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Safety Considerations for Helicopter Roll on Takeoffs

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A six-degree-of-freedom simulation of helicopter roll on takeoff is used for evaluation of a twin-engine helicopter continued takeoff trajectory, following one engine failure. For this study, an AH-64A Apache was used. The simulation is used for the determination of the required runway length that will enable safe continued takeoff using the remaining engine's power. A preliminary optimization was carried out for the definition of the liftoff airspeed and critical decision point height that minimize the required runway length.

Nomenclature

H_{CDP}	=	critical decision point height
H_P	=	pilot biodynamic model transfer function
K_G	=	ground effect factor
P_{GR}	=	all-engines-operating power used during ground roll
P_{OEI}	=	one-engine-inoperative contingency power
P_{TO}	=	maximum takeoff power
s	=	Laplace frequency variable
T_I, T_L, T_N, τ_P	=	pilot biodynamic model time constants
V_{CDP}	=	airspeed at critical decision point
V_{LO}	=	liftoff airspeed
V_{MIN}	=	minimum airspeed at which one-engine-inoperative level flight is possible
V_Y	=	best rate of climb airspeed
X_{CTO}	=	continued takeoff distance
X_{LO}	=	liftoff distance (distance for attaining wheel height of 1 ft)
X_{RTO}	=	rejected takeoff distance
X_{TO}	=	takeoff distance (distance required for attaining wheel height of 50 ft)

I. Introduction

HELICOPTER takeoffs are usually initiated from hover out of ground effect (OGE). When operated under heavily loaded (HLD) conditions (a combination of high gross weights, pressure altitudes, and ambient temperatures), helicopter performance is degraded down to a point where takeoff OGE is no longer possible. Under such conditions, takeoff is performed by either one of the following two techniques: 1) takeoff by acceleration from an in ground effect (IGE) hover or 2) roll on takeoff.

Both techniques take advantage of the reduction in torque (power) required by the helicopter as it accelerates from hover to forward flight. Hence, under HLD conditions, it is possible to accelerate horizontally until the flight speed [for short takeoff and landing (STOL)] or rolling speed (for a roll on takeoff) becomes sufficiently high to enable flight OGE.

In case an engine failure occurs during takeoff, the Federal Aviation Administration (FAA) regulations [1] require category A (large multiengine) helicopters to be able to either continue the takeoff (CTO) with the remaining engine(s) using the contingency power ratings or reject (abort) the takeoff (RTO). A critical decision point (CDP) is usually defined in terms of wheel height above the runway surface H_{CDP} and airspeed V_{CDP}, where the takeoff should be aborted if an engine fails before arriving at the CDP, and it should be continued if failure happens past that point. Takeoff distance is therefore the sum of the all-engines-operating (AEO) segment and the continued takeoff (CTO) segment lengths.

Figure 1 schematically demonstrates the helicopter trajectories for CTOs and rejected takeoffs (RTOs) according to FAA regulations for category A operations. The use of these regulations guarantees a safe operation with zero exposure time throughout the helicopter operating envelope.

Various investigations have been performed for category A helicopter takeoffs and landings. These investigations are considered takeoffs initiated from a hover IGE. Cerbe and Reichert [2] used a simple point of mass model and conducted an optimization of the CDP for a BO-105 helicopter. This work showed that, by using a numerical optimization, a preliminary definition of the CDP is possible that enables a significant reduction of the flight-test effort required for the definition of its recommended value. Furthermore, this work led to a reduction of the required runway lengths by 30–40% in comparison with those determined by flight tests alone.

Saal and Cole [3] were the first to introduce the concept of a variable CDP, which is dependent on the helicopter's operating conditions. This approach, which was used for the certification process of the Sikorsky S-76B, introduced a greater flexibility in its operation by allowing for a tradeoff between the maximum takeoff weight and the available runway length.

Okuno and Kawachi [4] used a model that accounted for the helicopter's longitudinal dynamics and the engine dynamics and showed that, by using optimal control methods for the determination of the CDP and the initial climb angle, the required runway lengths could be significantly reduced. Their research included the CTO and RTO distances, as well as the balanced field length.

Zhao and Chen [5,6] used a simple point of mass model representative of a UH-60A Blackhawk for a study of the impact of different combinations of takeoff speeds and initial climb angles on the resulting required runway length. They showed that the shortest possible required runway length is achieved when the difference between the takeoff speed and the takeoff safety speed (TOSS) is about 10 kt. They also indicated the tradeoff between the maximum takeoff weight and the available runway length, and they recommended follow-on research using a complete six-degree-of-freedom model of the helicopter.

Swales [7] described the airfield performance flight tests of the EH-101 that were performed as a part of its FAA, Civil Aviation Authority, and Italian civil aviation regulations (RATR-83-3048I) certification process. The flight-test program used a simulation that included a simplified logic for simulating the required maneuvers [STOL, vertical takeoff and landing (VTOL), CTO, and RTO]. After completion of the flight-test sorties and CDP definition, the simulation was tuned to match the flight-test results, and it could later be used for generation of the helicopter airfield performance section of the pilot's manual.

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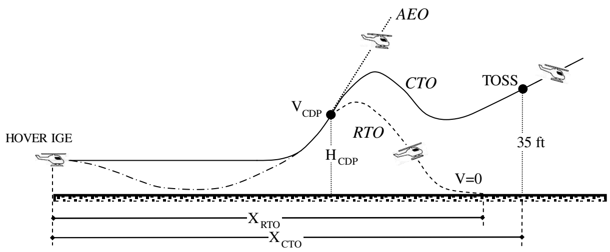


Fig. 1 Category A helicopter STOL procedures.

Several researchers studied VTOLs from helipads, which are characteristic of helicopter operations from very confined places such as rooftops or oil rigs.

In most cases, the researchers did not include a comparison between the numerically calculated trajectories with those from flight tests. When this kind of comparison was performed, a good correlation was observed.

All the efforts described previously did not involve any treatment of roll on takeoff, despite their relevance to some of the helicopters in the research. Furthermore, some of them preferred to use the main rotor thrust magnitude and inclination angle as the control variables rather than using actual pilot control commands for calculation of the forces and moments generated by the main rotor.

To enable the evaluation of rolling takeoff distances, a six-degree-of-freedom simulation has been developed incorporating helicopter and landing gear dynamic models, as well as a rather detailed paper pilot model, which is capable of flying the takeoff process in a variety of changing atmospheric conditions and other parameters. A brief description of the helicopter and landing gear dynamic models is provided (for a detailed description of the simulation, see [8]).

Reference [8] described the results obtained for AEO takeoff in terms of helicopter trajectory, helicopter and landing gear dynamics, and the influence of changes in the takeoff scenario parameters on the takeoff distance. It was demonstrated that, for each combination of helicopter gross weight and runway atmospheric conditions, an optimal liftoff airspeed that minimizes the AEO takeoff distance can be found.

The current paper is aimed at predicting the overall required runway length for a multiengine helicopter roll on takeoff. It is assumed that the takeoff is continued using one-engine-inoperative (OEI) power following one engine failure at the CDP. As no specific directions are given by the relevant military specifications or FAA regulations for the required CTO procedure for roll on takeoffs, Federal Aviation Regulation (FAR) 29 [1] requirements for a CTO (pertaining to takeoffs initiated from hover IGE) were adopted. According to these, following an engine failure, the pilot is required to accelerate the helicopter to the predetermined TOSS, which enables a minimal positive rate of climb of 100 ft/ min to be maintained. The helicopter then continues to climb using the available power of the remaining engine(s). The CTO distance is determined by the point at which all wheels have passed a height of 35 ft above the runway surface, when the helicopter's airspeed is equal to or larger than the TOSS. During the CTO process, the helicopter is required to keep a minimal wheel height of 15 ft, in case the CDP is above this height.

