Near-Optimal Takeoff Policy for Heavily Loaded Helicopters Exiting from Confined Areas

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By application of optimal control theory to an experimentally verified dynamic mathematical performance model, a simple, near-optimal takeoff control technique has been developed for heavily loaded helicopters operating from a confined area. This paper places primary emphasis on understanding the physical tradeoffs and implications involved. Two significant results are presented: 1) a two-segment, near-optimal takeoff control technique for heavily loaded helicopters exiting from a confined area, and 2) a means of estimating, from hover performance, the distance required to clear an obstacle in the departure path.

Introduction

EXCEPTIONAL care must be taken when operating helicopters from a terminal area bounded by natural or manmade obstacles, especially when operating at or near maximum gross weight. Combinations of high altitudes, hot days, and heavy payloads may degrade performance to the point where hovering flight cannot be maintained out of ground effect. Under these heavily loaded conditions, a running or STOL takeoff is required to exit an area. If obstacles exist in the departure path, extreme piloting skill is required (see Fig. 1).

This type of operational situation can occur in both civilian and military operations, particularly during rescue operation where it may be necessary to land at some high-density altitude and increase gross weight by picking up men, supplies, or equipment. The Army became interested in this problem as a result of combat situations, where, for example, rescue helicopters must be dispatched to remote, hostile landing areas to evacuate troops. Hot climates and high operating altitudes limit the rescue helicopter's performance; during rescue operations, payloads frequently are increased to the point where the helicopter becomes heavily loaded.

Some pilots were found to be much more adept at performing heavily loaded takeoffs than others. As it became apparent that a helicopter could be operated safely at these higher gross weights (i.e., mobility, safety, and utility could be improved) by improving pilot performance under heavily loaded conditions, the following questions were asked. What is the optimal takeoff procedure for a heavily loaded helicopter operating from a confined area? What is the good pilot doing that the others are not?

In response to these questions, Schmitz,[1,2] using the techniques of modern control theory, determined the optimal takeoff profile for a heavily loaded helicopter. The resulting profile consisted of a maximum acceleration segment parallel to but off the ground, followed by a decelerating climb segment (zoom) in which most of the altitude was gained. Unfortunately, the maneuver was too complex to be operationally useful. It required extreme piloting skill and accurate determination of many uninstrumented variables. To simplify the problem, decelerating flight was prohibited. This constrained, optimal control problem was reformulated and solved in Ref. 2, yielding a distinct two-segment takeoff trajectory (Fig. 2). The maneuver began by accelerating parallel to the ground, in ground effect, to a specified rotation speed. At the specified speed, all excess power was used to rotate and climb over the obstacle. During the climbout segment, velocity was held constant at the rotation speed. Some takeoff performance was sacrificed by constraining the solution, but the maneuver was extremely simple and easy to perform. The only unknown was the switching velocity, which was thought to be a function of gross weight, density altitude, temperature, obstacle height, and excess power. The basic solution was simple enough to warrant a careful investigation into the problems of developing takeoff aids for improving pilot and vehicle performance.

A study was undertaken to validate the theory presented in Ref. 1 and 2 by comparing it with existing flight test data.[3,4] In addition, a sensitivity analysis of takeoff performance to measurable performance variables was carried out. A preliminary report[5] indicated that the entire near-optimal maneuver could be reduced further into a very simple procedure, requiring little or no additional instrumentation. This paper details the results of the preceding work and of specially conducted flight tests verifying the usefulness and validity of the takeoff control policy.

Dynamic Performance Model

The dynamic performance of a heavily loaded helicopter operating in ground effect can be formulated, from simple momentum theory, in terms of the following power balance equation

$$P_a+\delta\nu_0-P_t-P_p-\nu_0-\frac{\partial\lambda_H}{\partial\alpha}D-\frac{\partial\lambda_H}{\partial\alpha}W\gamma$$

$$=\frac{\partial\lambda_H}{\partial\gamma}m\frac{dv}{dt}+\frac{\partial P}{\partial T}V\frac{d\gamma}{dt} \tag{1}$$

where

P_a = available engine power

$\delta\nu_0$ = increase in effective power due to ground effect

P_t = tail rotor power

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Index categories: VTOL Flight Operations; VTOL Handling, Stability, and Control; Aircraft Performance.

