NINETEENTH EUROPEAN ROTORCRAFT FORUM

Paper No. O5

AN INVESTIGATION OF PILOTING STRATEGIES FOR ENGINE FAILURES DURING TAKE-OFF FROM OFFSHORE PLATFORMS

by

D.G. Thomson†
N. Talbot *
C. Taylor†
R. Bradley‡
R. Ablett *

† Department of Aerospace Engineering
University of Glasgow
Glasgow
U.K.

* Civil Aviation Authority
Aviation House
Gatwick Airport
Gatwick
West Sussex
U.K.

‡Department of Mathematics
Glasgow Caledonian University
Glasgow
U.K.

September 14 - 16, 1993
CERNOBBIO (Como)
ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

An Investigation of Piloting Strategies for Engine Failures During Take-off from Offshore Platforms

D.G. Thomson, N. Talbot, C. Taylor
R. Bradley and R. Ablett

Summary

An analysis technique capable of simulating the effect of engine failure during take-off from offshore platforms is presented. Use is made of inverse simulation whereby the control actions required for a subject helicopter to follow a particular trajectory can be established. A mathematical representation of the Towering Take-off procedure, and details of the modified inverse simulation technique needed to cope with the modelling of an engine failure are described. Detailed piloting accounts of the strategy used to fly the Towering Take-off (with and without engine failures) are also given and are used to give qualitative validation of the analytical approach. Simulation results for a single engine failure of a transport helicopter during critical phases of a Towering Take-off are presented. Finally, some directions for future work and potential applications of the technique are discussed.

1. Introduction

Civil helicopters are at their most vulnerable during take off and landing operations where, in common with fixed wing aircraft, their performance may be affected by weather conditions or possible engine failure. Unlike fixed wing aircraft, helicopters often operate from small restricted areas, such as offshore platforms, and these operations as a consequence, lead to take-off and landings which are low speed and may have a significant hovering component. These limitations have safety implications as the resulting relatively low kinetic energy of the helicopter limits the options available to the pilot in order to cope with adverse factors. These problems are further compounded in poor visibility or at night or, in the case of offshore operations, in close proximity to the platform structure. The pilot's ability to perform a safe landing or climb out in the event of complete power loss and the manoeuvrability which is necessary to compensate for high wind or gust conditions is clearly degraded in these circumstances. In such prevailing conditions the emergency procedures associated with approach/landing and take-off/climb-out become critical.

In this paper the control strategies adopted in the event of a single engine failure during a take-off from an offshore platform are described in relation to the Towering Take-off procedure shown in Figure 1. They are discussed first from a pilot's point of view and then as predicted by an equivalent investigation based on an inverse simulation technique. Since the task of take-off from a confined area is largely defined by the need to follow a prescribed flight path or trajectory, inverse simulation is ideally suited to this situation. The flight path's trajectory effectively becomes the input to the simulation and the control displacements and states of the helicopter can be calculated. The current study is the latest application of inverse simulation [1] undertaken at Glasgow. Previous research topics have included model validation [2], agility [3], and handling qualities [4].

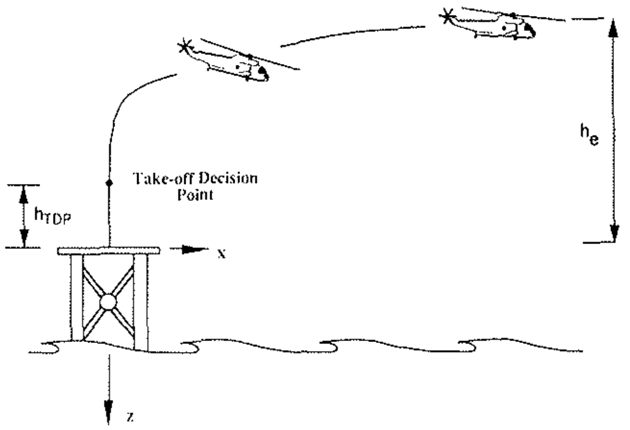


Figure 1 : The Towering Take-off

The starting point of any work involving inverse simulation is the development of a formal description of the manoeuvre(s) of interest, in this case the Towering Take-off. The model should be constructed in such a way as to capture the principal features of the pilot's task. This has been achieved by consideration both of pilot's comments on flying the manoeuvre, and the recommendations quoted in various regulatory documents. The piloting aspects of flying this manoeuvre, the derivation of the manoeuvre model, and sample inverse simulation results are presented in the following section. The piloting strategy to cope with engine failures during a towering take-off are discussed in section 3.

The crucial advance following the initial flight path modelling phase has been the development of a novel, combined forward-inverse simulation technique which, when allied to a modified engine model allows a simulation of a recovery to climb out when engine failure occurs at various critical points along the manoeuvre trajectory. The modified engine model and the use of a forward-inverse simulation technique are discussed in some detail in section 4.

2. The Towering Take-off Manoeuvre

The validity of the results from any inverse simulation will depend to a large degree on the accuracy of the manoeuvre description. For the current study careful consideration has been made of both piloting information and that contained in the regulatory bodies documents [5]. The piloting perspective on flying this manoeuvre is presented in the following sections.

2.1 Piloting Aspects of Flying the Towering Take-off Manoeuvre

The Towering Take-off is commonly used during multi-engine helicopter offshore operations as an efficient means of departing from elevated helidecks, giving the best possibility to survive an engine failure during the take-off manoeuvre. An engine failure during this low speed phase of flight will quickly result in unacceptable loss of rotor RPM (Nr) unless prompt pilot action is taken to lower the collective and therefore reduce the power required to that available from the remaining good engine of a twin engine helicopter. This reduction of collective pitch results in a loss of height so the pilot has to ensure that the aircraft will either land back on the helideck below, or ensure sufficient forward motion that the flight path will clear the deck edge by a safe margin. This latter case can only be achieved when sufficient height has been gained and therefore there is a critical height above the helideck, known as the Take-off Decision Point (TDP), before which the take-off must be rejected and a landing carried out onto the helideck, and after which the take-off can be continued, albeit descending past and below the deck edge into forward flight.

The optimum technique for any given situation and type of helicopter is dependent on various factors :

i) All-Engine Operating Power. There must be sufficient All-Engines Operating (AEO) power available to allow a vertical climb in the ambient conditions at the actual helicopter weight.

ii) Single Engine Power. There must be sufficient One Engine Inoperative (OEI) power to allow an adequately low rate of descent at touchdown for the Rejected Take-Off (RTO) case, and to allow deck edge clearance and subsequent climb away for the Continued Take-Off (CTO).

iii) Wind Speed. The wind speed over the heli-deck will affect the power required and any head wind component may allow increased weights or require modifications to the piloting strategy.

iv) View and Helideck Size. The view from the helicopter will be a non-performance related factor that will limit the maximum height for the TDP as the pilot requires to maintain a view of the helideck at all times up to the TDP or the maximum height reached during the reversal of direction necessary during an RTO. It follows that for a given helicopter, the smaller the helideck, the lower the maximum TDP.

v) Handling Qualities. Severe cross couplings between axes will influence the precision and ease with which the required manoeuvres can be carried out. A significant factor will be the ease with which the relevant power limit (engine or transmission) can be set. This will involve engine response characteristics and indeed the clarity and characteristics of the cockpit instruments the pilot will use.

The emphasis in this paper is on simulating the first two of these factors. Future studies will focus on the effects of prevailing wind and gusts, whilst the use of inverse simulation for handling qualities studies has already been explored [4]. The influence of "View and Helideck Size" is of course difficult to quantify using the type of analysis presented here and is much more suited to piloted studies.

