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BO105 CBS-5:
BO105 UPGRADE THROUGH NEW ROTOR BLADES

by

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Abstract

To further improve the BO105 helicopter mainly from the performance and comfort point of view, a new version of the aircraft was launched through fitting the four-bladed hingeless rotor system with advanced geometry rotor blades and installing an upgraded main gearbox. The newness of the rotor blades consists in an improved aerodynamic (airfoils, planform, twist) and structural/dynamic layout whereas the fundamental rotor characteristics like stiffness, damping, etc. remained unchanged.

The new rotor blades were extensively tested in wind tunnel, on whirl tower, and in flight. The new aerodynamic blade design results in a considerable reduction of power required which is equivalent to a payload increase up to 130 kg in hover condition. The optimised blade dynamics lead in combination with reworked C.F. pendulum absorbers to an essential decrease of the cabin vibration level. The application of advanced materials and the introduction of new manufacturing procedures/processes help to improve the reliability and to reduce the costs.

A survey of the rotor design rationale, the main characteristics, and the most important test results is presented concentrating upon the fields of handling qualities, vibratory loading, noise, and performance. In connection with the latter one, special emphasis is laid on operational aspects including an improved Category A capability.

1. Introduction

Since 1971, the twin engine BO105 helicopter has been sold more than 1300 times (all versions) and the total fleet has gathered up to now about 3.4 Million flight hours. The highest operation time that has been reached in service for single helicopters, is nearly 20000 hours.

Fig. 1: BO105 CBS-5 "EC Super Five"

To guarantee the attractiveness of this successful helicopter for a further couple of years, a new version of the aircraft was launched through upgrading the four-bladed hingeless rotor system by advanced geometry rotor blades in combination with an increased one-engine power rating for the main gearbox. This version is called BO105 CBS-5 or in combination with a specific equipment package "EC Super Five" (Figure 1). In the following, the main features and improvements of the CBS-5 in relation to the existing version (CBS-4) are presented.

2. Rotor Design Rationale

The decision to launch the CBS-5 was strongly influenced by the so-called KWS-1 programme, a military improvement programme for the PAH-1 antitank helicopters of the German Army. Within this programme, new rotor blades were developed which were tailored to the specific mission and operational requirements of the PAH-1. The technological improvements of these rotor blades include an advanced aerodynamic layout, an optimised dynamic tuning, and a new structural design. The main characteristics of the new rotor blade are summarised in Figure 2. A detailed description is given in Reference 1.

	Standard Blade	New Blade
Radius	4.9m	4.9 m
Solidity (thrust weighted)	0.07	0.07
Pitch axis pre-cone angle	2.5 deg	2.5 deg
Equivalent flapping hinge offset	~ 14.5 %	~ 14.5 %
Fundamental lead-lag frequency	0.70	0.69
Lock number	8.4	7.6
Blade planform	rectangular	tapered
Inboard blade chord	0.27 m	0.30 m
Taper ratio	-	2/3
Airfoils	NACA 23012	DM-H3/H4
Blade twist (linear)	- 10 deg	- 8 deg
c_T/σ (2500 kg, S. L. ISA)	0.079	0.079
Total blade weight (incl. absorber)	34.2 kg	38.3 kg
Rotor inertia	942 kgm^2	1038 kgm^2

Fig. 2: Main data of new geometry rotor blade

2.1 Aerodynamic Blade Layout

The objective of the aerodynamic blade optimisation was threefold: Firstly, to increase the payload, secondly, to improve the forward flight performance, and thirdly, to reduce the rotor noise generation. To meet these objectives, new generation airfoils, a tapered blade tip, and a higher blade twist were applied.