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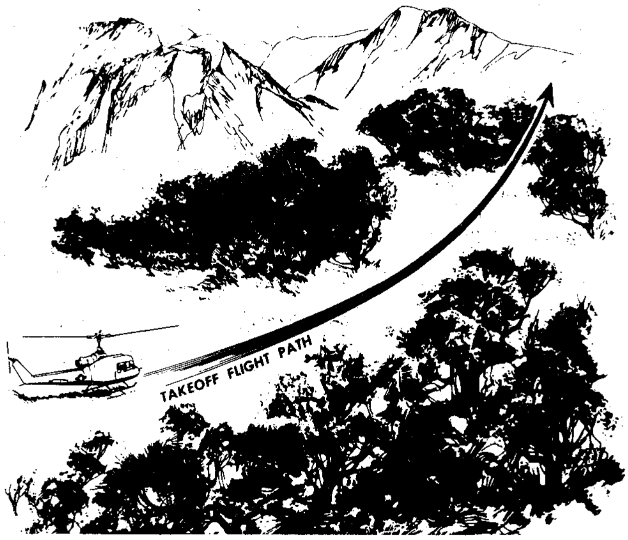

Fig. 1 Heavily loaded takeoff from a restricted area.

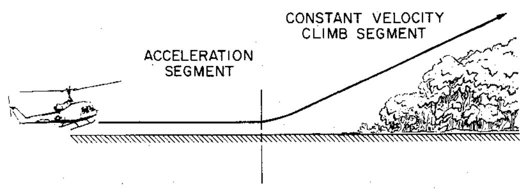

Fig. 2 Typical near-optimal takeoff trajectory.

P_p = profile power

ν_0 = induced power

$(\partial\lambda_H/\partial\alpha)D$ = parasite drag power

$(\partial\lambda_H/\partial\alpha)W\gamma$ = climb power

and the two terms on the right-hand side are power required to accelerate parallel and normal to the flight path, respectively. A complete derivation of Eq. (1) can be found in Ref. 1 or 2. In this paper, the physical implications of the resulting performance tradeoffs will be emphasized to help explain the significance of several critical parameters.

The first two terms in Eq. (1) are illustrated in Fig. 3. The available engine power shown here is a typical value for the UH-1C helicopter. The lower curves in the same figure represent additional effective power due to ground effect. The benefits of operating close to the ground are illustrated clearly. Near hover, an effective rise in power available results as the downwash impinges upon the ground plane, creating an "air cushion effect." At higher forward velocities, the rotor behaves as a high-aspect-ratio wing, and the power gain due to ground effect approaches some small nonzero value. The data points in Fig. 3 were taken by the U.S. Army Aviation Experimental Flight Activity (AAEFA) in a special test program conducted to help confirm the validity of the ground

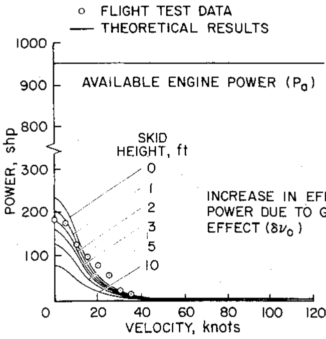

Fig. 3 Available engine power and effective increase in available power due to ground effect as a function of velocity (weight = 9170 lb, density altitude = 1780 ft).

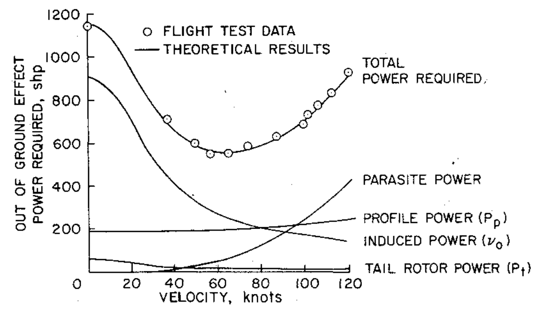

Fig. 4 Shaft horsepower required as a function of velocity (weight = 9170 lb, density altitude = 1780 ft).