To provide the necessary control commands for the CTO simulation, the paper pilot model described earlier was modified to include a CTO operation mode, in addition to the AEO operation mode demonstrated in [8]. This allows for the study of different aspects of the continued roll-on-takeoff problem, as well as a preliminary optimization of the takeoff technique. The optimization is aimed at minimizing the required field length while maintaining the helicopter's flight safety throughout the takeoff. Rejected roll on takeoffs (which are actually roll on landings) were not included in the current study and are left for future research.

II. Helicopter Model

Roll-on-takeoff dynamics encompasses all of the complexities of airborne helicopter flight as well as the complicating influence of the runway. The helicopter motion relative to the ground governs its landing gear dynamics and determines the forces that the landing gear exerts on the helicopter. The flowfield through the rotor and around the entire fuselage is significantly affected by the well-known ground effect phenomenon. Clearly, ground effect intensity is at its peak when a helicopter is in contact with the runway.

Two sets of equations of motion were developed: one set describes the helicopter's six-degree-of-freedom motion, and the other set describes each landing gear's (left, right, and tail) trailing arm motion.

A helicopter takeoff usually involves relatively slow variations of the state variables (translational velocities and angular rates). Since the present study involves aspects of flight mechanics rather than rotor vibrations or aeroelastic phenomena, a simplified rotor model is adequate for the description of the main and tail rotors during the takeoff process. Thus, a fairly simple blade element model has been developed assuming the following:

1) The blades are attached to the rotor hub by a flap hinge, located at an offset e relative to the rotor shaft. The flapping motion is affected by a linear flap spring and a linear viscous damper (both set to zero for the AH-64A).
2) The blade chord is constant.
3) The blade has a linear pretwist.
4) The two-dimensional lift curve slope is constant.
5) The induced velocity over the rotor disk is uniform, according to Glauert [9].
6) The blades are rigid in bending and torsion.
7) The lead–lag motion of the blades is neglected.
8) All blades are identical.
9) Compressibility, viscosity, and blade stall are neglected. An average (constant) blade drag coefficient is assumed, which accounts for these phenomena.

The main and tail rotors flapping equations are solved, assuming a first harmonic solution. The expressions for the flapping angles are used for obtaining closed-form expressions for the forces and moments that are produced by the rotors. The use of the MAPLE© [10] software allows the derivation of expressions without the need for neglecting low-order terms. Furthermore, it facilitates the incorporation of the resulting expressions in a FORTRAN program.

The interaction between the tail rotor and vertical stabilizer is accounted for by applying corrections to the tail rotor thrust and power, as well as to its wake intensity at the vertical stabilizer.

The ground effect is very important when dealing with takeoffs in cases of low excess power. Its importance is very significant for roll on takeoffs due to the very close proximity of the main rotor to the ground (in comparison with takeoffs that are initiated from hover IGE). It is obvious that roll on takeoff exploits ground effect to its maximum.

Ground effect is usually accounted for by using a ground effect factor K_G that expresses the reduction of the main-rotor-induced velocity IGE. The ground effect model used is the one suggested by Cerbe et al. [11].

Investigation of the roll-on-takeoff problem deals with the low airspeed range. For these low speeds, the intensity of the aerodynamic loads produced by the fuselage and external surfaces is relatively low, thus justifying the use of fairly simple aerodynamic models for these components without introducing excessive inaccuracies in the analysis.

The aerodynamic modeling of the fuselage and external surfaces is mainly based on the U.S. Army's aeronautical design standard (ADS)-10 format [12], which includes simple formulas for the calculation of their aerodynamic coefficients.

ADS-10 [12] modeling of the fuselage aerodynamics does not accurately account for the vertical drag due to the main rotor's wake impinging on the fuselage. This effect is very important, since it leads to degradation in performance, which is especially relevant for scenarios involving limited available engine power. Hence, an approximate vertical drag (download) model has been added to the helicopter model. In addition, since the external surfaces operate at a very wide range of angles of attack, the model was modified by using the method outlined by Prouty [13], which is capable of describing the aerodynamic properties of these surfaces below, at, and beyond the stall angle of attack. The model is adapted to the specific airfoil characteristics of each surface. In addition, the horizontal stablilator and wing aerodynamic models were corrected to include the ground influence by using DATCOM [14].

For the main rotor wake, a simplified model [15] has been adapted, which was developed based on wind-tunnel test results. The wake's swirl is neglected. The calculation of the induced velocity along the main rotor wake was performed using the mathematical model of Menaker and Rosen [16], which was calibrated using the experimental results of [15].

The landing gear configuration assumed is one incorporating a main forward landing gear and a tail landing gear. Each of these combines a trailing arm, shock strut, wheel, and tire. The folding motion of the trailing arm about the cross-tube assembly is induced by the normal force that is applied by the ground on the tire. This folding motion is resisted by the shock strut spring force (created by the compression of gas inside the strut cylinder) and damping force.

The tail wheel, which freely swivels at 360 deg for taxiing and ground handling, is locked by the pilot before takeoff once the helicopter is aligned with the runway centerline. Hence, the tail landing gear model used does not allow swiveling of the tail wheel.

Two kinds of external forces are developed at the contact point between the tire and the runway: normal forces and friction forces. The normal forces can be calculated at any given moment by evaluation of the tires compression, their rates of change, and the use of the tire load deflection curves. The friction forces are calculated assuming a simple Coulomb friction coefficient model between the tire and the runway, which is dependent on the tire's horizontal and lateral groundspeed components.

Each of the landing gear's equations of motion is derived by summation of the pitching moments exerted on the trailing arm axis by the runway and the strut, and their division by the trailing arm's polar moment of inertia, to provide the trailing arm's angular acceleration.

By using the helicopter's center of gravity position and velocity vectors, the calculation of the radii of the tires and their rate of change is performed. These are used for the determination of both the normal reactions and friction forces exerted by the runway on the helicopter. These forces are input into the equations of motion of the trailing arms, as they force these arms to fold. The runway reactions are counteracted by the strut forces that attenuate their transfer to the fuselage. The combined motion of the fuselage and the trailing arms define the wheel tires radii, which in turn respond by delivering updated forces to the fuselage through the landing gears. This complex dynamic system continuously reacts and counteracts until the helicopter becomes airborne and all landing gear reactions disappear.

III. Pilot Model

An AEO roll on takeoff includes the acceleration phase, the rotation and liftoff phase, and the initial climb phase. In the case of a CTO following an engine failure past the CDP, a fourth phase is added that includes the acceleration to the TOSS using the remaining engine's power and the continuation of the climbout up to 35 ft. As explained in [8], the longitudinal-vertical plane of motion is the one of interest for airfield performance simulation; hence, the collective and longitudinal stick commands are of prime importance. However, since all three planes of motion are highly coupled in helicopters, pilot lateral-directional control commands are also required as an input to the simulation due to their effect on the overall power required for the helicopter's flight. The maximum available power of the engines is divided between the main rotor, tail rotor, and accessories, and high tail rotor power requirement (due to excessive pedal commands) leaves less available power for the main rotor to be translated into thrust.

