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HELICOPTER PERFORMANCE EVALUATION FOR CERTIFICATION

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Abstract

Rotorcraft performance methodology currently in use at MBB is presented, with main emphasis placed on the aspect of evaluating helicopter performances for demonstrating compliance with certification requirements.

A short review of the analytical approach for determining helicopter performances is given on those areas, which are of particular interest for certification. This includes steady hovering performance, takeoff and landing performance (Category A and Category B), climb performance and limiting height-speed envelope (HV-diagram). Major influential parameters like gross weight, altitude and temperature effects are discussed and a correlation of calculated data and flight test results is made over a wide range of ambient conditions for different helicopters.

The paper is concluded by stating, that the existing analytical and empirical performance methods, if validated over a sufficiently wide range of significant parameters, are reliable means for determining performances and demonstrating compliance with the requirements over a wide range of atmospheric and operational conditions.

Notation

AEO	all engines operating
CDP	critical decision point
GW	gross weight
H_D	density altitude
H_P	pressure altitude
LDP	landing decision point
n	rotor rpm
P	power required or available
P.D.P.	power deficiency parameter
P.E.I.	Power excess index
V_{TOSS}	takeoff safety speed
V_Y	speed for best climb
σ	air density ratio, ρ/ρ_o

1. Introduction

Certification of rotorcraft is a large, costly, and time consuming effort. Within this process, the analysis of helicopter performance and demonstration of compliance with the appropriate performance regulations is of particular importance. FAA's airworthiness standards for both normal category rotorcraft (FAR Part 27) and transport category rotorcraft (FAR Part 29) list the rules and regulatory requirements which must be met by the applicant in order to achieve certification within the desired envelope. Basically, there are two means of compliance, as required in section 21 of Part 27/29: Compliance can be shown either by flight testing, or by calculation, based on, and equal in accuracy to, the results of testing.

Performance flight testing, including the critical combinations of proposed flight variables, and covering all applicable certification requirements, is a costly and time-consuming effort. The requirements for the preparation of aircraft, instrumentation, calibration, data recording, and the performance of engineering flight testing and final data evaluation result in extensive cost for the manufacturer.

On the other side, the progress made by industry in the last decade in developing improved performance prediction methods is impressive. People have progressed towards a better understanding of the fundamentals of helicopter performance and are able to physically treat and interprete the effects encountered over the range of ambient and operating conditions.

This paper will discuss the main areas of helicopter performance, relevant for certification, and will compare the quality of results which can be achieved by analytical prediction and by flight testing.

2. Relevant Performances

The verification of the helicopter's actual performance, and the identification of operating limitations are two main purposes of the compliance process. The following flight conditions are particularly considered by the performance requirements (References 1 and 2):

- Performance at minimum operating speed (hovering performance) in ground effect (IGE) and, if required, out of ground effect (OGE), is of particular interest; hovering ceiling must be determined for the range of altitudes, temperatures, and gross weights, for which certification is requested.

- Takeoff and landing performance is of main importance to establish the limit curve for all combinations of gross weight, altitude and temperature. Specific takeoff and landing performances must be demonstrated by transport category aircraft for the case that an engine fails during takeoff or landing.

- Climb performance with all engines operating (AEO), and (in case of multiengine helicopters) with one engine inoperative (OEI), must be determined to establish steady rates of climb at the best-rate-of climb speed and at the takeoff safety speed. Effects of weight, altitude, and temperature are again of particular interest.

- A limiting height-speed envelope must be considered if there is any boundary of height versus airspeed within which a safe landing cannot be accomplished, in case of an engine failure.

The performance capability of an aircraft basically depends on the density of the surrounding air which, in turn, is a function of the local ambient conditions (temperature and pressure). Very low temperatures can additionally affect flight performances, resulting from compressibility effects due to high local Mach numbers at the blade tip.

Proof of compliance with performance requirements therefore is basically a two-fold problem: The problem of density altitude and the problem of ambient temperature, as shown in Figure 1. As it is impossible, to conduct testing over the whole range of ambient conditions desired for certification, the question of analytical prediction and of data extrapolation/expansion into conditions not tested is of major importance during performance certification.

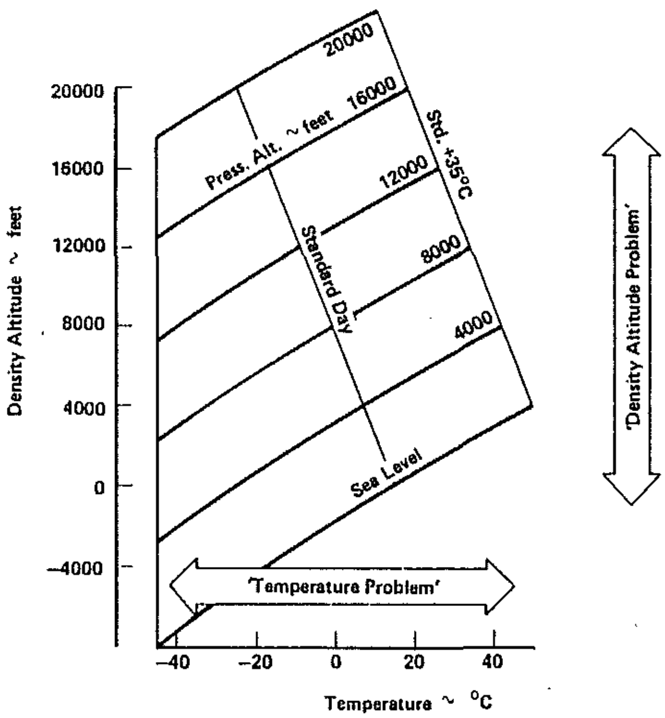


Figure 1 Ambient conditions affecting Performance

3. Steady Helicopter Performance

3.1 Calculation of Power Required

The calculation method used at MBB for evaluating the steady performance consists of a comprehensive, interdisciplinary helicopter simulation model, considering the following aspects

- Rotor bade aerodynamics
- Induced velocity field
- Tail rotor aerodynamics
- Fuselage and tail surfaces aerodynamics
- Rotor-fuselage-tail interferences

- Engine power supply
- Auxiliary power consumption
- Helicopter trim condition

A simplified flow diagram describing the total performance calculation model is shown in Figure 2.

