S-76B CERTIFICATION FOR VERTICAL TAKE-OFF AND LANDING OPERATIONS FROM CONFINED AREAS.

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Abstract

Passenger flights by KLM Helikopters in The Netherlands are performed according to US Federal Aviation Administration (FAA) airworthiness requirements for Transport Category A rotorcraft. KLM Helikopters operates four Sikorsky S-76B helicopters, mainly for off-shore transport. The S-76B has been certified by the FAA for Category A operations from airfields, but not for vertical operations. The National Aerospace Laboratory NLR has generated the data necessary for certification of vertical operations by the Netherlands Department of Civil Aviation (RLD).

For the project use was made of a computer simulation programme, that calculates two-dimensional flight trajectories after an engine failure during take-off or landing.

Based on the initial results of computer simulations flight tests were carried out, during which single engine failure was simulated. Test data were recorded by video on board and on the ground.

Calculated and flight test data were in good agreement over the considered range of masses, manoeuvres and atmospheric conditions. Procedures for Category A vertical operations with the S-76B were determined with the use of the computer programme and proposed to the RLD. They 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
BL	Balked Landing
CDP	Critical Decision Point
c.g.	centre of gravity
CL	Continued Landing
CT	Continued Take-Off
FAA	Federal Aviation Administration
FSTC	Foreign Science and Technology Center
H-V	Height-Velocity
IAS	Indicated Air Speed
ISA	International Standard Atmosphere
KLM	Koninklijke Luchtvaartmaatschappij (Royal Dutch Airlines, The Netherlands)
LDP	Landing Decision Point
MSL	Mean Sea Level
MTOW	Maximum Take-Off Weight
NLR	Nationaal Lucht- en Ruimtevaart Laboratorium (National Aerospace Laboratory, The Netherlands)
OAT	Outside Air Temperature
OEI	One Engine Inoperative
Q	torque
RLD	Rijksluchtvaartdienst (Department of Civil Aviation, The Netherlands)
rpm	revolutions per minute
RT	Rejected Take-Off
T5	power turbine inlet temperature
TOSS	Take-Off Safety Speed
TPP	Tip Path Plane

1 Introduction

Passenger flights by KLM Helikopters are performed according to FAA airworthiness requirements for Transport Category A rotorcraft. Category A provides the most rigid rules, requiring that after a single 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 certificated weight.

For many years KLM Helikopters operated a.o. Sikorsky S-76A helicopters equipped with Allison 250-C20S engines. Due to lack of power this helicopter was not certified for Category A vertical operations out of confined areas or from elevated platforms.
The S-76A has been replaced by the more powerful S-76B with Pratt & Whitney Canada PT6B-36A engines. However, this helicopter was still not certified for the Category A vertical operations.

An other helicopter in the inventory of KLM Helikopters is the Sikorsky S-61N. For the S-61N the FAA-approved Category A procedures for vertical operations at a maximum weight of 17300 lbs are presented in the Flight Manual. It has been demonstrated by Sikorsky that under the restrictions posed by the aforementioned procedures safe operation can be maintained if one engine fails at any point along the take-off or landing flight path.

A preliminary comparison of essential performance parameters of the S-61N and the S-76B has been made by KLM Helikopters and the National Aerospace Laboratory (NLR). The ratio of single engine power available and power required is considered to be a main criterion for Category A vertical operations. The results of this comparison showed that the S-76B at a weight between 10500 and 11300 lbs (the MTOW is 11700 lbs) was likely to perform about equally as the S-61N at 17000 lbs (the normal MTOW is 20500 lbs).

Based on the foregoing, NLR was asked to investigate under what One Engine Inoperative (OEI) limiting conditions the S-76B could be operated according to the FAA requirements for Category A vertical operations based on the analogy of the S-61N. For the project use was made of computer simulations, and of flight tests with simulated engine failure.

This paper describes the vertical take-off and landing manoeuvres, the computer simulation programme and the flight test programme, and provides some insight in the final results of the S-76B certification for Category A vertical operations.