As described earlier, the detailed paper pilot model has been modified to provide the required control commands for the helicopter's CTO under varying operating conditions and problem parameters. This model results in an autonomous takeoff process while maintaining the helicopter within operational limits. Four control channels were designed that provide collective, longitudinal, and lateral cyclic stick and pedal commands to fly the helicopter throughout the entire CTO process. Figure 2 presents a general layout of the human pilot model, which is based on the assumption of a pilot acting as a proportional-integral-derivative (PID) controller, with the aim of reducing the error between a given desired reference signal (airspeed, torque, lateral drift, etc.) and the actual helicopter state. This specific structure was chosen in order to ensure continuous operation of the pilot (controller) directed at achieving the desired reference state (with a zero steady-state error) on the one hand but provide very moderate control commands on the other. This is necessary due to the proximity of the helicopter to the ground and the need to eliminate the possibility of high angular rates and rapid side drifts. The pilot model also includes a biodynamic filter that accounts for the time delay in the pilot's response, as well as the manner in which the pilot's intensions are translated into actual control displacements in the cockpit through the motion of the arms and legs. The biodynamic filter adopted is the one suggested by McCruer and Krendel [17]:

$$H_P(s) = e^{-\tau_P \cdot s} \cdot \frac{T_L \cdot s + 1}{(T_I \cdot s + 1)(T_N \cdot s + 1)} \tag{1}$$

Another part of the control command is initiated by cross coupling the control channels, which was done in order to simulate pilot skills

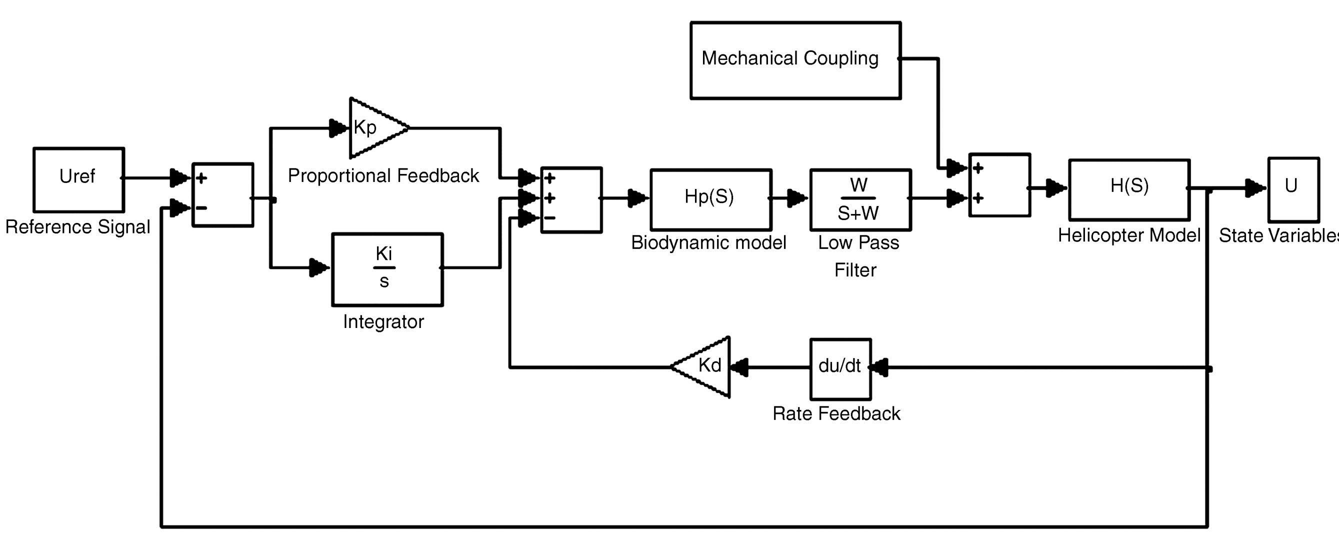


Fig. 2 Human pilot model general layout.

and experience, which are reflected by pilot advanced control commands in anticipation of the helicopter's response.

The control laws of the paper pilot channels are fairly complex and include inner and outer control loops and different kinds of limiters and low pass filters (LPFs). This is demonstrated by Fig. 3, which shows the control diagram of the longitudinal channel of the pilot model. As explained earlier, four similar crosslinked channels were designed for the collective, longitudinal, and lateral cyclic stick and the pedal commands.

The longitudinal control law is essentially a proportional-integral controller, basically aimed at achieving the desired true airspeed by the helicopter. It is augmented by pitch angle and pitch rate feedbacks that eliminate the danger of overtipping the helicopter due to excessive/rapid longitudinal stick commands. A rate of descent (ROD) feedback is introduced, as well as a disturbance compensation channel. The ROD feedback has the important role of keeping the helicopter within moderate rates of descent during the recovery procedure following an engine failure. Before its inclusion in the model, the OEI acceleration to the TOSS following engine failure was generally followed by a rapid descent, which resulted in the minimum wheel height above the runway being very low. This in turn required a long OEI climb back to the CTO termination criterion of a wheel height of 35 ft above the runway. The disturbance compensation channel was designed to provide the capability to cope with scenarios that involve takeoff in the presence of head/tail winds or runway slopes when specific pilot attention to these is required.

Similarly, the vertical (collective command) channel is a PID controller that is essentially designed to achieve the required (commanded) torque and, at the same time, keep the torque overshoots low.

The lateral and directional channels control the lateral stick and pedal commands, respectively. These two control channels are responsible for keeping the helicopter aligned with the runway centerline during all the takeoff segments while providing adequate damping of the yaw and roll rates, especially during the ground roll section. Both these channels are driven by the requirement of providing zero drift relative to the runway centerline by pointing the helicopter's nose and rolling it in the direction countering this drift. Thus, the reference signal to these channels is the helicopter's offset from the runway centerline, which is then translated into the desired roll and yaw fuselage angles. However, for the directional channel, it was observed during the simulations that it is sufficient to use a constant reference signal of zero heading in order for the model to drive the helicopter along the centerline; thus, the outer loop gains of this channel were set to zero. Choosing gains different than zero enables the helicopter to follow a predefined ground trajectory and might be required for future use of the simulation with different helicopter models.

These control laws, as described earlier, were initially developed to simulate a normal AEO roll on takeoff [8] and were later adapted to include a CTO mode as well. Because of the complexity and high nonlinearity of the combined helicopter-landing gear-runway model, a classic transfer function of this plant cannot be easily found. Hence, the common techniques that are used for control law design could not be used here. Furthermore, the design of the pilot model was not the main focus of this effort but rather a means to enable the roll-on-takeoff simulation by providing the necessary control commands. Thus, the determination of the control law gains was achieved using a trial and error approach that relied on simulations of a large number of scenarios and model tuning based on the best engineering judgment. Nevertheless, as will be shown later, the sensitivity of the roll-on-takeoff performance parameters (namely, the CTO distance and the helicopter trajectory) to gain changes were found to be satisfactorily low, as originally expected.

It should be stressed that the resulting model is not necessarily an optimal one, and better models could possibly be developed. The human brain is very complex, and its imitation requires the formulation and modeling of very detailed logics and a complicated decision tree. However, the present, somewhat simplified pilot model is capable of providing the necessary control commands for the helicopter's AEO and CTO segments (including the ground roll, initial climb, recovery maneuver following engine failure, and the OEI climbout). In addition, it is believed that the resulting pilot commands are more representative of the commands that are issued