2.2 The Piloting Strategy for a Towering Take-off

Without giving detailed consideration to all the factors noted in section 2.1, a general strategy that would be valid for many situations operating from a normal size helideck (22.2m diameter) is described below:

i) Initial Hover. The helicopter would start from a position sitting on the centre of the helideck with the cyclic control and yaw pedals close to central, and the collective lever fully down. To establish the initial hover, collective pitch is applied progressively whilst cyclic and pedal inputs are made to counteract any cross coupling between axes as the helicopter lifts off and to maintain the position over the centre of the helideck. The initial hover height will be 15 ft and the amount of collective applied will depend on the thrust required to achieve that height.

ii) Vertical Climb. From the initial hover, collective pitch is applied quickly, within approximately 2 seconds, until an engine or transmission limit is reached or the rate of climb is approximately 500 ft per minute. Cyclic and pedal inputs are made as required to maintain position over the centre of the helideck.

iii) Take-off Decision Point. A likely TDP would be 50 ft as indicated by Radio Altimeter. At the TDP, the pilot would make a positive forward cyclic input to achieve a nose down, accelerative attitude. A usual nose down attitude would be 15 degrees in order to accelerate the helicopter towards the initial climbing speed.

iv) Acceleration and Climb. After achieving the required nose down attitude at TDP, as speed increases, the pilot allows the nose to rise progressively until the helicopter ceases to accelerate as it reaches the initial climbing speed of

70 knots. The nose will rise due to flap-back caused by the effects of increasing airspeed through the rotor, to pilot longitudinal cyclic inputs, or to a combination of both depending on the characteristics of the particular helicopter. During the acceleration, lateral cyclic and pedal inputs are made to achieve wings level balanced flight. The collective may require adjustment to keep within engine and transmission limits and to establish a desirable initial rate of climb of 1000 feet per minute.

2.3 A Mathematical Description of the Towering Take-off Manoeuvre

In the piloting description given above the towering take-off is defined in terms of four distinct phases. In the following mathematical description the Initial Hover phase is not modelled, partly as this simplifies the overall definition, but also because this is considered as the least critical phase of the manoeuvre. As a consequence of this simplification it is assumed that the manoeuvre is initiated from a hover condition 5m (approximately 15ft) above the helideck. An earth fixed axes set is located at this point with the x-axis pointing in the direction of flight, the z-axis vertically downwards and the y-axis completing a right-handed frame. The inverse simulation requires time histories of the vehicle's velocity and acceleration throughout the manoeuvre related to this axes set [1].

On consideration of both the pilot's comments and the regulatory information [5] it was decided that the most fundamental parameters associated with the towering take-off are the helicopter's velocity and climb rate, and hence the model now described is based on knowledge of these parameters. More specifically it is necessary to specify values for the altitude, h_{TDP}, and vertical velocity, v_{TDP}, at the TDP, and also the flight velocity, V_E, climb angle, γ_E, and altitude, h_E, at some notional exit point. As will become apparent it is also necessary to supply values for the peak accelerations expected during certain phases of the manoeuvre, and the time it is likely to take for the helicopter to reach these values. These figures are performance related and will depend to a large degree on the take-off mass of the vehicle. It is interesting to note that this approach of defining a manoeuvre in terms of performance goals which must be met is adopted by the authors of the U.S. Mil. Spec 8501 Handling Qualities Requirements [6] in their description of Mission Task Elements.

Having specified the vertical velocity and height at the TDP the other two phases (Vertical Climb and Acceleration and Climb) are defined in such a way that they match one another at the TDP to produce a smooth transition.

i) The Vertical Climb Phase $(0 < t \le t_{TDP})$

The most convenient approach to modelling the vertical climb phase is to specify a vertical acceleration profile such as that shown in Figure 2(a). In this representation it is assumed that from a trimmed hover condition, the application of collective will cause an increasing vertical acceleration up to some maximum value, $\dot{V}_{max}$, (depending on the collective setting). As the required vertical velocity, v_{TDP}, is approached the ideal situation is to reduce the vertical acceleration (by lowering collective) to zero hence giving a constant vertical velocity climb. This climbing phase is completed when the TDP height (h_{TDP}) is reached and the vehicle transitions to forward flight. A piecewise smooth polynomial function of time was used to obtain the profile shown in Figure 2(a) for the vertical acceleration. Its construction is given below:

$$0 < t \le t_1 \qquad \dot{V}(t) = \left[-2\left(\frac{t}{t_1}\right)^3 + 3\left(\frac{t}{t_1}\right)^2\right] \dot{V}_{max}$$

$$t_1 < t \le t_2 \qquad \dot{V}(t) = \dot{V}_{max} \tag{1}$$

$$t_2 < t \le t_{CP}$$

$$\dot{V}(t) = \left[1 - \frac{3}{2}\left(\frac{t-t_2}{t_{CP}-t_1}\right)^2 + \frac{1}{2}\left(\frac{t-t_2}{t_{CP}-t_1}\right)^3\right] \dot{V}_{max}$$

Cubic polynomial functions were chosen as they have been found to give an adequate degree of continuity whilst being relatively simple to implement. The values of the maximum acceleration, $\dot{V}_{max}$, and the time for the collective pulse, t_{CP}, must be supplied, and it is assumed that the pulse is symmetrical such that

$$t_1 = t_{CP} - t_2.$$

It is then possible to obtain the value for t_2 by enforcing the condition that at $t = t_{CP}$, the constant vertical velocity v_{TDP}, should have been acquired. This is achieved by integration of the acceleration profile :

$$\int_0^{t_{CP}} \dot{V}(t)dt = v_{TDP}$$

Although on completion of this collective pulse the required vertical velocity will have been reached, it is unlikely that a safe altitude will have been gained. It is therefore assumed that the helicopter continues its vertical climb at constant velocity as indicated in Figure 2(b) until the required altitude, h_{TDP}, is reached (at a time t_{TDP}). This time is readily obtained by noting that in a vertical climb

$$v(t) = \int^t \dot{V}(t)dt$$

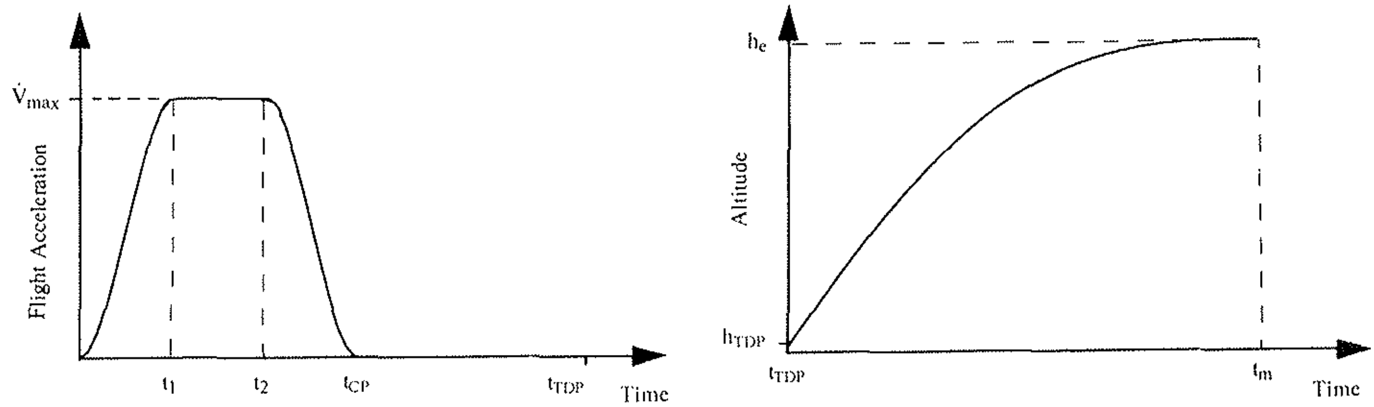
and

$$\int_0^{t_{TDP}} v(t)dt = h_{TDP}.$$

A purely vertical climb from the take-off point is ensured by adding the further constraints that $\dot{x}(t) = 0$ and $\dot{y}(t) = 0$, throughout this phase.