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

Based on S-61N practice, the normal take-off from or the normal landing into a confined area with all engines operative, would be as follows:

- normal take-off:
  the helicopter climbs vertically at a prescribed torque level to the Critical Decision Point (CDP); when passing the CDP, torque is increased to maximum take-off rating and the helicopter is tilted nose-down; while still climbing the forward speed will increase; when passing the Take-Off Safety Speed (TOSS) the undercarriage is retracted;
- normal landing:
  the helicopter approaches the Landing Decision Point (LDP) at 30 kts level flight; after passing the LDP the helicopter is slowed down by tilting the nose upwards without climbing; torque is decreased so that the helicopter starts descending; when zero ground speed is reached, the helicopter will descend vertically till touchdown.

After one engine failure the power of the remaining engine increases automatically to the maximum (if needed) value and the OEI take-off or landing procedure would be as follows:

- continued take-off (CT):
  when engine failure occurs at or beyond rotation in the CDP, the helicopter is tilted nose-down immediately (further than for normal take-off); the rotor rpm is allowed to drop to a predetermined value; the helicopter accelerates while descending; at a predetermined airspeed the helicopter is tilted back to level attitude while still accelerating; the rate of descent will decrease and eventually the helicopter starts climbing; when passing the TOSS the undercarriage is retracted;
- rejected take-off (RT):
  when engine failure occurs before rotation in the CDP, the helicopter will stop climbing and starts descending due to lack of power; during the descent rotor rpm is held constant; at a predetermined wheel height collective pitch is increased; rotor rpm will drop and the helicopter slows down for a cushioned landing;
- balked landing (BL):
  when engine failure occurs before the LDP the pilot may choose to perform a balked landing; the manoeuvre is comparable to the continued take-off, although the nose-down angle and the height loss will be smaller due to the initial speed of 30 kts;
- continued landing (CL):
  * when the engine failure occurs before the LDP, the pilot may choose to perform a continued landing; level flight at 30 kts is maintained up to the LDP;
  * when the failure occurs at or after the LDP a continued landing must be carried out;
  in both cases the OEI continued landing is comparable to the normal landing; the helicopter is slowed down; when the helicopter starts descending, maximum available 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 then is identical to the rejected take-off.

Figure 1 gives an example of the flight path for a normal take-off and for an OEI continued take-off.

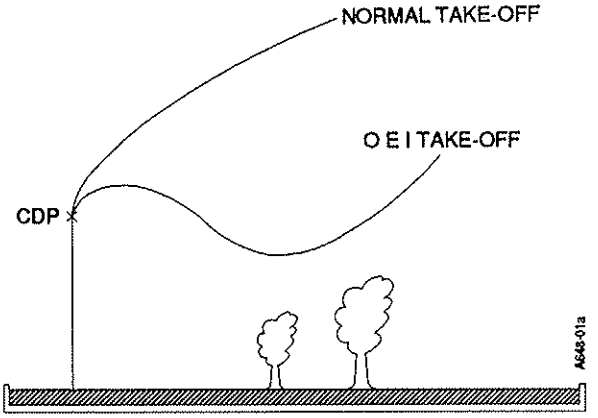

Fig. 1 Schematic representation of vertical take-off flight path

3 Computer simulation programme

3.1 General

NLR has developed a computer programme, so called START-OEI, for the calculation of the helicopter flight trajectory after one-engine failure during vertical take-off or landing. Manoeuvres that can be simulated are:

- continued take-off;
- forward and vertical rejected take-off;
- continued landing;
- balked landing.

For the continued landing and balked landing manoeuvres the calculation methods of the forward rejected take-off and continued take-off can be applied respectively.

The calculation is based on the energy method, 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 heart of the computer programme is the calculation method for the helicopter power required. At the moment the programme is only suitable for single-rotor/tail-rotor or Fenestron helicopters.

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

- a match programme for the evaluation of parameters in the power required calculation (e.g. induced power factor or climb efficiency factor); the appropriate parameter values are reached when a reason-able correlation is obtained between calculated power required and provided data in the relevant flight speed range for selected flight conditions and helicopter weights;
- a programme for the calculation of symmetrical flight trajectories by solving the equations of motion in the vertical plane; the forces in these equations depend on the power required calculation and on the exchange of energy between one source and the other; the nature of the manoeuvres is pre-programmed, but the actual flight path is governed by the chosen values of the control parameters;
- a partial optimization routine; in order to reduce the number of computing runs, an optimization of some of the control parameters can be carried out automatically.