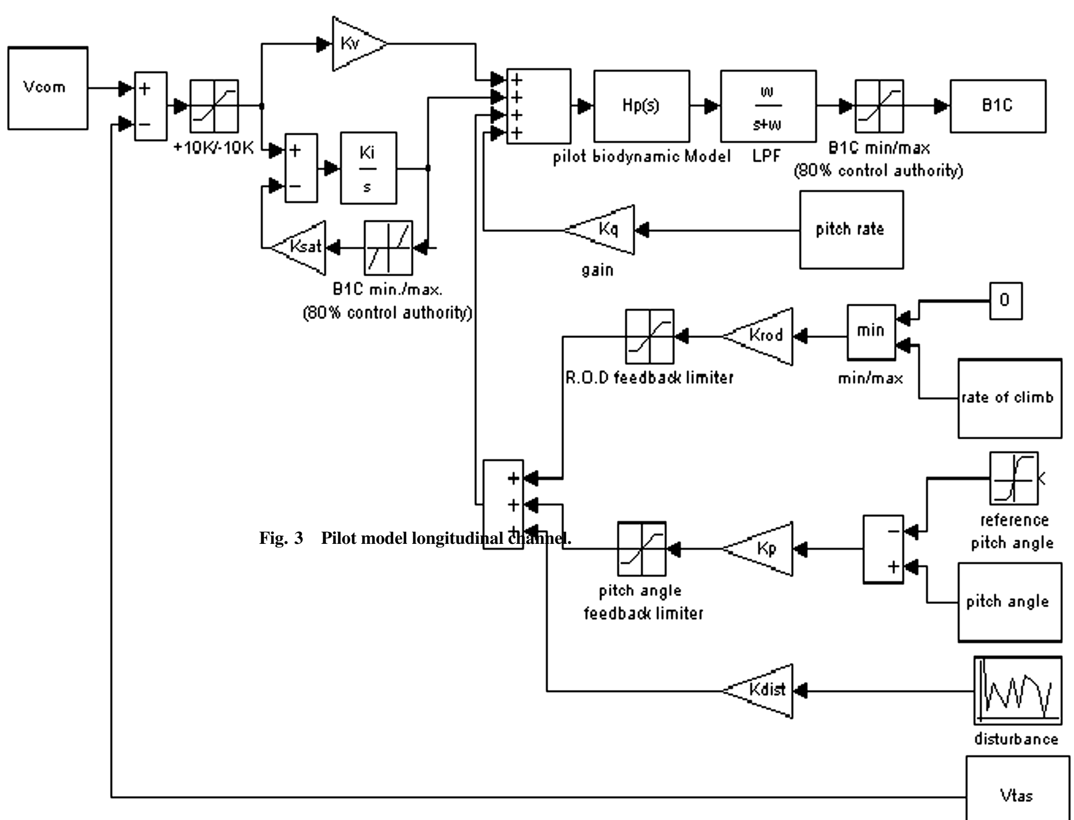


Fig. 3 Pilot model longitudinal channel.

by real pilots, in comparison with commands that are calculated based on optimal control theory and helicopter point mass models. As no reference validation cases could be identified at that time, this observation was enhanced by consulting flight-test pilots.

IV. Definition of Continued Takeoff Procedure

Figure 4 presents the typical AEO and CTO trajectories for helicopter roll on takeoffs. The FAA regulations [1], which were originally developed for takeoffs initiated from IGE hover, were revised in the current study such that the helicopter is initially at rest, and the first segment of the takeoff is a ground roll section. This section ends once the helicopter has reached a predefined liftoff airspeed V_{LO}, and it is followed by an initial AEO climb segment up to the CDP. The CDP is defined in terms of its height above the runway H_{CDP} and the helicopter's true airspeed upon CDP passage V_{CDP}. In [8], the initial climb speed was set to be 3 kt [knots, true airspeed (KTAS)] higher than V_{LO} in order to allow a smooth transition from forward acceleration during the ground roll to a constant airspeed initial climb. For the purpose of the current study, V_{CDP} was set to be equal to the liftoff speed. This was done in order to facilitate the study of the optimal takeoff path, without introducing significant differences in the results obtained.

In a normal AEO takeoff (Fig. 4a), the initial constant airspeed climb continues until all wheels have cleared a height of 50 ft above the runway surface. The takeoff distance is measured from the helicopter's initial position at rest to the point where the 50 ft wheel height was attained.

An engine failure that occurs before crossing the CDP dictates rejecting (aborting) the takeoff (RTO) and performing an emergency landing (touching down during ground roll and bringing the helicopter to a complete stop by using the brakes and controls). RTO procedures were not examined as a part of the current study.

In the event of an engine failure past the CDP, the takeoff is continued. The helicopter is accelerated to its TOSS, in which a minimal rate of climb of 100 ft/ min can be sustained using the contingency power rating of the remaining engine. This power rating is usually limited to a very short time. For the AH-64A Apache (the helicopter used for the current study), which is equipped with T700-GE-701C engines, the OEI contingency power rating can be used up to 2.5 min. After that, the maximum available torque is reduced to the OEI intermediate power rating (30 min limit).

For the CTO, two distinct possibilities exist:

1) The case when $V_{\mathrm{CDP}} \leq$ TOSS (Fig. 4b) requires the rapid acceleration of the helicopter to the TOSS in order to achieve the minimum OEI rate of climb, which will allow continuation of the climbout. During the acceleration, altitude is traded for velocity, a process during which the helicopter descends toward the runway. The minimal wheel height above the ground is limited by FAR 29 [1] to 15 ft (when the CDP is above 15 ft). The CTO ends at the point where all the helicopter's wheels have cleared a height of 35 ft above the runway with an airspeed that is equal to or larger than the takeoff safety speed.

2) When $V_{\mathrm{CDP}} >$ TOSS (Fig. 4c), the helicopter is already flying above the airspeed at which a minimal rate of climb of 100 ft/ min is guaranteed. Accordingly, the climbout is continued using the remaining engine's power while gradually accelerating to V_Y, the airspeed for the best rate of climb. The CTO termination point is again set at a 35 ft wheel height, which is quickly achieved by the helicopter subsequent to liftoff due to its high initial rate of climb.

The CTO scenario in the simulation is defined by the following parameters:

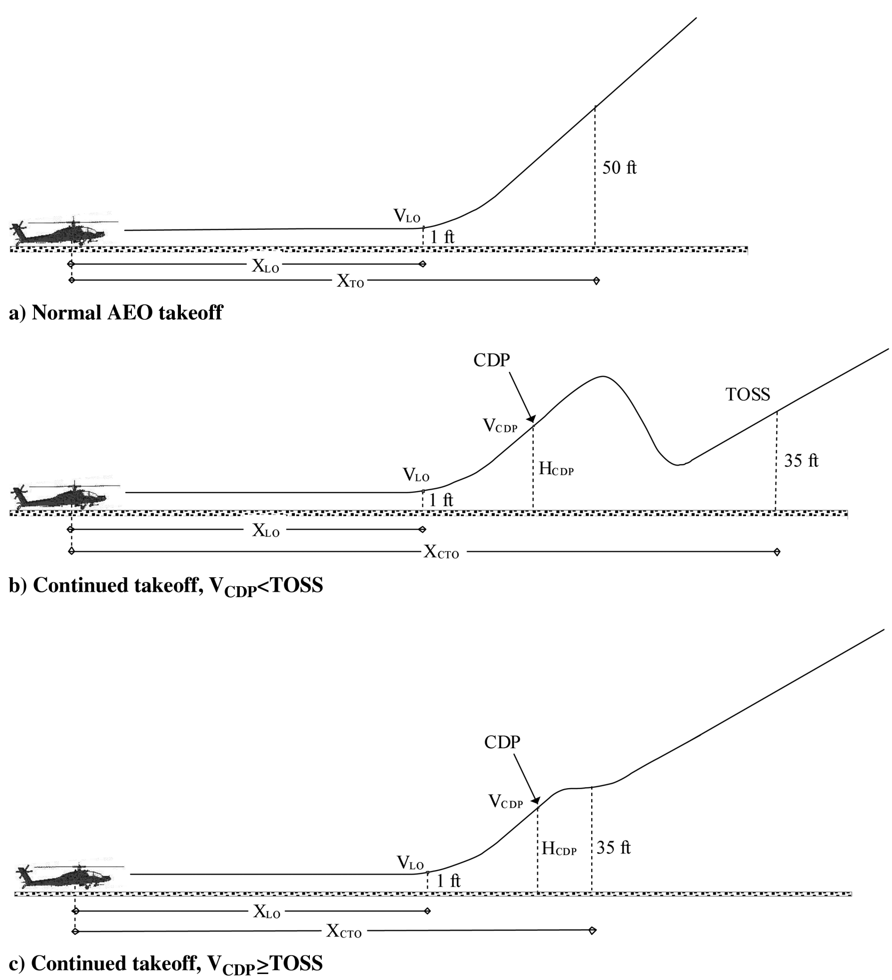


Fig. 4 Typical AEO and CTO trajectories for helicopter roll on takeoffs.