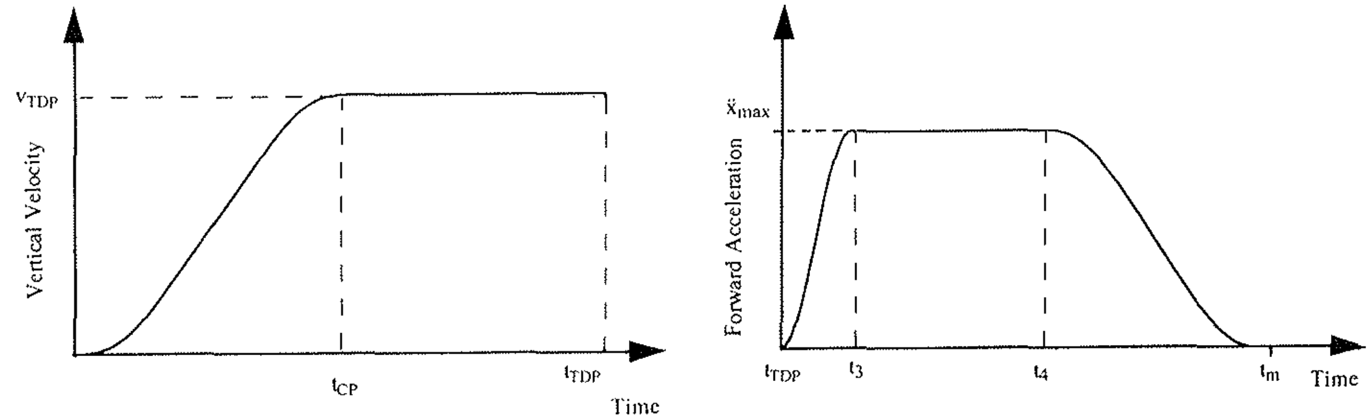
ii) The Acceleration and Climb Phase $(t_{TDP} \le t < t_m)$

After the TDP the helicopter begins to accelerate forward whilst still climbing until the notional exit point is reached. The requirement is to obtain some function which gives a realistic geometrical profile for this phase whilst still satisfying the mathematical constraints imposed by the definition. If we consider first the altitude



a) Flight Acceleration

c) Altitude



b) Vertical Velocity

d) Forward Acceleration

Figure 2 : Flight Path Parameter Profiles for the Towering Take-off

function, this must satisfy the three conditions already imposed at the end of the vertical climb phase (i.e. at $t = t_{TDP}$, $z = -h_{TDP}$, $\dot{z} = -v_{TDP}$ and $\ddot{z} = 0$), whilst also meeting the requirements at the exit. The exit flight state is a constant velocity, V_E, climb at some angle γ_E, whilst at the exit point the altitude should be h_E. This gives the exit conditions

$$t = t_m, \quad z = -h_E, \quad \dot{z} = -V_E \sin \gamma_E, \quad \ddot{z} = 0.$$

The most convenient form for the altitude profile, z(t) is therefore a fifth order polynomial, Figure 2(c), where the six constant coefficients are selected to satisfy the six conditions specified above. Note that a higher order polynomial has been chosen here as this will permit the altitude at the exit point to be directly specified and thereby ensure a realistic geometrical profile is obtained.

The most appropriate way of ensuring that the velocity requirement at the exit is met has proved to be by specifying a longitudinal acceleration profile, $\ddot{x}(t)$. The chosen profile is shown in Figure 2(d), and is identical in form to that used for the acceleration in the vertical climb phase. Consequently, the functions for $\ddot{x}(t)$ are similar to those given by equations (1). This profile gives a rapid change in acceleration from zero up to a maximum value, $\ddot{x}_{max}$, (as before this value is specified and is related to the performance capabilities of the helicopter) which is maintained until the commanded forward speed is approached and the acceleration is reduced until a constant flight speed is attained. As with the vertical climb, the time taken to achieve maximum acceleration, $(t_3 - t_{TDP})$, and the time taken to establish constant velocity at the exit, $(t_m - t_4)$, must be supplied. It is then possible, given that V_E and γ_E are also known, to obtain a value for the time spent at constant acceleration, $(t_4 - t_3)$, from the expression

$$\int_{t_{TDP}}^{t_m} \ddot{x}(t)dt = V_E \cos\gamma_E$$

The final condition imposed during the flyaway section is that there should be no lateral motion and hence $\dot{y}(t) = 0$.

The definition of the Towering Take-off is completed by the additional constraint that heading should be maintained constant throughout.

The use of smooth piecewise polynomial representations of manoeuvres may seem an unrealistic over-simplification of the actual situation. Previous work on helicopter nap-of-the-earth manoeuvres and Mission Task Elements [4], including comparison between the actual flight trajectories and the polynomial models, has indicated that this approach can give realistic and valid profiles.

2.4 Inverse Simulation of the Towering Take-off Manoeuvre

It is necessary to provide only a few basic parameter values to use the definition of the Towering Take-off given above. In the following example the parameter values are

$h_{TDP} = 10m$, $v_{TDP} = 2.5$ m/s (≡ 500ft/min),

$\dot{V}_{max} = 2$ m/s^2, $t_{CP} = 2$ s, $\ddot{x}_{max} = 3$ m/s^2,

$t_3 - t_{TDP} = 2.5s$, $t_3 - t_m = 14s$, $V_E = 70$ knots,

$h_E = 70m$, $\gamma_E = 8$ deg (≡ 1000ft/min at 70 kts).

These values are representative of those routinely encountered during take-off from offshore installations. Note that the TDP height is referred from the starting height of the climb (5m) and therefore represents an altitude of 15m above the helideck. Time histories of several of the flight path variables are shown in Figure 3. The time to reach TDP is 5 seconds and the manoeuvre completion time is approximately 25 seconds. From the vertical acceleration profile, the initial pulse takes 2 seconds (as indicated by the piloting description given in 2.2(ii)) by which time the vertical velocity is 2.5 m/s. The TDP is reached at about 5 seconds, after which the acceleration and climb phase begins with a rapid increase in forward acceleration, the maximum value being set at 3 m/s^2 to be reached after 2.5 seconds. The velocity increase in conjunction with the relatively slow initial increase in height leads to a rapid decrease in climb angle from 90 degrees at the TDP to a value slightly below the required exit condition of 8 degrees at approximately 15 seconds. Thereafter, as the required constant velocity is approached, and the climb rate begins to increase, and the climb angle slowly approaches its final constant value. The resulting flight path is also shown in Figure 3.

This manoeuvre information may be used to drive the Helinv inverse simulation thereby producing time histories of the helicopter's states and controls. At the heart of the Helinv simulation is a non-linear generic helicopter mathematical model. This simulation [8] incorporates an actuator disc rotor model with quasi-steady flapping, dynamic inflow [9], rigid constant chord blades with root cut-out and 2-D aerodynamic properties. Also included in the simulation are representations of a twin-engine powerplant [10] and an Automatic Flight Control System. The helicopter configurational data used in this paper is characteristic of a large transport vehicle of the class likely to be employed in offshore operations. A brief summary of this data is given in Table 1.

Parameter	Value
Aircraft Mass (kg)	9000
Rotor Radius (m)	9.5
Rotor Solidity	0.363
Flapping Stiffness (kNm/rad)	160
Maximum Power Output (SHP)	2800
Rotor Speed at Flight Idle (rad/s)	22

