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HANDLING QUALITIES AND FLIGHT PERFORMANCE - IMPLICATIONS OF THE OPERATIONAL ENVELOPE

by
Alan Faulkner and
Walter Sinn

Messerschmitt-Bölkow-Blohm GmbH
Munich, West Germany

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Messerschmitt-Bölkow-Blohm GmbH
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Abstract

Flying qualities and flight performance are two of the most important aspects in helicopter design and operational use. Guarantees of adequate characteristics must be given and substantiated across the total operational envelope. Both civil and military regulations are, in many cases, no more than guidelines, which have to be matched with the operator requirements and transferred into engineering parameters.

The paper discusses the impact of the operational conditions on the subcomponents and presents important implications for the layout and design of the aircraft. The substantiation of handling qualities and flight performance at the critical loading (weight, c.g.) and atmospheric (altitude, temperature) conditions is essential. Modern analytical methods are now able to cover the majority of these aspects, however, flight testing is very often mandatory. Various test campaigns with the MBB helicopters BK117 and BO105 LS at some of these extreme conditions (altitude up to 22000 ft, temperatures of –45 to +50 °C) are presented and the establishment of the operational boundaries is demonstrated.

Notation and Abbreviations

AGL	–	Above Ground Level
C.G., c.g.	–	Center of Gravity
C_T/σ	–	Blade Loading Coefficient $T/(\varrho \cdot n \cdot c \cdot R\ (\Omega \cdot R)^2)$
HQ	–	Handling Qualities
FAR	–	Federal Aviation Regulations
FWD	–	Forward
IAS	kts	Indicated Air Speed
N_R	%	Rotor Speed
OAT	deg C	Outside Air Temperature
OEI	–	One Engine Inoperative
HOGE	–	Hover Out of Ground Effect
HIGE	–	Hover In Ground Effect
rpm	–	Revolutions per Minute
SAS	–	Stability Augmentation System
TOT	deg C	Turbine Outlet Temperature
V_{NE}	kts	Never Exceed Speed
XMSN	–	Main Gearbox
Z_P, H_P	ft	Pressure Altitude

1. *Introduction*

The modern high performance helicopter must be able to perform a variety of roles whilst remaining competitive with other forms of transport. The primary attributes of the helicopter, to provide vertical lift and hover capabilities, must be available over the widest possible operational envelope. The first generation of commercial helicopters was severely limited by the performance of the power plant which, in many cases, was only able to provide sufficient power to permit take-off at a useful gross mass under moderate altitude and temperature conditions. Since then, the development of modern engines has been such that the potential operational envelope has been vastly opened up. This has permitted the designer more freedom in the layout of the helicopter to taylor the design to meet the specific market requirements. However, the desire to extend the operational envelope in one direction is very often at the expense of other attributes. Clear design aims must be set by the market analysis to ensure that the optimized design is able to maximize on the potential operations. This may well result in a customer interrogation phase to separate the "nice to haves" from the "musts" and an education phase explaining the consequences of requesting extremely opposing characteristics. Naturally, any product attempts to cover the widest possible market by providing the broadest operational envelope which is permitted under the limitations section of the pilots flight manual. The establishment of these limitations is based on theoretical analyses and component testing and is ultimately demonstrated during certification. The extension of the operational envelope in one direction, however, may be at the expense of another part of the envelope and, in many cases, the final manual values may be the best compromise that is available to offer the most versatile solution.

2. Establishing the Design Concept

Matching of customer and market requirements with the helicopter layout is an essential task at the beginning of a design concept. Firstly, the operational requirements must be defined from the mission analysis, and secondly, weightings placed on the individual aspects to enable the selection of the optimized design. Unfortunately, diverse mission requirements may lead to different design solutions and a compromise must be sought if a multi-role concept is a primary design aim. Fig. 1 presents the questions to be answered in defining the operational envelope goals.

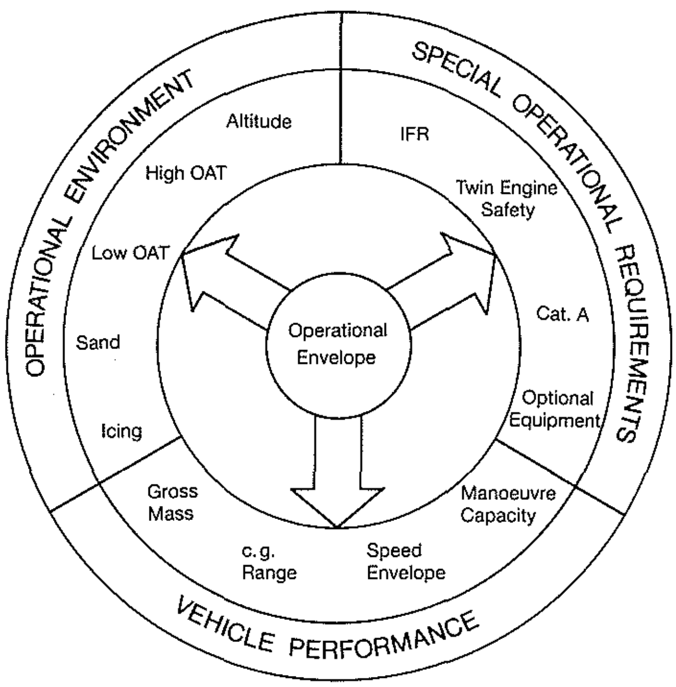

Fig. 1

Firstly, the performance of the helicopter must be defined. This is basically what the helicopter has to do in terms of transporting a particular payload and how well it performs its task, i.e. under what conditions of speed, climb and manoeuvre capacity.

Secondly, the mission environment, operational conditions, altitude and temperature range, must be specified.

Thirdly, special requirements, in particular those related to safety consideration such as twin-engine safety and Cat A performance, have to be considered.

After defining the operational requirements, the design goals have to be set. This leads to operational limitations owing to different reasons, the most important of which are listed below:

- helicopter limitations
  - installed power
  - weight/c.g. sideways speed
  - airspeed temperature/altitude
- (no) customer request
  - OAT
  - take-off and landing altitude
  - manoeuvrability
- sales requirements
  - competition reasons
  - design to cost
- availability of test environment
  - altitude
  - temperature
- limitation of subsystems
  - engines
  - instruments
- impact of cost on certification
  - HIGE/HOGE
  - icing
  - optional equipment