1) P_{GR} is the AEO power used during the ground roll.
2) P_{TO} is the maximum takeoff power used during the liftoff and initial climb segments up to the CDP.
3) P_{OEI} is the OEI contingency power used during the CTO segment (limited to 2.5 min).
4) $V_{LO} = V_{CDP}$ represents the liftoff speed, which is set equal to the initial climb speed and is constant up to crossing of the CDP.
5) H_{CDP} is the CDP height above the runway surface.
6) TOSS is the takeoff safety speed.

P_{TO} and P_{OEI} are determined by the use of the engine performance charts, which are mainly influenced by the airfield's atmospheric conditions (pressure altitude and ambient temperature) and the engines deterioration levels. P_{GR} influences only the ground roll section, and it has no effect on the CTO segment. Therefore, we will consider its value as a preset one (see [8] for details). The TOSS is purely a function of the helicopter's gross weight, configuration, and the ambient conditions. Hence, the liftoff airspeed and the CDP height are the free parameters of the problem.

The piloting commands for the simulation are provided by the control channels described earlier. For the vertical channel, the reference (command) torques are P_{GR}, P_{TO}, and P_{OEI} during the ground roll, takeoff, and CTO section, respectively. Switching between the first two torques is performed once the liftoff airspeed is reached, and a second switching (P_{TO} to P_{OEI}) is performed when the helicopter reaches the CDP.

Similarly, the reference signal for the longitudinal channel is V_{LO} during the ground roll and initial AEO climb section, and it is the TOSS during the CTO section. Here again, switching is done at the CDP.

The paper pilot gains had to be modified in order to allow the model to cope with the event of an engine failure. This is especially important in the case where V_{CDP} is lower than the TOSS, since a rapid forward longitudinal stick command is required in order to quickly initiate the recovery maneuver in which the helicopter is descending while accelerating to this target speed. To this end, the paper pilot model's gains are linearly increasing from the liftoff point up to the arrival at the CDP. This increase is performed as a function of the helicopter's wheel height, since it is obvious that as the height above the runway is increased, piloting commands will gradually become less restrained until a normal free-flight technique (gain) is attained.

For the case of the liftoff speed being higher than the TOSS, FAA regulations [1] call for a moderate acceleration to V_Y, which is combined with the OEI climbout. In this case, the gains in the pilot model had to be reduced in order to preclude its eagerness to provide firm control commands that will initiate a fast acceleration to V_Y through a generous longitudinal cyclic command. Once again, the gains had been programmed to linearly vary with wheel height, from the liftoff point to the CDP. It should be emphasized that the pilot model's gains were primarily set while considering performance and handling qualities during a normal AEO ground roll takeoff, where the runway acts as a restrainer. When the helicopter is airborne this restraining effect vanishes, and the gains have to be reduced in order to maintain a similar moderate aircraft response as that during the ground roll segment.

V. Results

The results are demonstrated for an AH-64A Apache helicopter operating at sea level and standard atmospheric conditions (15°C), with a gross weight of 21,000 lb. For these conditions, the takeoff torque P_{TO} is 100% [which is equivalent to 2828 shaft horsepower (SHP)], the contingency torque limit P_{OEI} is 61% (1725 SHP), and the corresponding TOSS is 61 kt (KTAS). The ground roll torque P_{GR} was set at 50%.

Figures 5a–5n present the simulation results for a CTO with liftoff airspeed of 45 KTAS. The CDP was set 74 ft above the runway. As explained earlier, an engine failure occurring before crossing this point requires the pilot to reject the takeoff and bring the helicopter to a complete stop, whereas an engine failure past it requires the continuation of the takeoff using the remaining engine's contingency power rating. As shown later, setting the CDP at exactly 74 ft produces the minimal required runway length for completing the CTO process.

Figures 5a and 5b show the collective pitch angle and the main transmission torque time histories. At the beginning of the takeoff, the paper pilot model, which constantly provides the control commands throughout the simulation, issues a collective increase command, and the collective is raised until the ground roll torque level (set at 50%) is attained. Once the predetermined liftoff airspeed of 45 KTAS is reached, the collective is raised once again in order to increase the torque level to the maximum takeoff power rating of 100%. When the CDP is crossed, engine failure is assumed; thus, the collective is lowered in order to reduce the torque to the contingency torque rating of 61%, which is maintained during the rest of the simulation.

Figures 5c–5e show the longitudinal cyclic stick command and the resulting true airspeed and pitch angle of the helicopter. During the ground roll section, the longitudinal stick is pushed forward in order to initiate and maintain the helicopter's horizontal acceleration along the runway. To overcome the tip back of the rotor disk as velocity increases, the longitudinal cyclic stick command increases with increasing speed. As the helicopter approaches the liftoff airspeed of 45 KTAS, the pilot model reduces the longitudinal stick command in order to stop the acceleration.

The initial climb section is initiated when the collective is raised, and the helicopter begins its climbout. The increase of the main rotor thrust creates a negative pitching moment; thus, the pitch angle is reduced. It could be observed that the longitudinal stick command time history, which drives the helicopter to be stabilized at the desired airspeed of 45 KTAS, is somewhat oscillatory. However, these oscillations have little effect on the performance parameters, which are of interest. Again, it is emphasized that the main purpose of the simulation is the ability to estimate the AEO and CTO trajectories, where the pilot model is the means of deriving the required control commands for these trajectories.

Once the CDPs is reached, and an engine failure is assumed; the pilot model commands a swift nosedown motion in order to initiate acceleration to the TOSS of 61 KTAS. The sharp pitchdown motion of the fuselage is easily observed, as well as the gradual increase of the pitch angle, as airspeed is gained. As power is limited, this acceleration is followed by a descent, which ends once the TOSS is reached, and the helicopter is trimmed in a steady OEI climb.

Figures 5f and 5g present the (forward) main landing gear and tail landing gear wheel heights above the runway. As explained earlier, past the CDP, the helicopter is rapidly brought by the pilot to an accelerated descent in order to quickly achieve the TOSS. The descent ends at a wheel height of exactly 35 ft above the runway (for this particular example), and the OEI climbout is initiated. It should be emphasized that, in this case, the minimal wheel height is determined by that of the tail wheel (see Fig. 5g), which is slightly lower than the main landing gear wheel height at the lowest point of the trajectory.

In Fig. 5h, the rate of climb is presented with the maximum rate of climb of 1200 ft/ min during the AEO climb segment, −900 ft/ min during the rapid descent while accelerating to the TOSS, and 100 ft/ min (as required by FAR 29 [1]) during the OEI climbout.

Figure 5i shows the horizontal distance covered by the helicopter during the entire takeoff. The liftoff distance is 2100 ft, and it is determined by the point at which all wheels are 1 ft above the runway. CDP crossing is at 2450 ft, and the overall CTO distance (determined by the point at which a wheel height of 35 ft has been attained) is 3600 ft.

Finally, Figs. 5j–5n present the lateral-directional control commands, fuselage roll and yaw angles, and the helicopter's lateral drift from the runway's centerline. It is demonstrated that the model's capability to keep the helicopter well aligned with the runway centerline, even through the airborne segments, is quite good. The somewhat oscillatory control commands during the transition from one segment to the other have, as explained before, little effect on the resulting takeoff performance.