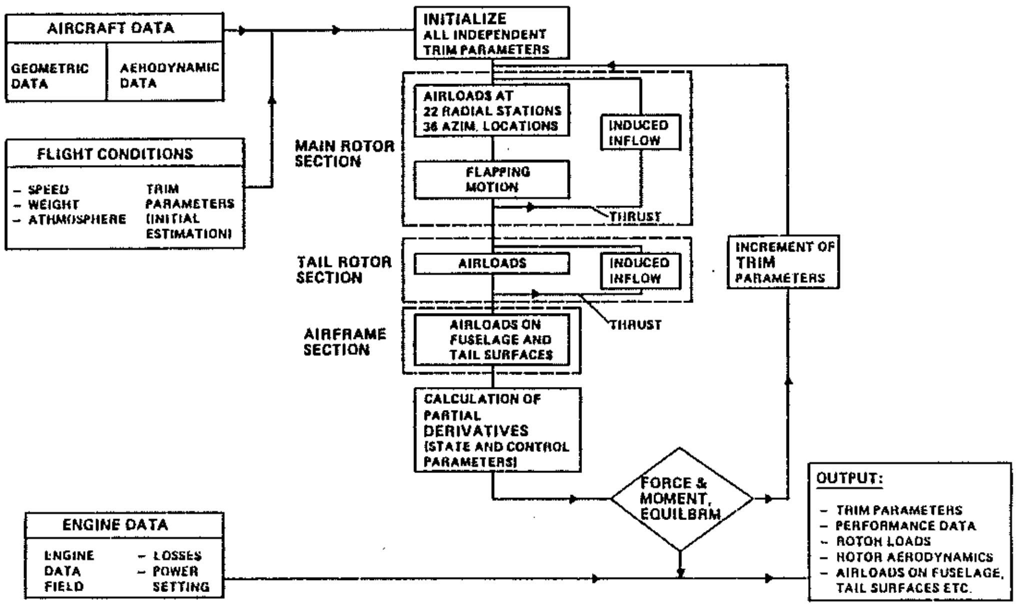
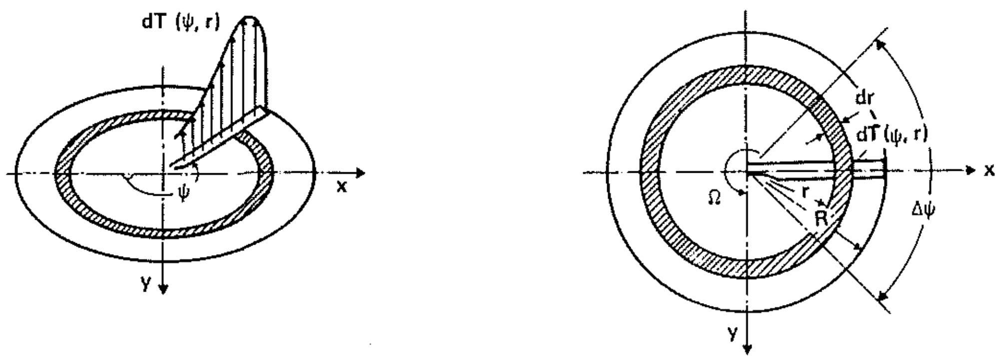


Figure 2 Flow diagram showing key elements of performance calculation

In the following sections a short review of those modelling details is given which are of particular interest for the above mentioned performance items. The problems of high speed forward flight performance calculation are not specificly addressed.

Induced Power - The main power contribution to the total power, during hover and low speed flight conditions, is the induced power component at the main rotor. This part can amount to more than 70 percent of the total helicopter power in the hovering condition.

The prediction method used for induced power calculation is a local momentum theory (Figure 3), which provides a non-uniform downwash flowfield. The local induced velocity is iterated with the local blade element thrust for varius rotor disc elements. At hover and low flight speeds the simple momentum theory underestimates the induced flow and, therefore, empirical data derived from model rotor tests (Figure 4) are used in these working states. Studies have shown, that with such relatively simple induced flow models the induced power calculation is sufficiently accurate. Wake models, much more complicated in their build-up and extremely computer time consuming, do not necessarily result in an improved quality of induced power calculation.



$$V_{zi}(\psi,r) = \frac{dT\ (\psi, r)}{2\rho \cdot r \cdot dr \cdot \Delta\psi \sqrt{V_{x_{Ro}}^{2} + [\, V_{z_{Ro}} - V_{zi}(\psi, r)^{2}\,]}}$$

Figure 3 Local momentum theory assumptions

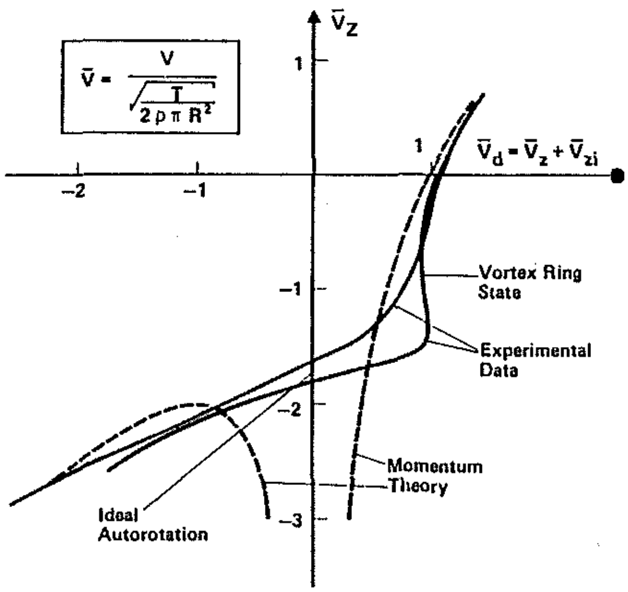


Figure 4 Empirical data for the induced inflow calculation

Profile Power - The blade element theory, used for calculating local airloads, is based on experimental airfoil section characteristics. The need for correct airfoil data representation results from the fact that even in the hover and low-speed flight regime, particularly under extreme ambient conditions, non-linear aerodynamics and compressibility effects are of significant influence on performance. Examples for lift and drag coefficients, as obtained from two-dimensional wind tunnel testing are presented in Figure 5 as function of angle of attack and Mach number. As is well known, compressibility effects cause a substantial drag rise, the onset being dependent on blade lift and Mach number. It will be shown, that a strong power increase can occur at low temperatures, due to high local Mach numbers at the blade tip.

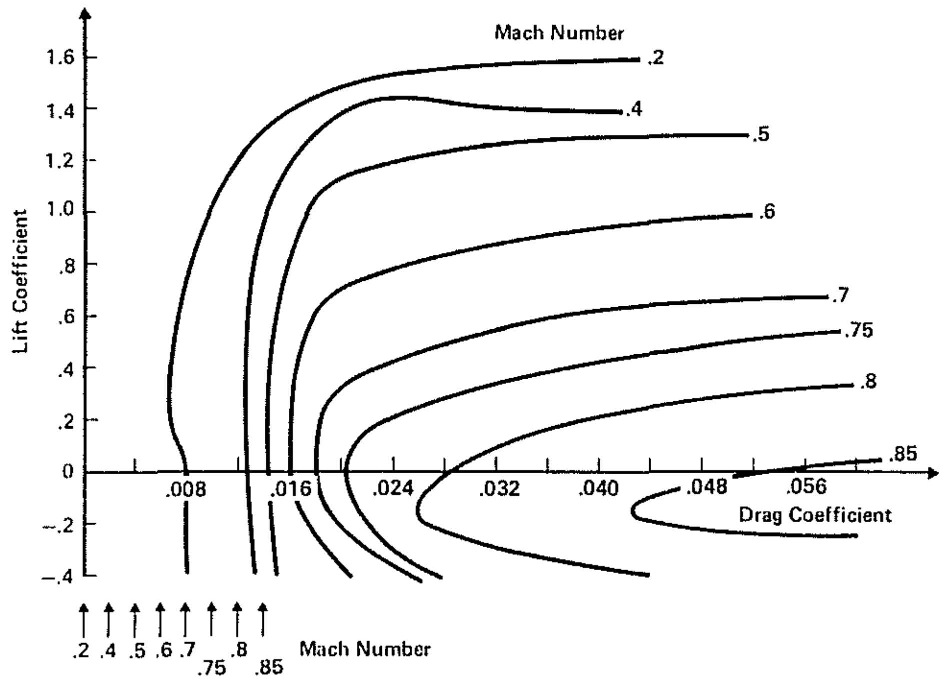


Figure 5 Basic aerodynamic characteristics of the NACA 23012 airfoil

Tail Rotor - The correct representation of the tail rotor is of high importance for the speeds from hover to the transition range, because high anti-torque is required during these flight conditions. The tail rotor thrust can significantly influence the trim and the power situation, especially for certain tail rotor-fin configurations with high blockage effects of the tail fin on the tail rotor inflow. At flight conditions with sidewind from the critical direction tail rotor control and thrust capability is often a limiting factor for the achievable gross weight at high altitudes.