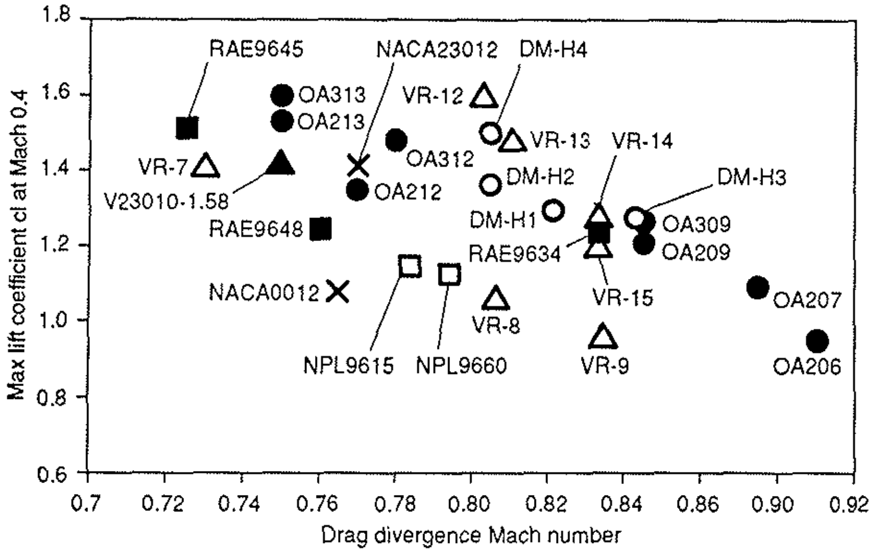


Fig. 3: Maximum lift coefficient vs drag divergence Mach number for several rotor blade airfoils

The airfoils used, one for the blade outboard section with 9 % thickness (DM-H3Tb) and one for the blade inboard section with 12 % thickness (DM-H4Tb), were developed by DLR in co-operation with MBB Helicopter Division (now: EUROCOPTER Deutschland). The requirements were specified in terms of maximum lift at low Mach numbers, lift-to-drag ratio at medium Mach numbers, transonic drag at near zero lift, and maximum allowable pitching moment. The favourable characteristics of both airfoils are demonstrated in Figure 3 where the maximum lift coefficient is plotted versus the drag divergence Mach number in comparison to other well-introduced and new airfoil families. For the DM-H3Tb airfoil for example, the so-called Mach tuck, i.e. the beginning of rapid change of pitching moment versus Mach number at constant lift (Reference 2), has been shifted to higher flight speeds by about 50 km/h in relation to the NACA 23012 airfoil (Figure 4).

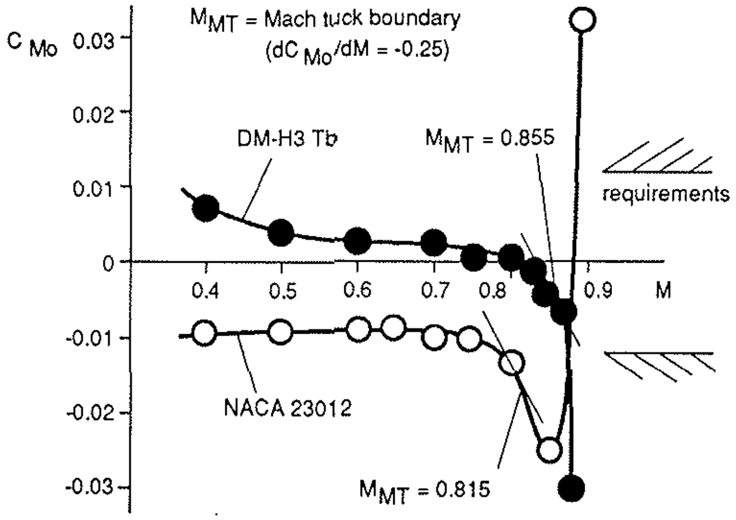


Fig. 4: Zero lift pitching moment behaviour of DM-H3Tb airfoil compared to NACA 23012

The blade planform and in particular the tip geometry have a strong influence on power consumption and on noise generation. Parametric studies have shown that an outboard reduction of the blade area can improve performance not only in hover (Figure 5). Similar favourable effects on power consumption and noise emission can be achieved through a high blade twist due to a "smoother" lift distribution over the blade radius.