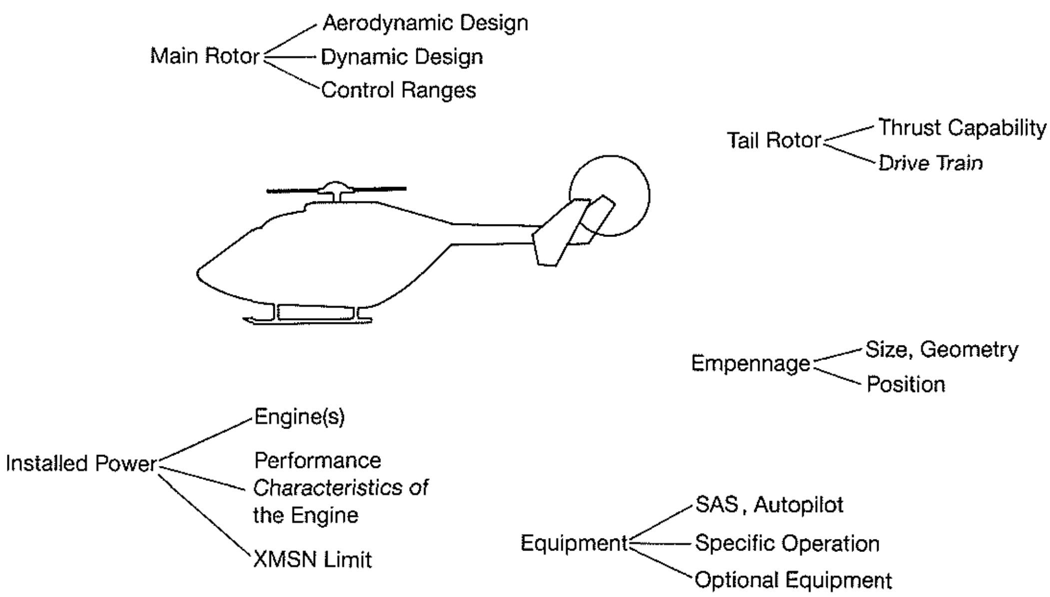

Fig. 2

Having established the general concept of the helicopter (gross mass, range, endurance), each sub-component must be taylored to match the limitations of each other component. Fig. 2 summarizes the critical components to be considered. For example, a desire to provide high yaw rates by designing a large tail rotor may well significantly influence the transmission and the structural design of the tail boom. Each component must be dimensioned so that no single component provides a significant "weak link" in the design chain.

3. Limiting Conditions in the Operational Envelope

Experience gained over several helicopter generations has allowed the helicopter manufacturers to be able to define "critical" conditions for intensive design investigations and identify potential problem areas for flight test evaluation.

The following paragraphs attempt to summarize the most significant limitations with respect to performance and handling qualities.

Gross Mass (Fig. 3)

The maximum gross mass limit is established either owing to engine or transmission power margins or, where sufficient power is available, owing to the rotor thrust capability. Typically, at blade loadings above $C_T/\sigma = 0,1$ handling qualities start to deteriorate owing to the onset of retreating blade stall at high speed. Further indications of rotor limits being reached are the increase in loads and reduction in effectiveness of longitudinal cyclic and collective controls. To improve the situation, the effective blade loading must be decreased by either increasing blade area, i.e. chord, number of blades etc. or by increasing tip-speed. All three methods are commonly used to upgrade existing helicopters.

At the other end of the scale, the basic fuselage structure will dictate the minimum flyable helicopter gross mass. From the main rotor point of view though, the minimum gross mass will establish the lower collective and rotor speed limits. These are determined from the relationship of normalized gross mass $\frac{m}{\left[\frac{\varrho}{\varrho_0}\left(\frac{n}{100}\right)^2\right]}$ against collective angle for autorotation.

Not least of all, the minimum gross mass limit will depend on the minimum loading conditions that can be demonstrated.

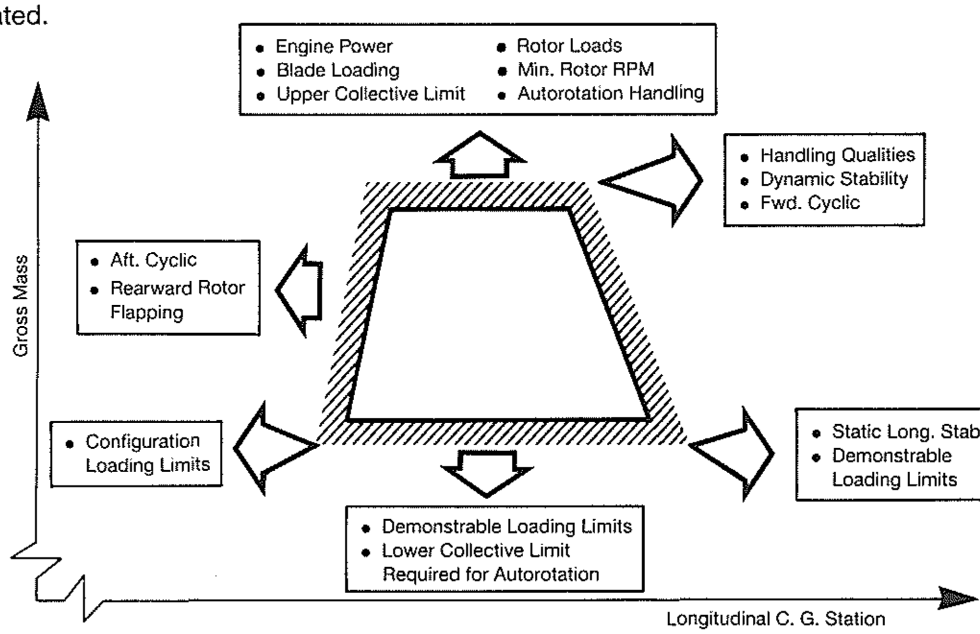

Fig. 3

C.G. Range (Fig. 3)

For a multi-purpose transport helicopter, both broad longitudinal and lateral c.g. ranges are essential to accomodate the variety of equipment fits. The forward c.g. limit results basically from load considerations as a consequence of the rearward rotor flapping. However, forward c.g. becomes a critical loading condition for determining cyclic control margins in rearward flight near the ground. Conversely, aft c.g. is most critival for the forward cyclic control margins in high speed flight.

The position of the aft c.g. line is limited by the handling qualities dynamic stability characteristics at maximum gross mass, and the static longitudinal stability at minimum gross mass. It should be noted, however, that the influence of the c.g. on the static stability of a hingeless rotor helicopter is negligable. This last loading condition, of extreme aft and light, also presents some difficulties in demonstration even when the testing is carried out with minimum fuel and instrumentation.

Operational Altitude (Fig. 4)

Maximum operating altitude, service ceiling, is limited primarily by engine power and in particular the maximum engine temperature limits. The helicopter should at least be able to sustain a 100 ft/min climb at the best rate of climb speed, typically 65 KIAS.

Second in importance is the blade loading coefficient C_T/σ which increases directly with density altitude. For example, at 15000 ft ISA the atmospheric density ratio falls to 63% of the sea level value, thus increasing C_T/σ by nearly 60% for the same gross mass. In order to remain within acceptable blade loading limits, a specially designed high altitude helicopter will therefore have to operate with a lower useful payload than one designed for sea level conditions.

In general, either density altitude or gross mass can be traded off to retain acceptable blade loading. However, a density altitude limit below 10000 ft would severely limit the helicopter mission options.

Parallel to the deterioration in rotor handling qualities, the efficiency of the empennage falls in proportion to the density ratio so that a progressive degradation of the dynamic stability occurs.