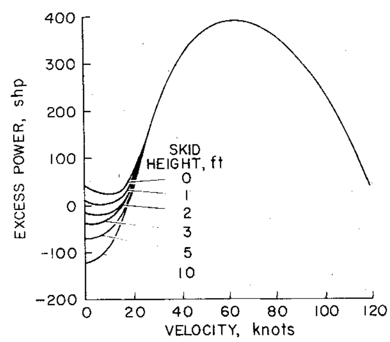

Fig. 5 Excess power available as a function of forward speed and skid height (weight = 9170 lb, density altitude = 1780 ft).

effect equation. The sum of these two source terms is the total effective power available in ground effect. The remainder of the terms on the left-hand side of Eq. (1) represent the power required to maintain level, steady-state flight. They are illustrated, with the exception of the steady-state climb power, in Fig. 4.

The parasite and profile powers represent the energy required to propel the fuselage and nonlifting rotor through the air; the induced power represents the energy expended to maintain lift; the tail rotor power is the energy required to conteract the main rotor torque. Again, the sum of these four

Table 1 Summary of flight test conditions

Test conditions			Excess power		
Gross weight lb	Density altitude ft	Ambient temperature °C	ΔC_p	Maximum sustained hovering skid height, ft	ΔN_l %
7430	10,650	1.46	2.49×10^{-5}	4.0	1.41
7590	9,525	-5.23	4.40×10^{-5}	6.3	2.56
7230	9,599	-4.16	7.09×10^{-5}	15.1	4.11

terms is the power required to maintain steady, level flight. The symbols also are from AAEFA performance tests.[3]

The difference between the power available (Fig. 3) and the power required (Fig. 4) is the power the pilot has to climb, accelerate, or maneuver. This differential, or "excess power," is shown in Fig. 5 as a function of forward speed. The excess power is observed to increase rapidly with forward speed, because of the dropoff of the induced power required. As parasite drag becomes significant, the excess power peaks and begins to fall off. At very low forward speeds, the excess power available is a function of the rotor height (shown in Fig. 5 as variations in skid height) above the ground. The pilot's problem in executing a maximum performance takeoff is to use this excess power in tost effective manner to clear any obstacles in this departure path.

Experimental Verification of the Model

Before exploring the sensitivity of the near-optimal takeoff trajectory to parametric variations, the validity of the performance model [Eq. (1)] was checked quantitatively. Fortunately, flight test data already existed.[3] The documented flight test profiles began with a stabilized 2-ft hover and a specified excess power coefficient ΔC_p. The pilot accelerated at the 2-ft height (± 0.5 ft) until 2 to 5 knots below a chosen rotation speed. He then began to rotate the helicopter, simultaneously reducing acceleration to zero at the desired velocity, and then maintained a steady-state climb angle until the imaginary 50-ft obstacle was cleared.

The near-optimal takeoff and the flight test profiles are quite similar. Both trajectories are essentially two-segment maneuvers: a maximum acceleration segment and a climbout segment. Only the second segments differ to any degree. During the second segment of the near-optimal maneuver, velocity remains constant as the aircraft is rotated to the steady-state climb angle. In the flight tests, rotation and climb began before the desired climbout speed was attained. The maneuvers were considered sufficiently similar that the test data were used to check the validity of the performance model.

Figure 6 compares the data generated by the theoretical performance model (solid curves) with the flight test data (symbols) of Ref. 3. The distance to clear a 50-ft obstacle is plotted against rotation speed for three excess power conditions. Table 1 lists the operating parameters of each power condition. Considering the accuracy with which this type of flight test data can be gathered, the correlation between the data and the performance model was judged very good. At almost all combinations of excess power and rotation velocity, the performance model slightly underestimated the test results, as might be expected. (In the flight tests, rotation and climb commenced before the near-optimal rotation speed was attained.) In the low-power tests, the accuracy of the data becomes very critical, since errors are integrated over a long takeoff time. The following paragraphs show that the discrepancies between the theoretical model and the test data are probably within the accuracy of the testing and data-gathering techniques of Ref. 3.