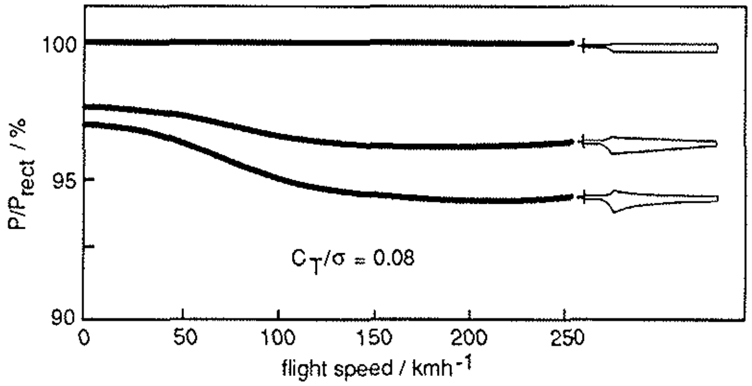


Fig. 5: Influence of blade tapering on rotor power consumption

Intensive theoretical studies by use of a modern CFD method based on the solution of the Euler equations (Reference 3) led to a sweep back of the most outboard part of the leading edge. In principle, a sweep back of the leading edge in combination with a reduced thickness in the tip region promises not only some performance benefit but also a reduction of unfavourable transonic effects at the advancing blade tip.

The application of these aerodynamic improvements to the new rotor blade results in the following design:

- rectangular planform up to 80 % radius (300 mm chord),
- linear taper between 80 % and 100 % (2/3 taper ratio, i.e. 200 mm chord at the tip),
- DM-H4Tb airfoil up to 80% radius,
- DM-H3Tb airfoil from 98.5 % to 100 % radius (linear transition from 12 % to 9 % airfoil),
- linear twist of -10 deg,
- 75 deg sweep back of the leading edge between 98.5 % and 100 %.

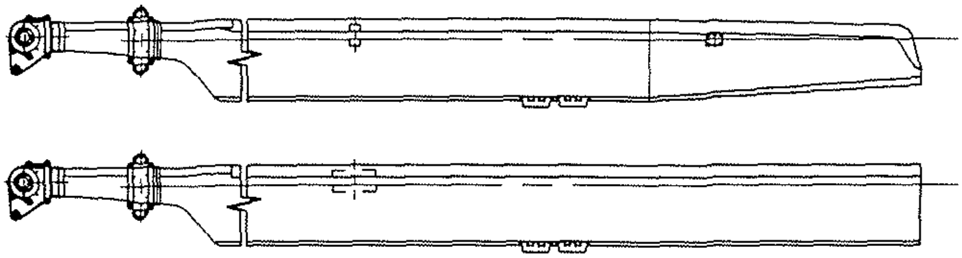


Fig. 6: Planform comparison between new and standard rotor blade

The new blades have the same thrust-weighted solidity (hover) than the existing BO105 production rotor. A geometrical comparison of the new tapered blade with the standard rectangular blade is shown in Figure 6. In Figure 7, the calculated local Mach number distribution on the upper surface of the advancing blade tip is shown for both, the new and the standard rotor blade.

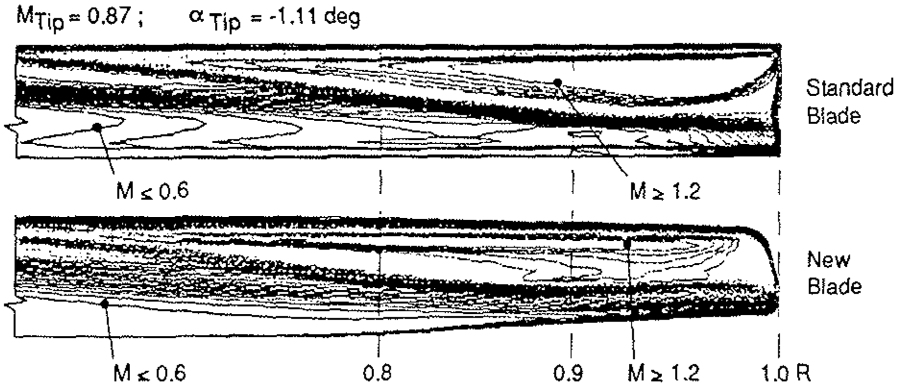


Fig. 7: Local Mach number distribution on the upper surface of the advancing blade