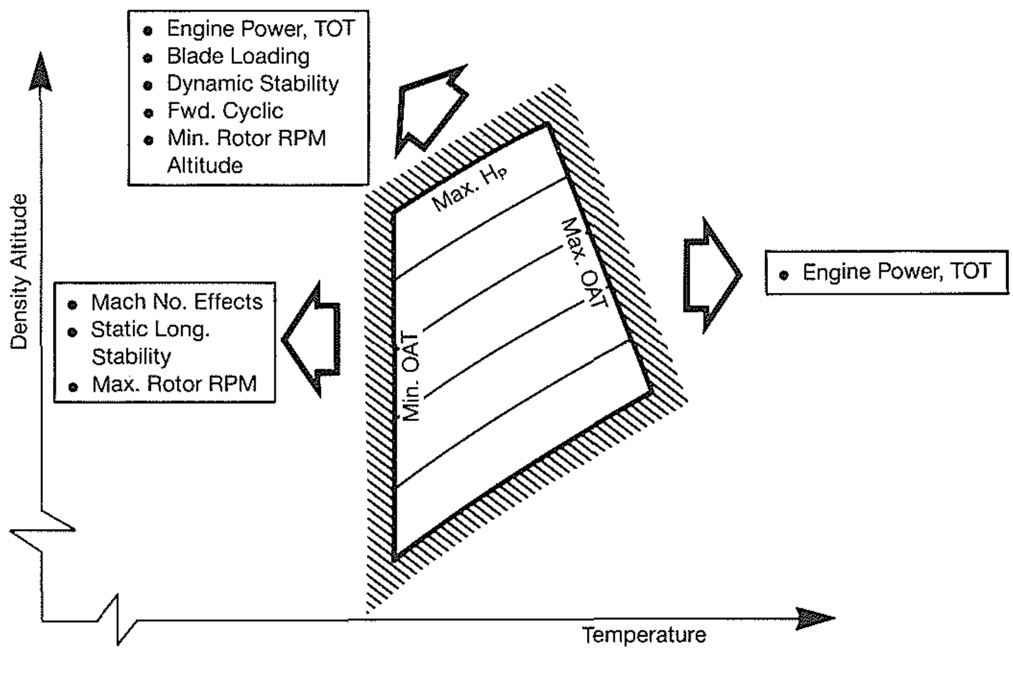

Fig. 4

Temperature (Fig. 4)

Apart from the reduction in power available, engine TOT limits, and the ever present cooling limitations of equipments, high temperature operations in themselves do not present any handling qualities limitations. On the other hand, low temperature operations i.e. below –30 °C, can present serious problems. The principle reasons for this are rotor Mach number effects which change the blade aerodynamic torsional moments and thus the effective blade pitch angle. Static longitudinal stability, particularly at low altitude, and maximum permissible rotor rpm can be influenced as a result of low temperature operations.

Altitude and Temperature Limitations for Take-off and Landing (Fig. 5)

The altitude and temperature power limiting aspects for the operational envelope are also important for near the ground operations. In addition, OEI power also becomes significant since this provides the safety margin for hover operations and Cat. A starts.

Operating near the ground calls for side or tail wind conditions to be demonstrated; the FAR request a minimum of 17 knots for example. Lateral and aft cyclic requirements, under wind conditions or for translational flight, increase marginally with altitude but the effectiveness of the tail rotor for producing thrust deteriorates measurably and the tail rotor control required for right sideways flight increases substantially with altitude. Very often the tail rotor is the limiting component for take-off and landing at high altitudes.

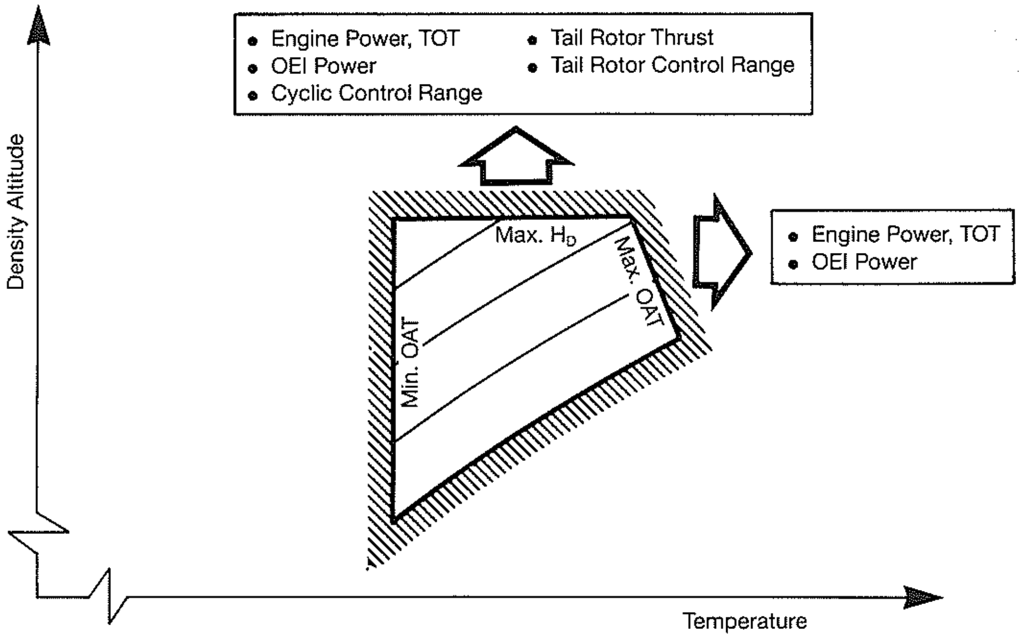

Fig. 5

The maximum approved gross mass for take-off and landings will vary for several reasons (Fig. 6). At low altitude, maximum gross mass is limited by the transmission rating or, in the case of high temperature operations, by the engine TOT limits. Variation of gross mass with altitude is minimal. However, when reaching tail rotor control or thrust limits as discussed above, gross mass must normally be reduced on the basis of constant normalized mass, i.e. $\frac{m}{\left[\frac{\varrho}{\varrho_0}\left(\frac{n}{100}\right)^2\right]}$. This leads to rather conservative margins.

Finally, the maximum take-off and landing altitude for which a helicopter is certified may well depend simply on the availability of a suitable test site and the costs involved in obtaining the test data. Some of the testing possibilities are discussed later in this paper.

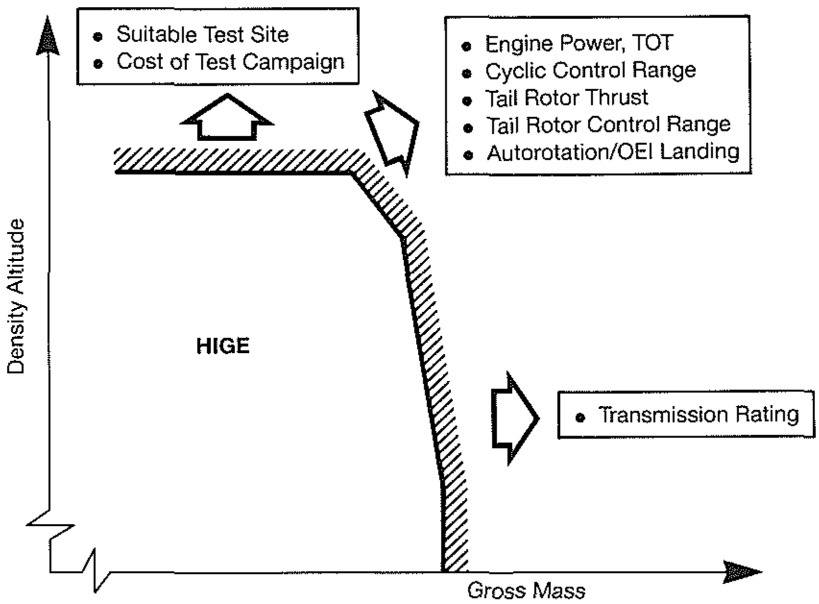

Fig. 6

Speed Limitations on Operations near the Ground (Fig. 7)

The maximum permissible wind speed for hover operations is dependent on the control margins at the fwd./lateral c.g. envelope limits. Design targets are normally for the same wind speed limitation in all directions and for symmetric control margins. This requires control range to be biased slightly to the left to compensate for the right sideward thrust from the tailrotor.

Rotor downwash effects cause a skewing of the cyclic critical wind azimuth directions by approximately 45°. Quartering manoeuvres are therefore critical.

