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A COMPUTER PROGRAMME FOR THE CERTIFICATION OF HELICOPTER VERTICAL TAKE-OFF AND LANDING OPERATIONS AND AN APPLICATION TO THE S-76B HELICOPTER

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Abstract

In order to support civil and military customers, the National Aerospace Laboratory NLR has developed a computer programme START-OEI, partially under contract of The Netherlands Department of Civil Aviation (RLD). This programme is used for the determination of the relevant flight procedures and the two-dimensional continued and rejected flight paths after an engine failure in the vertical take-off or landing of a multi-engined helicopter. The calculation is based on the energy method, where energy of one source can be exchanged for that from another source. The programme can be run on a Personal Desk computer.
This computer programme has been applied for the certification in The Netherlands of KLM/ERA Helicopters' S-76B for land based vertical operations from confined areas.
Based on the initial calculated flight procedures and flight paths, flight tests were carried out during which engine failure was simulated. Test data were recorded by video on board and on the ground.
With the use of the computer programme performance data for various weights and wind conditions (including performance data for pilot training) have been calculated. Take-off and landing procedures for Category "A" vertical operations with the S-76B were determined and proposed to the RLD. These were approved and supplemented to the Flight Manual just four months after the flight tests.

Notations

C_T	rotor thrust coefficient
D	drag
I_{fus}	inertia of fuselage
I_{rot}	inertia of main rotor, tail rotor and drive train based on main rotor speed
P	power
T	rotor thrust
V	speed of undisturbed airflow
W	weight
g	gravity
h	height
k_i	induced power factor
m	mass
q	pitch rate
t	time
v_i	mean induced velocity at rotor disk
α	angle between tip path plane and undisturbed airflow
γ	angle between undisturbed airflow and X-axis
θ	angle between tip path plane and X-axis
σ	rotor solidity
Ω	main rotor speed

SUBSCRIPTS

acc	accessory
av oei	available under One Engine Inoperative
cl	climb
i	induced
i_0	induced, hover
mr	main rotor
par	parasite
q	pitch of helicopter
tr	tail rotor
req T	required, based on thrust
T	based on thrust
X	in direction of X-axis (earth axis)
Z	in direction of Z-axis (earth axis)

ACRONYMS

AC	FAA Advisory Circular
AGL	Above Ground Level
AHS	American Helicopter Society
AT	IBM Personal Computer type AT
BLSS	Balked Landing Safety Speed
CDP	Critical Decision Point
CFR	Code of Federal Regulations
c.g.	centre of gravity
CT	Continued Take-Off
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
fpm	feet per minute
FSTC	Foreign Science and Technology Center
IAS	Indicated Air Speed
IGE	In Ground Effect
ISA	International Standard Atmosphere
KLM	Koninklijke Luchtvaartmaatschappij (Royal Dutch Airlines, The Netherlands)
LDP	Landing Decision Point
MSL	Mean Sea Level
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory, The Netherlands)
OEI	One Engine Inoperative
Q	torque
R/C	Rate of Climb
R/D	Rate of Descent
RLD	Rijksluchtvaartdienst (The Netherlands Department of Civil Aviation)
rpm	revolutions per minute
RTO	Rejected Take-Off

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T5	power turbine inlet temperature
TOSS	Take-Off Safety Speed
TPP	Tip Path Plane
US	United States

1. Introduction

FAA airworthiness requirements for Transport Category "A" rotorcraft provide the most rigid rules for passenger flights. They require that after a one-engine failure the flight can be continued with a guaranteed climb capability or that a safe landing on the take-off or landing area is assured at the certified weight.

In The Netherlands all civil passenger flights have to be performed with helicopters certified according to CFR Part 29 Category "A". According to FAA Advisory Circular AC-29A, a Category "A" helicopter can be certified for an airfield take-off technique and for a vertical take-off technique from a ground level heliport or an elevated heliport (Ref. 5). For many operations in The Netherlands the possibility of a vertical take-off and vertical landing technique is required, for example the operations from oil rigs in the North Sea and land based operations out of confined areas.

For many years KLM/ERA Helicopters has operated Sikorsky S-61N and S-76A helicopters, of which the latter has been replaced by the B-type.
Due to lack of power, the S-76A equipped with Allison 250-C20S engines was not certified for Category "A" vertical operations out of confined areas or from elevated platforms, but only for oblique Category "A" operations.
The S-76B is equipped with two Pratt & Whitney Canada PT6B-36A engines with dual channel Full Authority Digital Engine Control (FADEC). However, this helicopter was still not certified for the Category "A" vertical operations.
For the other helicopter in the inventory of KLM/ERA Helicopters, the Sikorsky S-61N, the FAA has approved Category "A" procedures for vertical operations at a maximum weight of 17300 lbs and relevant performance data are presented in the Flight Manual.

In the military field, comparable conditions may occur. For example, consider a multi-engined navy helicopter in the hover above the sea for a dipping sonar operation. The hover height is a compromise between a short cable length and enough height above the sea for a safe fly-away without hitting the waves when an engine fails. The fly-away manoeuvre is comparable with the continued take-off for the civil helicopter, when an engine failure occurs in the critical decision point.

In order to support customers in this area, NLR has developed a computer programme, partially under contract of The Netherlands Department of Civil Aviation (RLD), for the calculation of the flight path and establishment of the flight procedures after an engine failure during the vertical take-off or landing.

This paper describes the vertical take-off and landing manoeuvres, the computer programme and an application with respect to the S-76B certification for Category "A" vertical operations out of confined areas.

2. General lay-out of vertical take-off and landing manoeuvres

In general, the normal vertical take-off from or the normal landing with all engines operative, would be as follows.