To fulfill these stringent requirements, a blade element model is used for the tail rotor, capable for calculation of thrust and power consumption under all wind conditions. The blockage effect of the side fin on the tail rotor inflow is considered by a blockage factor for determination of the net thrust available for anti-torque.

Airframe Characteristics - The correct airframe aerodynamic forces calculation is not only important at high forward flight speeds, but also in hover and low speed flight. Flight path angles in conjunction with rotor downwash determine the effective angle of attack and, hence, the fuselage airload components. To accurately predict these forces and moments, actual fuselage aerodynamic characteristics are required and the contracted induced downwash of the rotor with variation over the fuselage segments has to be accounted for. The existing model uses a complete representation of body force and moment characterisitcs; the aerodynamic forces on the tail surfaces are calculated by an empirical model simulating the aerodynamic effects achieved from wind tunnel tests.

Ground effects - Helicopter performance and controllability during near ground hovering conditions, under low to moderate wind velocities, are of particular importance for safe takeoff and landing operations. During the in ground-effect hover condition, the induced velocity of the main rotor is reduced by the wall effect of the ground surface, resulting in a reduction of the required power. The aerodynamic phenomena of ground effect get even more complicated under presence of wind. A ground vortex occurs on the wind side of the downwash cylinder, which locally increases the induced inflow on the rotor disc, thus reducing the beneficial effect of wind on the power required. Figure 6 shows measured power versus sideward wind speed for in and out-of-ground effect. A meaningful representation of the power curve in sidewind is achieved by the assumption of constant power required equivalent to the in-ground-effect power under zero wind.

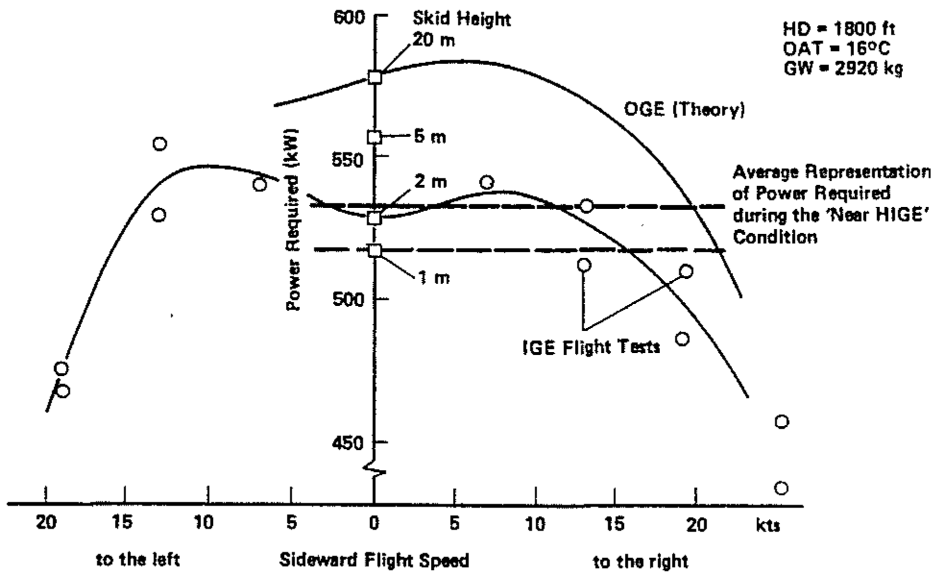


Figure 6 Total power consumption in sideward flight near the ground

Total power requirement - The total required power, which has to be equalized by the engine power delivery, is obtained from the main and tail rotor power including gearbox losses and auxiliary drive power (Figure 7).

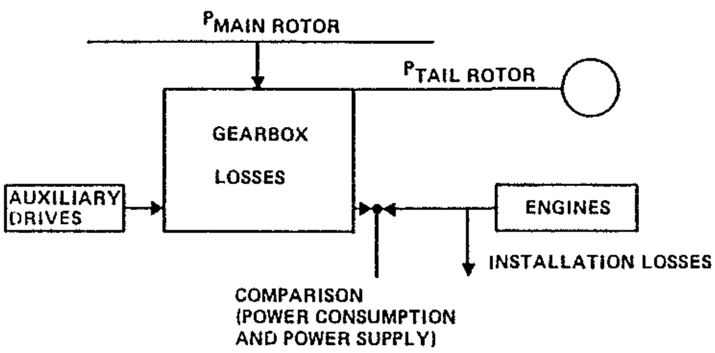


Figure 7 Split-off of helicopter and engine power contributions

3.2 Determination of Power Available

For the determination of the power supplied by the engines, usually the relevant data from the engine manufacturer are used. Figure 8 shows an engine performance data field as function of pressure altitude and air temperature (uninstalled engine).

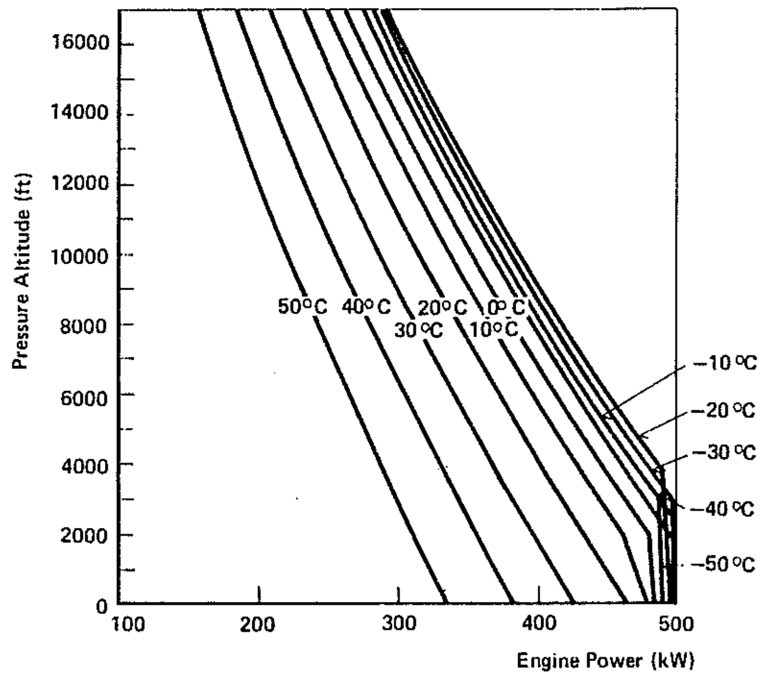


Figure 8 Engine power chart (Lycoming LTS 101–650)

The available power of the installed engine is the uninstalled power reduced by the losses associated with the installation of the engine in the helicopter. Reasons for the installation losses can be pressure loss and temperature rise of the intake air and pressure loss in the exhaust duct, for example. The installation losses, which depend on the specific installation situation of each actual helicopter, have to be determined in flight tests.

One method of determining installation losses is demontrated in Figure 9. The power measured in flight test is compared to the calibration curve of the uninstalled engine, and the power difference represents the installation losses.