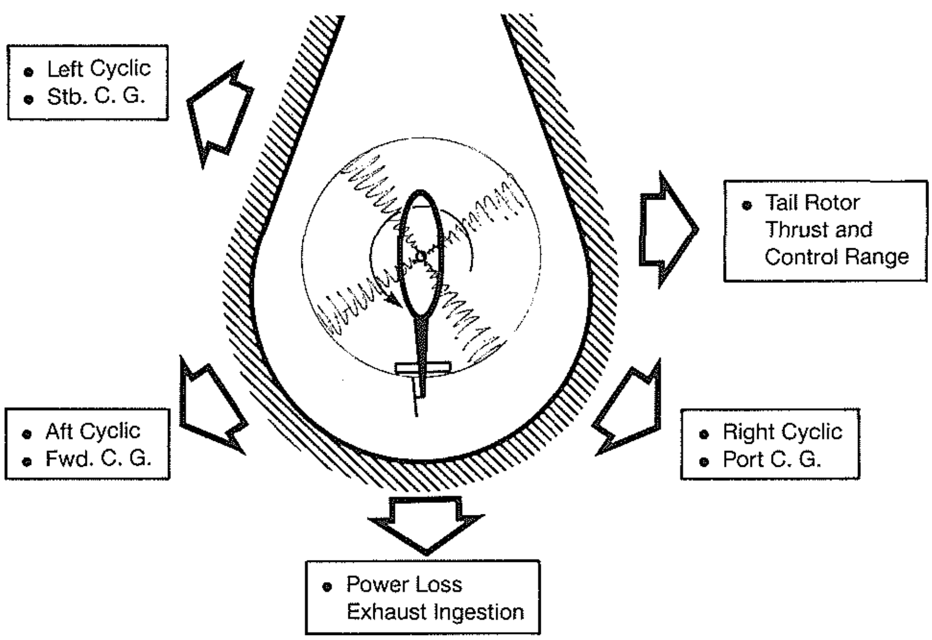

Fig. 7

Sufficient control power must be available at the approved wind speed to permit recovery from gusts. The limiting factor is, however, normally not the cyclic control but the thrust limits of the tail rotor as described above.

Some helicopter designs are limited, particularly in rearward flight, by power loss caused by exhaust ingestion into the engine intakes.

Airspeed Envelope (Fig. 8)

The boundaries of the airspeed envelope are classically set by the maximum power available during climb and cruise, and by the associated descent rate for autorotation. These two maximum limits can, however, be limited further by handling qualities.

In climb, both static longitudinal and dynamic stability characteristics have caused restrictions in the envelope.

In cruise and up to V_{NE} the limitations are once again stability, but this time as a result of the blade loading at the higher tip-speed ratio and the influence of the higher advancing blade Mach number.The compromise is either to reduce blade loading (i.e. gross mass or altitude limits) or reduce the flight speed by restricting power or artificially introducing a lower V_{NE}.

Autorotation often results in marginal static longitudinal stability especially at the high rotor over-speed rpm. If high tail rotor deloading for cruise has been a design aim, the V_{NE} zero power trim state will require significant negative tail rotor thrust and negative pitch range.

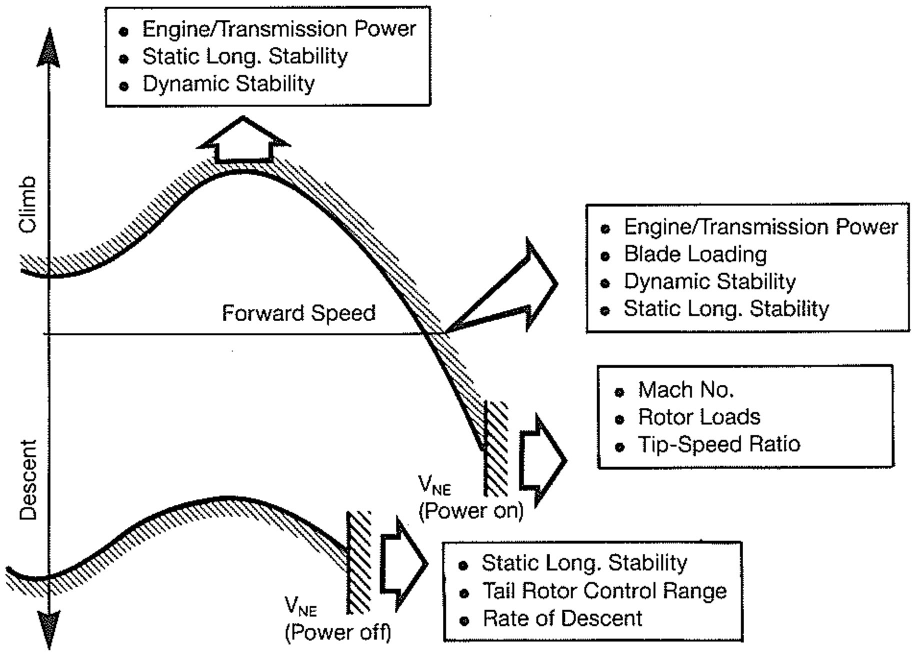

Fig. 8

Variation of Forward Speed with Altitude (Fig. 9)

At low altitude transmission limits, Mach number effects at cold temperatures and high tip-speed ratios set the speed boundaries.

If a high speed helicopter is essential, the design is forced therefore to accept a high tip-speed ratio and/or reduce blade loading by reducing max. gross mass. Hence a driving high speed requirement can result in a less economic helicopter as the useful to empty weight factor will be less attractive.

Current research is being directed to providing rotor blade aerodynamic profiles which are able to accept higher blade loadings and operate at higher Mach numbers in order to extend the higher speed boundary.

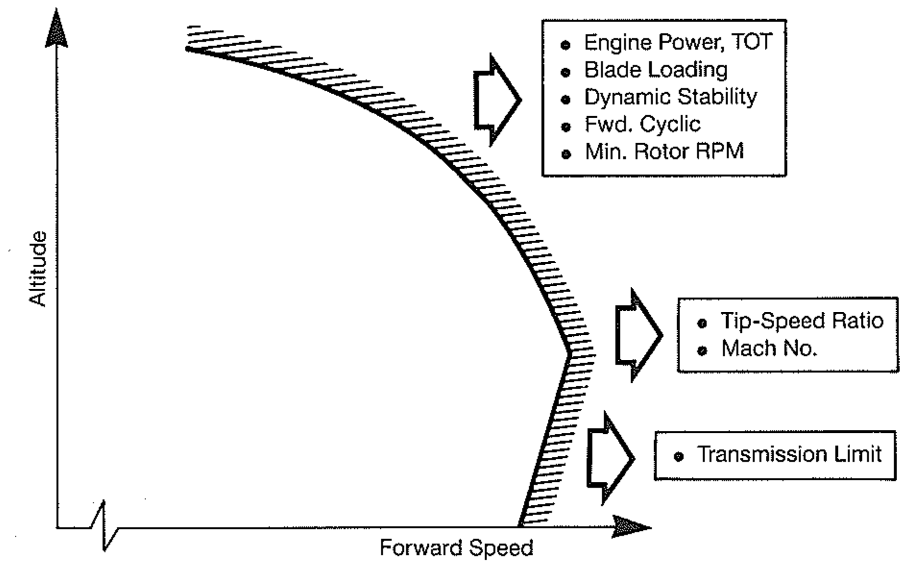

Fig. 9

As altitude increases, available engine power decreases as a function of the engine TOT characteristics which may influence horizontal speed capabilities correspondingly. On the other hand, if the engine is still able to provide substantial power, a handling qualities limit will be observed when the control response and dynamic stability deteriorate as the blade loading increases.