Table 1 also lists three alternative indicators of excess power: excess power coefficient ΔC_p, excess percentage of turbine speed, ΔN_I, and maximum sustained hovering skid height. The excess power coefficient is the difference between nondimensionalized engine power capability and engine power output at a sustained hovering skid height. This coefficient often is used by engineers to parameterize takeoff flight test data.[3] Because turbine speed N_I is a direct estimate of available power, a pilot can compare turbine speed at a sustained hovering height with the "certified" maximum to estimate excess power. Another estimate of power available is obtained by measuring the maximum sustained hovering skid height. This measure of excess power automatically accounts for variations in density, gross weight, and engine operating condition. As shown later, near-optimal takeoff distances can

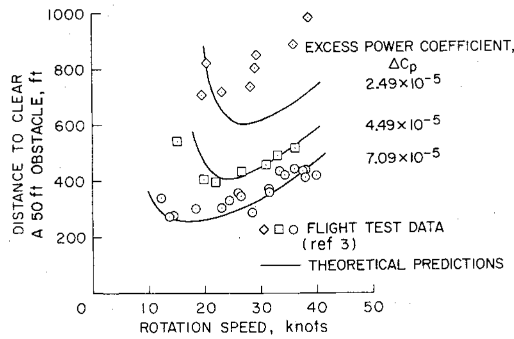

Fig. 6 Distance to clear a 50-ft obstacle, as a function of excess power and rotation velocity.

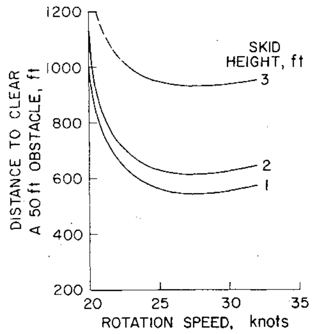

Fig. 7 Takeoff distance as a function of skid height during acceleration (weight = 7430 lb, density altitude. 10,650 ft, maximum sustained hovering skid height = 4.0 ft.).

be estimated quite easily if excess power is measured by this latter technique. Notice that high sustained hovering heights are synonymous with large excess powers and relatively small takeoff distances.

Parametric and Control Sensitivity

Excess power and rotation speed have an important effect on takeoff distance (Fig. 6). As expected, lowering the excess power dramatically increases takeoff distances. For example, if a ΔC_p of 2.0 were used in the performance model instead of 2.49, for the same density altitude and gross weight conditions the predicted takeoff distance would extend 800 ft. Rotation or climbout velocity is also a sensitive takeoff parameter. If rotation and climbout occur at other than the optimal climbout velocity, takeoff distance increases. The increase is most dramatic at velocities less than the optimal, where the induced power is still relatively high and the excess power is nearly minimal (Fig. 5). At this point, only a shallow climb angle can be maintained. At higher rotation speeds, the excess power goes up and much steeper angles are possible, but some of the advantage of the higher climb angle is offset by a longer acceleration distance. If the optimal rotation speed is exceeded, the takeoff distance begins to lengthen because of the excessive acceleration distance. The increase, however, is not dramatic.

The effect of acceleration height on takeoff distance is illustrated in Fig. 7. Utilizing the excess power to increase hovering skid height from 2 to 3 ft decreases ground effect power by approximately 30%. This decrease in effective power available increases takeoff distance by 300 ft if the 3-ft skid height is maintained during the acceleration segment. Wind also can cause large variations in takeoff distance, as shown in Fig. 8. Headwinds significantly reduce takeoff distance, whereas tailwinds do the opposite.

It quickly becomes obvious that the level of accuracy with which flight test data can be obtained could account for the small discrepancies between the distances recorded during the tests and those predicted theoretically. Ambient wind effects and inaccurate holding of skid height during acceleration

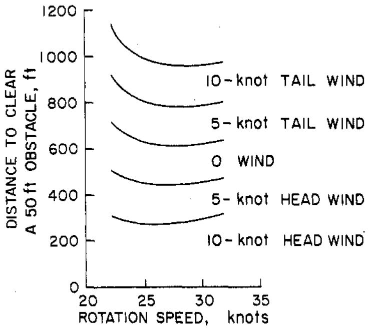

Fig. 8 Takeoff distance as a function of wind (weight = 7430 lb, density altitude = 10,650 ft, maximum sustained hovering skid height = 4.0 ft).