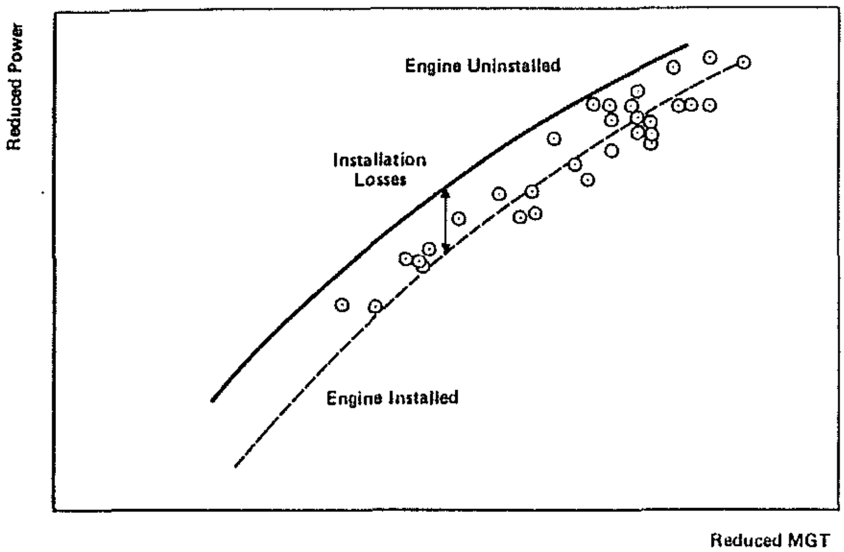


Figure 9 Engine installation loss definition

3.3 Confirmation by Flight Tests

Validation of the power required calculation is the first step in verifying performance methods. The two prime parameters - altitude and temperature - are shortly reviewed below.

Altitude Effects - Confidence in the described performance prediction method has been established by extensive correlation studies for different MBB helicopter models. As an example, Figure 10 shows the BK 117 helicopter power versus gross weight curve, for the hover out-of-ground-effect condition. Test data from various density altitudes between 1500 ft and 11000 ft are collected, the data being referred by the density ratio.

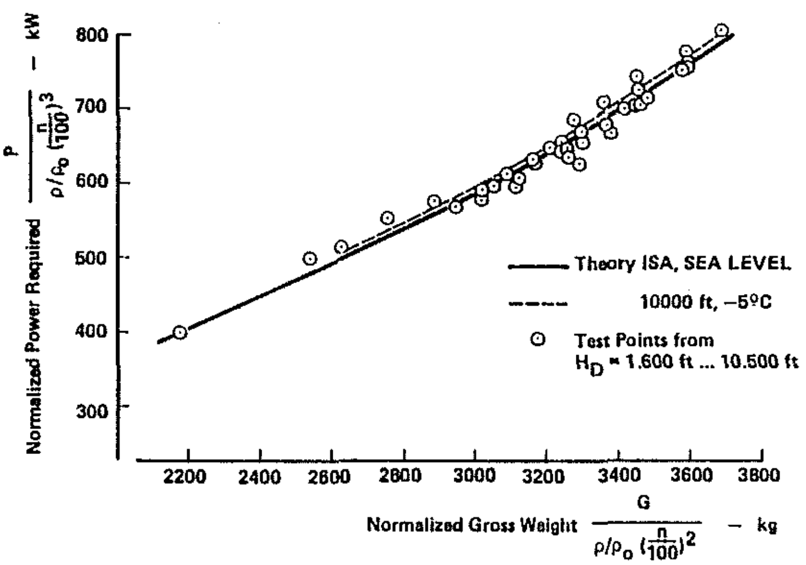


Figure 10 Power required versus gross weight (Hover OGE)

A comparison with the calculated power curve for the SL/STD condition is made, indicating a high accuracy of the prediction model over the whole thrust range from near minimum gross weight to 3700 kg normalized gross weight, which corresponds to the maximum gross weight/density ratio (GW/σ) possible at higher altitudes.

Correlation of predicted and test data of power required in-ground-effect (1 m skid height) is made in Figure 11, including test data between 1500 ft and 10 000 ft density altitudes. The test data are referred to the equivalent SL/STD condition and compared to the predicted curve. Again, high accuracy in predicting hover IGE power required is noted up to high values of gross weight/density ratios.

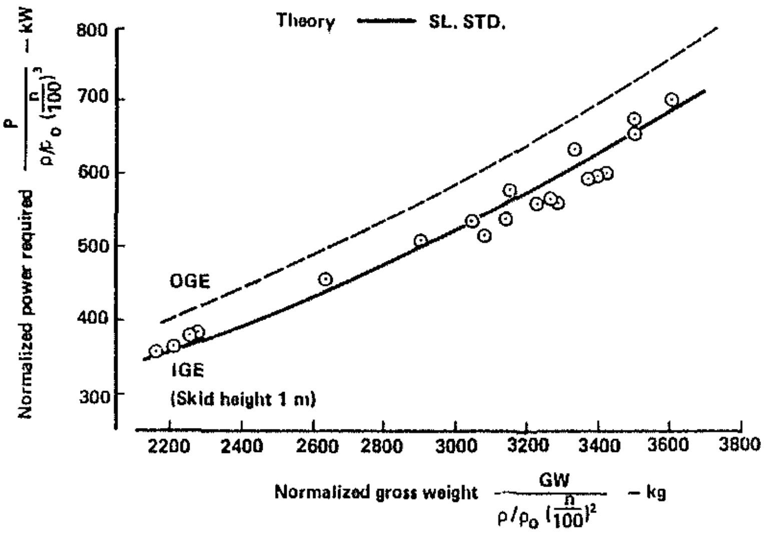


Figure 11 Power required versus gross weight (Hover IGE)

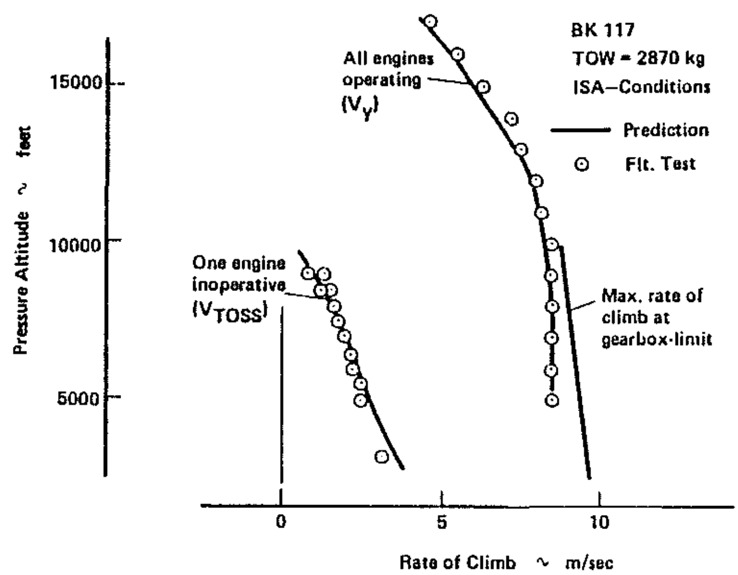


Figure 12 Climb performance versus altitude

Analysis and test of climb performance at the best climb speed (V_Y) with both engines operating, and at the takeoff safety speed (V_{TOSS}) with one engine operating at a 2 1/2-minute power rating are shown in Figure 12. Determination of continued minimum climb capability (100 fpm) with one engine inoperative at V_{TOSS} is of particular importance for the take-off and landing performance of transport category aircraft. In both cases, climb performance is well predicted over a wide altitude range.

Temperature Effects - Temperature effects on helicopter performances must be separately adressed during the certification process, particularly if expansion to temperature extremes is desired. In this respect, the low temperature problem is of particular importance. As has been indicated, compressibility effects cause a drag rise at the blade tip at low temperatures, due to increase of the local Mach number, and therefore result in an increase of power required at low temperatures. The onset of severe Mach number effects is demonstrated in Figure 13, showing calculated power required versus ambient temperature, with density altitude held constant. Change of power is insignificant within the range of positive temperatures, however, a substantial power increase is seen at temperatures below -20°C, corresponding to a blade tip Mach number slightly below 0.70 for the given aircraft.