Load Factor Capability (Fig. 10)

The load factor capability is directly related to the blade loading coefficient, and experimental work shows that the limiting blade loading coefficient is strongly dependent on forward speed in particular the tip-speed ratio. Several levels of limitations are apparent. Firstly, the maximum available power will limit the manoeuvres and banked turns which are possible without loss of altitude. Secondly, as the load factor is increased, a handling qualities deterioration will be seen wherby control response becomes less effective. It may well be observed that this deterioration is not only dependent on the load factor and forward speed but also on the power settings. The onset of rotor stall is clearly announced. At much higher load factors, the pilot will eventually reach the boundary above which it is no longer possible to trim a steady state condition for the helicopter. This is the rotor stall limit, which is also indicated by other factors; typically rotor control loads increase dramatically as well as vibration levels. It is possible to active higher load factors, however, these can only be reached for a few seconds during transient

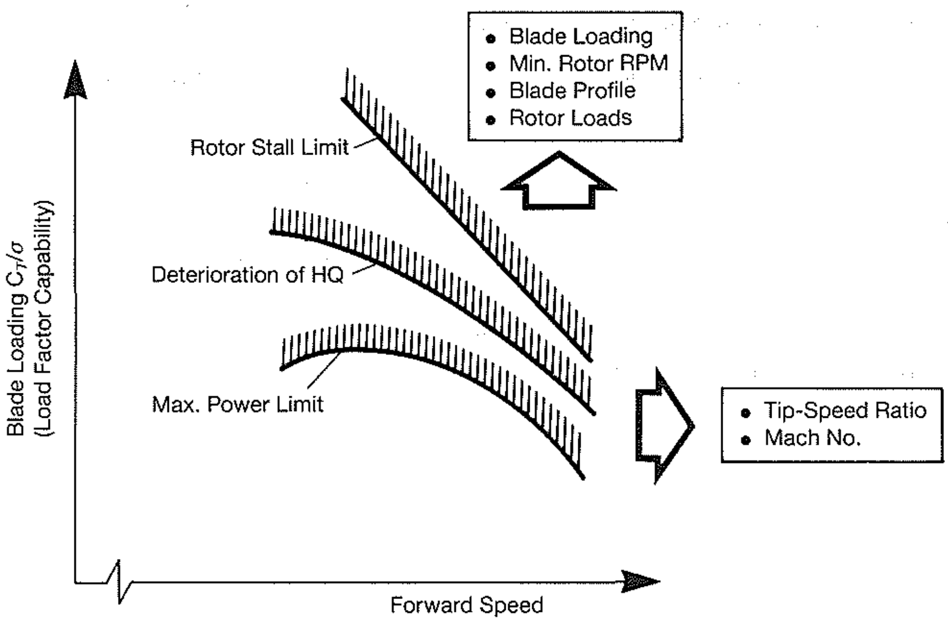

Fig. 10

manoeuvres. Current research activities are directed towards improving blade profiles to increase the maximum blade lifting coefficient, reduce detrimental Mach number influences and thereby improve load factor capability.

Height Velocity Envelope (Fig. 11)

Three main factors influence the size of the height velocity envelope. Firstly, a twin engine installation with good OEI power reserves will bring the most useful improvement. Secondly, the available energy stored in the rotor must be high by having a large rotor inertia and by designing for low minimum r.p.m.s. The third method is to design the fuselage and undercarriage to absorb more energy during a crash landing and thus protect the crew.

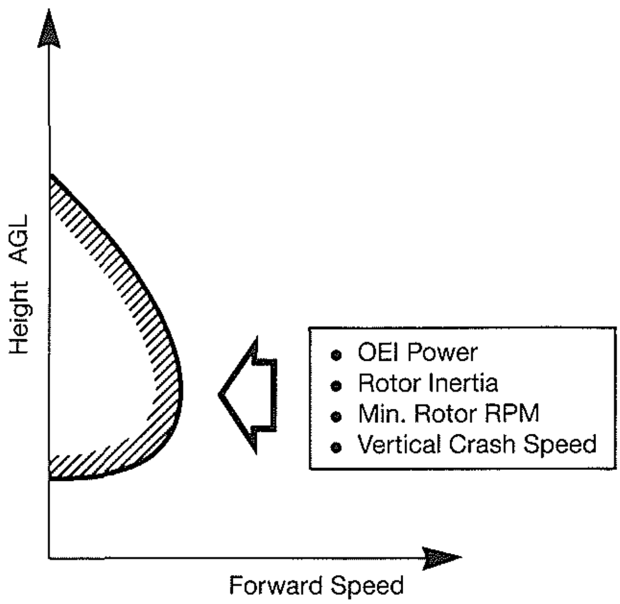

Fig. 11

4. Substantiation of Operational Limits

For both confirmation of helicopter development and the eventual certification of the helicopter, evidence has to be provided to confirm the design quality and safety together with the operational limitations. The approach used and the scope of the testing will itself depend on the desired operational envelope. The design targets for special purpose operation e.g. high altitude, high/low temperature, icing conditions will necessitate proportionally more effort in certification.

Different requirements and regulations exist, defining the rules for showing proof of compliance, these are;

- Design requirements of the helicopter manufacturer for substantiation of the performance and quality of the product
- Regulations of civil and military aeronautical authorities for demonstration of the basic airworthiness (FAR, BCAR, MIL-specs etc.).
- Additional customer requirements for special operations and military missions.

The proof of compliance with these requirements certainly demands the major activity during the development and certification phases. However, consideration must be given at the start of the project to the various methods by which compliance can be demonstrated. In some cases experimental investigations or flight testing will be obligatory, in other cases compliance may be shown by theoretical analysis or model testing. The potential methods for demonstrating compliance with the regulations are as follows (Fig. 12):

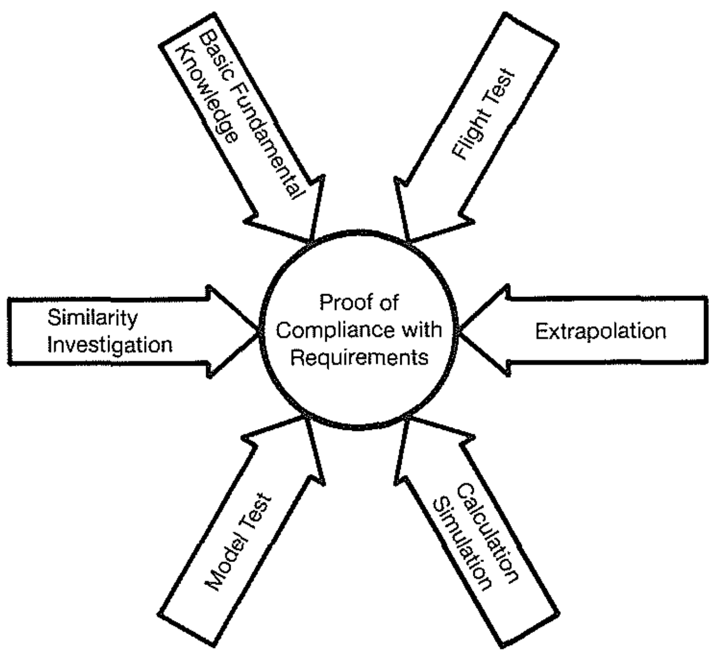

Fig. 12

Systematic flight testing can be applied over a wide range of the operational envelope. This approach is mainly used for determining flight characteristics under critical combination of adverse parameters, determination of installed power losses and checking of power requirements. However, flight testing can only be performed at isolated points in the envelope and the availability of the desired test conditions cannot always be guaranteed.