The computer programme can be used on an AT-type Personal Desk Computer. The computing time is approx. half a minute for one specific trajectory and 20 minutes for one optimization run.

3.2 Helicopter power required

The power required calculation employs 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. In combination with the method applied at NLR for the determination of the rotor induced velocity, this 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.

3.2.1 Rotor induced velocity. For those flight conditions where the rotor has a positive angle of attack as in a powered descent, the momentum theory is no longer valid. For calculation of the rotor induced velocity use is made of the method developed by V.I. Shaydakov (Ref.1). This method is based on the assumption of an ideal

fluid with a constant induced velocity across the rotor wake and without slipstream rotation. Ring vortices of circulation leaving the blade tips are carried with the undisturbed airflow in the same direction and with the same speed. The ring vortices maintain their original dimensions and attitude in space. For those conditions where the rotor wake and the undisturbed flow have a different direction, as in powered descents, a second ring vortex system is assumed downwards along the rotor wake.
The results of this theory are presented in figure 2 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 angle of attack 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.

3.2.2 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 de 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

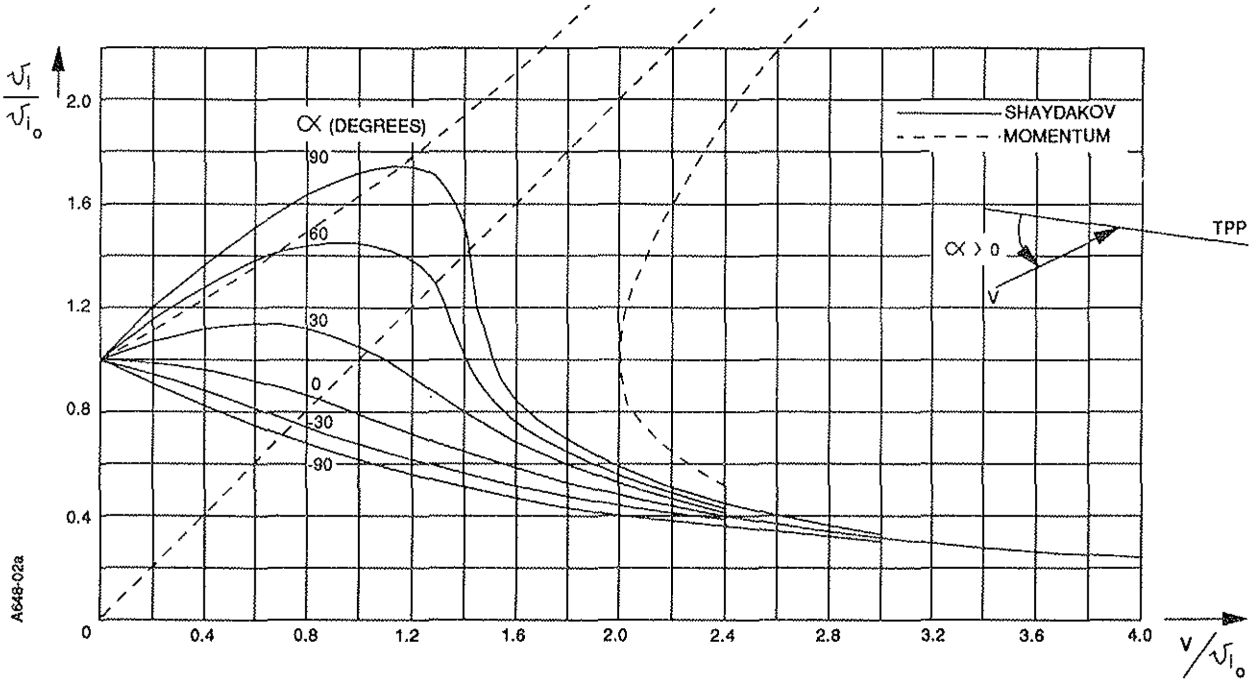

Fig. 2 Rotor induced velocity according to Shaydakov and momentum theory

according to reference 2 and either decreases linearly with increasing flight speed or is kept constant.

3.2.3 Ground effect. Ground effect is taken into account in the induced power calculation. The hover value of the ground effect determined according to reference 3 is assumed to decrease linearly to zero at a speed of 40 kts.

3.3 Trajectory calculation

3.3.1 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.

