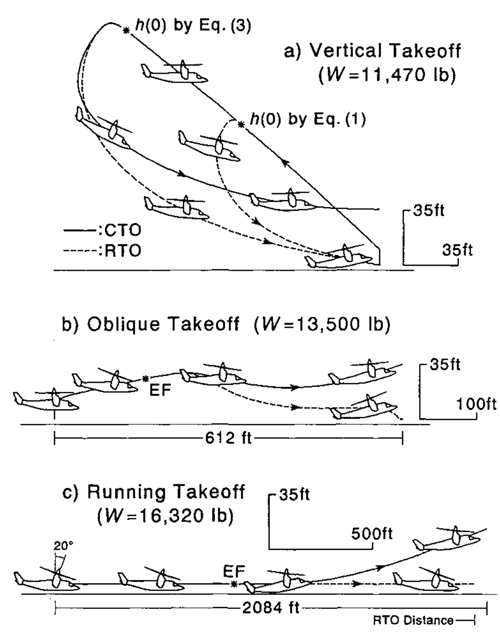

Fig. 1 Optimal takeoff procedures for a transport category tiltrotor.

Received Nov. 25, 1991; synoptic received April 14, 1992; accepted for publication May 21, 1992. Full paper available from AIAA Library, 555 West 57th St., New York, NY 10019.

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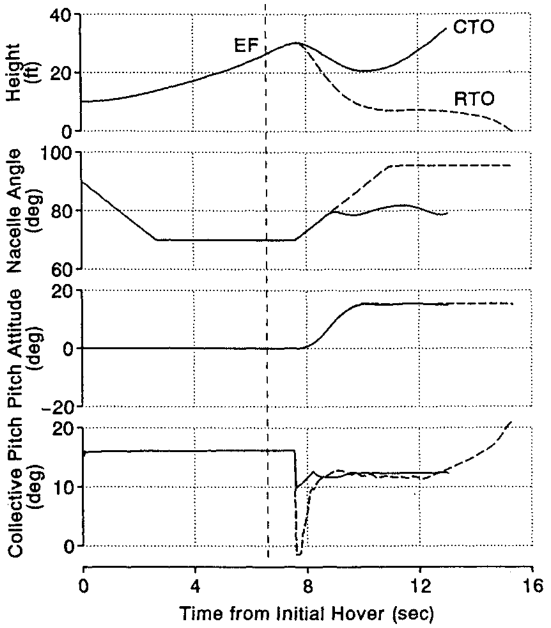

Fig. 2 Time histories of optimal continued and rejected takeoffs during an oblique takeoff.

optimized to minimize the CTO and RTO distances following power failure.

For the CTO

$$I = \min x(t_f) \tag{7}$$

$$h(t_f) \geq 35 \text{ ft}, \quad w(t_f) \leq 0, \quad u(t_f) \geq V_2 \tag{8}$$

For the RTO

$$I = \min[x(t_f) + u(t_f)^2/(2 \cdot 0.2\, g)] \tag{9}$$

$$[u(t_f)u_{\max}]^2 + [w(t_f)/w_{\max}]^2 \leq 1, \quad h(t_f) = 0 \tag{10}$$

where a constant 0.2 g deceleration is assumed in Eq. (9) during the ground run following touchdown.

Figure 1b shows results in which the flight speed at engine failure (EF) is determined so that the CTO and RTO distances are equal. Since the required takeoff distance is defined as the longer of these two distances,[1] it is minimized in this balanced field length (BFL) condition. Figure 2 shows the time histories of these CTO and RTO, where it can be seen that the nacelle angle is optimally controlled with a 1-s delay after engine failure. If the nacelle is fixed in the tilted position ($i_n \simeq 70$ deg, conversion mode takeoff), a longer RTO distance is required due to a decreased deceleration occurring during the pitch-up maneuver. On the other hand, a longer CTO distance is required when the nacelle is fixed in the upright position ($i_n = 90$ deg) throughout takeoff (helicopter mode takeoff) because the negative pitch attitude reduces the wing lift contribution.

Running Takeoff Optimization

The maximum weight for a running takeoff is limited by the OEI climb performance requirements.[1] The nacelle angle

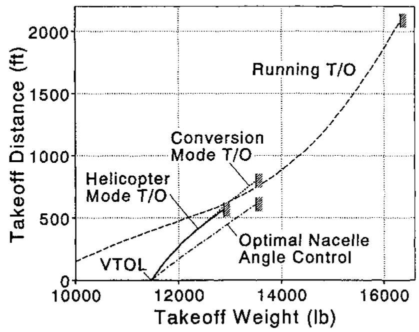

Fig. 3 Takeoff distance vs takeoff weight for various takeoff procedures.

during the running takeoff was therefore adjusted to maximize the best rate-of-climb, while the critical decision speed, rotation speed, and pitch attitude after rotation were subsequently determined to minimize the CTO distance, with results shown in Fig. 1c. The minimum required takeoff distance of the running takeoff is not realized in the BFL condition because the CTO distance is minimized at a lower critical decision speed than that resulting in the BFL condition.

Takeoff Distance vs Takeoff Weight

Figure 3 shows each takeoff (T/O) procedure's minimum required takeoff distance as a function of takeoff weight. The finalized optimal takeoff procedure according to the available field length and the associated maximum takeoff weight are summarized as follows:

1) Vertical takeoff realizes zero-field-length operation at a 11,500-lb maximum weight.

2) A 600-ft field length accepts a 13,000-lb maximum weight using either the helicopter or conversion mode oblique takeoff, although an additional 500 lb is acceptable if the nacelle angle is optimally controlled following power failure.

3) When a 2000-ft runway is available, up to a 16,000-lb takeoff weight is allowed using a running takeoff.

It should be noted that the operating conditions used for these results were sea level and 20°C OAT, at which 2000-shp takeoff/1250-shp OEI powers were assumed. The presented method establishes optimal takeoff procedures for any given set of the described conditions; hence it is expected to significantly contribute to safe and efficient tiltrotor operation in the transport category.

References

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[4] Okuno, Y., and Kawachi, K., "Optimal Takeoff of a Helicopter for Category A V/STOL Operations," *Journal of Aircraft* (to be published).