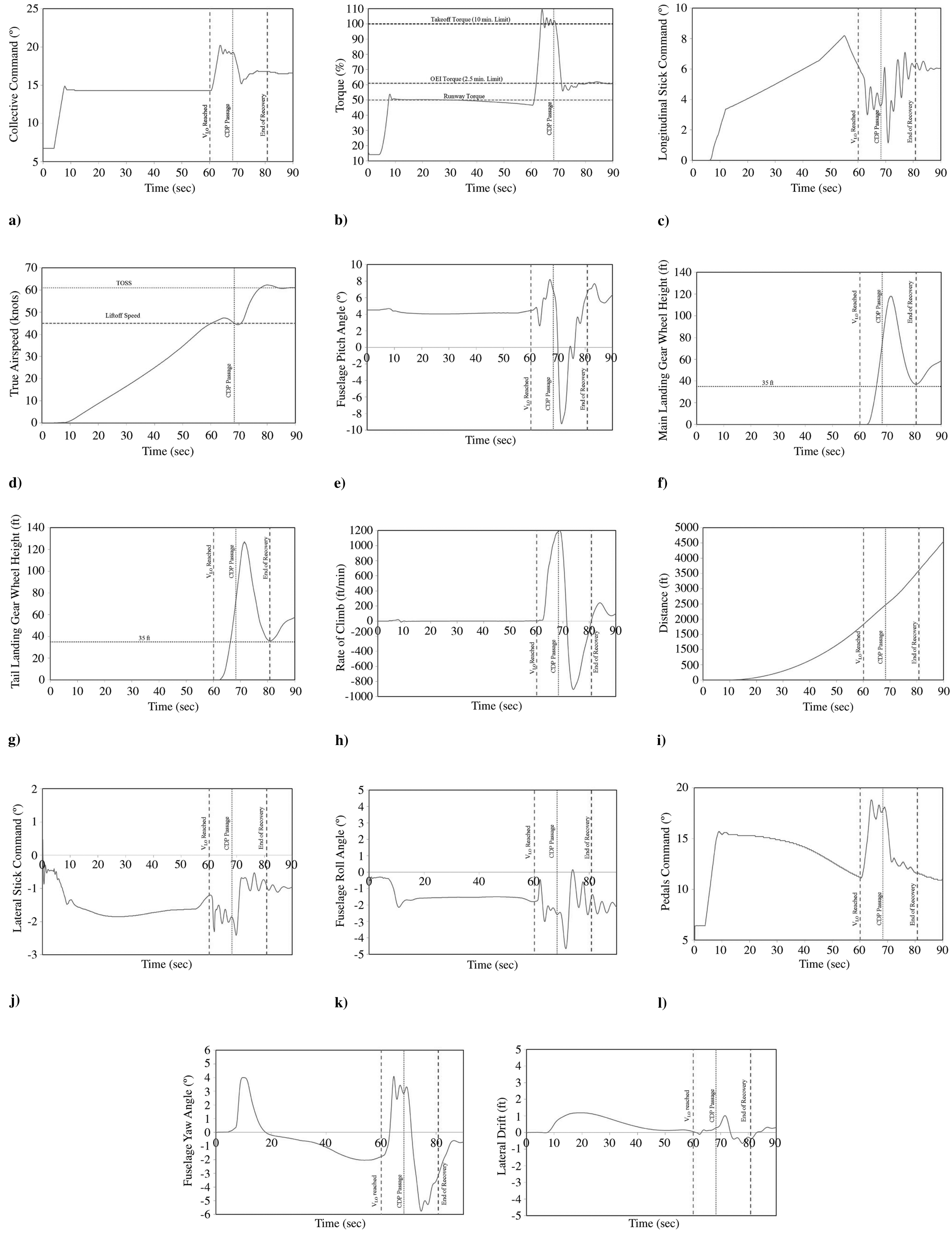


Fig. 5 Continued roll-on-takeoff dynamics for sea level and standard atmospheric conditions (helicopter weight 21,000 lb, liftoff speed 45 KTAS, and CDP height 74 ft).

Table 1 Simulation results of sensitivity to paper pilot gains

	Nominal gains	Reduced (90%) gains		Increased (110%) gains	
	Value	Value	Variations from nominal, %	Value	Variations from nominal, %
Distance, ft	3614	3681	1.85	3465	−4.12
Time, s	80.9	83	2.60	76.7	−5.19
Min. wheel height, ft	34.4	34.8	1.16	34.6	0.58

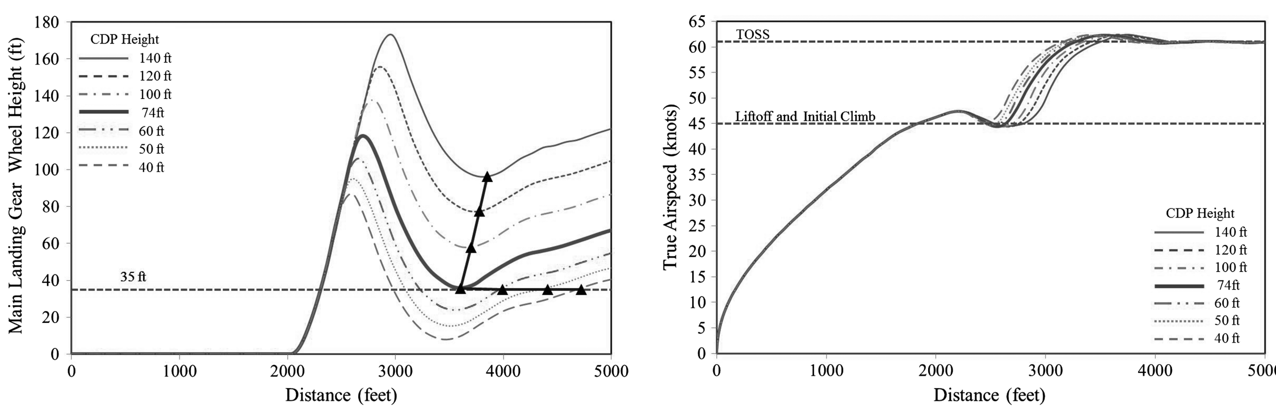
Because of the fact that the pilot model's gains were determined based on a trial and error approach, the question arises as to the influence these values have on the simulation results. To study the model's sensitivity to gain changes, the preceding scenario was rerun by using gains that are 10% lower and 10% higher than the nominal values. All the gains were decreased/increased simultaneously. Table 1 summarizes results of this sensitivity study.

The changes in the most important parameter (the CTO distance) are $-150/+67$ ft. The time required to complete the CTO is changed by $-4.2/+2.1$ s, and the minimal wheel height above the runway during the CTO phase is practically unchanged. An increase of 67 ft (20 m) over the nominal required runway length of 3614 ft (1102 m) is considered very small; thus, it can be concluded that the helicopter performance parameters presented in what follows have very little sensitivity to the pilot model's gains used.

It should be mentioned that the FAR 29 [1] requirement for a minimal wheel height equal to 15 ft (for CDP heights above 15 ft) is not imposed during the simulation. As will be shown in what follows, this requirement is automatically fulfilled by the definition of an optimal CDP.