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

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:

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

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

$$mV\frac{dV}{dt} = mV_x\frac{dV_x}{dt} + mV_z\frac{dV_z}{dt} \qquad (3.3)$$

According to Newtons law we can write for each component:

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

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

In which D is the helicopter parasite drag, γ the flight path angle and V the total airspeed.

Substituting these equations into equation (3.1) gives the relationship between the main rotor rpm decay, tilt angle of the rotor thrust with respect to the vertical and the magnitude of the rotor thrust T for given flight speed components V_x and V_y:

$$P_{av\ oei} = (P_{mr}+P_{tr})_T + P_{acc} + \left(\frac{1}{2}I_{rot} + I_{fus}\right) * q\frac{dq}{dt} + TV_x\sin\theta + TV_z\cos\theta + I_{rot}\Omega\frac{d\Omega}{dt} \qquad (3.6)$$

3.3.2 Control strategy. Following an interview with KLM Helikopters' pilots, the control model is developed on the cues which the pilot receives and on which he checks the performance of the manoeuvre and takes his decisions, and on the behaviour of the helicopter as a result of collective and cyclic control actions.

In a symmetrical rejected or continued take-off manoeuvre the pilot cues are:
- pitch attitude of the helicopter;
- flight speed;
- main rotor rpm;
- height above the take-off or landing surface to cushion the landing.

In this One Engine Inoperative (OEI) manoeuvre, 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 effects of these inputs from the cues available to him:
- in the vertical rejected take-off the main rotor rpm decay;
- in the forward rejected and continued take-off the rotor rpm decay and the time to change the helicopter attitude to the desired position.

The third category which determines the flight path are the constraints within which the manoeuvre has to be performed successfully. These are:

- specified control action delay after engine failure;
- maximum pitch rate in the forward rejected and continued take-off; this may be restricted by operator requirements (passenger comfort) or by rotor characteristics;
- 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.

The manoeuvre starts in the critical decision point possibly with a flight speed, head wind and a rate of climb or descent. Gradual or abrupt engine failure can be selected, while the power of the remaining engine is increased gradually. During a one second collec-tive delay, which is simulated by a constant rotor thrust coefficient, the rotor rpm decay is kept at a constant value until the chosen (constant) rpm for descent is reached.
In the continued 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 chosen lead of the take-off safety speed is reached. From this point in the flight path the thrust vector is tilted backward 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 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 is tilted backward when reaching the ground.

3.3.3 Flight path calculation. The flight path is calculated by integration from one time step to the other. Given the total airspeed, rotor rpm, rpm decay and thrust vector tilt the magnitude of the rotor thrust T can be determined with equation 3.6. 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 is calculated from the initial attitude in the CDP, taking into account the thrust vector tilt and an experimental correlation between flight speed and fuselage pitch attitude.

3.4 Partial optimization routine

The flight path calculation is straight forward without any control feedback. Starting from a chosen CDP and initial conditions, the appropriate values of the control variables are determined by manual iteration in order to fulfil the touchdown requirement (vertical speed) and overflight requirement (minimum height AGL). Due to the large number of control variables, this method is rather cumbersome.

Figure 3 gives the flow diagram of the optimization.

In order to reduce the number of calculation runs, a simple partial optimization routine has recently been developed but not yet evaluated.
From the large number of variables, a limited number may already be chosen by the operator. These are for example the CDP conditions, rotor rpm at the fly-away or descent stage, height above the ground when commencing the landing flare in the rejected take-off, and pitch rates.

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 that can perform the continued and vertical rejected take-off from the CDP.