Table 1: Leading Parameters for Transport Helicopter Configuration

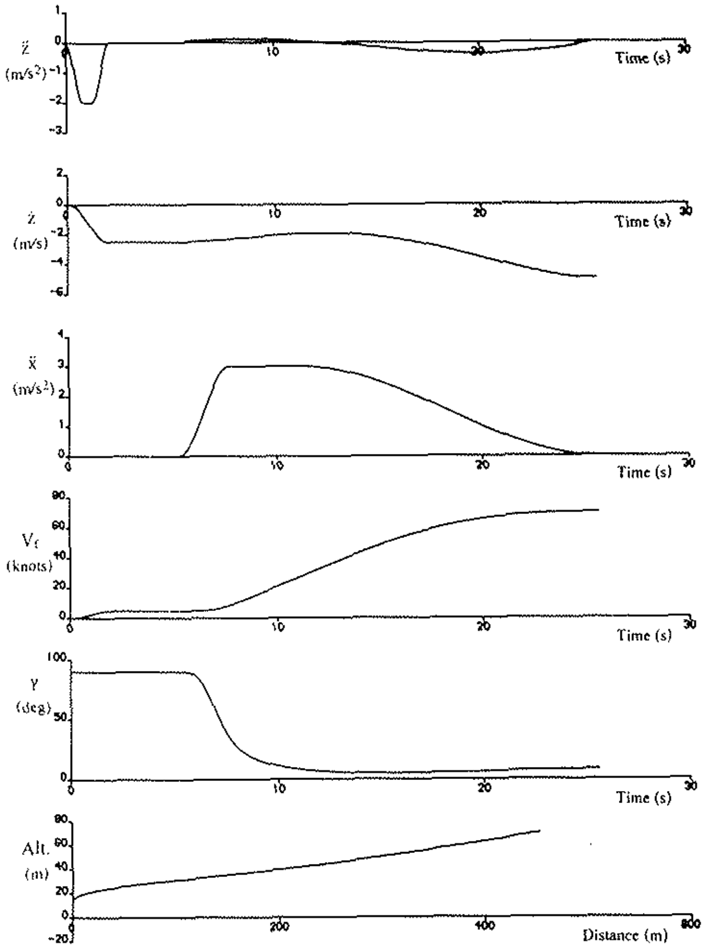


Figure 3 : Flight Path Parameter Time Histories for a Towering Take-off

The inverse simulation results for the transport configuration flying the towering take-off described above are shown in Figure 4. The vertical climb section of the manoeuvre is clearly visible from these plots : over the first 5 seconds there is little cyclic motion and hence little change in attitude, whilst at the same time there is firstly a pulse in collective lever to produce the desired vertical acceleration, followed by an offset in collective setting from the trim position producing the constant vertical velocity climb. The effect of the collective pulse on engine torque and rotorspeed are also apparent with both engines peaking at about 95% of their maximum torque, and the rotorspeed falling by a small amount. After the TDP there is a pulse in forward cyclic stick of 25% to induce a nose down pitch attitude of about 15 degrees in order to achieve the commanded forward acceleration. After this pulse there is a short aft stick pulse to arrest the nose down motion followed by a more sustained but slow forward stick motion to account for the disc flapping backwards as forward speed is increased. The nose down attitude is maintained until about 12 seconds at which point a slow aft stick motion begins to raise the nose. Note that the stick forward pulse which initiates the acceleration is much more aggressive than the subsequent stick back motion - this is to reflect the likely piloting strategy of clearing the helideck as quickly as possible after the decision to climb away has been taken. During the acceleration and climb phase the collective is initially

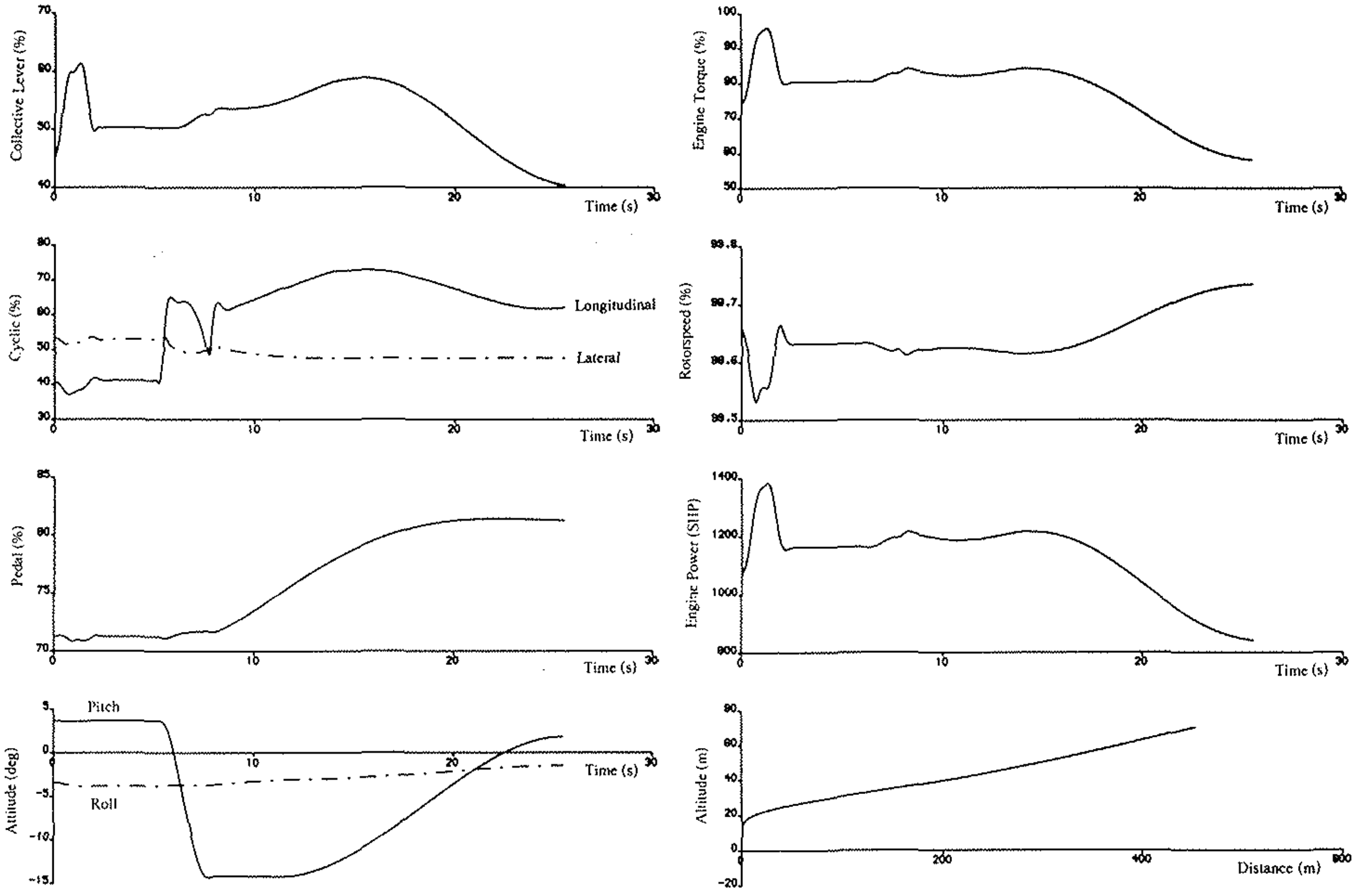


Figure 4 : Inverse Simulation Results for Transport Configuration Flying Normal Towering Take-off

increased to produce the desired climb rate, but is subsequently reduced towards the end of the manoeuvre as speed increases, and the desired flight state is reached. With the reduction in collective, the engine torque and power fall whilst the rotorspeed increases slightly. It is also noticeable from Figure 4 that there are only very small changes in the lateral cyclic position and roll attitude, whilst there is a gradual change in pedal position as forward speed is increased.

Comparing the discussion above with the piloting comments in 2.1 and 2.2 it is clear that the key features of an initial 2 second pulse in collective and a subsequent pulse in forward cyclic leading to a 15 degree pitch down attitude are correctly predicted by the inverse simulation through its defined trajectory. The manoeuvre as defined reaches about 95% of nominal maximum torque and therefore complies with the AEO requirement in 2.1(i). The conclusion is that the methods employed have satisfactorily captured the piloting strategy of the normal Towering Take-off procedure. The more complex situation of the failure of an engine during take-off is now considered.

3. Piloting Strategy for Recovery from Engine Failure During a Towering Take-off

Having discussed both the piloting aspects and the inverse simulation of the normal towering take-off procedure, the piloting approach in the event of an engine failure is now described before the techniques associated with the inverse simulation of this situation are outlined.

3.1 Failure Before TDP

The objective on recognising an engine failure before TDP is to reverse the upwards vertical motion promptly, conserve and maintain rotorspeed (Nr) during a vertical descent and carryout a smooth touchdown on the helideck using all the power available from the remaining engine and stored energy in the rotor. Taking these in turn:

a) Flight Path Reversal. The pilot will make a rapid downwards collective lever input on recognising the engine failure. The size of the input will depend on the rate of climb at the point of recognition. In general, rate of climb will increase as the vertical climb portion of the towering take-off progresses, so it follows that the larger inputs are required close to the TDP. Cyclic control and yaw pedal inputs are made to compensate for cross couplings to ensure that the helicopter remains over the helideck.

b) Conserving Nr and Vertical Descent. Once the flight path has been reversed, it will be necessary to conserve adequate Nr and therefore stored energy to cushion the touchdown. To achieve this, the collective is set such that the remaining engine is producing maximum power, usually by reducing Nr by 1% - 2% below the normal governed setting. With this power set, the descent is monitored and cyclic control and yaw pedal inputs are made as necessary to maintain the vertical descent. The rate of descent will depend on the power deficit and would typically be 800 feet per minute.

c) Touchdown. The helicopter is allowed to descend vertically as described above until reaching a height of approximately 15 ft above the helideck at which point a large collective-up input is made. The purpose of this is to use rotor kinetic energy to produce additional thrust for a short period of time in order to achieve a smooth touchdown. The point at which the collective input is made depends on the rate of descent and rotor inertia and will vary between helicopter types. After touchdown, the collective is lowered fully.