Extrapolation of flight test results is used to extend the tested range and the results to the corners of the operational envelope. Extrapolation usually covers the following parameters:
weight, center of gravity, altitude, temperature, power, speeds etc.

Calculation. Modern analytical methods are available for the prediction of results and, if validated over a sufficiently wide range, can be used for demonstrating compliance with regulations. Typical examples are engine performance models, cyclic trim position and helicopter power requirements calculation, etc.

The fundamental difference between extrapolation and calculation is considered in more detail in a later section.

Simulation. This term covers mathematical computer models of the helicopter which, in combination with complex performance calculations, can compute flight paths as a function of simulated pilot inputs (e.g. HV diagram, Cat. A take-off and landing distances).

There is no doubt that in future helicopter real time **flight simulators,** which can faithfully simulate flight characteristics, will be used more in the substantiation of critical situations.

Model tests. Scaled down models of the helicopter can be used for different investigations, e.g. wind tunnel tests, tests for emergency floats.

Similarity. Comparitive investigations may be of a theoretical, as well as of a practical nature and show proof of compliance on the basis of considerations of similarity to already certified helicopters.

The method of showing compliance with regulations has to be selected very carefully. Although, if it is desirable to show extensive and reasonable proof, economical reasons and schedule forecast have also to be taken into consideration. External circumstances, for example atmospheric conditions during the test phase, suitable test site, availability of test helicopters and measurement equipment will also influence the method employed for the proof of compliance.

Extrapolation – Calculation

The principle difference between extrapolation and calculation should be examined more closely. For extrapolation of test results to the corners of the operational envelope simple, pure mathematical functions or normalisation methods can be used. These methods are useful for a limited extrapolation range, but cannot identify trends caused for example by stall or Mach number effects. Consequently, improved prediction methods for calculation of performance and flight characteristics consisting of comprehensive, interdisciplinary helicopter simulation models have been developed by the industry in the last decade.

The advantage of such methods is shown in Fig. 13. The required power for hover is shown vs OAT and the prediction of a simple extrapolation method compared with calculation based on blade element theory. It can be seen that the extrapolation of flight test data to lower OAT's leads to a misleading result. The calculation, however, which considers the complete helicopter model, matching power requirements, engine performance, aerodynamics, including nonlinear effects, such as compressibility, leads to an accurate prediction.

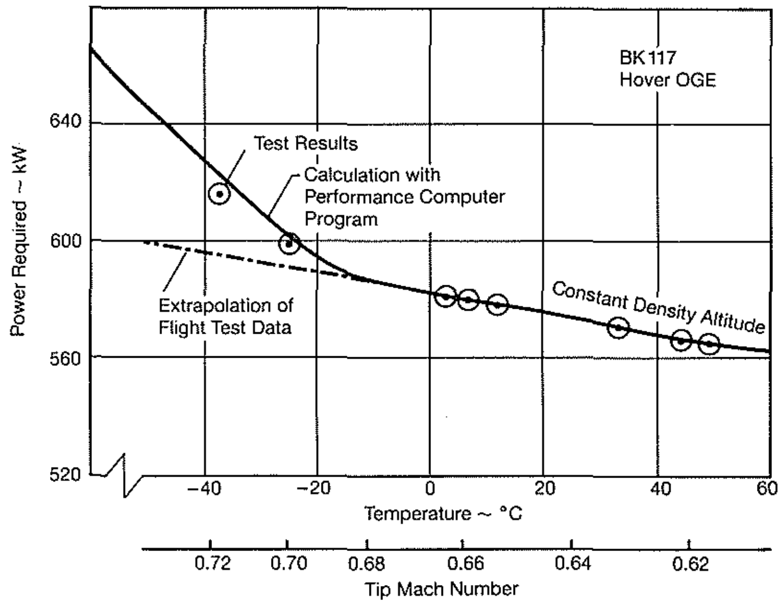

Fig. 13

5. Demonstration of Operational Limits

To demonstrate compliance by flight testing, data for extreme external conditions e.g. temperature or altitude are needed, in addition to the basic test results, usually gathered at the home base. The data presented in this paper, have been established during BK117 certification testing, and some BO105 LS data obtained at extreme high altitudes.

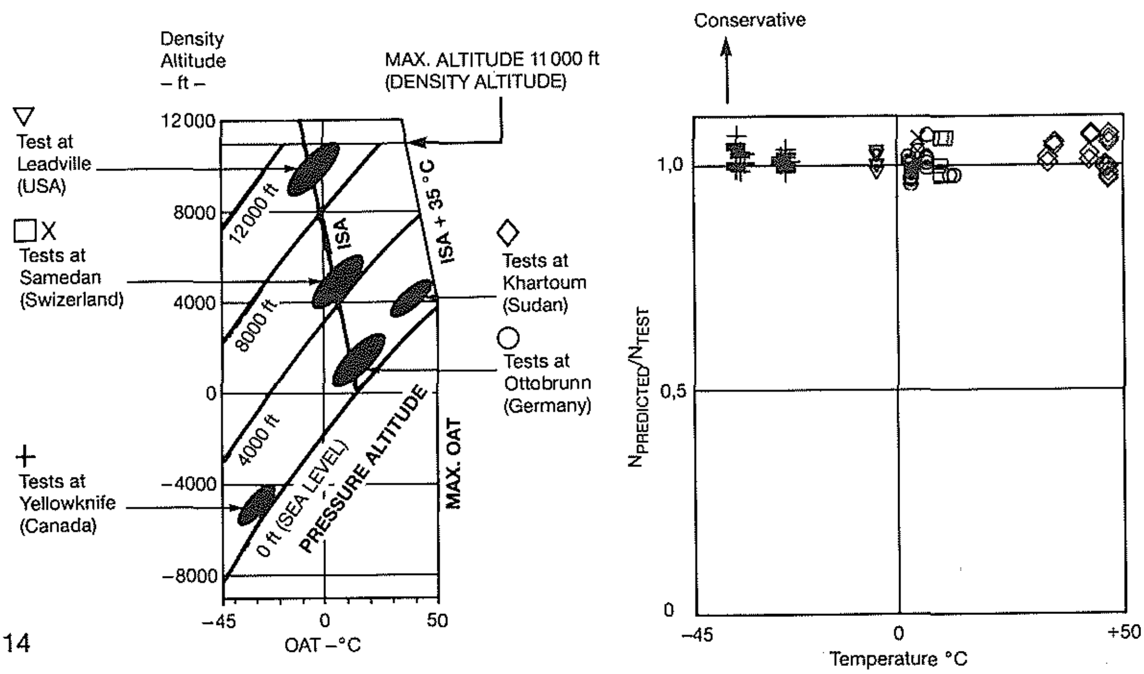

Fig. 14

The altitude and temperature ranges, for which the BK117 is certified, are shown in Fig. 14 for takeoff and landing operations, and in Fig. 15 for normal operation. Flight testing of the basic helicopter was conducted at the MBB home base at Ottobrunn. In order to acquire test data over a wide temperature range, additional tests were performed at Khartoum (Sudan) for high temperatures, and at Yellowknife (Canada) for low temperatures. Such extreme atmospheric conditions (–40 to +48 °C) should be available at low altitudes in order to provide a wide altitude range for gathering test data for climb or level flight performance (Fig. 15). Additional demonstrations of the helicopters ability to operate near the ground, e.g. take-off, landing and hovering, inclusive of emergency procedures, were conducted at high altitude test sites. The BK117 for example was tested at Samedan (Switzerland) at approximately 5000 ft density altitude and at Leadville (USA) at about 10000 ft. With these tests the total operational envelope of the BK117 helicopter could be demonstrated.