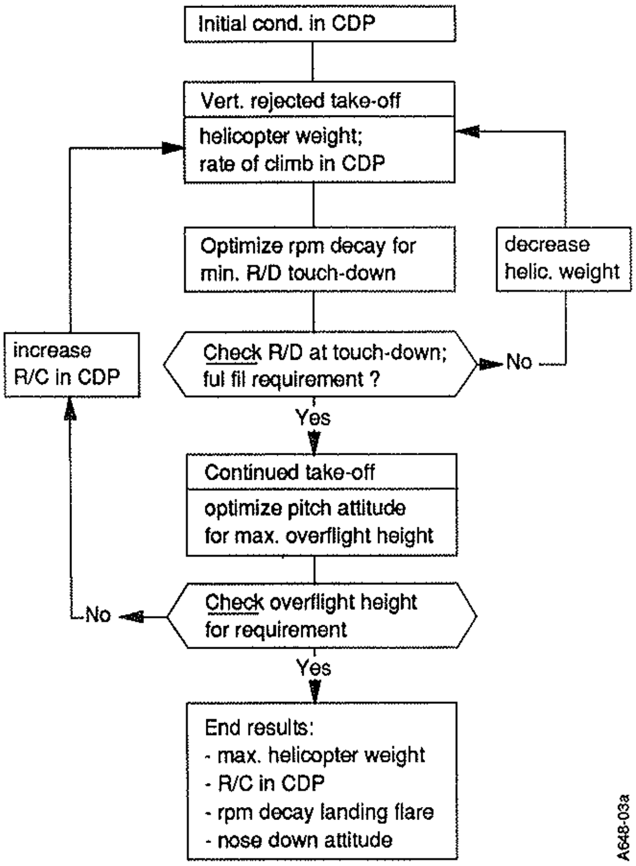

Fig. 3 Scheme of optimization

4 Initial computer simulations

In order to determine whether the S-76B would be able to land or fly-away after a one engine failure, and to determine the optimum lay-out of each manoeuvre, simulation cases were run for various weights and atmospheric conditions (only for prevailing conditions in The Netherlands). The general lay-out of the manoeuvres had to be similar to those for the S-61N as far as possible. For each of the four OEI procedures described in chapter 2, there existed several parameters for which the optimal values had to be defined. They are the following:

- continued take-off:
  * height of the CDP;
  * climb speed at the CDP;
  * nose-down angle;
  * speed at which to pull nose up;
- rejected take-off:
  * height of the CDP;
  * climb speed at the CDP;
  * wheel height at which to start flare;
- balked landing:
  * height of the LDP;
  * nose-down angle;
  * speed at which to pull nose up;
- continued landing:
  * height of the LDP;
  * nose-up angle to decelerate helicopter;
  * flare height;

The combination of CDP height and climb speed at the CDP, and the height of the LDP had to be optimized. If the height of and the climb speed at the CDP are high, then the continued take-off will not pose any problem. Otherwise, if these are low, then the rejected take-off will not pose any problem. Analogue arguments are valid for the LDP in relation to the balked and continued landing.

Several 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 OEI climb performance of the S-76B;
- rpm during continued take-off:
  this value was taken from the Flight Manual (100 % at OEI conditions);
- time to rotate helicopter:
  this parameter is related to the rotor characteristics; its value was determined during flight tests;
- minimum rpm at touchdown:
  this value was taken from the flight manual (68 % at OEI conditions);
- 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. 4). 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. The objective of these tests was threefold:
- validation of the S-76B computer model;
- demonstration of the helicopter's capabilities after one engine failure;
- demonstration that the manoeuvres derived theoretically are correct and feasible when flown by a standard trained pilot.

The following paragraphs deal with the various aspects of the flight test programme.

5.2 Data acquisition

Relevant data were registered both on board (flight parameters) and on the ground (flight path).
On board a video system was installed which recorded part of the co-pilot's instrument panel. The registered instruments were the following:
- analogue radar altimeter;
- digital clock with seconds on display;
- attitude director indicator, which includes a digital readout of the radalt;
- airspeed indicator (analogue);
- torquemeter (digital and analogue);
- triple tachometer (analogue).

Loading conditions were written down at regular intervals to facilitate the calculation of the weight and centre of gravity position. The fuel quantity indicators were checked before each test run and their values written down.

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

A flight test programme was carried out on 2 separate days. A total of 46 test runs was made divided in continued and rejected take-offs, and continued and balked landings. Engine failure was simulated by sharply retarding one throttle to the idle position.

To cover a range of conditions, several parameters were varied during the course of the flight testing:
- initially power available was limited to maximum continuous power (about 600 kW) making use of the so-called T5-bias box; later on, power was increased to the 30 minutes OEI rating (about 740 kW at MSL/ISA conditions);
- weight and centre of gravity were varied by burning or adding fuel or by means of ballast;
- the height of the CDP and LDP was varied;
- ambient conditions changed during the day and from one day to another; the maximum allowable wind speed for the tests was 10 kts;
- two pilots were involved in the flight test programme, each of them acting as pilot flying for about half of the total number of flights;
- for the landing manoeuvre, engine failure was simulated both at the LDP and some distance before the LDP;
- on the second day no balked landings were flown, as this manoeuvre had previously turned out to be easy to fly and to pose no kind of problem.