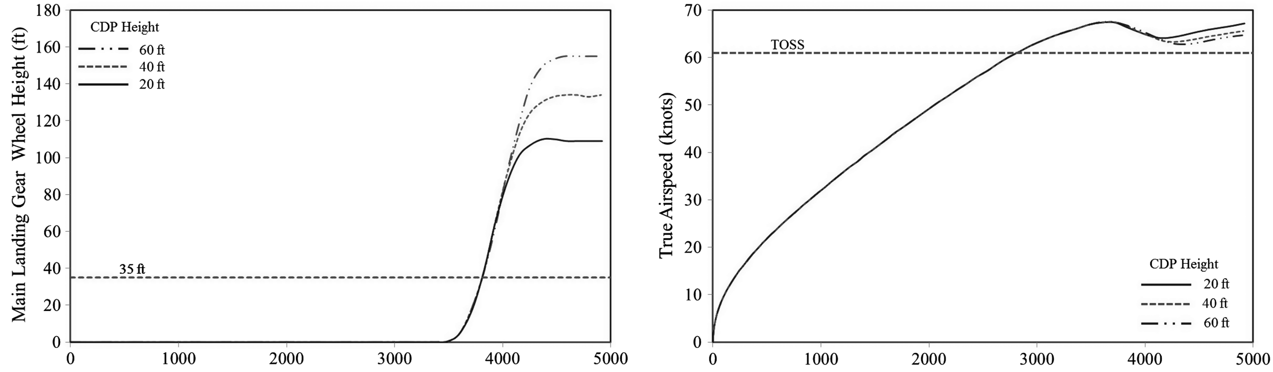
The CDP can be set at a wide range of wheel heights, and it is likely that an optimal CDP can be found, which minimizes the CTO distance. Figures 6a and 6b show the effect of the CDP height on the resulting trajectory and true airspeed of the helicopter. The liftoff airspeed is 45 KTAS, and the CDP heights are varied from 40 to 140 ft. The CTO distance of each trajectory is designated by triangles on the corresponding curve. In all of the cases, the TOSS is reached in proximity to the lowest point of the CTO trajectory, and a constant airspeed climbout is commenced. The CTO distance is determined by the point at which the helicopter clears a height of 35 ft above the runway. For CDP heights that result in CTO trajectories that do not descend below the 35 ft level, the CTO distance is determined by the point at which the TOSS has been attained and a positive rate of climb exists.

It can be easily observed that the minimal CTO distance is achieved when the CDP is chosen such that the lowest point of the trajectory is tangent to the 35 ft wheel height line. Figure 6a shows that setting the CDP at 74 ft results in such a trajectory. Lower CDP heights require the helicopter to climb back to 35 ft, thus requiring a longer distance. Setting the CDP above this height makes the initial AEO climb up to the CDP longer, thus resulting in an increase of the overall CTO distance. As mentioned earlier, the requirement for a minimal trajectory height being higher than 15 ft for the relevant CDPs is instantaneously met by always keeping the helicopter above the CTO termination wheel height criterion of 35 ft.



a) b)

Fig. 6 Influence of CDP height on helicopter CTO trajectory, V_{CDP} < TOSS (helicopter weight 21,000 lb and liftoff speed 45 KTAS).



a) b)

Fig. 7 Influence of CDP height on helicopter CTO trajectory, $V_{CDP} \geq$ TOSS (helicopter weight 21,000 lb and liftoff speed 65 KTAS).

As indicated previously, when the liftoff airspeed is higher than the TOSS, the pilot's response to an engine failure would be much more moderate. For this range of speeds, the helicopter is already flying at an airspeed that provides at least the minimal required climb rate. Hence, the pilot would slowly accelerate to V_Y, the airspeed for the best rate of climb, while continuing to climb using the remaining engine's power. Since the initial rate of climb following the liftoff is high, the helicopter climbs the 35 ft up to the CTO termination point very fast (even if an engine failure occurs immediately after liftoff); thus, the CDP height has a negligible effect on the overall CTO distance. This is demonstrated by Figs. 7a and 7b, which present the helicopter's trajectory and airspeed for CDP heights of 20, 40, and 60 ft. The liftoff airspeed was set at 65 kt (4 kt higher than the TOSS). It is easily observed that, for all cases, the trajectories up to the 35 ft wheel height mark are essentially the same. Thus, it is concluded that for liftoff airspeeds higher than the TOSS, the definition of an optimal CDP is unnecessary. Hence, for the CTO distance calculation for this airspeed range, it is recommended to define the CDP at exactly 35 ft. This would instantaneously lead to compliance with FAR 29 [1] requirements, since at engine failure, the helicopter has already technically completed the recovery maneuver, and it is above the TOSS at the required wheel height of 35 ft.

As could be expected, for liftoff airspeeds higher than the TOSS, the CTO distance grows with the liftoff airspeed. This is demonstrated by Figs. 8a and 8b, which show the CTO trajectory and velocity for liftoff speeds of 65 and 70 KTAS. In this example, the CDP was set 20 ft above the runway. It can be observed that a higher liftoff speed enables a quicker recovery of the acceleration following the engine failure. Thus, the two trajectories become very similar as altitude is gained.

Once an optimal CDP is defined for each liftoff airspeed, an optimal liftoff airspeed can now be chosen such that the resulting CTO distance would be the shortest possible. Figures 9a and 9b present the CTO distance and the optimal CDP height as functions of the liftoff airspeed, respectively. The solid line in these figures shows the results for liftoff airspeeds that are lower than the TOSS where, for each speed, the specific (airspeed dependant) optimal CDP was used. The dashed line shows the results for liftoff airspeeds that are higher than the TOSS, where for all airspeeds, the CDP was set at 35 ft.

For the liftoff airspeed range noted by the shaded area (between 53 kt and the TOSS of 61 kt), the resulting CTO distance is inconclusive when using the existing pilot model. In this liftoff airspeed range, an oscillatory behavior of the helicopter's wheel heights was observed near the lowest trajectory point, making the identification of this point difficult. This is demonstrated in Figs. 10a and 10b, which show the main landing gear and tail landing gear heights, respectively, for liftoff airspeeds of 53 and 56 kt. Hence, in order to be conservative, it is assumed that the CTO distance is constant in this airspeed range. Another key point is the optimal CDP height being very low in this airspeed range, thus being purely theoretical. An engine failure immediately following liftoff will find the helicopter way beyond the CDP, with an airspeed which is very close to the TOSS. The immediate response of the helicopter to the collective increase to the maximum takeoff power rating is the acceleration of the helicopter by 2–3 kt beyond the liftoff airspeed, until the added power is translated to a steady rate of climb. At a liftoff airspeed higher than 53 kt, this would mean that the helicopter's airspeed will be higher than V_{MIN}, the minimum airspeed at which an OEI level flight can be maintained.

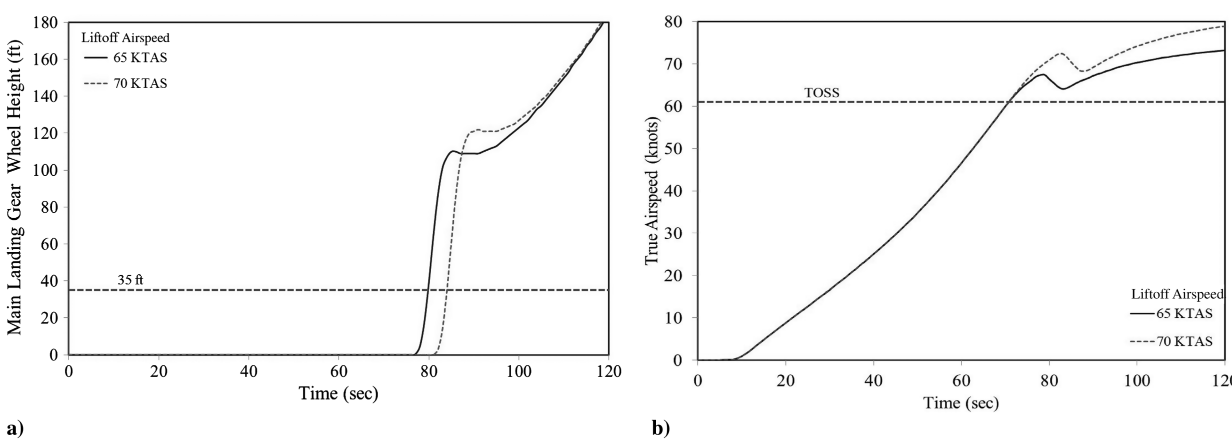


Fig. 8 Influence of liftoff speed on helicopter CTO trajectory, $V_{\mathrm{CDP}} \geq$ TOSS (helicopter weight 21,000 lb and CDP height 20 ft).