3.2 Failure Just After TDP

The key objectives with an engine failure just after TDP are to ensure rotorspeed remains within acceptable limits and to translate from the hover into forward flight. If the performance scheduling is correct, increasing speed reduces the power required to the point where the helicopter will be able to climb using the power available from the remaining engine. Increasing speed also causes a forward translation that is used to ensure that the helicopter misses the edge of the helideck. The pilot action at TDP is to pitch the nose down, typically to an angle of 15 degrees, using a positive forward cyclic input whether or not an engine has failed. If an engine has failed, such that the failure is recognised as or after the forward cyclic input is made, the correct course of action is to continue with the take-off rather than try to land back on the helideck. In this case, the helicopter will follow a descending flight path as speed is gained, and the pilot will have to lower the collective shortly after the engine failure to prevent the rotorspeed falling below the acceptable minimum. Some loss of rotorspeed is probably desirable as when airspeed is low most rotors are more efficient at lower rotorspeed. As airspeed increases, the nose will tend to rise and in any case will be positively raised at, typically, 35 knots to reduce height loss and establish airspeed at that required for the single engine climb, typically 70 knots. The sequence of events can be summarised as :

a) Engine failure is recognised as forward cyclic is made at TDP,
b) nose is pitched down to 15 degrees,
c) collective is lowered to keep Nr within limits,
d) nose will rise as speed increases and at 35 knots longitudinal cyclic inputs are made to establish speed at 70 knots,
e) when 70 knots has been established, a steady climb is maintained using maximum engine power.

During this manoeuvre, which involves predominantly longitudinal cyclic and collective pitch inputs, appropriate lateral cyclic and yaw pedal inputs will be made to maintain wings level balanced flight.

3.3 Failure Well After TDP

An engine failure well after TDP will have similar objectives to the case above but clearly the closer the helicopter is to the desired climbing speed of 70 knots, the less will be the need for the pilot to increase airspeed by pitching the nose down and the less will be the height loss. The collective lever will, however, have to be lowered to prevent Nr dropping below the acceptable limits.

4. Inverse Simulation of Engine Failures During Towering Take-off Manoeuvres

In the following section the modifications required to the existing Helinv algorithm [1] necessary for it to be applied to the simulation of recovery procedures in take-off manoeuvres are discussed.

4.1 Simulating Engine Failure

The engine model initially incorporated in Helinv is based on that described in Reference 11. For the current study involving engine failures, it has been necessary to replace the original single engine model with a twin engine version where either engine can be failed separately. This has been achieved by duplicating the original model, retaining its structure but adjusting the values of its parameters so that the combined model functions exactly as the original [10]. That is, the time constants of its dynamics are identical but the torque produced by each engine is half of the original with the fuel intake equally shared. Engine failure is simulated by setting the fuel flow of the failed engine to zero, so that its contribution to the overall torque falls to zero in a realistic manner. The unaffected engine increases its contribution to the torque to compensate for the failure as shown in Figure 5. At the same time, the opportunity has been taken to introduce some realistic non-linearities into the engine model by incorporating a torque limitation based on setting a maximum allowable fuel flow.

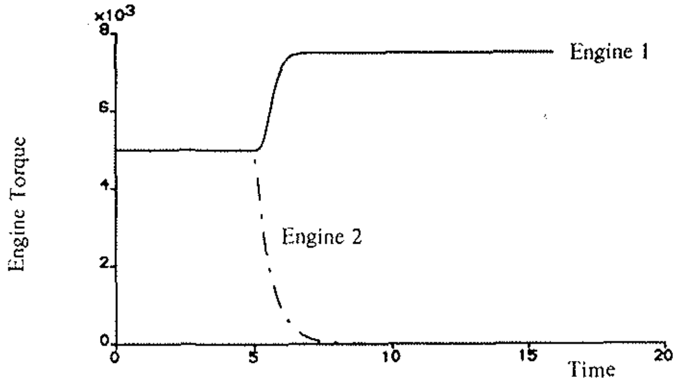


Figure 5 : Torque Time Histories for Engine Failure

In addition to developing an engine model which can replicate failures, it is also important to incorporate the event of an engine failure into the context of the manoeuvre simulation in a realistic manner. Earlier sections of this paper have described the general approach of specifying flight paths as trajectories defined via piecewise polynomials connected with an appropriate degree of continuity, and calculating, from the helicopter mathematical model, the pilot's control movements - or in general terms - strategy. The modelling view of this situation is that of the pilot anticipating the control movements needed to accomplish the manoeuvre as the flight path is traversed. However it is clear that when an engine fails he cannot instantaneously adjust his strategy to the modified performance of his vehicle. That is, until he has recognised and reacted to the failure, his strategy will be that consistent with the original manoeuvre. After the elapse of the reaction time, he will adopt a new strategy - either planning to return to the original flight path or mentally redefining his piloting goals and preparing a strategy leading to a new trajectory. This adaptation of the pilot to the new circumstances is captured in the current work by successive intervals of inverse simulation, forward simulation and inverse simulation. The first period of inverse simulation takes the pilot up to the failure point in the normal manner of inverse simulation described earlier. In the second period, the helicopter is flown with its engine failed but a control strategy based on its original manoeuvre; it is this second interval which emulates the reaction time of the pilot. In it, the pilot is acting according to the original strategy for the helicopter whereas the helicopter is responding with its modified performance. Naturally this will lead to a divergence of the helicopter from its flight path as originally defined and in the next phase of the manoeuvre the pilot reacts to the new situation by adopting a strategy which ultimately leads to a new recovery flight path or a return to the original.

4.2 Calculation of Divergence

In order to mirror authentically the different phases of a manoeuvre incorporating engine failure, a new simulation package has been developed. It is one which can perform inverse simulation up to a certain point in time and then switch to normal forward simulation, using the control inputs that would have been calculated for a continuation of the inverse simulation. After a specified interval of time (the reaction time) the simulation reverts to inverse simulation in order to adopt a new flight path for the continuation of the flight - either to return to the original manoeuvre or to pursue a different strategy - for example by descending in order to build up a safe flying speed.

It is necessary to ensure a realistically smooth transition between the different phases of the simulation. The first transition, from inverse to forward is naturally smooth since the initial values of the state variables for the forward simulation are available from the final point of the inverse simulation. The second, from forward to inverse, requires a smooth transition from its diverged flight path to the new one. In addition, the supplementary constraint, in this case a prescribed heading, may be violated during the forward phase so that its return to that required in the inverse phase must be introduced smoothly. Part of the current work has been to study the effect of bringing the departures of the variables back to what they should be with varying degrees of severity and the development of techniques for ensuring a smooth transition have included a parameter to control the rate at which the new flight path is captured.

4.3 Development of Blending Functions

The requirement is for a function h(t) to blend smoothly from f(t), the current flight path, to g(t), the target flight path over an interval $t = t_{pr}$ (the time at which the pilot responds to the engine failure) to $t = t_R$ (the time at which the recovery trajectory is achieved) as illustrated in Figure 6. Let $h(t) = g(t) + \phi(t)$, and let the required degrees of derivative continuity at $t = t_{pr}$ and $t = t_R$ be M and N respectively, then:

$$h^m(t_{pr}) = g^m(t_{pr}) + \phi^m(t_{pr}); \qquad \text{for } m = 0 \text{ to } M$$

and

$$h^n(t_R) = g^n(t_R) + \phi^n(t_R); \qquad \text{for } n = 0 \text{ to } N$$

so that ϕ satisfies:

$$\phi^m(t_{pr}) = h^m(t_{pr}) - g^m(t_{pr}) \qquad \text{for } m = 0 \text{ to } M$$