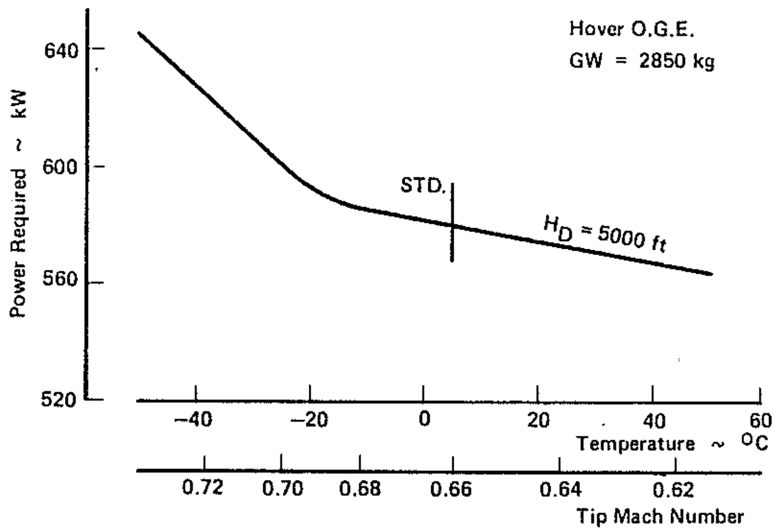


Figure 13 Effect of ambient temperature on power required (calculated)

The analytical representation of temperature effects was verified by direct theory-to-test comparisons including various cases of two different MBB helicopter models. Test conditions for hover out-of-ground effect with given gross weight, rotor rpm, pressure altitude and ambient temperature were calculated, and the differences (ratio of power predicted/power tested) were collected versus the air temperature in Figure 14. Data from -30°C to +45°C were available for this correlation study. The diagram shows the theory-to-test deviations to be well within a ± 4 % error band. Obviously, power calculation at high temperature extremes is entirely uncritical, due to the very low Mach numbers. At the low temperature (high Mach number) range, the theory is even conservative, when compard to the flight test. It can be assumed that this effect is attributed to relieving three-dimensional flow effects at the blade tip.

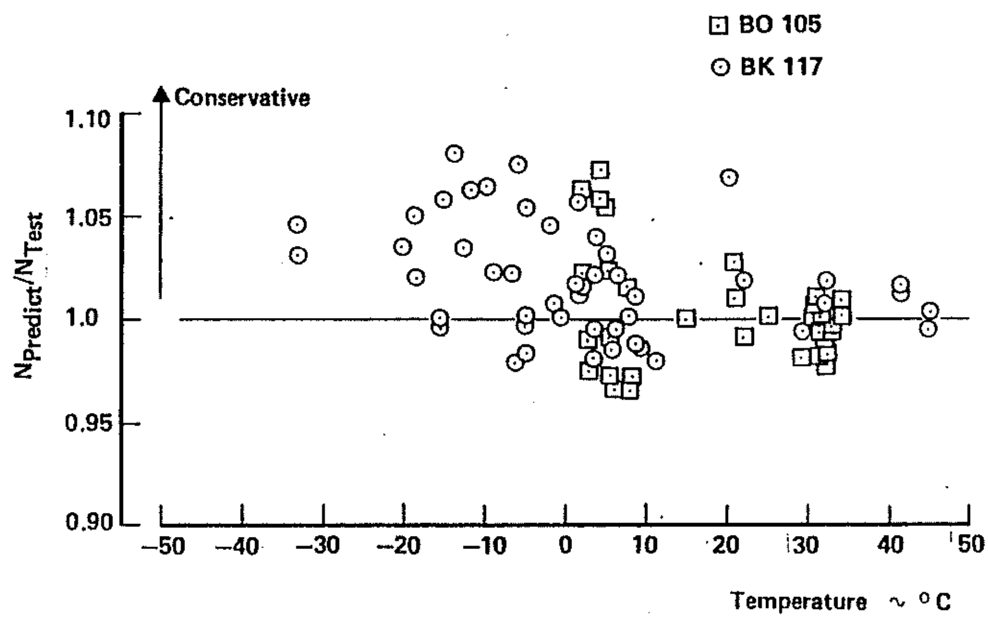


Figure 14 Theory versus test comparison over temperature range (Hover OGE)

It can be concluded from these correlations, that the analytical capabilities for determining hover performance over a wide range of ambient conditions are very encouraging. There seems to be no reason to limit performance calculation and data expansion to certain altitude increments over the conditions tested, as long as the analysis has been verified over the maximum possible gross weight/density (GW/σ) ratios. Similarly, high accuracy in the calculation of high and low temperature effects is noted, with Mach number effects being modelled adequately.

4. Takeoff and Landing Performance

4.1 Procedures

Regulatory standards include certain requirements to assure a safe takeoff and landing performance of helicopters. Especially in case of transport category aircraft certification, quite specific requirements and conditions are detailed in the corresponding regulations. In FAR Part 29, there are two categories of rotorcraft: Category A, requiring multiengine design, have a continued flight capability with a minimum rate of climb in the event of an engine failure, and Category B rotorcraft (single or multiengine designs), which are not required to continue the flight with an engine failed.

Takeoff: Category A - The flight path for a category A takeoff procedure is schematically shown in Figure 15. The procedure must assure that, if an engine fails after the takeoff at any point below a critical decision point (CDP), the helicopter must be landed (rejected takeoff), and if an engine failure occurs beyond the CDP, a safe climbout with a 30 ft obstacle clearance must be attained (normal takeoff). The total distance from the takeoff spot to the final stop or to the point, where a 35 ft height is cleared, is defined as the takeoff distance.

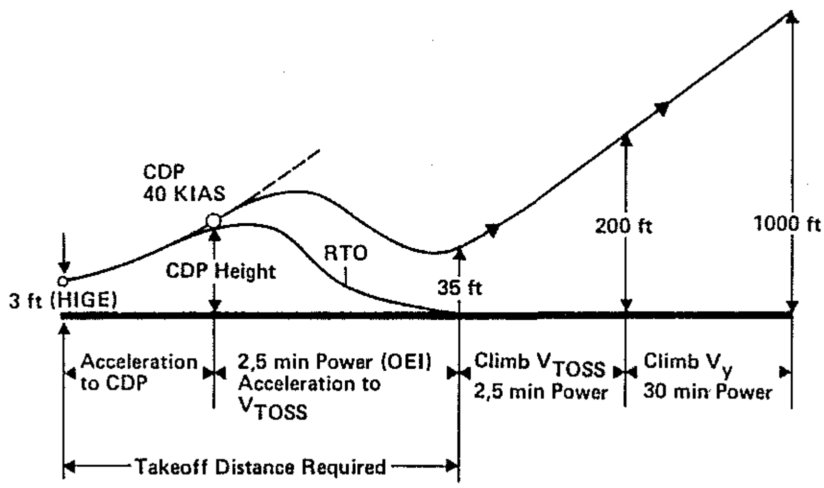


Figure 15 Takeoff procedure Category A

Takeoff: Category B - The takeoff procedure for category B is defined as a normal takeoff from a hover position with all engines operating. The takeoff distance is established from the hover position to a point where the aircraft climbs over a 50 ft obstacle above the ground.

Landing: Category A - An idealized landing flight path is shown in Figure 16. If an engine fails during the landing approach at or prior to the landing decision point (LDP), the aircraft with one engine inoperative can either land or climb out with a minimum climb speed (balked landing). If the engine fails after the LDP, a OEI landing must be made. The landing distance is measured from the point where the aircraft is 50 ft above the landing surface, and the point where the aircraft comes to a complete stop.