- Normal vertical take-off.
  A typical take-off profile, which is equal for a ground level and elevated heliport is shown in figure 1 and 2.
  The manoeuvre begins from the hover in ground effect with the addition of sufficient engine power to initiate a vertical climb to the Critical Decision Point (CDP). When passing the CDP the helicopter is tilted nose-down and the power is increased to the certified maximum power rating for all engines operative. While climbing, the forward speed is increased. The landing gear may be retracted after attaining the Take-Off Safety Speed (TOSS).

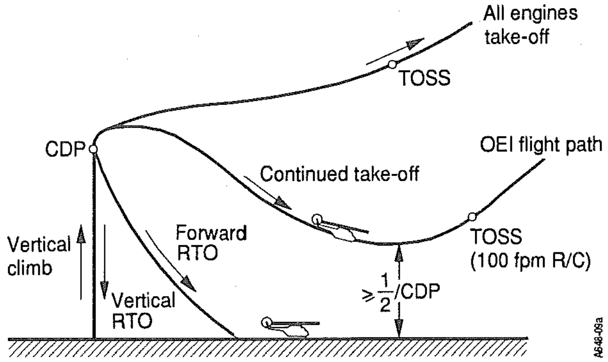

Fig. 1 Category "A" ground level heliport take-off profile

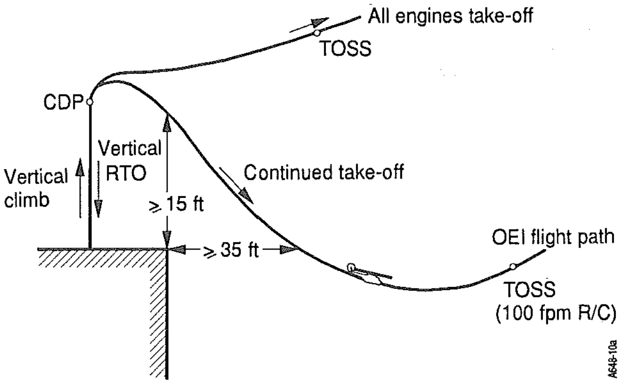

Fig. 2 Category "A" elevated heliport take-off profile

- Normal vertical landing.
  A typical vertical landing profile is shown in figure 3. This profile is equally applicable to ground level and elevated heliports. The helicopter approaches the Landing Decision Point (LDP) with all engines operating at a stabilized single-engine approach condition. After passing the LDP the helicopter is slowed down by tilting the nose upwards and starts descending. The rate of descent is controlled with the engine power. When zero ground speed is reached, the helicopter is levelled and descends vertically till touchdown.

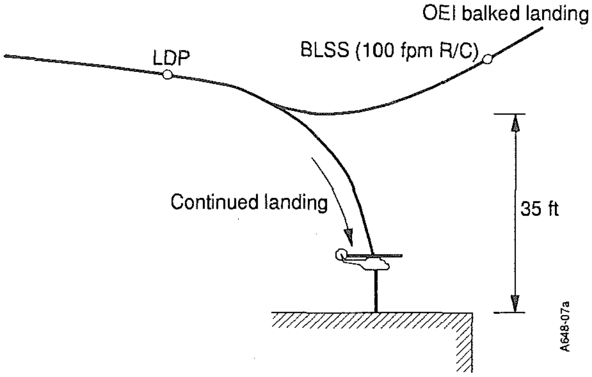

Fig. 3 Category "A" ground level and elevated heliport vertical landing profile

After one-engine failure the power of the remaining engine increases automatically to the certified OEI maximum power rating, if needed. Collective control corrections are only carried out after a certain pilot reaction time. For certification purposes a minimum 1-second delay is taken into account.
In general, the OEI take-off and landing procedures after one-engine failure would be as follows.

- Rejected take-off (RTO).
  When engine failure occurs before rotation in the CDP, the pilot is stop-oriented. The helicopter stops climbing and starts descending while rotor rpm decreases, due to a lack of power. During the descent rotor rpm is kept constant at a prescribed value. At a predetermined wheel height above the take-off surface the collective pitch is increased to cushion the landing, while allowing a rotor rpm drop until the power-on lower limit.
  When sufficient take-off area is available, a forward rejected take-off may be applied instead of the vertical rejected take-off. In this case, after pilot reaction time the helicopter is slightly tilted nose-down in order to gain some forward flight speed. Before cushioning the landing the helicopter is levelled; after touchdown the aircraft is decelerated as fast as possible to a complete stop.

- Continued take-off.
  When an engine fails at rotation in the CDP or at any subsequent point in the normal take-off profile, the helicopter is tilted nose-down further than during the all-engines normal take-off. For an engine failure in the CDP the nose-down tilt is immediate, as the helicopter is already in the rotation.
  Due to a lack of power the rotor rpm drops during the pilot reaction time. While descending, the helicopter accelerates at a predetermined constant and lower rotor rpm until at a predetermined indicated airspeed the helicopter is tilted back to level attitude. The rate of descent will decrease and eventually the helicopter starts climbing. When the TOSS is attained, at a minimum height of 35 ft above the take-off surface and a positive rate of climb the landing gear may be retracted.
  For most applications the rotorcraft is not allowed to descend more than one-half of the CDP height while accelerating to the TOSS. In addition, the rotorcraft is not allowed to descend below the height at which a landing flare normally is initiated.
  For the elevated heliport the lowest point of the OEI profile may not be lower than 50 ft below the take-off surface and 35 ft above the surrounding area, and with specified minimum edge clearances.

- Balked landing.
  When an engine fails in the approach at conditions up to and including the LDP the pilot may choose to perform a balked landing or a continued landing. The balked landing flight profile may be not lower than 35 ft above the landing surface at which the Balked Landing Safety Speed (BLSS) is attained with a positive rate of climb. The balked landing manoeuvre is comparable to the continued take-off, although the helicopter nose-down angle and the height loss will be smaller due to the initial flight speed at the moment of engine failure. The balked landing profile is equal for the ground level and elevated heliport.