2.2 Noise Aspects

The noise emission of the BO105 helicopter with standard rotor is about 4 dB below the present ICAO certification limits. In the seventies, when the BO105 was introduced into the market, such noise levels were representative for a low noise design. Meanwhile, after more than 20 years of production, due to the growing overall noise loading, noise restrictions become increasingly stringent. Thus, external noise generation was an important aspect for the design of the new blade in particular in case of the flyover noise where the margin to the corresponding ICAO limit is small compared to other flight conditions.

In general, noise reduction goes conformably to the decrease of power required. The reduced thickness due to taper and thinner airfoil at the tip yield a reduction of thickness noise that is proportional to the local normal velocities on the blade surface, and also of shock wave generation at high speed flight. In addition, a reduced blade chord in the tip region leads to a less concentrated tip vortex due to a lower tip loading and thus to a reduced vortex interaction with the following blade and by that to a decrease of blade slap noise mainly in descent flight.

Finally, the lower power consumption of the new rotor reduces the required tail rotor thrust at the same gross weight and consequently the tail rotor noise generation.

2.3 Vibration Control by Dynamic Blade Optimisation

One of the important parameters in evaluating the success of a helicopter design are the vibration characteristics. The rotor excitation loads in combination with the vibratory airframe modes are determining for the cabin vibration level. The objective for the dynamic optimisation of the advanced geometry rotor blade was to decrease the rotor excitation such that the 4/rev cabin vibration level does not exceed 0.1 g in each direction over the whole forward speed range.

A fundamental design measure for influencing the dynamic behaviour of a rotor blade is the adequate frequency placing of the higher natural bending modes in flap and lead-lag direction. The most important ones are the 2nd and 3rd flap and the 2nd lead-lag bending modes. In case of the four-bladed rotor, the dominant rotor excitation in the non-rotating system is a 4/rev roll/pitch moment which is due to the specific rotor "filtering" properties mainly influenced by the 2nd and 3rd flap bending modes (cyclic rotor modes).