6 Processing of flight test data

All relevant data of the flight tests were available on video tape (flight instruments and flight path) or on paper (helicopter mass and ambient conditions). After each of the flight testing days the data 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. For each of the test runs a time history was drawn of all data available.

Next the computer simulation programme was run to reproduce the time traces. 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 the fly-away and wheel height at which flare for landing was initiated, were used as input for the programme. Small fluctuations can not be modelled and for that reason mean values were used instead. 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. An example is shown in figure 4. As can be seen in this figure, the helicopter's air speed indication system is not usable at speeds below about 20 kts.

In general the correlation between flight test data and calculations was good.

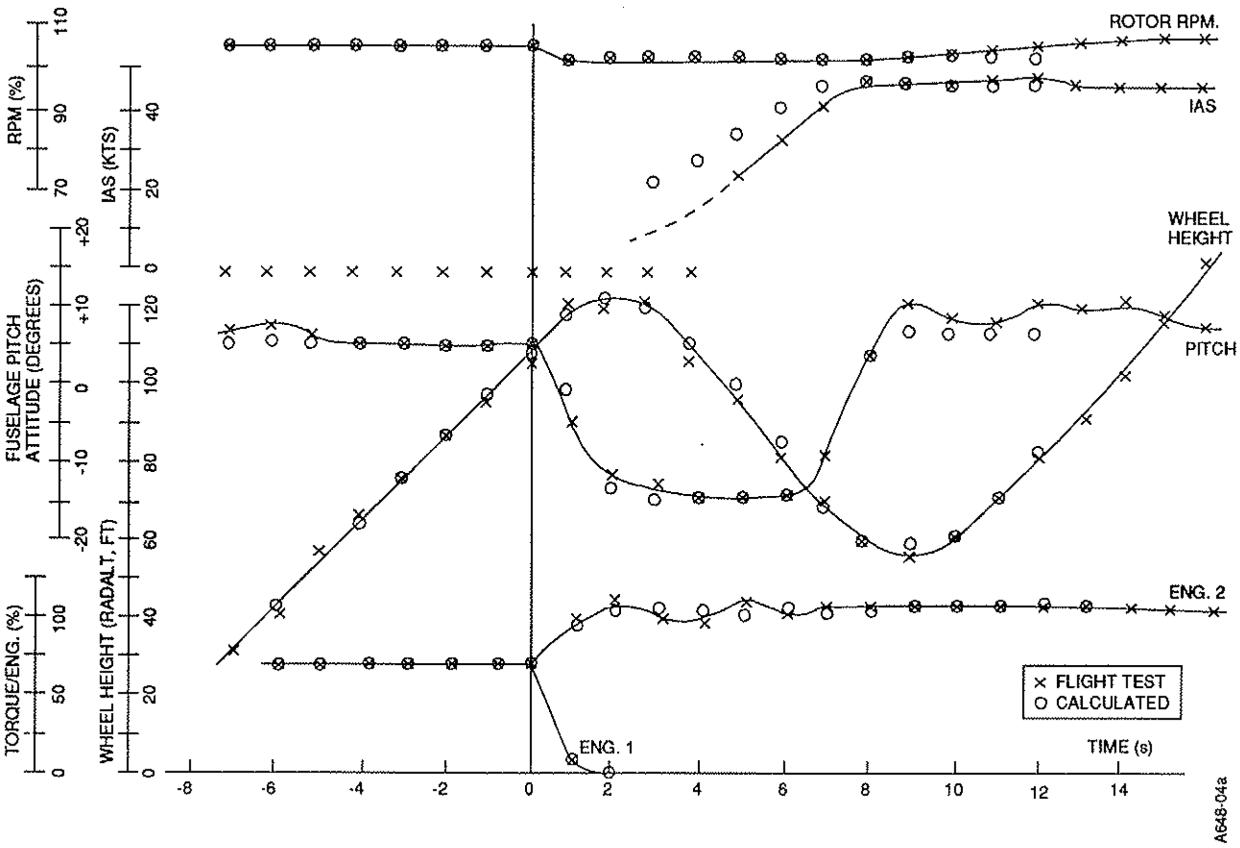

Fig. 4 Time history trace of continued take-off

7 Final results

The flight tests were carried out for a limited range of weights and ambient conditions. Based on these results additional calculations were made to determine the maximum take-off and landing weight for Category A vertical operations with the S-76B helicopter for a wide range of weights and ambient conditions. In order to be able to allow (high) obstacles surrounding the take-off or landing zone, the height of the CDP and the LDP was fixed at 100 ft.