- Continued vertical landing.
  The continued vertical landing profile is equal for the ground level and the elevated heliport.
  * When engine failure occurs before or at the LDP and the pilot has decided to perform a continued landing, level flight is maintained at the stabilized single-engine approach condition up to the LDP.
  * When the engine fails after the LDP the aircraft becomes committed to land and a continued landing must be carried out.
  The OEI continued landing is comparable to the normal landing. From the LDP the helicopter is slowed down, and when the helicopter starts descending maximum available OEI power is applied and rotor rpm is held constant. As the ground speed is reduced to zero, the helicopter descends vertically; the remaining part of the procedure is identical to that of the vertical rejected take-off.

3. Description of the mathematical model

3.1 Technical approach

NLR has developed a computer programme, called START-OEI, which calculates two-dimensional helicopter flight trajectories after a one-engine failure in the CDP/LDP during a vertical take-off or vertical landing.
The following OEI flight profiles can be calculated:
- forward and vertical rejected take-off,
- continued take-off,
- balked landing,
- continued landing.

The continued landing procedure is comparable with the vertical rejected take-off. So for the calculations the same rejected take-off manoeuvre can be used, provided that the appropriate values of the control parameters are applied.
For the calculation of the balked landing, the continued take-off manoeuvre can be applied.

The calculation of the flight path is based on the energy concept discussed in para 3.3, where energy of one source can be exchanged for that of an other, e.g. a decrease in rotor speed for a lower rate-of-descent. The helicopter is "flown" in the vertical plane of the earth axes system by controlling the linear accelerations in the X and Z directions. A control strategy results in a continuous specification of the control parameters in order to achieve the desired flight trajectory. The helicopter is simulated by a point mass model in its centre of gravity with forces acting on it, being the main rotor thrust corrected for the main rotor download on the fuselage, the aerodynamic parasite drag and the helicopter weight. Since the energy method does not provide for fuselage angle of attack data, an empirical relationship is provided for this purpose starting from the thrust vector tilt and fuselage attitude in the CDP or LDP.
The direction of the rotor thrust vector during the manoeuvre is specified by the control strategy, and the magnitude of the rotor thrust determines the power required. The difference between power available from the remaining engine(s) and power required can be supplied by the extraction of energy from one of the energy sources available to the pilot. So, the accuracy of the flight path calculation depends strongly on the accuracy of the calculated power required in the various flight conditions. At the moment the mathematical model only includes single-main-rotor/tail-rotor or single-main-rotor/Fenestron helicopters without a wing.

In principle, START-OEI is composed of the following three parts:

- A power required match routine.
  Starting from a set of physical parameters of the helicopter, aerodynamic data and correction parameters (e.g. induced power factor, rotor download factor etc.), calculated performance results are evaluated against provided performance data for steady flight conditions. The appropriate parameter values and aerodynamic data are reached when a reasonable correlation is obtained between calculated power required and provided data in the relevant flight speed range for selected flight conditions and helicopter weights.
- Flight path calculation.
  The symmetrical flight trajectory is calculated by solving the equations of motion in the vertical plane. The nature of the rejected and continued take-off and landing manoeuvres is preprogrammed, but the actual flight path is governed by the chosen values of the control parameters.
- A partial optimization routine.
  The flight path calculation for a chosen set of control parameters without any control feed back is straightforward, but rather time consuming. In order to reduce the number of computing runs, the programme recently has been amended with a partial optimization routine. The optimization of some of the control parameters can be carried out automatically.

In order to be independent of a fix-based mainframe computer, the programme is written in Turbo Pascal language to be run on an AT-type Personal Desk Computer with a minimum of 640k memory. This gives the opportunity to carry the computer with you to the test site. The computing time is approx. ten seconds for one specific trajectory and 5 minutes for one optimization run.

3.2 Helicopter power required calculation method

The power required is calculated from a set of closed-form equations, using the well-known combination of momentum theory for the rotor induced power and a simple blade element theory for the rotor profile power as shown in many text books, e.g. reference 1. In combination with the determination of the rotor induced velocity according to the theory of Shaydakov as applied at NLR, this power required calculation method provides a sufficiently accurate basis for helicopter performance and flight trajectory calculations.
In the following paragraphs some points will be discussed in more detail.

Rotor induced velocity. For flight conditions where the undisturbed airflow enters the rotor disc from above as for a helicopter in the climb (negative rotor angle of attack), the induced velocity can be determined according to the Glauert theory. But for those flight conditions where the rotor has a large positive angle of attack as in a powered descent, the momentum theory is no longer valid. For calculation of the rotor induced velocity NLR uses the method developed by V.I. Shaydakov (Ref. 2). This method, stated by the author as a first attempt to establish a theory for the aerodynamics of a rotor in a steep descent, is based on the assumption of an ideal fluid with a constant induced velocity across the rotor wake and without slipstream rotation. In a first instance, a rotor in a forward autorotation is assumed. The flow carries vortex rings of circulation upward along a skewed vortex cylinder with diameter equal to the rotor diameter as they separate from the rotor blade tips and with a velocity of the undisturbed airflow plus half the induced velocity. When power is supplied to the rotor as in a powered descent, the theory assumes that a second set of vortex rings will separate in a downward direction from the blade tips. The induced velocity in the plane of the rotor disc is the result of the upper and lower vortical cylinders.
The results of this theory are presented in figure 4 where the rotor induced velocity (made non-dimensional with the ideal hover value) is given as a function of the non-dimensional undisturbed airspeed and the angle of attack α of the rotor tip path plane. This angle is positive for the airflow coming from below as in a descent. For negative angles of attack the Shaydakov results are in very good agreement with induced velocities calculated with momentum theory.
For positive angles of attack Shaydakov gives reasonable results for not too high values of the undisturbed airflow. In the powered descent situations where the non-dimensional airflow remains below approx. 0.5 (as in a powered descent after one-engine failure) the Shaydakov method can be used with confidence.