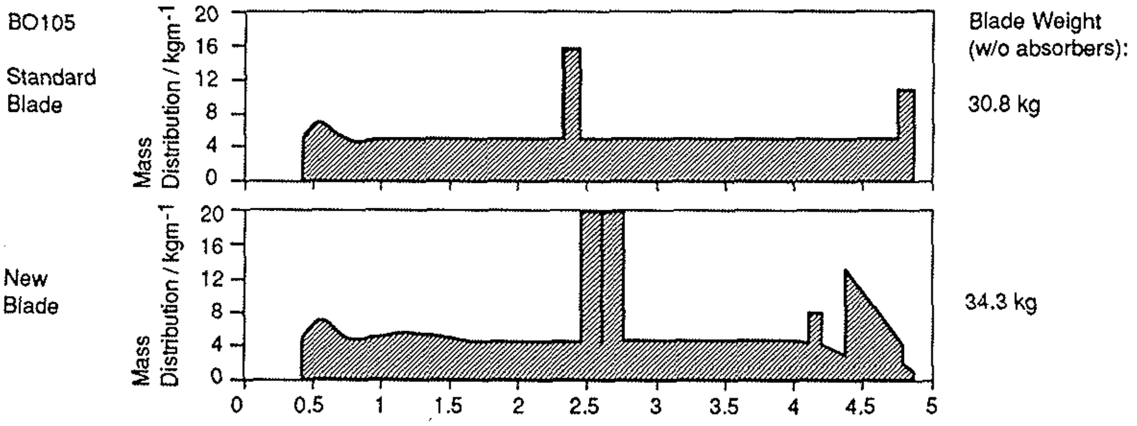


Fig. 8: Spanwise blade mass distribution

For the new rotor blades, the main goal was to further improve the tuning of the BO105 standard blades especially through decreasing the 2nd and increasing the 3rd flap bending frequency. This was realised by adding some tuning weight at 50 % radius and at the tip and by adapting the flapping stiffness distribution to the particular geometry of the tapered blade tip (Figure 8). The frequency placement of the relevant blade bending modes as well as the corresponding moment and shear force transmissibilities are summarised in Figure 9. The 2nd flapping frequency was reduced from 2.74 to 2.61 and the 3rd flapping frequency was increased from 4.94 to 5.32 (calculation results), whereas the 2nd lead-lag frequency remained nearly unchanged. At least from theory, significant reductions especially of the transmissibilities for the 2/rev and 3/rev flap bending moments are predicted.

The BO105 CBS production helicopter is normally equipped with blade neck mounted centrifugal force pendulum absorbers tuned to 3/rev for vibration reduction. As an additional measure, for the new rotor blade, these pendulum absorbers were redesigned to improve their efficiency. The pendulum mass was increased by 0.85 kg. Thereby, the maximum amplitudes are reduced leading to a better linearity at high excitation. Both, the improved blade tuning and the more effective pendulum absorbers contribute to an overall reduction of the BO105 CBS-5 cabin vibration level compared to the helicopter equipped with standard blades.

	2nd Flapping Frequency	Moment Trans-missibility M23	Shear Force Trans-missibility Q24	3rd Flapping Frequency	Moment Trans-missibility M35	Shear Force Trans-missibility Q34	2nd Lead-lag Frequency	Moment Trans-missibility Q23	Shear Force Trans-missibility Q25	1st Torsional Frequency
Standard Blade	2.74	1.96	0.74	4.94	3.36	1.62	4.20	1.95	2.28	3.70
New Blade	2.61	1.49	0.62	5.32	2.76	1.56	4.23	1.96	2.42	4.60

Fig. 9: Frequencies and transmissibilities of the relevant blade bending and torsional modes

2.4 Blade Structural Design

The airfoil section of the advanced rotor blade has in comparison to the standard blade a completely new structural design coupled with modern manufacturing methods accompanied by an improved manufacturing quality.

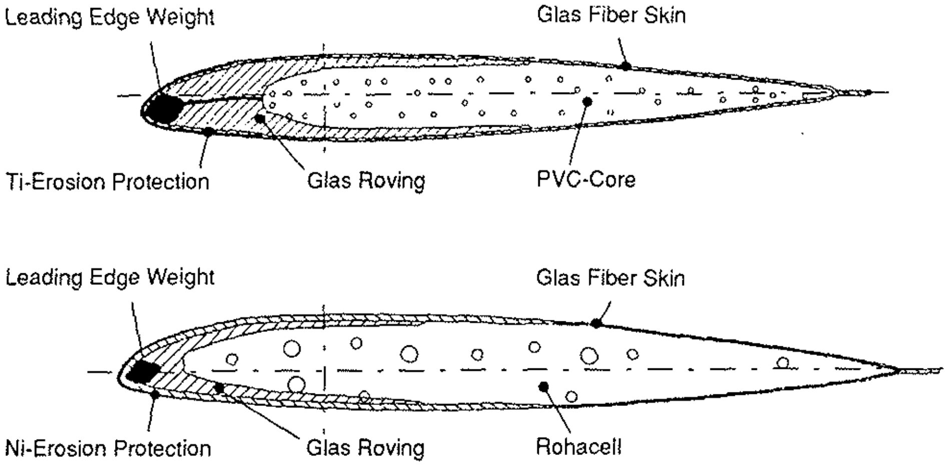


Fig. 10: Comparisons of blade cross sections

In Figure 10, the cross section (homogeneous blade section) of the new blade is compared to the corresponding cross section of the standard blade. The main differences between the two versions are as follows: The wet-in-wet construction is replaced by a Prepreg design mainly due to an easier handling and an essentially reduced evaporation rate of solvents during the manufacturing process. The glass fibre C-spar is maintained but it is less voluminous. Rohacell foam is used instead of PVC foam as core material. The thickness of the glass fibre skin is reduced from 1 mm to 0.75 mm without affecting the handling stability. To retain the torsional and bending stiffnesses of the tapered blade tip, carbon fibre material is used for additional straps and for the skin between 0.8 R and 1.0 R.