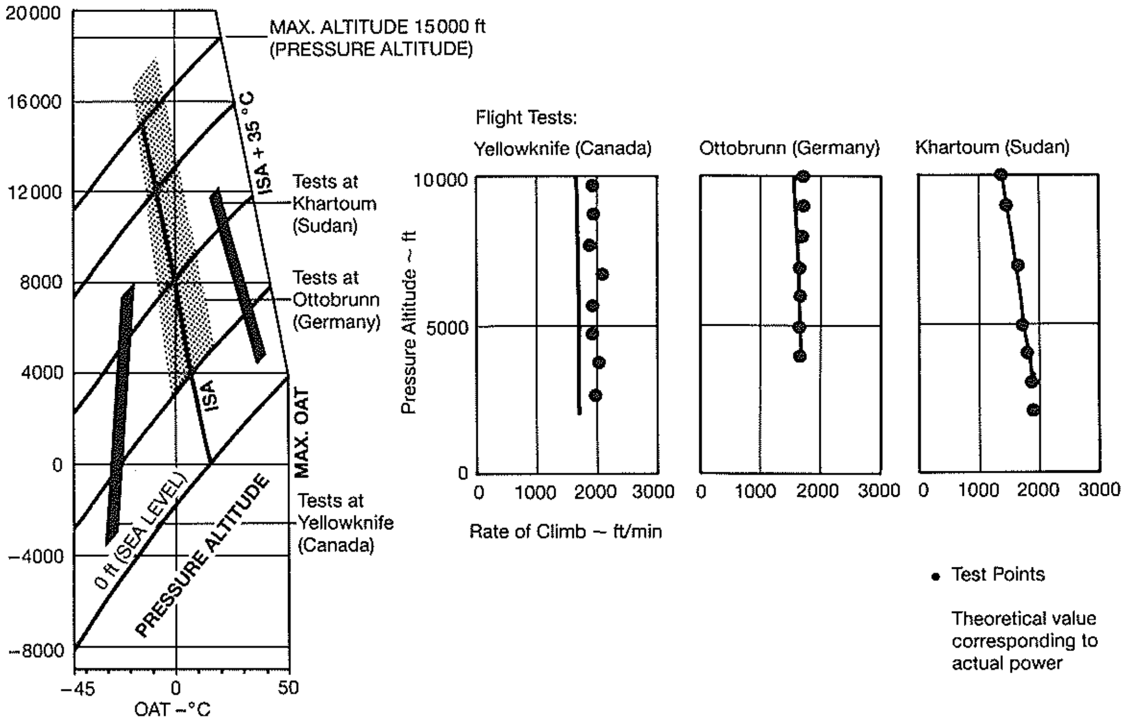

Fig. 15

For helicopters designed for an even wider operational environment, additional demonstration will be necessary as the certification authorities only allow a very narrow band for extrapolation. One example is the BO105 LS helicopter, the "hot and high" version of the BO105.Besides the altitude tests at Samedan and Leadville, this helicopter was taken to a test base in Chile, where at approximately 18000 ft density altitude the helicopters high altitude capabilities were demonstrated. Such tests always consist of a full performance evaluation inclusive of emergency procedures such as engine failures and the evaluation of the HV envelope boundaries.

Comparison of Flight Test Data with Calculation Results

For calculation of helicopter performance and flight mechanics, a flexible computer program is extensively used at MBB.

The helicopter calculation method used is based on a comprehensive, interdisciplinary helicopter simulation model. Aerodynamic modelling techniques are based on blade element theory and on the application of wind tunnel data for the airframe aerodynamics representation.

For performance, the program computes the power requirements and determines the performance boundaries taking into account engine manufacturers performance data for the desired flight condition. An automatic trim procedure is applied. For flight mechanics, manoeuvres, such as take-off and landing, flight paths or HV performance can be calculated. The model is also used for the calculation of trim condition, stability and control response characteristics.

To demonstrate the efficiency of modern calculation models some examples for comparison of predicted values with flight test data are discussed.

Performance. Test data gathered throughout a wide spectrum of atmospheric conditions are used to confirm the calculation method for the power required. After establishing the installed power losses the engine manufactures "deck" for a "spec-engine" can be used to produce the performance charts.

Fig. 14 shows a comparison of predictions from the computer program with actual flight data, gathered as shown above. The comparison of the hover performance data shows very good correlation over a temperature range of 90 °C. A small exception is the trend to slightly conservative predictions at extreme low temperatures. Throughout the whole temperature range, however, the error in the prediction of hover performance is less than 5 %.

Fig. 15 shows the confirmation of calculated climb performance by flight test at various OAT's. Good agreement can also be seen here, between calculation and flight test throughout a temperature range of 60 °C. Again the slightly conservative tendency at very low temperature is observed.

The prediction of hover performance over an extremely large altitude range up to more than 18000 ft density height is presented in Fig. 16. It is obvious that the calculation model provides valid results over the altitude range.

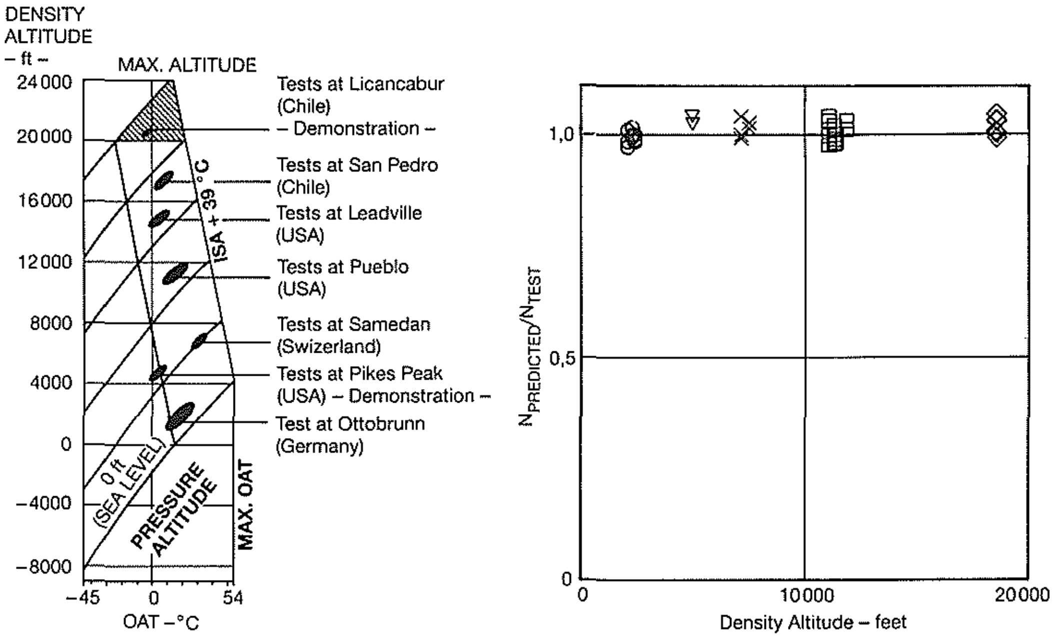

Fig. 16

Flight Characteristics. Mathematical models are also used for prediction of flight characteristics and for investigation of the influence of the operational envelope.