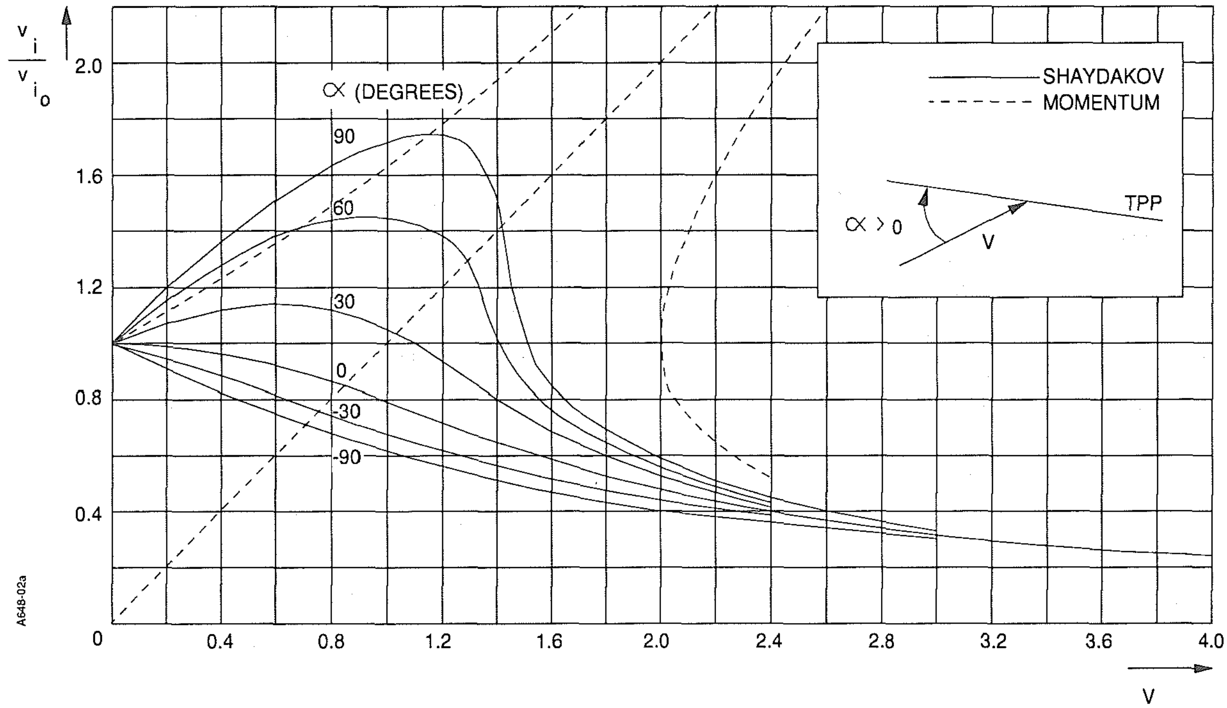

Fig. 4 Rotor induced velocity according to Shaydakov and momentum theory

Induced power. The rotor induced power is calculated with $P_i = k_i . T . v_i$ in which T is the actual rotor thrust, v_i the mean induced velocity according to Shaydakov and k_i is the induced power factor accounting for non-uniform induced velocity, tip loss effects, blade root cut-out etc. This factor is determined for the hover value of C_T/σ in a first instance according to reference 3 and either decreases linearly with increasing flight speed or is kept constant.

Profile power. The profile drag coefficient of the airfoil is expressed in a closed form and is derived from 2-dimensional aerodynamic data including Mach and stall effects. The profile power is based on the rotor thrust and a mean blade angle of attack.

Tail rotor power. The tail rotor induced velocity is calculated with the Glauert approximation, taking into account the effect of vertical fin blockage on tail rotor thrust. The induced power factor is determined as for the main rotor. The profile power is based on a constant profile drag coefficient.

Ground effect. Ground effect is taken into account in the main rotor induced power calculation. The hover value of the ground effect is determined according to reference 4 and is assumed to decrease linearly to zero at a speed of 40 kts.

3.3 Energy Concept

In a One Engine Inoperative (OEI) situation the power available from the remaining engine(s) $P_{av\ oei}$ may be lower than the helicopter power required. In this case the deficiency in power required can be supplied by a decrease of one of the energies of the helicopter, which are the helicopter potential and kinetic energy and the rotor kinetic energy:

$$P_{av\ oei} = P_{req\ T} + mg\frac{dh}{dt} + mV\frac{dV}{dt} + I_{rot}\Omega\frac{d\Omega}{dt} \tag{3.1}$$

The power required $P_{req\ T}$ is based on the rotor thrust T which may be higher or lower than the helicopter weight. The power required can be expressed as the sum of the main rotor power P_{mr} and tail rotor power P_{tr}, helicopter parasite drag power P_{par}, power for accessories P_{acc} and power for tilting the rotor and fuselage P_q:

$$P_{req\ T} = (P_{mr} + P_{tr})_T + P_{par} + P_{acc} + P_q \tag{3.2}$$

The change of helicopter kinetic energy is the sum of the contributions in the horizontal and vertical plane:

$$mV\frac{dV}{dt} = mV_x\frac{dV_x}{dt} + mV_z\frac{dV_z}{dt} \tag{3.3}$$

According to Newtons law we can write for each component:

$$mV_x\frac{dV_x}{dt} = (T_x - D_x)V_x = \\ = TV_x \sin\theta - DV\cos^2\gamma \tag{3.4}$$

$$mV_z\frac{dV_z}{dt} = (W - T_z - D_z)V_z = \\ = WV_z - TV_z\cos\theta - DV\sin^2\gamma \tag{3.5}$$