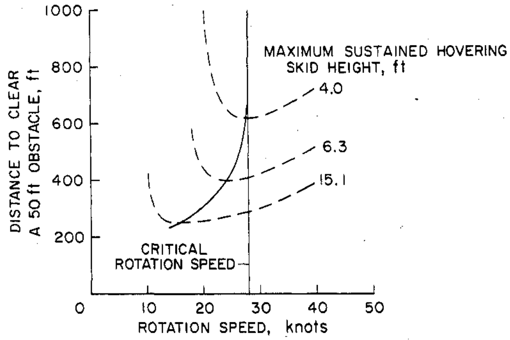

Fig. 9 Critical rotation speed for the UH-1C.

could produce significant variations in takeoff distance. In addition, the takeoff profiles that were flown in the flight tests were not near-optimal trajectories in the strictest sense, but were approximations. With these facts in mind, the performance model is believed very satisfactory.

Critical Rotation Speed

The data of Fig. 6 suggest that takeoff distances are relatively insensitive to climbout velocity if that climbout velocity is larger than a certain minimum value. This same figure is replotted below; the minimum distance and corresponding optimum rotation velocity are indicated for three maximum sustained hovering skid heights.

The locus of the optimum rotation velocities asymptotically approaches a maximum (28 knots for the UH-1C) as the excess power approaches zero. (Maximum sustained hovering skid height approaches 2 ft.) This asymptotic value is defined as the "critical" rotation speed. Accelerating to velocities greater or equal to the critical value, the pilot is assured of exceeding the optimal rotation speed under the prevailing conditions. The harsh penalty in takeoff distance that occurs when rotation and climb are initiated at less than optimal rotation speeds is always avoided. Although takeoff distance may be extended by accelerating past the optimal velocity, the penalty is not as great as rotating too soon. In addition, at the higher climbout velocities, the pilot can trade kinetic for potential energy as the obstacle approaches, thus reducing the sensitivity of takeoff distance to deviations from the near-optimal policy.

Figures 7-9 show that the critical rotation speed is insensitive to variations in excess power, acceleration height, and wind, as well as variations in density altitude and ambient temperature. In all cases, climbing out at the critical rotation speed nearly maximizes takeoff performance.

Figure 10 illustrates the variation of takeoff distance and corresponding rotation velocities for several obstacle heights. Note that the best rotation speed increases slightly as the height of the obstacle increases. In the limit, as the obstacle becomes very large, the critical rotation speed asymptotically approaches the best climb angle velocity (40 knots for the UH-

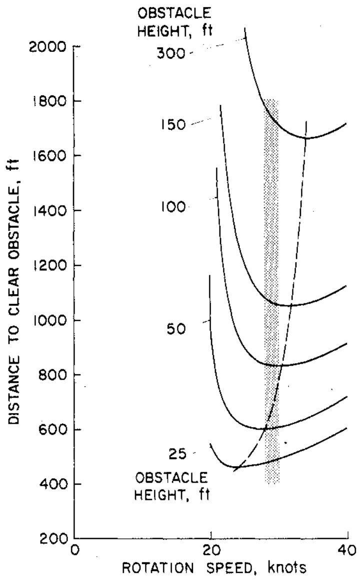

Fig. 10 Takeoff distance as a function of obstacle height and rotation speed (weight = 7430 lb, density altitude = 10,650 ft, maximum sustained hovering skid height = 4.0 ft).

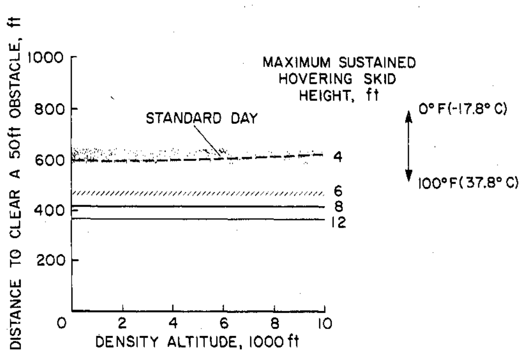

Fig. 11 Distance to clear a 50-ft obstacle using near-optimal technique (UH-1C).

1C helicopter). Generally, most areas are surrounded by obstacles 25 to 100 ft high. Over this range, a 28-knot rotation speed yields near-optimal takeoff performance under all heavily loaded conditions.