Some examples of the operational envelope control position calculation throughout the range of the flight envelope are shown below.

Fig. 17 shows the calculation of tail rotor control position at steady state 20 kts sideways flight and compares with actual measured data. The calculation was performed for the given loading conditions, shown on the left hand part of the figure. The trends of tailrotor control position against altitude compares well with the measured flight test data.

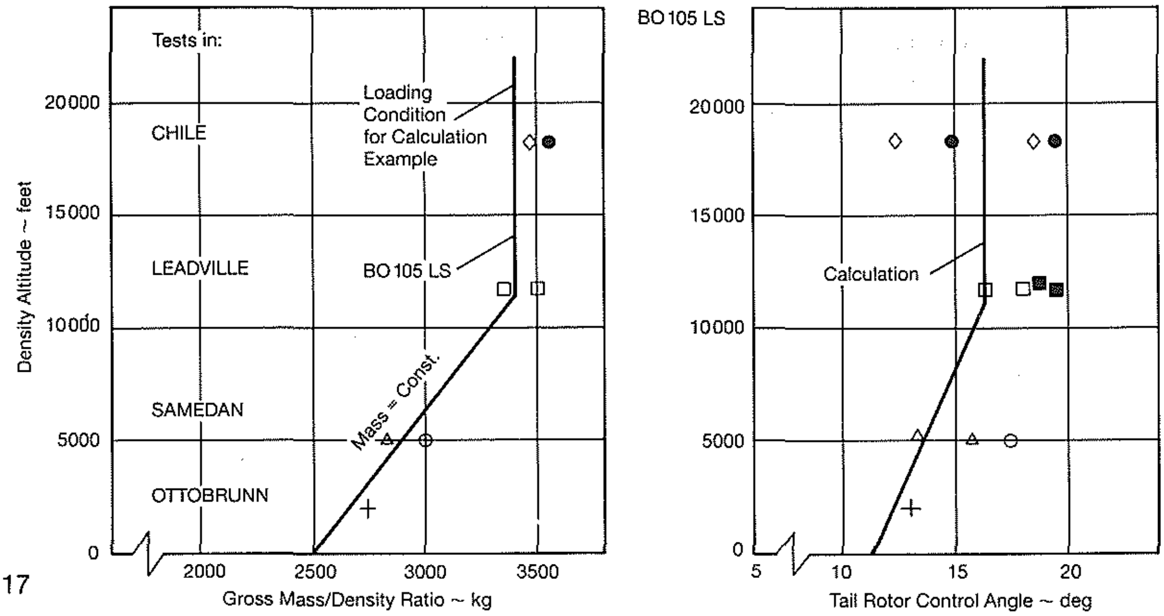

Fig. 17

A similar comparison of calculated lateral control position with measured data is shown in Fig. 18.

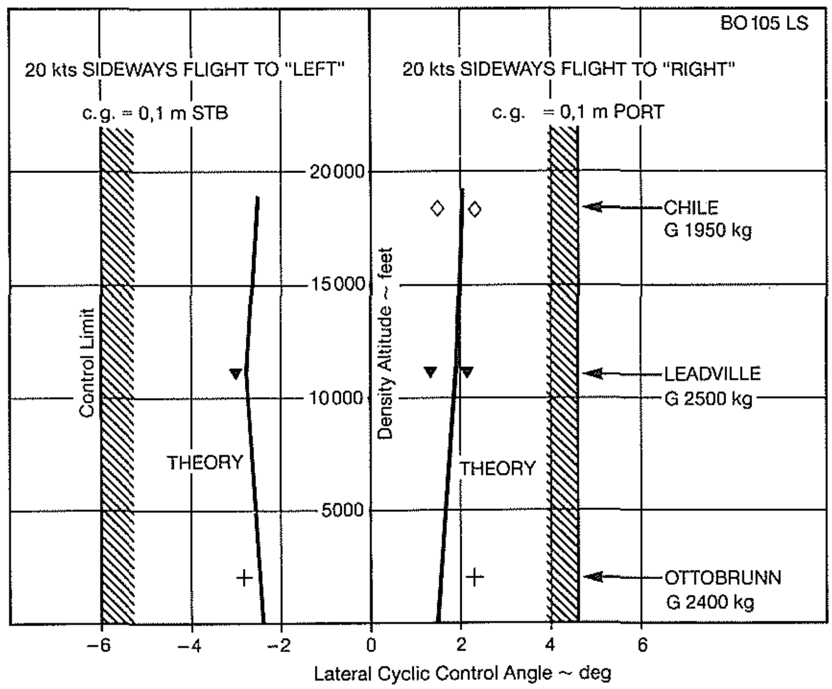

Fig. 18

Finally, an example of flight path simulation is given in Fig. 19. A nose down runaway of a SAS actuator in the pitch axis and the resulting change of pitch attitude and load factor have been calculated and compared with actual flight test.

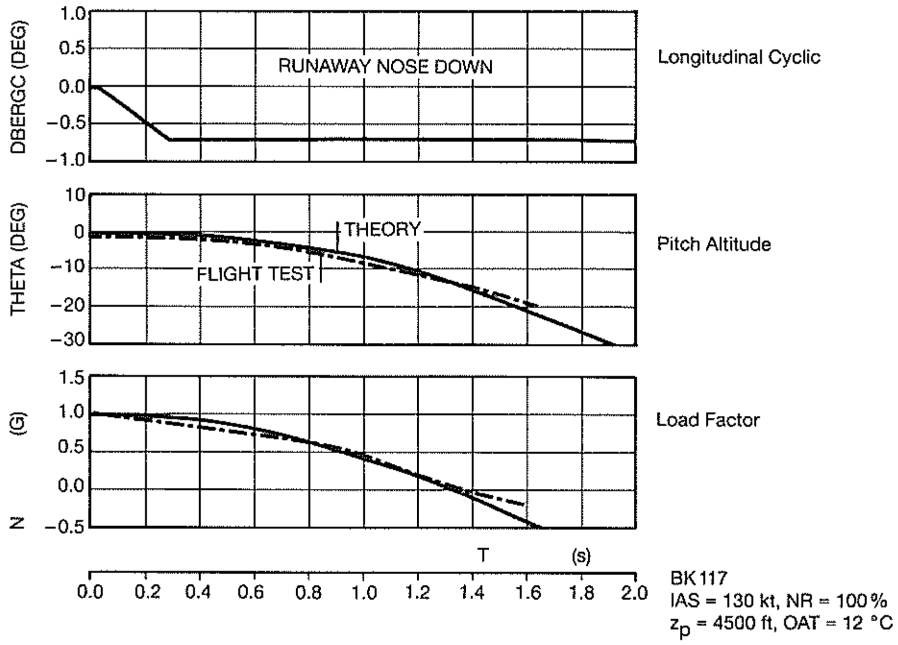

Fig. 19

Concluding Remarks

This paper has summarized the principle factors influencing the operational envelope of the helicopter. It has shown that increases in performance must normally be at the expense of other characteristics, usually gross mass and efficiency. Hence a clear target of requirements must be established at the start of the project.

Improvements in mathematical models and their confirmation through flight testing covering the whole of the flight envelope, should provide in the near future a cost effective alternative to the series of flight test campaigns which are often mandatory for certification. Acceptance must, however, be found with the certification authorities which, to date, follow a very conservative policy with regard to extrapolation. The object of the testing described in this paper has been an attempt in this direction.

BK117 Cold Weather Tests at Yellowknife, Canada

BO105 LS High Altitude Flight Testing
near San Pedro, Chile at ~18000 ft

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