And the energy rate for the tilting rotor, e.g. in pitch direction can be approximated by:

$$P_q = \frac{1}{2} I_{rot}\, q\, \frac{dq}{dt} \tag{3.6}$$

In which D is the helicopter parasite drag, T *the rotor thrust minus the correction for rotor* download on the fuselage, γ the flight path angle, V the undisturbed airspeed and I_{rot} the rotor polar moment of inertia.
Substitution of the equations above into equations (3.1) and (3.2) gives the relationship between the main rotor rpm decay, tilt angle θ of the rotor thrust with respect to the vertical and the magnitude of the corrected rotor thrust T for given flight speed components V_x and V_y:

$$P_{av\ oei} = (P_{mr} + P_{tr})_T + P_{acc} + (\frac{1}{2} I_{rot} + I_{fus})$$
$$* q \frac{dq}{dt} + TV_x \sin\theta - TV_z \cos\theta + I_{rot}\Omega \frac{d\Omega}{dt} \tag{3.7}$$

3.4 Control strategy.

Following an interview with KLM/ERA Helicopters' pilots, the control model has been developed on the cues which the pilot receives and on the behaviour of the helicopter as a result of pilot collective and cyclic control actions based on these cues.

In a scheduled symmetrical rejected or continued take-off manoeuvre the pilot uses the following cues:
- pitch attitude of the helicopter;
- indicated airspeed;
- main rotor rpm;
- height above the take-off or landing surface.

In the One Engine Inoperative (OEI) manoeuvres, where the power available of the remaining engine(s) is less than the power required for normal take-off, the pilot controls the extraction of energy from the available sources with collective and cyclic control inputs. But in fact he controls the magnitude and direction of the rotor thrust in space with a feedback from his cues. These are:
- in the vertical rejected take-off the rotor rpm and height, and in the forward rejected take-off additionally the helicopter attitude;
- in the continued take-off the rotor rpm, the helicopter attitude and the flight speed.

Further, the flight path is determined by constraints within which the manoeuvre has to be performed successfully. These constraints are:
- specified control action delay after engine failure;
- maximum pitch rate in the forward rejected and continued take-off; this is restricted by rotor and helicopter characteristics, pilot behaviour or by operator requirements (passenger comfort);
- minimum main rotor speed (during OEI flight or touchdown);
- maximum vertical speed at touchdown;
- minimum height above terrain in the continued take-off due to operational requirements, or maximum height below the take-off surface for an elevated heliport.

In the mathematical model, the control parameters are the rotor rpm, the thrust vector tilt with respect to the vertical and their derivatives.
The manoeuvre calculation starts in the critical decision point possibly with a ground speed, head wind and a rate of climb or descent. Gradual or abrupt engine failure can be selected, with the power of the remaining engine increasing gradually. The one second collective delay after engine failure is simulated by a constant rotor thrust coefficient which determines the rotor rpm decay. After this time period the rpm decay is kept above a specified minimum value until the chosen (constant) rpm for descent is reached.
In the continued take-off and forward rejected take-off, immediately after the engine failure longitudinal cyclic is applied, which is simulated by a tilt of the rotor thrust vector according to a sine function. Parameters are the time period or the maximum pitch rate.
In the continued take-off the forward thrust vector tilt is maintained at a constant rotor rpm until a specified lead of the take-off safety speed is reached. From this point in the flight path the thrust vector is tilted backwards gradually to the position according to steady flight at the take-off safety speed while maintaining rotor rpm at the descent value. The manoeuvre is terminated when a prescribed rate of climb (100 ft/min) or a required height above the ground is reached.

In the vertical rejected take-off manoeuvre the rotor rpm is kept constant during the descent until, from a prescribed height, the landing is performed with a chosen rpm decay. In a forward rejected take-off the rotor thrust vector tilt is maintained at a constant rotor speed and is tilted backwards at a specified height. When the ground is reached a running landing is performed and the helicopter is decelerated to a full stop.

3.5 Flight path calculation.

The flight path is calculated by integration from one time step to the other. Given the power available, total airspeed, rotor angle of attack, rotor rpm, rpm decay and thrust vector tilt, the magnitude of the rotor thrust T can be determined with equation 3.7. With the solved value for T the new point in the flight path is calculated with the helicopter equations of motion using a time step of 0.05 sec.
The fuselage pitch attitude during the manoeuvre is calculated from the thrust vector tilt and an experimental correlation between flight speed and fuselage pitch attitude, taking into account the initial attitude in the CDP. Additional results that are obtained are the travelled vertical and horizontal distance and the separation between tail rotor and the deck edge in the case of an OEI continued take-off from an elevated heliport.

3.6 Partial optimization routine

The flight path calculation is straightforward without any loop. Starting from initial conditions in a chosen CDP and a chosen helicopter weight, the appropriate values of the control variables are determined by manual iteration in trying to fulfil the touchdown requirement (vertical speed and rpm) and overflight requirement (minimum height AGL). If the requirements cannot be met for one of the manoeuvres, the helicopter weight, the rate of climb at the CDP and/or the height of the CDP has to be adapted. A solution is reached when for combinations of CDP and weight the requirements of the rejected take-off and continued take-off are fulfilled simultaneously. Due to the large number of variables, this method is rather cumbersome.

In order to reduce the number of calculation runs, a simple partial optimization routine (see figure 5) has recently been developed to optimize between the vertical rejected take-off and continued take-off, but this routine has not yet been completely evaluated.