Estimating Takeoff Distance

One of the most difficult decisions a pilot has to make is whether or not to chance taking off from a restricted area under heavily loaded conditions. He must decide, usually on the spur of the moment, whether he has sufficient excess power to clear the obstacles in his departure path. Theoretically, he should consider the height of the obstacle, direction and magnitude of the relative wind, density altitude, the helicopter's excess power, and gross weight. With this information, the distance required to clear a particular obstacle can be predicted accurately. However, in most operational situations, the data necessary for such a calculation are difficult to quantify, making it impossible to predict takeoff distance accurately.

The current technique used by Army pilots to determine whether a safe takeoff can be initiated is to measure turbine speed N_I at a 2-ft hover and consult a "go-no go" placard, which relates this estimate of power to the helicopter's maximum power capability $N_{I_{max}}$ corrected for local ambient temperature. Because the placard has been configured to yield a conservative estimate of takeoff capability, a 3% ΔN_I ($N_{I_{max}}$—N_I) is required before heavily loaded takeoffs are to be attempted. As seen from Table 1 and Fig. 6, 3% ΔN_I represents a relatively large amount of excess power. In an

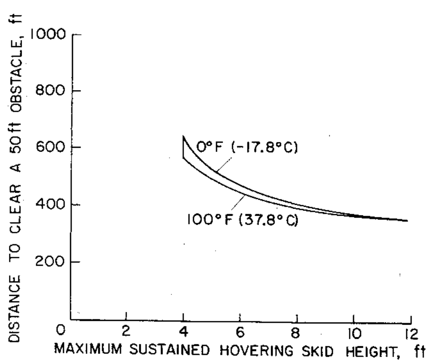

Fig. 12 Distance to clear a 50-ft obstacle using near-optimal technique (UH-1C).

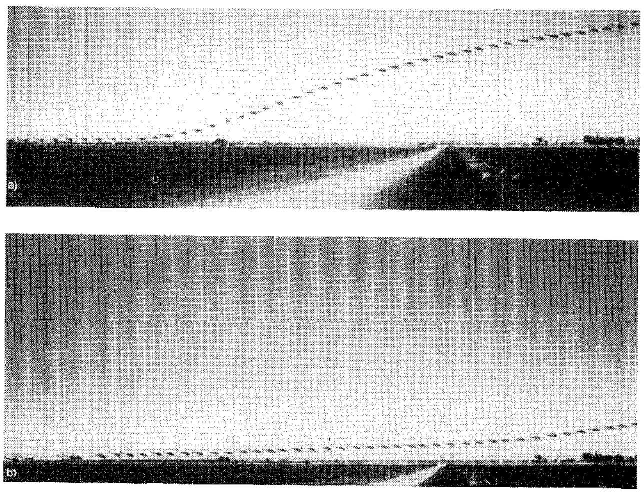

Fig. 13 Comparison of near-optimal and coordinated climb techniques: a) takeoff using the near-optimal level acceleration technique; b) takeoff using the coordinated climb technique.

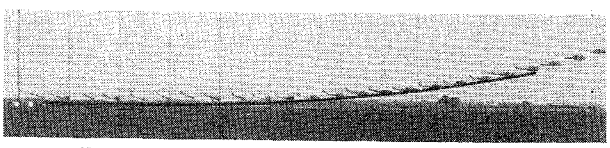

Fig. 14 Initial segment of takeoff trajectory.

open area, the pilot would have little trouble performing a coordinated climb takeoff. However, in a confined area, no guarantee of clearing obstacles in the departure path is made. In fact, under ideal conditions, takeoff distance to clear an obstacle of fixed height depends upon engine operating condition, density altitude, and piloting technique. Near-optimal takeoff profiles minimize takeoff distance, but estimates of actual takeoff distance are not uniquely related to ΔN_I.

In practical situations, excess powers on the order of 3% ΔN_I are not always possible. However, heavily loaded takeoffs from a confined area still may be required. Through experience, many pilots have learned to correlate heavily loaded takeoff performance capability with maximum sustained hovering skid height. Because maximum skid height in hover accounts for variations in density altitude, gross weight, and excess power, it is a natural indicator of takeoff performance.