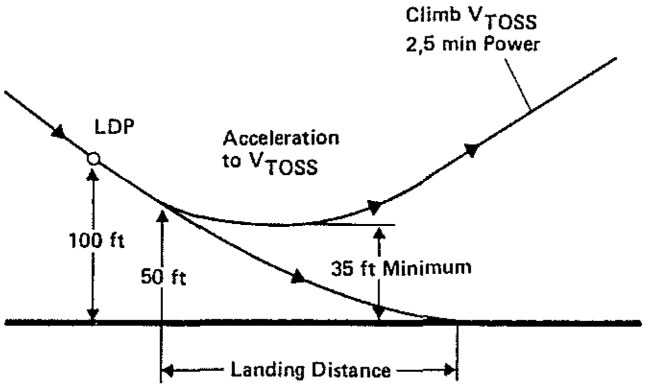


Figure 16 Landing Procedure Category A

4.2 Method for Determination of Takeoff and Landing Performance

The primary factor which determines the takeoff and landing procedures is the actual power situation. Usually, during the all-engines-operating segments, a certain amount of power excess is available. In contrast, during the one-engine-inoperative phases, a power deficiency is present. Pilot flying techniques may also affect the takeoff and landing performance; different techniques are sometimes required, to achieve the optimum distances.

The current method for the determination of takeoff and landing performance used at MBB is a combined empirical-theoretical approach. The method assumes that the segments of takeoff in ground effect with all engines operating are determined by the power excess index

$$P.E.I = \frac{1}{GW} \left(P_{AEO} - P_{HIGE}\right),$$

whereas the flight path segments with an engine inoperative are characterized by the power deficiency parameter

$$P.D.P = \frac{1}{GW} \left(P_{HOGE} - P_{OEI}\right).$$

Based on the results of flight testing, relationships between takeoff and landing distances and actual P.E.I. and P.D.P. factors are established. For a given power excess/deficiency parameter the takeoff/landing paths can be assumed as independent from the ambient conditions.

4.3 Flight Test Data

A typical category A rejected takeoff case of the BK 117 helicopter is presented in Figure 17. Shown are time histories of the engines torque, rotor rpm, collective pitch handling, and the resulting flight path. The critical decision point and a 1-second pilot reaction time delay are indicated in the diagram. The rejected takeoff distance from the hover point to a complete stop on the ground was 900 ft for this case.

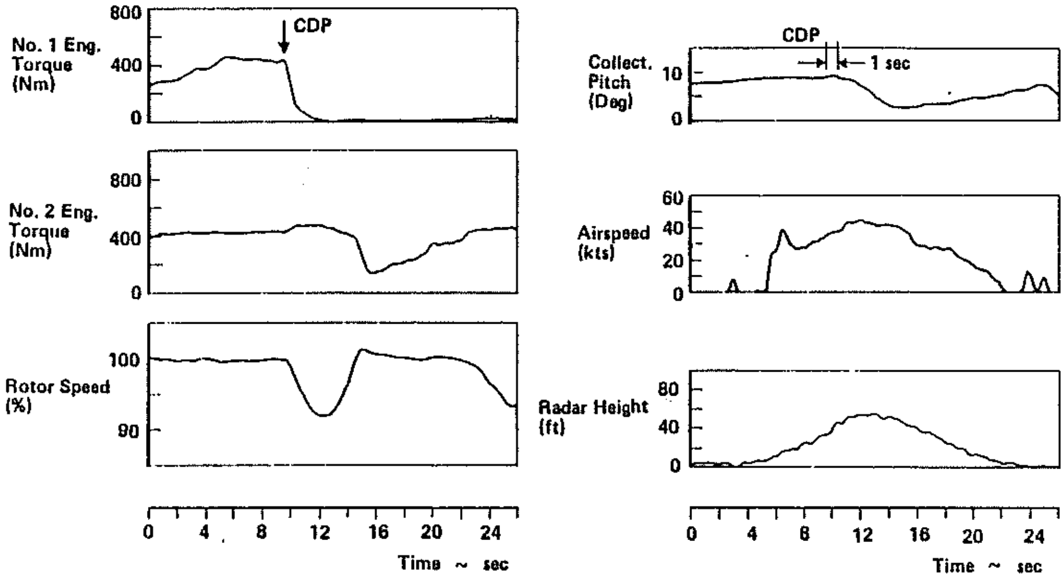


Figure 17 Time History of Cat. A rejected takeoff (flight test at 2800 ft density altitude, reduced engine topping)

Usually, owing to local atmospheric conditions at the test site, the critical power limits cannot be achieved during such tests. A simulation of the more unfavourable power conditions is therefore accomplished by adjusting the engine topping, together with variations in the aircrafts gross weight. In the case shown above, the engine topping was reduced to 65 % of actual maximum power, in order to simulate a high power deficiency parameter condition.

Figure 18 presents the category B takeoff distance (all engines operating) as a function of the power excess index, showing an increase of the takeoff distance with lower amount of power excess. The takeoff distances for category A rejected takeoff are drawn as a function of the power deficiency parameter in Figure 19, showing an increase of distance with higher P.D.P. values. It is particularly noted from Figure 19 that flight test results obtained at high density altitude (10.000 ft) agree well with the test data obtained at low altitude, under simulation of the high altitude condition by reduced engine topping adjustment.

Takeoff and landing performances over the complete range of gross weight and ambient conditions are determined by calculating the P.E.I. and P.D.P. factors for the given conditions and deriving the distances from the empirical relationships as shown in Figure 18 and 19.

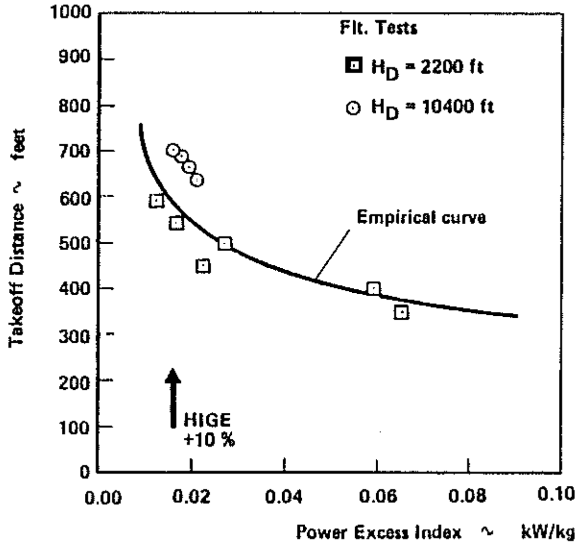


Figure 18 Category B takeoff-distance versus P.E.I.

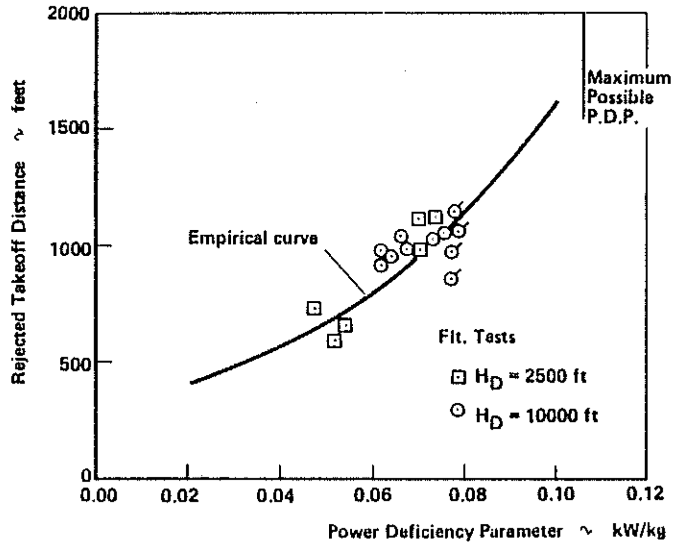


Figure 19 Category A rejected takeoff-distance versus P.D.P.