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. Computer simulations were made to produce a graph which gives the required twin engine climb-out torque versus take-off gross weight and wind speed (figure 5). If the torque, indicated in this figure, is used to climb from a 5 ft hover to the CDP, then the rate of climb at the CDP at MSL/ISA conditions will be about 820 ft/min.

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.

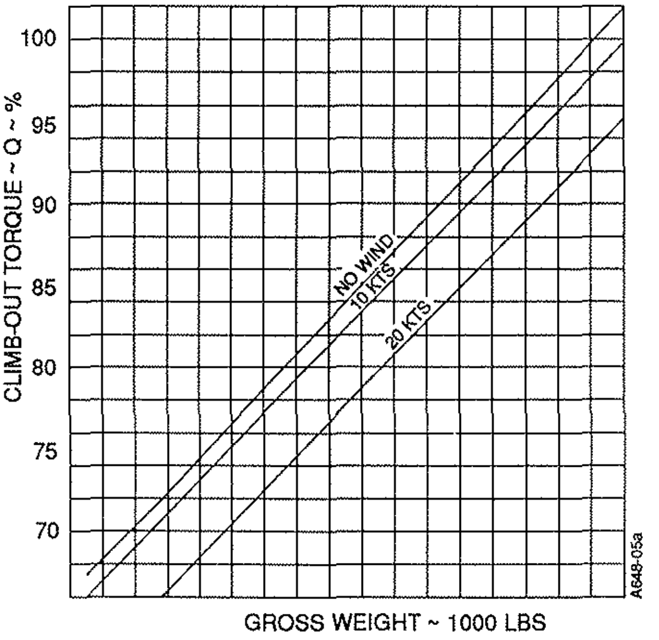

Fig. 5 Twin engine climb-out torque vs. take-off gross weight for S-76B vertical operation

The calculations were carried out for parameters, which were either optimized or derived from the flight tests. The following details were used for each manoeuvre, with instantaneous engine failure at the CDP or LDP:

- continued take-off:
  the helicopter is rotated to a 15 degrees nose-down attitude in 2 seconds; in the same time the other engine's torque increases to the maximum allowable value (within gearbox limitations) and rotor rpm is allowed to drop to 100% (for the S-76B the normal rotor rpm equals 107%); at 30 kts indicated airspeed the helicopter is levelled off again (about 5 to 7 degrees nose-up) in 3 seconds, while still accelerating to the Take-Off Safety Speed of 40 kts; when reaching 100 ft/min rate of climb at 40 kts airspeed, the calculation is stopped;
- rejected take-off:
  the torque of the other engine increases to reach the maximum allowable value when the helicopter is descending (about 3 seconds after passing CDP); rotor rpm is held constant at 107%; at about 30 ft wheel height collective pitch is increased to cushion the landing; rpm drops 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 continued take-off but with 5 degrees nose-down attitude and 35 kts indicated airspeed at which the helicopter is levelled off;
- continued landing:
  the helicopter is rotated to 15 degrees nose-up attitude to slow down; torque of the other engine increases such that the helicopter will not climb; rotor rpm is held constant at 107%; when the helicopter starts descending maximum allowable engine torque is applied; slightly before reaching zero ground speed the helicopter is rotated back to hover pitch attitude for a vertical descent; at 30 ft wheel height collective pitch is increased in the same way as in the rejected take-off.

The final results were presented in graphs which show the maximum take-off and landing weight for FAA Category A Vertical Operations as a function of pressure altitude, outside air temperature, wind speed and obstacle height. An example is shown in figure 6. These graphs and a description of the procedures were supplemented to the S-76B Flight Manual after approval by the Netherlands Department of Civil Aviation (RLD).