Figure 11 shows the distance required to clear a 50-ft obstacle as a function of density altitude and temperature for several maximum sustained hovering skid heights using the near-optimal takeoff technique. The resulting curves, which are functions of ambient temperature, are most sensitive to temperature changes at small hovering skid heights. Measuring the maximum sustained hovering skid height eliminates the use of density altitude and gross weight in estimating takeoff distances.

The same data are replotted in Fig. 12 in a more operationally useful form. The maximum and minimum takeoff distances for temperature variations of 0° to 100°F indicated in Fig. 11 are plotted against hovering skid height to yield a simple, banded curve. By determining maximum hovering skid height and then referring to this one plot, a pilot can estimate his near-optimal takeoff distance over a 50-ft obstacle, under no-wind conditions. This information, with the pilot's experience and judgement, can help the pilot decide whether or not takeoff should be attempted.

Comparison with Standard Technique

The Army recommends the coordinated climb technique when making heavily loaded takeoffs from a confined area. To compare that technique with the near-optimal technique, a simple flight test was performed using a UH-1B loaded with lead brick so that it could sustain a maximum hovering skid height of about 5 ft. Pilots were instructed to fly a sequence of takeoffs, alternating between the two techniques. A 16-mm movie camera and a Fairchild Motion Analyzer Camera were used to record the takeoffs. The dramatic difference between the two control policies is shown graphically in Fig. 13.

When the near-optimal technique is used, the distance required to clear an imaginary 50-ft obstacle was less than one-half that required by the conventional technique. Figure 14 is an enlargement of the first part of a near-optimal takeoff. The superimposed curve is the profile predicted by the mathematical performance model. At the end of the overlaid curve, the ship would be clearing the imaginary obstacle. Such excellent correlation is probably fortuitous; generally, the correlation found in Fig. 6 is more likely. Of importance is the fact that the profile shapes are very close.

Comments

As previously observed, many "good" helicopter pilots have learned, by experience, to minimize takeoff distance when their helicopter was heavily loaded. An interesting question now is, why haven't more pilots learned this technique? Some possible explanations can be found by referring to Figs. 15 and 16, which diagram both takeoff trajectories.

The coordinated climb technique (Fig. 15) usually is initiated from a 2-ft steady-state hover. The takeoff begins when the pilot simultaneously applies full power and horizontally accelerates, maintaining a constant 2-ft height above the ground. At the inception of "translational lift" (10-15 knots for the UH-1C), a nose-up pitching moment causes the tip-path-plane of the helicopter to rotate, initiating the climb segment. A 40-knot flight attitude is assumed as the vehicle accelerates and climbs out at full power.

The resulting maneuver is similar to a normal acceleration and climb profile used for standard takeoffs. In both cases, the pilot coordinates his controls following the natural tendency of the helicopter to climb at the inception of translational lift, enough forward cyclic is applied to counteract reasons for the continued use of the coordinated climb technique under heavily loaded conditions.

The beginning stages of the near-optimal takeoff profile (Fig. 16) are similar to the coordinated climb technique for heavily loaded helicopters. The helicopter initially is brought to a 2-ft hover. The maneuver commences when all available power is utilized to accelerate the helicopter horizontally at constant 2-ft height. However, at the inception of translational lift, enough forward cyclic is applied to counteract the nose-up pitching moment and maintain the 2-ft acceleration height. The helicopter continues to accelerate in ground effect at full power to higher forward airspeeds, where additional effective power is available. At the critical rotation speed (28 knots), the helicopter is rotated. Climbout is performed at constant velocity at full power.

The distinguishing feature of the near-optimal takeoff profile is the forward cyclic control at the inception of trans-

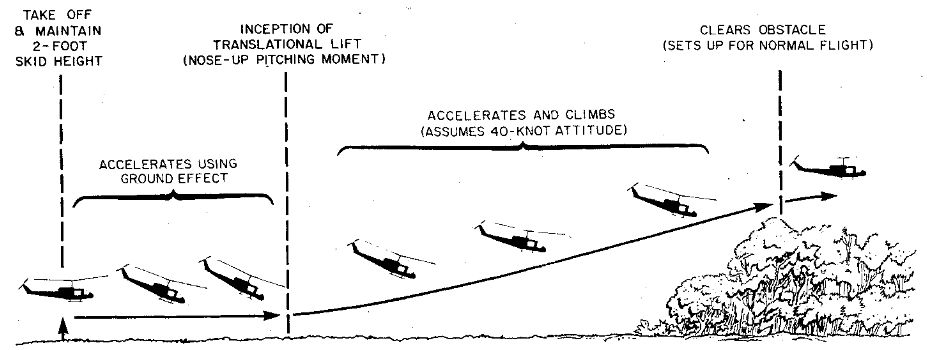

Fig. 15 Coordinated climb takeoff technique.