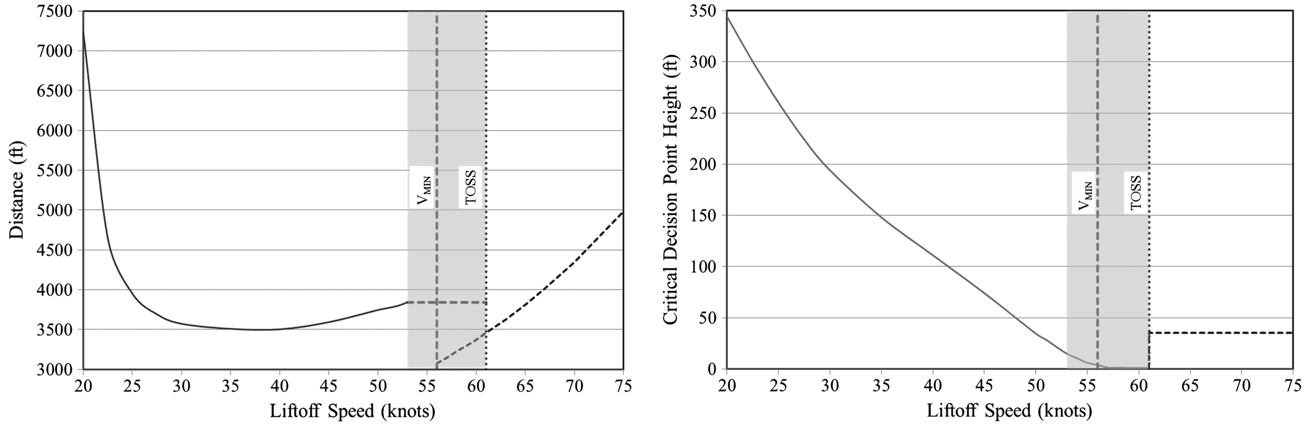
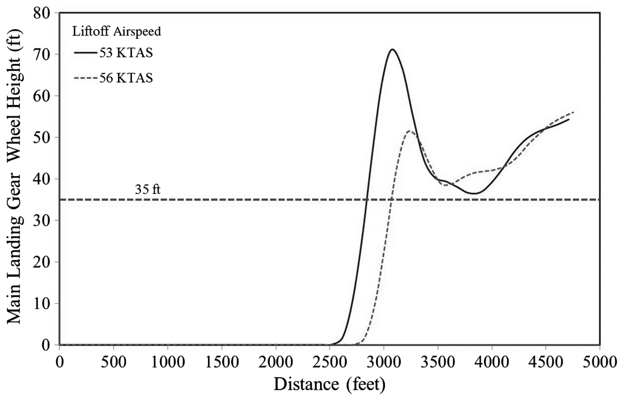


Fig. 9 Optimal CTO distance and corresponding CDP height (helicopter weight 21,000 lb).



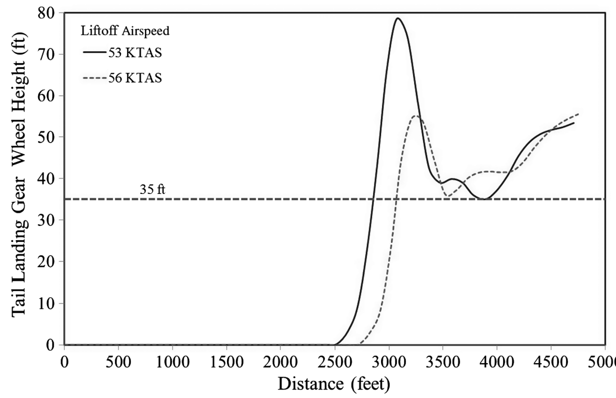


Fig. 10 Wheel height oscillations at liftoff speeds near TOSS (helicopter weight 21,000 lb).

Here, acceleration during descent is not necessary, since OEI flight is already possible, and attainment of the TOSS would be fairly quick.

Figure 9 shows that a minimal CTO distance of 3500 ft exists for two optimal liftoff airspeeds, one in each airspeed range.

For the lower airspeed range, where $V_{\mathrm{LO}} <$ TOSS, the optimal liftoff airspeed and the CDP height are 38 kt and 130 ft, respectively. For the higher airspeed range ($V_{\mathrm{LO}} \geq$ TOSS), the optimal liftoff airspeed should be the TOSS (61 kt), and the CDP height is defined at 35 ft.

Since runway safety considerations should also include the RTO distances and ground handling qualities, it is reasonable to assume that the lower liftoff airspeed would result in a much lower RTO distance and better ground roll handling. Hence, the optimal liftoff airspeed for a minimal CTO distance in the given conditions (a helicopter gross weight of 21,000 lb, sea level, and standard atmospheric conditions) should be set at 38 kt. The concept of a balanced field length where the CTO and RTO distances are the same is generally applied for fixed wing aircraft in order to define the minimal required runway length that would allow safe operation in the event of an engine failure. Because of the inherent differences in the CTO and RTO trajectories of fixed wings and helicopters, a balanced field length would not necessarily be the minimal required runway length that will allow a safe helicopter roll on takeoff. A simplified calculation shows that, for the liftoff speeds below the TOSS, the CTO distance is much longer than the RTO distance.

Setting the CDP at 130 ft may be inconvenient (too high) for the pilot. Increasing the liftoff airspeed from 38 to 45 kt would lower the CDP height by 34% to 74 ft while increasing the takeoff distance by only 3%.

It is concluded that two optimal liftoff airspeeds exist, which minimize the CTO distance. The choice of the recommended liftoff airspeed should be made by including considerations of RTO distance and helicopter ground handling qualities at high speeds, which are beyond the scope of the current study. It is expected that, for these considerations, the lower liftoff airspeed would be preferred. In case these do not lead to a clear preference of one of these two optimal airspeeds, it is recommended that the TOSS would be chosen as the optimal liftoff speed. This will provide a much better climb performance in case of an engine failure, in comparison with the lower optimal liftoff airspeed.

VI. Conclusions

FAA requirements for category A helicopters were used as guidelines for a continued roll-on-takeoff simulation of an AH-64A Apache helicopter.

The influence of the CDP height on the resulting CTO distance was examined. It was shown that for liftoff airspeeds lower than the TOSS, the shortest CTO distance was achieved when the CDP was chosen such that the wheel height at the lowest point of the trajectory was exactly 35 ft. For liftoff airspeeds higher than the TOSS, the CTO distance was essentially not affected by the CDP height. By following these definitions for the optimal CDP heights, two optimal liftoff airspeeds could be found, which minimized the CTO distance. One of these speeds was at the airspeed range, which was lower than the TOSS, and the other was equal to the TOSS. The resulting CTO distances for these two distances were very close.

A difficulty exists in the determination of the CTO distances for airspeeds between V_{MIN}–3 kt and the TOSS. However, it could be conservatively assumed that this distance is constant over that airspeed range.

Finally, it is concluded that the choice of the recommended optimal liftoff airspeed should be made by including considerations of RTO distances and the helicopter's ground handling qualities. In case these do not indicate a clear preference of one of the two optimal airspeeds, the TOSS is recommended to be used as the optimal liftoff airspeed due to the much better OEI climb performance over that of the lower speed.

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