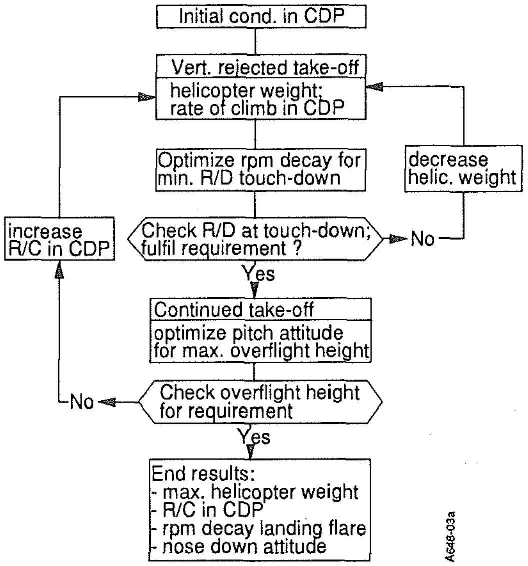

Fig. 5 Flow diagram of the optimization.

From the large number of variables, a limited number may already be chosen by the operator. These are for example the height of the CDP, rotor rpm at the fly-away or descent stage, pitch rates, and height above the ground when commencing the landing flare in the rejected take-off.

The routine estimates the optimal combination of the rate of climb in the CDP, nose-down attitude in the continued take-off and rate of rotor rpm decay in the landing flare for the highest helicopter weight.

4. Sikorsky S-76B certification: initial computer simulations

The START-OEI computer programme has been applied for the certification of the Sikorsky S-76B helicopter vertical take-off and landing operations from land based confined areas. First of all, the S-76B mathematical model had to be prepared making use of data from several sources (viz. flight manual and maintenance manual, engine performance specification, Sikorsky company and general literature). The thus completed model was verified by comparing the calculated steady state power required with data provided by Sikorsky. Some results are shown in figure 6 for level flight at MSL/ISA condition.

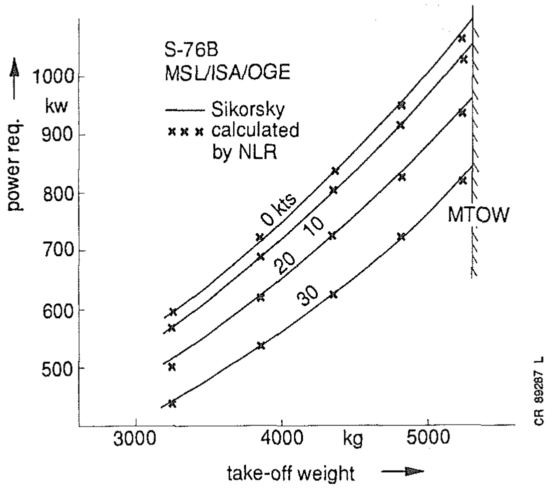

Fig. 6 Comparison of calculated power required with Sikorsky data for several air speeds

In order to determine whether the S-76B could be operated according to the requirements for Category "A" vertical operations, and to determine the optimum lay-out of each manoeuvre, simulation cases were run for various weights and atmospheric conditions. The general lay-out of the manoeuvres had to be similar as far as possible to those for the S-61N, the other aircraft in KLM/ERA Helicopters' inventory. For the four OEI procedures described in chapter 2, several parameters had to be optimized. They are the following:

- height of the CDP and LDP;
- climb speed at the CDP;
- nose-down angle for fly-away;
- speed at which to bring nose up during fly-away;
- wheel height at which to start the landing flare;
- nose-up angle to decelerate helicopter.

The CDP height and climb speed at the CDP had to optimized in combination. If the height of and the climb speed at the CDP are high, then the rejected take-off will pose a problem. Otherwise, if these are low then the continued take-off will pose a problem. Analogue arguments are valid for the height of the LDP in relation to the balked and continued landing.

Several other parameters were more or less fixed already:

- Take-Off Safety Speed: this value was set at 40 kts (based on the accuracy of the speed indicator at low air speeds and on the S-76B OEI climb performance);
- rpm during continued take-off: this value was set at 100 % (taken from the Flight Manual);
- time to rotate the helicopter: this parameter is related to the rotor characteristics, and was determined during flight tests;
- minimum rpm at touch down: this value was set at 68 % (taken from the Flight Manual);
- maximum rate of descent at touch down: it was mutually agreed to fix this value at zero.

Other factors that had to be taken into account are the criteria for FAA Category "A" operations as laid down in Advisory Circular AC-29-2A (Ref. 5). These are a.o.:

- procedure must be based on power available of installed minimum specification engine;
- power of failing engine decreases instantaneously to zero;
- minimum height during continued take-off is 35 ft above any obstacle within the take-off distance, but not below one half times the CDP height;
- minimum height when overflying obstacles during a balked landing is 35 ft above the obstacles surrounding the landing surface;
- some margins on the parameter values must be available without endangering the manoeuvre.

The computer simulations showed that the continued and rejected take-off are the most demanding manoeuvres.

5. Flight tests

5.1 Objective

Based on the calculated results a flight test programme was set up, with the following objectives:

- validate the computer model of the S-76B helicopter;
- demonstrate the helicopter's capabilities after one-engine failure;
- demonstrate that the theoretically derived manoeuvres are correct and feasible when flown by a standard trained pilot.

Various aspects of the flight test programme are elucidated in the following paragraphs.

5.2 Data acquisition

For the data acquisition use was made of video systems, both on board (flight parameters) and on the ground (flight path).
The video system on board recorded part of the co-pilot's instrument panel:

- analogue radar altimeter;
- attitude director indicator, including a digital readout of the radalt;
- analogue airspeed indicator;
- digital clock with seconds on display;
- digital and analogue torquemeter;
- analogue triple tachometer.

Loading conditions and fuel quantities were written down at regular intervals to facilitate the calculation of the weight and centre of gravity position.
For flight path registration a video camera was installed in the field. Black and white blocked flags were installed at predetermined positions for reference.
Ambient conditions were written down at regular intervals.