4.4 Confirmation by Tests at Extreme Altitudes and Temperatures

Confidence in the takeoff and landing performance method has been established by flight test demonstration of the BK 117 helicopter both at high density altitude and at extremely hot temperature conditions. Test data from high altitude for category A and category B takeoff are shown in Figures 20 and 21, comparing measured and predicted distances. High accuracy of T/O and landing performance prediction is noted and a small scatter of test data is also seen, indicating that the selected procedures are appropriate and operationally feasible. Flight tests at ambient temperatures up to +45°C also showed close agreement to the predicted data.

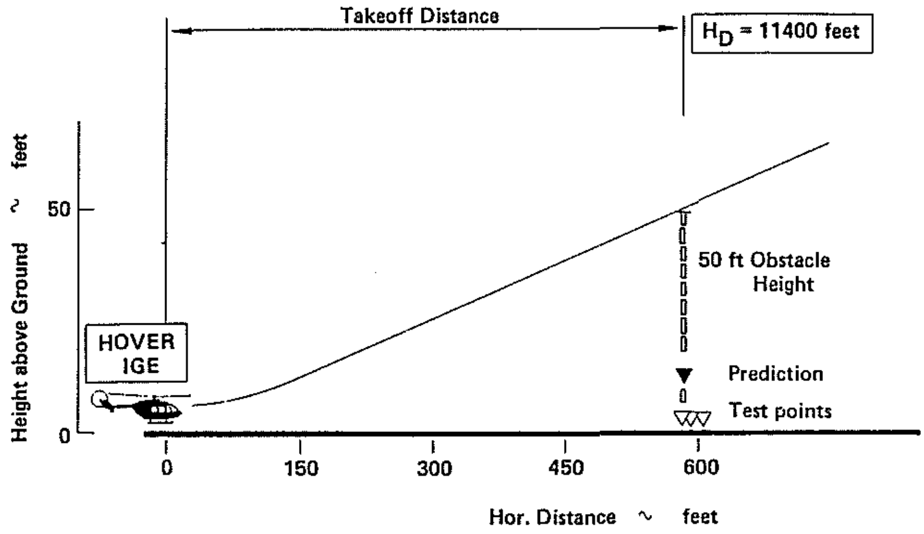


Figure 20 Takeoff performance (Cat. B) at high altitude

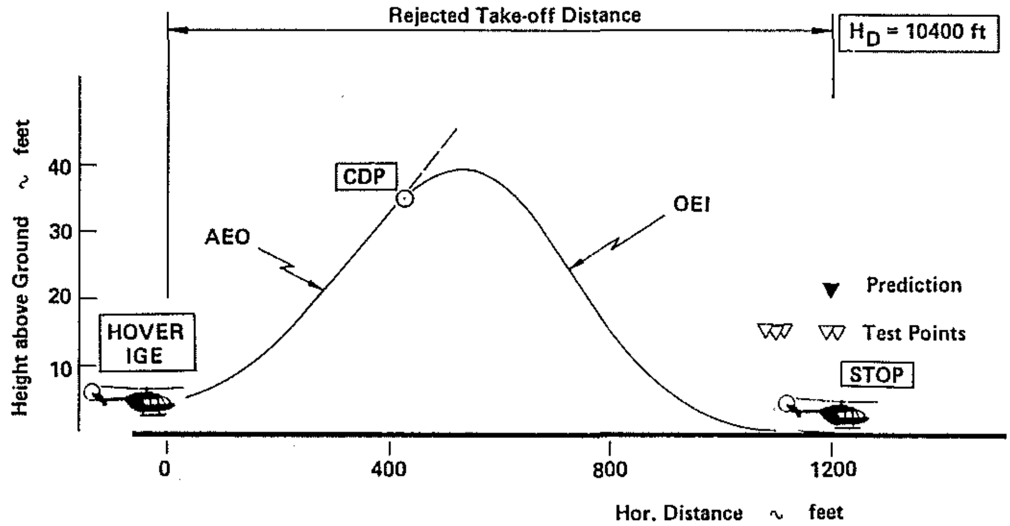


Figure 21 Takeoff performance (Cat. A) at high altitude

5. Limiting Height-Speed Envelope

The height-velocity diagram defines an envelope of height above ground and airspeed, from which a safe landing in case of a one engine (or full power for normal category B helicopters) failure cannot be assured. Three portions are distinguished in the diagram: A takeoff portion, a level flight portion and a high speed portion. Key areas which are of particular interest for the aircraft performance, are the high altitude hover point, the low altitude hover point and knee point of the curve, see Figure 22.

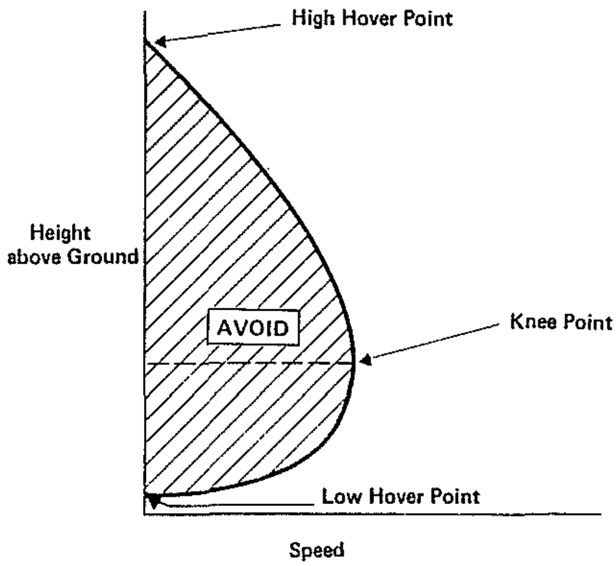


Figure 22 Critical points in the HV-Diagram

5.1 Analytical Prediction

The estimation of the HV-diagram by analytical means is relatively complex and requires a high level of helicopter modelling technique. The current model analysis in use at MBB for the simulation of the low speed portion is a simplified helicopter global model, guided in many aspects by correlation with flight test data. Within this paper, only some important areas should briefly be described.

The accurate prediction of the power required in hover and low speed prior and subsequent to the engine failure is of particular importance for the HV-envelope estimation. Induced and propulsive power required are obtained from a modified momentum theory, considering corrections for non-uniform inflow and tip losses, and approximating ground effects in the induced velocities. Blade element theory is used to obtain blade profile power. Power required and power available from the remaining engine(s) are balanced, giving variations in rotor speed. The aircraft equations of motions in the longitudinal and vertical directions are integrated, giving the flight path parameters. Several empirical coefficients are included into the model, to achieve as far as possible correlation with flight test data.

The sequence of the mathematical simulation model includes different phases of flight: A fixed control segment is assumed immediately after the engine failure. For maneuvers from the high hover and from the knee point, a dive acceleration is initiated to achieve minimum effective flare speed. Finally, a flare is carried out with preselected pitch attitude and collective pitch increase to reduce the descent velocity.