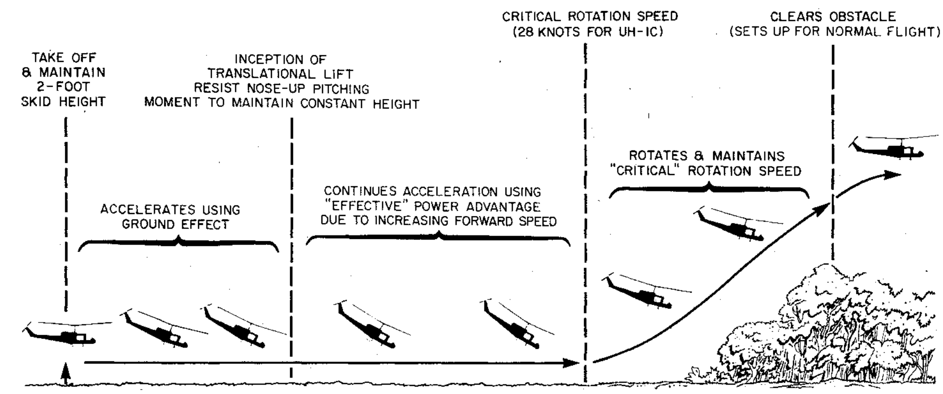

Fig. 16 Near-optimal takeoff technique.

lational lift. The helicopter is forced to use all available power to accelerate to higher translational velocities before steady-state climb is initiated. Upon analysis, the resulting maneuver appears quite obvious. Advantage is taken of the large excess power available at higher forward velocities to establish a larger steady-state climb angle. To the pilot flying the helicopter, this may not look like the "best" maneuver. He is asked to accelerate to higher airspeeds toward the obstacle he is to clear and to resist the natural tendency of the helicopter to fly at the inception of translational lift.

The authors have been passengers on many simulated, heavily loaded takeoffs. (Heavily loaded conditions were simulated by arbitrarily limiting the collective control to correspond to some maximum in ground effect hovering skid height. Takeoffs then were flown by utilizing this collective setting.) In most cases, when operational pilots were asked to perform a simulated, heavily loaded takeoff, they flew a variation of the coordinated climb technique. However, after some verbal instructions and very little practice, they were able to improve their takeoff performance substantially. After further practice, pilots agreed that the simple, near-optimal takeoff profile yielded the best heavily loaded takeoff performance from a restricted area.

Conclusions

The work reported in this paper summarizes several related, but somewhat independent, research accomplishments since the heavily loaded takeoff problem first was identified. Some of the important and necessary technical results are: 1) the development of a practical algorithm for the solution of helicopter optimal control problems; 2) the application of that algorithm to yield optimum takeoff trajectories; 3) the development and experimental verification of the heavily loaded dynamic performance model; 4) the identification of the near-optimal takeoff trajectory; and 5) the analysis demonstrating the sensitivity of the near-optimal profile to parametric variations. However, the major significance of this research lies in its application to solve conclusively the real problem of operating heavily loaded helicopters in restricted areas. In this context, there are two major findings.

1) A simple, near-optimal takeoff control policy has been developed for heavily loaded helicopters operating from a restricted area. The maneuver consists of two distinct operational segments: a maximum acceleration segment and a climb segment. Rotation and climb commence at the "critical" rotation speed, which is dependent upon the type of helicopter but is independent of operation conditions. Near-optimal takeoff performance is assured if the simple, two-segment maneuver is employed.

2) A means has been presented for estimating the distance a given helicopter needs to clear a 50-ft obstacle. This estimate is dependent only upon the maximum steady-state hovering height capability of the helicopter. Devising a simple graphic chart that contained this information and installing it in current aircraft would significantly aid every pilot who makes heavily loaded takeoffs.

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