and

$$\phi^n(t_R) = 0; \qquad \text{for } n = 0 \text{ to } N.$$

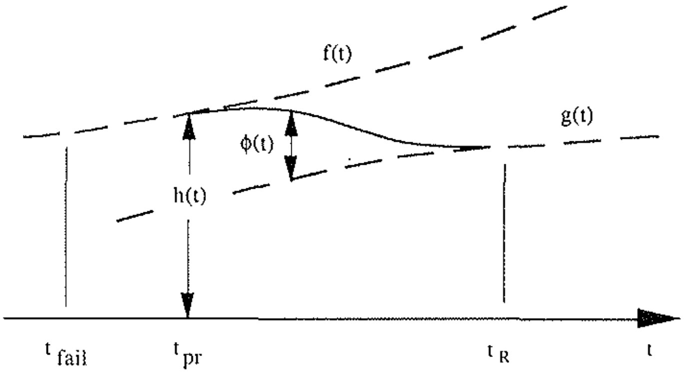


Figure 6 : Blending Function for Recovery Flight Path

Now bias the blend by writing $\phi(t) = e^{-\delta t}\, p(t)$, for some polynomial p(t), from which it is easy to write:

$$\phi(t) = e^{\delta t}\, p(t)$$

$$\phi'(t)\, e^{\delta t} + \delta\, \phi(t)\, e^{\delta t} = p'(t)$$

$$\phi''(t)\, e^{\delta t} + 2\delta\, \phi'(t) e^{\delta t} + \delta^2 \phi(t)\, e^{\delta t} = p''(t)$$

$$\cdots$$

$$e^{\delta t} \Sigma_M C_r\, \phi^r(t)\, \delta^{(M-r)} = p^{(M)}(t)$$

where r is the highest degree of derivative continuity required at the merging points. The biasing of the blend gives the required parameter to adjust the speed at which

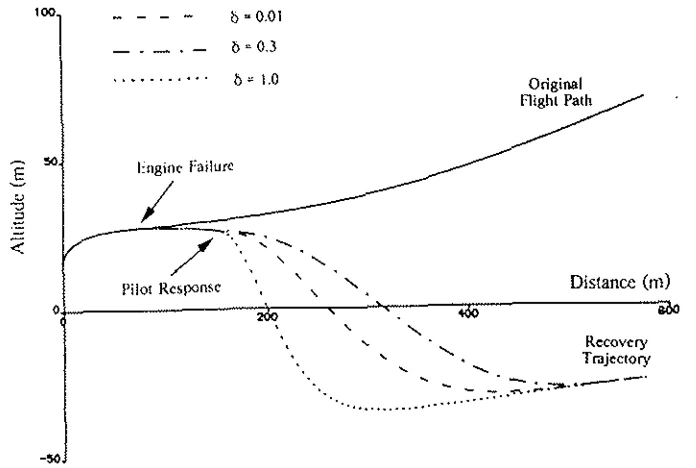


Figure 7 : Effect of Value of δ on Recovery Trajectory

the new trajectory is adopted - where 'new' includes the case where the original trajectory is rejoined. To illustrate this Figure 7 shows the effect on the trajectory of an engine failure where no action has been taken by the pilot for 5 seconds. This is of course an unrealistic reaction time but does clearly demonstrate departure from the originally defined trajectory. The final trajectory is one of similar slope to the original but at a lower altitude, and the effect on the blending function of varying the bias, δ, is clear from this plot - higher values allowing the final condition to be acquired earlier. The type of blending described above is used for the trajectory co-ordinates x, y and z and in addition the applied constraint- either heading or sideslip, and there is the opportunity if so desired to use different values of δ for different variables where, for example, it may be desirable to bring the heading round to a preferred direction as a priority above that of the velocity components. In the current work the degree of continuity imposed at each end is three so that p(t) is a polynomial of degree five.

4.4 Inverse Simulation of Engine Failures

The simulation results presented in this section are for the transport helicopter described in Table 1. After its failure it is assumed that the engine is shutdown immediately by some automatic system, and that the pilot responds to this failure after a further 1 second. For all 3 cases the initiated manoeuvre is identical to that described in sections 2.4 and shown in Figure 3, and hence, up to the point where the engine has failed and the pilot has responded, the control inputs are as given in Figure 4. An appropriate function is then blended from the point of pilot reaction, to a defined exit condition as described in section 4.3, and the control inputs required to fly this path are calculated. It should be noted that the representation of the engine governor in the simulation is configured such that rotor overspeed is prevented by reducing engine torque when rotorspeed reaches its flight idle limit. This

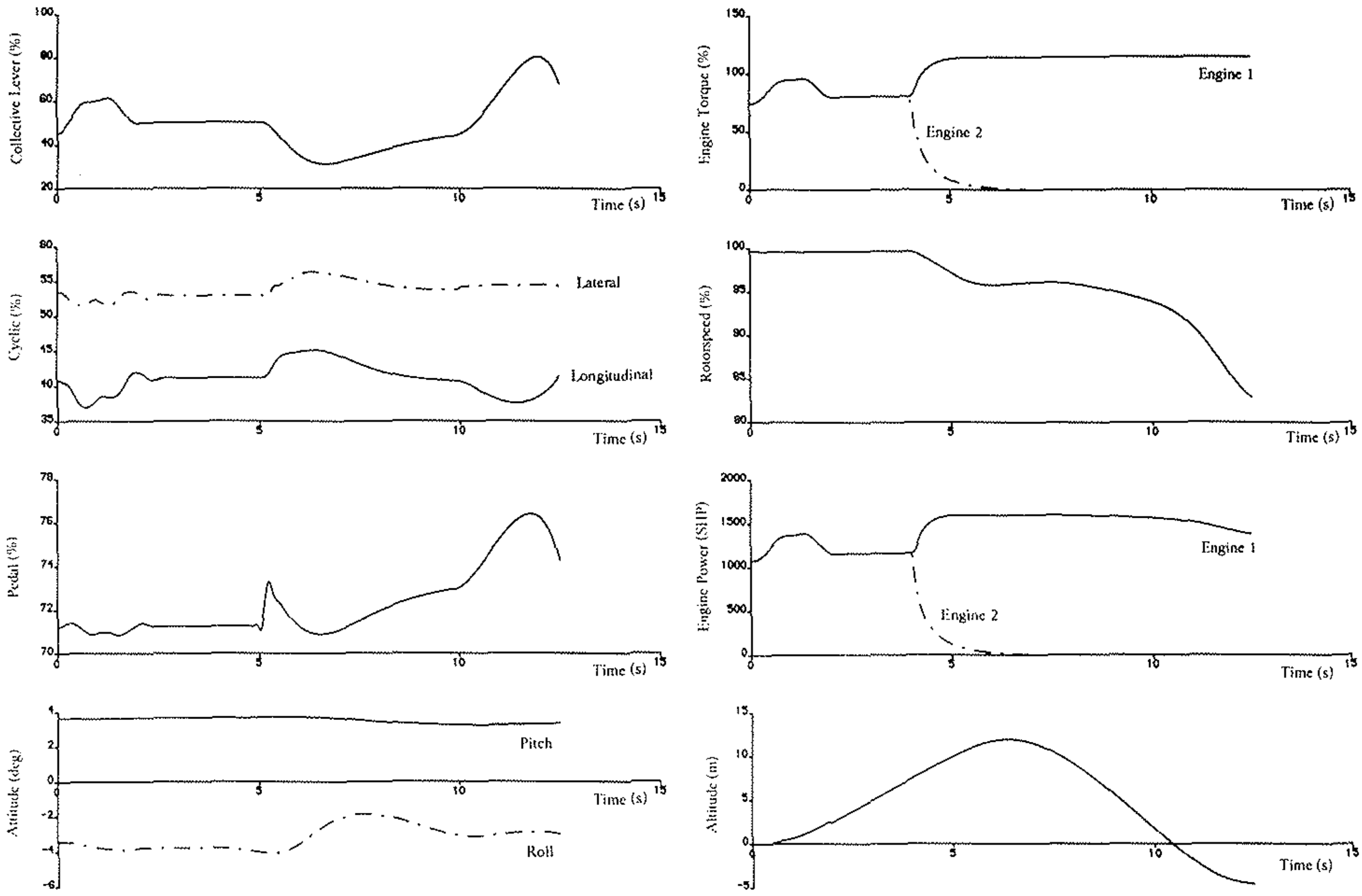


Figure 8 : Inverse Simulation Results for Transport Helicopter Flying a Towering Take-off with Engine Failure at 4 Seconds (Just Before TDP)

feature can be observed in some of the plots discussed below. In the simulations the torque supplied by an engine is limited to a contingency maximum 15% above its nominal limit. This value corresponds to the OEI value referred to in 2.1(ii).

a) Failure Before TDP

For this case the engine failure occurs 1 second before the TDP (i.e. 4 seconds into the manoeuvre) and recovery is by means of a rejected take-off, landing back on the heli-deck. This give the following exit conditions

$h_E = -5\text{m}, \quad v_E = -1.5 \text{ m/s} \ (\equiv -300 \text{ ft/min}).$

Note that the manoeuvre is initiated from a height of 5m above the helideck (15ft, approx.) and hence the final altitude of -5m places the helicopter back on the platform deck. The results from this simulation are given in Figure 8. The pilot's reaction (at 5 seconds) to the engine failure in this case is to reduce collective to conserve rotorspeed and arrest the upward motion. The upwards travel of the helicopter is completed at about 6.5 seconds just after collective reaches its minimum position and rotorspeed levels off. There is then a gradual increase in collective as the helicopter descends (causing rotorspeed to fall slowly) followed at about 10 seconds, as the deck is approached, by a much faster increase in collective (and decrease in rotorspeed) to cushion the touchdown. After the failure of the engine the torque of the remaining engine rises to its contingency maximum and remains there until the manoeuvre terminates.