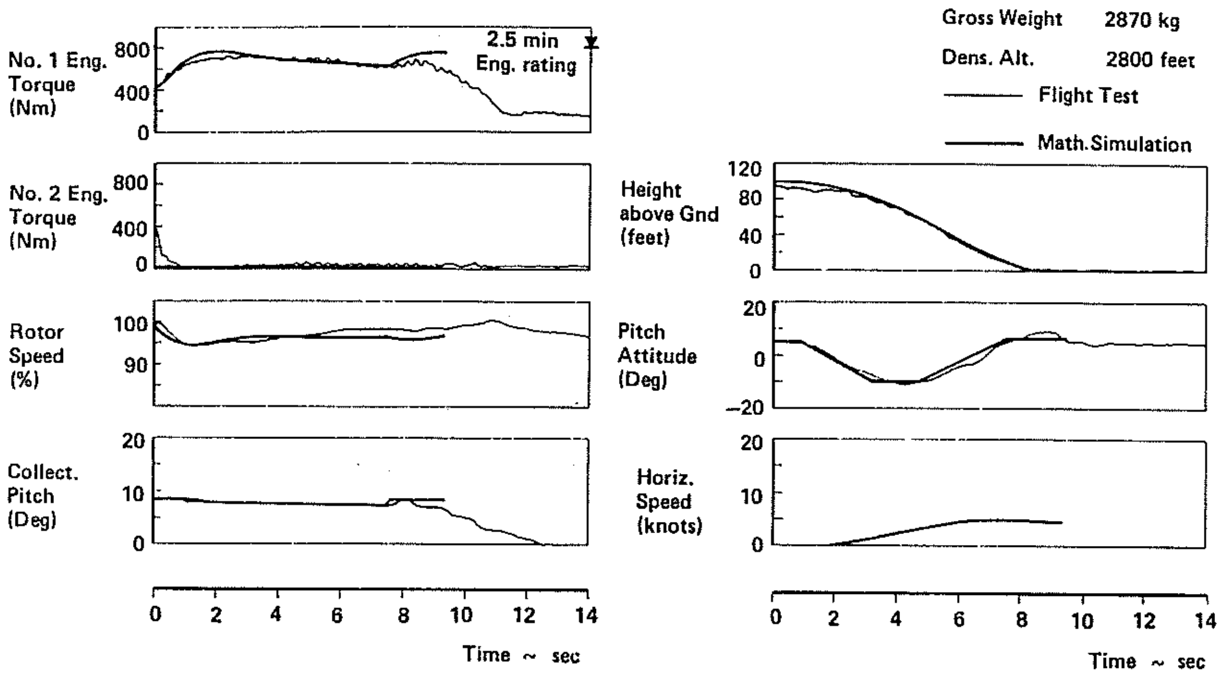


Figure 23 Engine failure at the high hover point—test versus simulation

Figure 23 shows the correlation of flight test data from normal test altitude with the mathematical simulation run. The maneuver used as an example is an engine failure at the high hover point, performed with the BK 117 helicopter with maximum gross weight, at a density altitude of 2800 ft and OAT = +20°C. Inputs to the computer model were time histories of the collective pitch similar to the test time history, and limiting pitch rates and attitudes. Failure of engine No. 2 is seen as a step drop, with the power of the remaining engine increasing up to the 2,5 min rating. The theory-to-test comparison shows very good agreement, the time histories of the height above ground, and the engine and rotor behaviour are precisely simulated.

Determination of the HV-diagram for gross weights and atmospheric conditions other than tested is conducted by use of the analytical method, based on the procedures and piloting techniques worked out during the initial flight tests.

5.2 Verification by Flight Tests

Verification of predicted HV-boundaries was conducted with the BK 117 helicopter both at high density altitude (10.500 ft) and at high temperature (+44°C). The results of flight demonstration at these extreme conditions are shown in Figure 24. For gross weights consistent with the weight-altitude-temperature limit curve, the high hover, low hover, and knee points of the estimated boundaries were tested. Each limiting test point was approached from the safe side. The results indicate that the HV-boundaries were realistically determined; sufficient margins existed for a safe OEI landing from the predicted boundary.

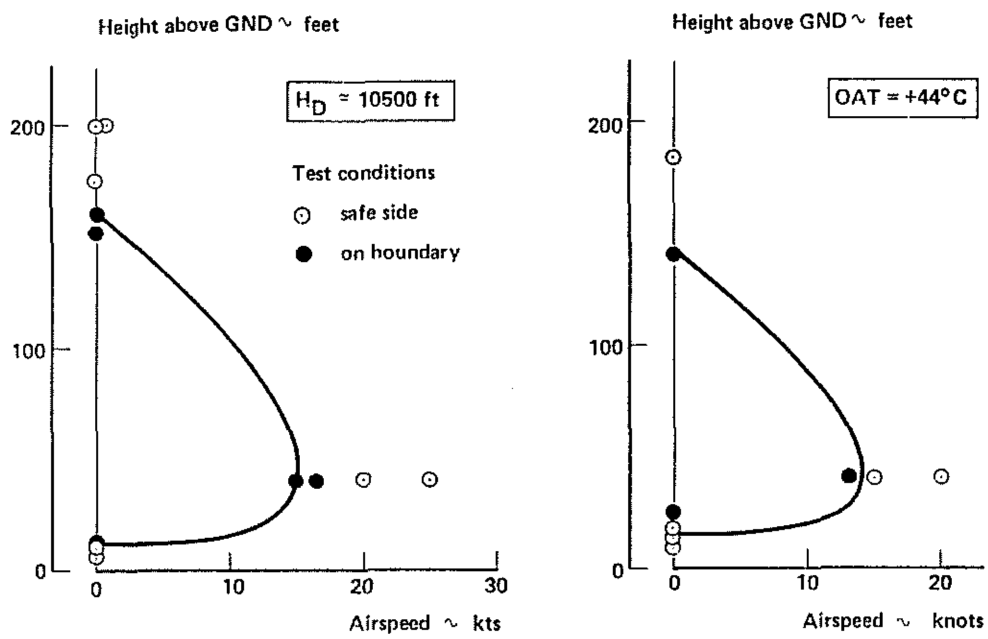


Figure 24 Verification of HV-Envelope at high altitude and hot temperature
(o symbol denotes condition on the safe side;
● symbol denotes condition on boundary)

It is obvious from these comparisons, that the described simulation model is a valid method for determining height-speed diagrams. With the significant parameters adapted to flight test data at normal test conditions, HV-diagram predictions can be made for any other ambient and gross weight conditions.

6. Conclusion

The paper has addressed those areas of helicopter performance which are of particular interest for certification of normal and transport category helicopters. Analytical methods and simulation models for determining performance at minimum operating speed (hover), climb, takeoff and landing performance, and limiting HV-diagram were shortly reviewed and major influential parameters affecting these performance items were discussed and compared to the results of flight testing.

The following conclusions can be drawn from the preceding discussions:

- The analytical modelling details included in the steady performance method allow for accurately predicting the hovering and medium flight speed/climb conditions, which are particularly considered by the performance requirements. Influences of altitude and temperature are adequately accounted for through suitable representation of air density effects, non-linear blade aerodynamics including Mach-number effects, and ground effects.

- The concept and fundamental assumptions of the combined analytical and empirical takeoff and landing performance method have been validated. The method allows for predicting takeoff and landing distances over a wide range of ambient conditions.

- The simulation method presented for the determination of height-speed envelopes (HV-diagram) is based on combination of performance calculation and flight dynamics simulation. With major coefficients adapted to flight tests, the method allows for the determination of HV-diagrams for an extended range of ambient conditions.

- It can generally be concluded that the existing analytical and empirical performance methods, once verified over a relevant range of significant parameters, are suitable means to evaluate performance data and to demonstrate compliance with helicopter performance requirements over the complete range of atmosperic conditions, for which certification is desired.

7. References

(1) U.S. Department of Transportation, Federal Aviation Administration, Federal Aviation Regulations, Part 27 - Airworthiness Standards: Normal Category Rotorcraft
1972

(2) U.S. Department of Transportation, Federal Aviation Administration, Federal Aviation Regulations, Part 29 - Airworthiness Standards: Transport Category Rotorcraft
1974