5.3 Flight test programme

During the flight test programme a total of 46 test runs was made (continued and rejected take-offs, and continued and balked landings). Engine failure was simulated by sharply retarding one throttle to the idle position.

A range of conditions was covered by variation of several parameters during the course of the flight testing:

- power available (initially limited to maximum continuous power making use of the so-called T5-bias box; later on, power was increased to the 30 minutes OEI rating, which is the only and therefore maximum emergency power rating);
- weight and centre of gravity (by burning or adding fuel or by means of ballast);
- height of the CDP and LDP;
- ambient conditions (the maximum allowable wind speed for the tests was 10 kts);
- pilots (two pilots were involved in the programme, each of them acting as pilot flying for about half of the total number of flights);
- moment of engine failure for the landing manoeuvre (simulated both at the LDP and some distance before the LDP).

6. Processing of flight test data

After each of the flight testing days the data available on video tape (flight instruments and flight path) or on paper (helicopter mass and ambient conditions) were processed. The results of the first day were used for an intermediate update of the computer simulation programme before the predictions for the next flight testing day were made. The results of the second day were used for a final validation of the programme. In both cases the approach for the data processing was the same.

The data on the video tape (time, radalt, fuselage pitch, torque, rpm, airspeed) were read out at one second intervals, with the time scale datumed to zero seconds at the point of engine failure. The read-out of the radalt was corrected for fuselage pitch angle influence. The computer simulation programme was run to reproduce the test data. The initial conditions at the time of engine failure, the fuselage pitch attitude versus time, the engine's power rate of decay and acceleration, minimum rotor rpm during fly-away and wheel height at which flare for landing was initiated, were used as input for the programme. The simulation programme then produced time history traces of the calculated rotor rpm, airspeed, radar altitude (wheel height), fuselage pitch attitude and torque per engine. Figure 7 shows a comparison between data coming from the flight tests and those coming from the computer simulations. In general the correlation between flight test data and calculations was good, as can be seen in this figure. It is to be noted that the helicopter's air speed indication system is not usable at speeds below about 20 kts.

7. final results

The flight tests were carried out for a limited range of weights and ambient conditions. Based on these flight test results, additional calculations were made to determine the maximum take-off and landing weight for Category "A" Vertical Operations for a wide range of ambient conditions. The height of the CDP and the LDP was fixed at 100 ft in order to be able to allow (high) obstacles surrounding the take-off or landing zone.

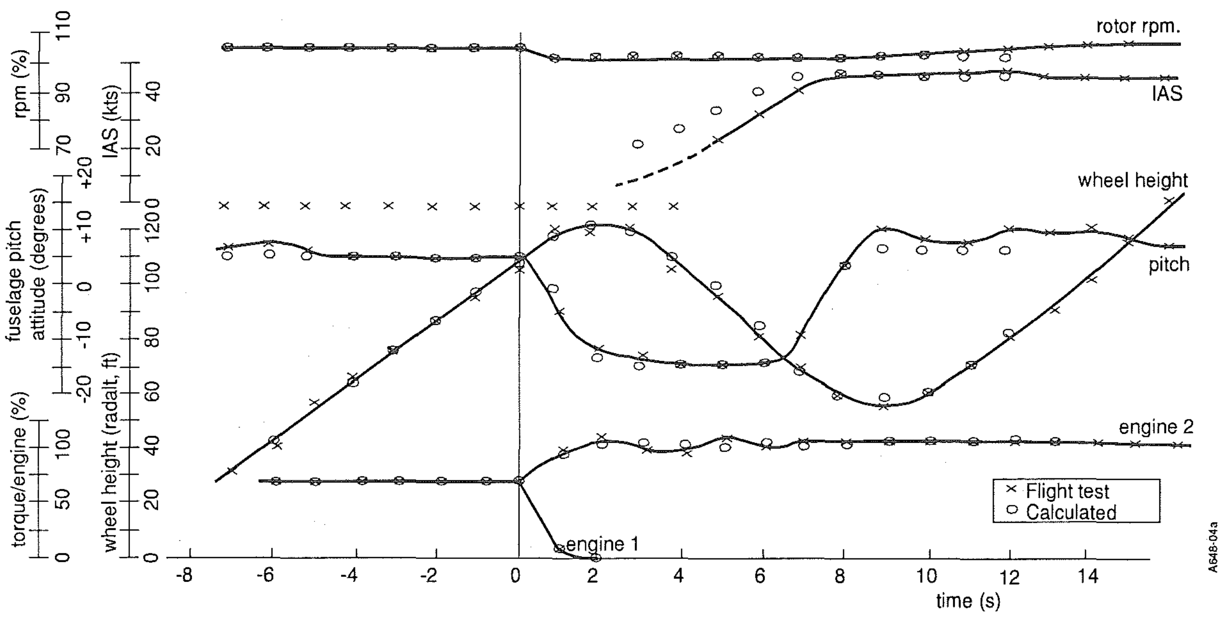

Fig. 7 Time history trace of continued take-off

The optimum rate of climb at the CDP for the no wind/MSL/ISA condition was calculated to be about 820 ft/min, giving the same weight limit for the continued and the rejected take-off. This same rate of climb was used for all weights and wind conditions at MSL/ISA. For other ambient conditions the rate of climb at the CDP will be different. This effect has been taken into account in the calculations for the maximum allowable weight.
The calculations were carried out for parameters, which were either optimized or derived from the flight tests. The following details were used for the manoeuvres, with instantaneous engine failure at the CDP or LDP:

- continued take-off:
  rotate to a 15 degrees nose-down attitude in 2 seconds; increase the other engine's torque to the maximum allowable value (within gearbox limitations) and let rotor rpm drop from 107 % to 100 %; at 30 kts indicated airspeed level off (about 5 to 7 degrees nose-up) in 3 seconds, while still accelerating to the Take-Off Safety Speed of 40 kts; at 100 ft/min rate of climb (at an airspeed of 40 kts or more) the calculation was stopped;
- rejected take-off:
  when the helicopter descends (about 3 seconds after passing the CDP), increase the torque of the other engine to the maximum allowable value; maintain rotor rpm at 107 %; at about 30 ft wheel height increase collective pitch to cushion the landing; let rpm drop at a rate consistent with a touchdown with zero rate of descent and rotor rpm not below 68 %;
- balked landing:
  the procedure is comparable to the continued take-off, but the nose-down attitude is 5 degrees and the indicated airspeed at which the helicopter is levelled off is 35 kts;
- continued landing:
  rotate to a 15 degrees nose-up attitude to decelerate; increase the torque of the other engine such that the helicopter does not climb; maintain rotor rpm at 107 %; apply maximum allowable engine torque when the helicopter starts descending; rotate helicopter back to hover pitch attitude slightly before reaching zero ground speed (for a vertical descent); at 30 ft wheel height increase collective pitch in the same way as in the rejected take-off.

The final results for the S-76B FAA Category "A" vertical operations were presented in graphs, which provide:

- for normal operations: the maximum take-off and landing weight as a function of pressure altitude, outside air temperature, wind speed and obstacle height, making use of the maximum OEI power rating;
- for single engine pilot training: the maximum take-off and landing weight as a function of ambient conditions, making use of the T5-bias box;
- the required twin engine climb-out torque versus take-off gross weight and wind speed (this torque is to be used to climb from a 5 ft IGE hover to the CDP).

These graphs and a description of the procedures were supplemented to the S-76B Flight Manual after approval by the RLD.

8. Deviations from calculated manoeuvres

The calculations have been carried out for a near-optimal set of parameter values. During real flight, deviations from these values may and will occur. But these deviations may not impose any danger to the aircraft or the persons aboard.
It was assumed that a total one-engine failure takes place exactly at the CDP or LDP (requested by Advisory Circular AC-29-2A). If the decay of the engine is slower or if the failure takes place at any other point of the flight path, the manoeuvre conditions improve and therefore the manoeuvre becomes less critical. The same holds if the remaining engine performs better than the minimum specified value (as it usually will do).

Other deviations may result from differences in piloting technique in comparison with the prescribed one. The influences differ for each of the manoeuvres. The most important deviations (those which have a deteriorating effect) will be analyzed hereafter.

Continued take-off:

- rotor rpm:
  dropping the rotor rpm to a value higher than 100 % increases the dropdown by several feet; for this reason it is very important to keep the rotor rpm at or slightly below 100 %;
- fuselage pitch-down angle:
  if the nose-down attitude is a few degrees larger, the dropdown increases by about 1 ft;
- time for pitching nose-down:
  taking 2.5 instead of 2 seconds increases dropdown with about 4 ft; the pilot is fixated to pitch down when passing the CDP (also when no engine fails); therefore a time of 2 seconds is a realistic upper boundary; this was proven during flight tests;
- time to level the helicopter:
  taking more than 3 seconds is unrealistic as was proven during flight tests;
- flight speed at which to level off the helicopter:
  bringing nose up at a higher speed increases dropdown a few feet;
- influence of c.g.:
  normal hover attitude of the KLM/ERA Helicopters' S-76B ranges from 5 to 7 degrees nose-up, depending on c.g.; the difference in dropdown between these two configurations is less than 1 ft.

Rejected take-off:
the calculations have been made for touchdowns with zero rate of descent and minimum rotor rpm (68 %); according to Sikorsky the undercarriage of the S-76B is capable of withstanding landings with 390 ft/min rate of descent without damage up to the maximum weight of 11700 lbs; for that reason ample margin is available during touchdown (e.g. a touchdown with 85 % instead of 68 % rotor rpm gives a rate of descent at touchdown of about 300 ft/min).

Balked landing:
as concluded earlier this manoeuvre is not critical and therefore ample margin is available.

Continued landing:
as concluded earlier this manoeuvre is not critical; furthermore, the undercarriage is capable of withstanding 390 ft/min rate of descent at touchdown; so ample margin is available here.

Other deviations may arise from instrument errors. These errors are small when compared to the deviations mentioned before and their influence on the flight path is negligible.

Another important aspect is that pilots, who will fly the S-76B during Category "A" Vertical Operations, will be trained and qualified for these procedures. During the flight test programme it was shown that the flight paths after the first one were all about equal. This is a clear indication that training for these procedures is worthwhile.

It is not likely that large deviations from the values used for the calculations will occur if the procedures are followed closely. Small deviations however are imaginable, but their influence is only small. The most important parameter to pay close attention to is the main rotor rpm.

9. Conclusions

Partially under contract of The Netherlands Department of Civil Aviation (RLD), the National Aerospace Laboratory NLR has developed the computer programme START-OEI. This programme, that can be run on an AT-type Personal Desk computer, calculates the 2-dimensional continued and rejected vertical take-off flight profiles and the continued and balked landing flight profiles after one-engine failure of a multi-engined helicopter.

The calculation method is based on a performance model of the helicopter in combination with energy considerations, where energy of one source can be exchanged for that of another or can be used to supplement the power available. The helicopter is controlled along the flight path by parameters which simulate the cues that the pilot uses in real flight.

The computer programme has been applied successfully for the Netherlands' certification of KLM/ERA Helicopters' S-76B helicopters for Category "A" vertical take-off and landing operations from confined areas. Based on computer simulations and flight tests, safe procedures have been established at the highest possible mass and a range of atmospheric conditions. These procedures have been proposed to the RLD, together with performance data for pilot training. After approval by the authorities, the data have been supplemented to the Flight Manual.

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