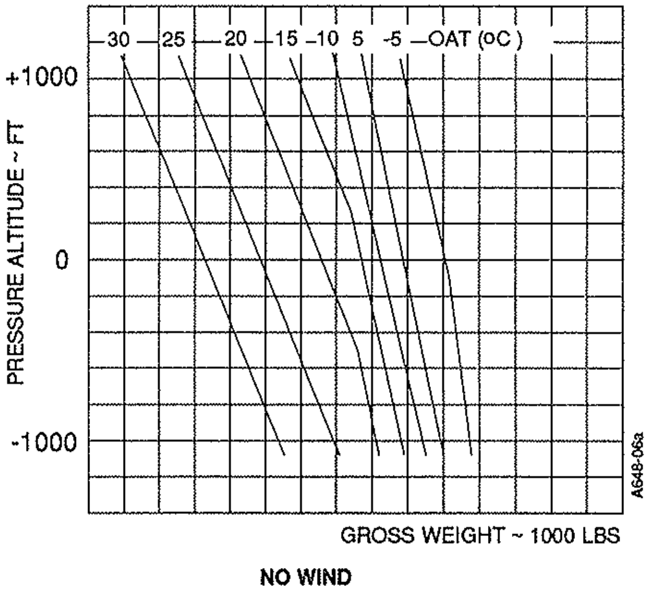

Fig. 6 Maximum take-off and landing weight for S-76B vertical operation

8 Deviations from calculated manoeuvres

The calculations have been carried out for an optimal set of parameter values. During real flight, deviations from these values may occur. But these deviations may not impose any danger to the aircraft or the persons aboard.

As required by Advisory Circular AC-29-2A it was assumed that a total one engine failure takes place exactly at the CDP or LDP. Any slower decay of the engine or a failure at any other point of the flight path improves the manoeuvre conditions and therefore is 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 compared to the prescribed piloting technique. The influences differ for each manoeuvre. Deviations which have a deteriorating effect will be analyzed hereafter.

Continued take-off:

- rotor rpm:
  dropping rpm to a value higher than 100% increases the dropdown by several feet; so it is necessary to keep the rotor rpm at or slightly below 100%;
- fuselage pitch-down angle:
  a few degrees more nose-down attitude enlarges the dropdown by about 1 ft;
- time for nose down pitching:
  taking 2.5 instead of 2 seconds increases dropdown with about 4 ft; as the pilot is fixated to pitch down when passing the CDP (also when no engine fails) 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 start levelling the helicopter:
  pulling nose up at a higher speed increases dropdown a few feet;
- c.g. influence:
  normal hover attitude of the KLM Helikopters' S-76B ranges from 5 to 7 degrees nose-up; the difference in dropdown between these two configurations is less than 1 ft.

Rejected take-off:

the calculations were 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 at the calculated weights (e.g. landing 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.

Finally, deviations may arise from instrument errors. These errors are smaller than the parameter deviations mentioned before and their influence on the flight path is negligible.

Pilots, who will fly the S-76B during Category A vertical operation, will be trained and qualified for the 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. Large deviations from the values used for the calculations are not likely to occur if the procedures are followed closely. Small deviations are imaginable, but their influence is only small. Main rotor rpm is the most important parameter to pay close attention to.

9 Conclusions

KLM Helikopters operates a.o. 4 Sikorsky S-76B helicopters for which the Flight Manual did not provide procedures for FAA Category A vertical operations out of confined areas. Preliminary investigations, both by KLM Helikopters and by the National Aerospace Laboratory (NLR), showed that Category A operations should be possible.

Further theoretical and flight test investigations were carried out to investigate the vertical take-off and landing procedures for the S-76B. The ambient conditions (pressure altitude, outside air temperature and wind speed) were varied to give a representation of prevailing conditions in the Netherlands. It was concluded that the S-76B is indeed capable of performing Category A vertical operations at weights up to about 11000 lbs for the no wind condition and up to 11700 lbs for the 20 kts wind condition.

Descriptions of the procedures without and with one engine failure and figures for the maximum take-off and landing weights were provided. These were supplemented to the Flight Manual after approval by the Netherlands Department of Civil Aviation (RLD). The procedures for the Category A vertical operations, together with the maximum take-off and landing weights, allow a safe flight after single engine failure at any point of the flight path without any known exposure to danger.

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