There is good agreement with the piloting description of 3.1. The decrease of collective results in Nr being maintained within 3% of its reference value until it is dissipated in the final increase of collective applied in order to minimise the impact on touch down. The maximum rate of descent is approximately 800ft/sec, as required.

b) Failure Just After TDP

For this case the simulated engine failure occurs 1 second after the TDP (i.e. 6 seconds into the manoeuvre) and the recovery from this initially follows the nose down acceleration of the normal take-off, but is then followed by a much slower climb from below the level of the platform. The demanded exit condition in this case is

$h_E = -25m, \quad V_E = 70 \text{ knots}, \quad v_E = 1.5 \text{ m/s} \ (\equiv 300 \text{ ft/min}).$

Note that the given exit height is a displacement form the starting point of the manoeuvre (5m above the deck) and therefore represents a location approximately 20m below the level of the heli-deck. The simulation results are shown in Figure 9. The pilot's response occurs during the normal initial pulse of longitudinal cyclic which initiates the acceleration. The first action taken is to apply a second sharp pulse in cyclic to reinforce the nose down pitch attitude (in this case to 20 degrees) to ensure the deck edge is cleared. This input is

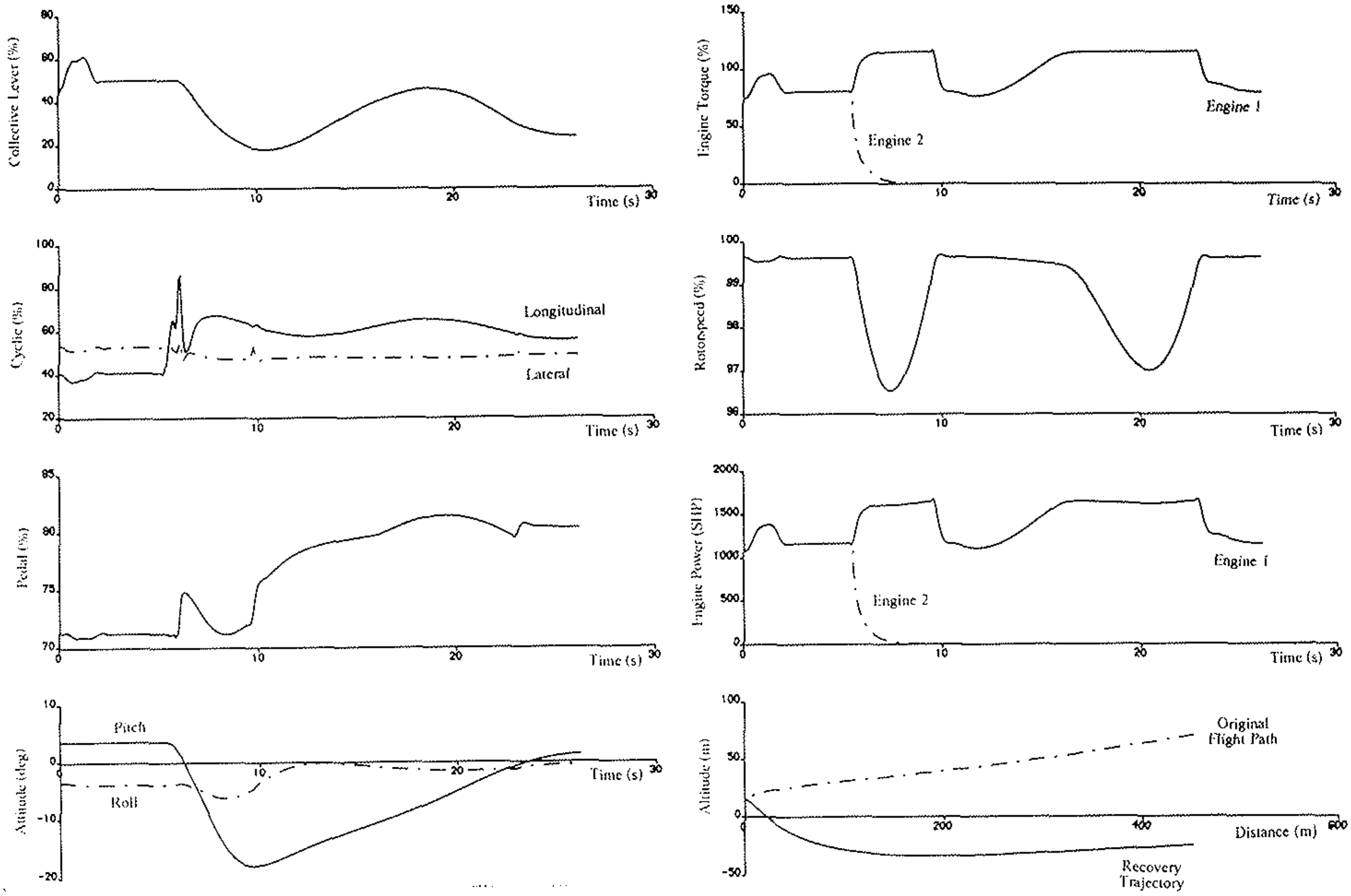


Figure 9 : Inverse Simulation Results for Transport Helicopter Flying a Towering Take-off with Engine Failure at 6 Seconds (Just After TDP)

accompanied by a rapid drop in collective to maintain rotorspeed. The lower collective settings in this case takes the helicopter to a much lower altitude, and combined with smaller longitudinal cyclic inputs produces a much lower rate of climb than in the normal take-off. The effect of the engine governor is clearly visible with the engine torque being reduced when the rotor speed exceed its flight idle value. Two intervals may be observed when the torque of the good engine reaches its contingency limit. The first begins just after failure, and as a consequence the rotor decelerates as the kinetic energy is absorbed to compensate for the torque deficit needed to initiate the next stage of the manoeuvre. After a further 1.5 seconds, the strategy of reducing the collective begins to pay dividends and surplus torque is available to accelerate the rotor back to its reference speed - which it reaches 1.5 seconds later. The demands of the climb-out phase produce the second interval of torque limiting later in the manoeuvre (between 17 and 24 seconds of the elapsed time) and again the plot of the rotor speed shows the initial surrender of kinetic energy to exigencies of the trajectory and its restoration as the manoeuvre severity ameliorates.

Again the results of the simulation may be seen to be generally consistent with the description of 3.2. As a result of the decrease of collective pitch the rotor speed is generally maintained at its reference value apart from the transitory reductions to 3% below nominal during the periods of torque limiting noted above. The pulse of cyclic to give forward pitch is a little larger in this case to give an accelerated entry into the descent phase.

It is worth noting that the flight path reveals this situation to be close to the limiting case for this type of manoeuvre. There are two intervals of torque limitation during which the rotorspeed falls significantly and the recovery flight path, in reality, would be close to the surface of the sea.

c) Failure Well After TDP

For this case the simulated engine failure occurs 10 seconds after the TDP (i.e. 15 seconds into the manoeuvre) and recovery from this position is achieved by continuing with the take-off but assuming a lower climb rate and velocity. The demanded exit condition is

$h_E = 50$ m, $V_E = 50$ knots, $v_E = 1.5$ m/s (≡ 300 ft/min).

Referring to Figure 10, there is little cyclic activity required to assume the adopted recovery manoeuvre. The main action is a reduction in collective associated with the adoption of a less demanding climb-out trajectory, so as to prevent an unacceptable droop in rotor speed. The feature of the torque reaching its contingency limit may be observed again in the interval 16 to 24 seconds of the manoeuvre. In this case the rotor speed falls by more than 6% before excess torque is available to begin to recover

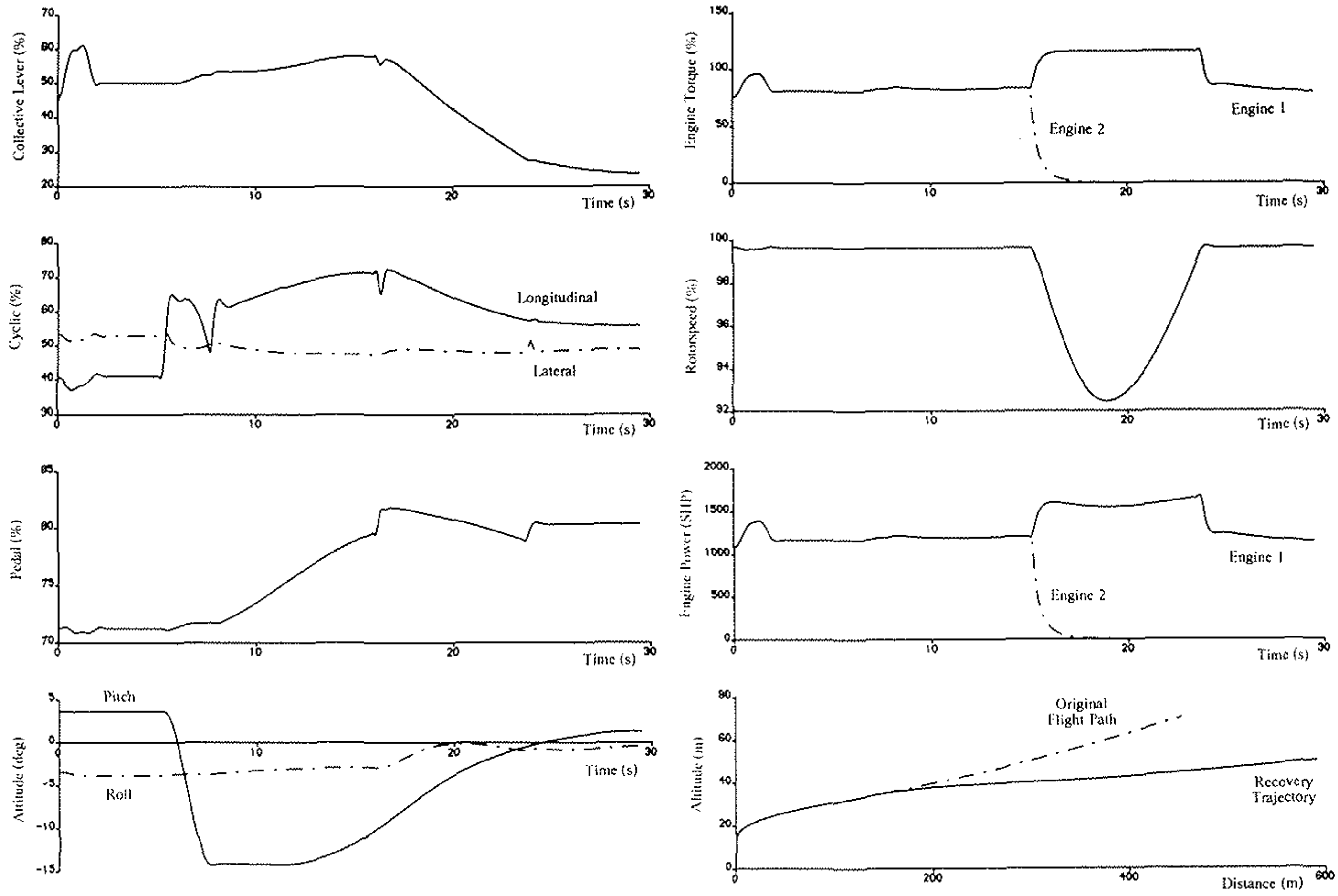


Figure 10 : Inverse Simulation Results for Transport Helicopter Flying a Towering Take-off with Engine Failure at 15 Seconds (Well After TDP)

the nominal rotor speed. Note that the step changes in engine torque produce corresponding step changes in pedal to balance the rotor torque, and a lessening in the rate of reduction of collective. The plot of the flight paths shows quite clearly how the reduction in available engine torque leads to a much lower flight velocity and rate of climb. The simulation results are consistent with the piloting description of 3.3.

5. Conclusions

The success of capturing the important features of piloting strategy and helicopter performance in the normal Towering Take-off procedure and in the case of engine failure has provided an encouraging foundation for extending the range of manoeuvres being investigated and for detailed studies of the Towering Take-off under varying conditions and loadings. Currently, formal descriptions of normal and balked landings - with and without engine failure - are being developed and a programme is in hand for investigating the effect on piloting strategy of varying ambient wind and gust conditions. The maximum weights associated with a successful implementation of a particular take-off strategy is also being investigated. For the work reported in this paper several specific conclusions may be drawn:

i) Piecewise description of the different phases of the normal and OEI Towering Take-off has resulted in a trajectory description which acceptably predicts a typical piloting strategy. A blending parameter allows the effect of different recovery strategies to be investigated.

ii) The development of a combined inverse/forward/ inverse simulation package has allowed pilot reaction time to be included in the study in a natural manner.

iii) The simple twin engine model adequately predicts the surrender of rotor kinetic energy when torque limits are reached. So that the avoidance of excessive rotor speed droop may be used as a criterion for manoeuvre design and hence influence piloting strategy.

Acknowledgements

The research described in this paper is funded by the U.K. Civil Aviation Authority through an ARB Fellowship Award.

References

1. Thomson, D.G., Bradley, R., "Development and Verification of an Algorithm for Helicopter Inverse Simulation", Vertica, Vol. 14, No. 2, May 1990.

2. Bradley, R., Padfield, G.D., Murray-Smith, D.J., Thomson, D.G., "Validation of Helicopter Mathematical Models", Transactions of the Institute of Measurement and Control, Vol. 12, No. 4, 1990.

3. Thomson, D.G., "An Analytical Method of Quantifying Helicopter Agility", Paper 45, Proceedings of the 12th European Rotorcraft Forum, Garmisch-Partenkirchen, Federal Republic of Germany, September 1986.

4. Thomson, D.G., Bradley, R., "The Development and Potential of Inverse Simulation for the Quantitative Assessment of Helicopter Handling Quantities", Proceedings of the AHS/NASA Conference 'Piloting Vertical Flight Aircraft : Flying Qualities and Human Factors', San Francisco, January 1993.

5. Anon, "British Civil Airworthiness Requirements Part 29", Civil Aviation Authority

6. Anon, "Aeronautical Design Standard, Handling Qualities Requirements for Military Rotorcraft", ADS-33C, Aug. 1989.

7. Thomson, D.G. Bradley, R. "Modelling and Classification of Helicopter Combat Manoeuvres" Paper 5.9.1, Proceedings of the 17th ICAS Conference, Sept. 1990.

8. Thomson, D.G., "Development of a Generic Helicopter Mathematical Model for Application to Inverse Simulation", University of Glasgow, Department of Aerospace Engineering, Internal Report 9216, June 1992.

9. Taylor, C., Thomson, D.G., Bradley, R., "Rotor Inflow Modelling Enhancements to Helicopter Generic Simulation Mathematical Model", University of Glasgow, Department of Aerospace Engineering, Internal Report 9215, September 1992.

10. Taylor, C., Thomson, D.G., Bradley, R., "The Simulation of Recovery Procedures from Engine Failures During Helicopter Offshore Operations", University of Glasgow, Department of Aerospace Engineering, Internal Report 9310, July 1993.

11. Padfield, G.D., "A Theoretical Model for Helicopter Flight Mechanics for Application to Piloted Simulation", Royal Aircraft Establishment, TR 81048, April 1981.