The material for the erosion protection shield was changed from titanium to nickel due to a better durability and due to more favourable shaping possibilities in particular for the blade tip. For lightning protection, the carbon fibre outboard blade section is completely shielded by Cu-mesh. To guarantee a reproducible high contour accuracy, the new blade is manufactured by use of special moulds with plug-in technique.

3. Test Results

The new rotor blades were intensively tested as a 40 % Mach scaled model in the German-Dutch Wind Tunnel (DNW) as well as in full scale on whirl tower and in flight. Special emphasis was laid on the verification of rotor performance, thrust capacity, handling qualities, vibratory loading, noise emission, and Category A capabilities. In the following, representative test results are presented for both, the new and the standard blades in comparison to theory.

3.1 Thrust Capacity

The aerodynamic blade optimisation led not only to a reduction of power required but also to an increase of the thrust capacity. This is confirmed by wind tunnel tests using Mach scaled model rotors with the same thrust-weighted solidity. In Figure 11, the blade loading is shown for advance ratios of 0.25, 0.29 and 0.34. In all cases, a slightly higher maximum thrust could be achieved with the new blades. For $\mu = 0.25$, the maximum thrust was limited by the rotor balance.

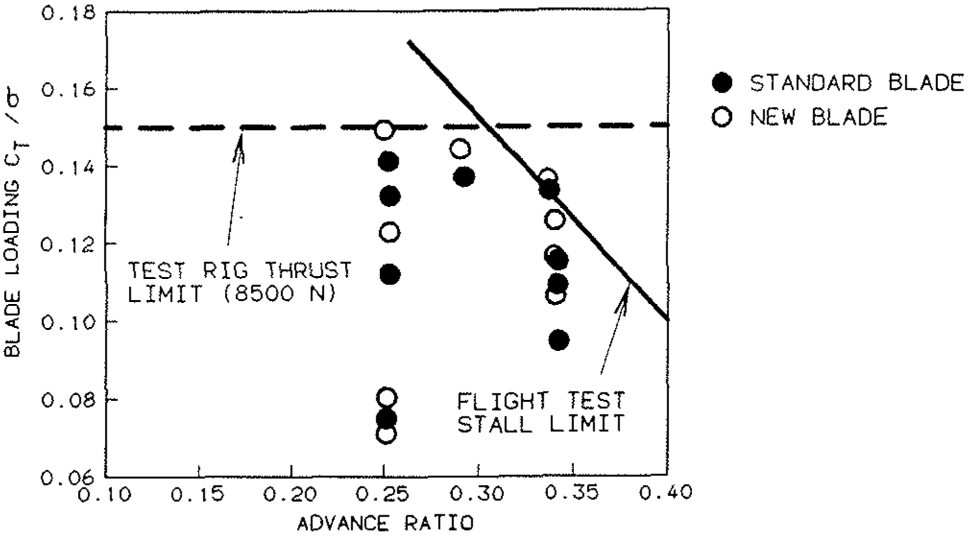


Fig. 11: DNW model rotor tests : Blade loading vs advance ratio

3.2 Performances

The power required was measured in hover for gross weights between 1850 kg and 2550 kg. In Figures 12 and 13, hover power in and out of ground effect is plotted versus gross weight for the new and standard rotor blades. All results are reduced to S.L. ISA condition. The solid lines are average curve fits of the measuring points. In both cases, for the advanced rotor blades, a significant power reduction can be seen in comparison to the standard blades resulting in a payload increase of up to 130 kg (HIGE). In ground effect, the maximum hover altitude ceiling increases by about 2000 ft to 8000 ft and out of ground effect, by about 3000 ft to 5400 ft in comparison to the BO105 with standard blades at a gross weight of 2500 kg (ISA condition).

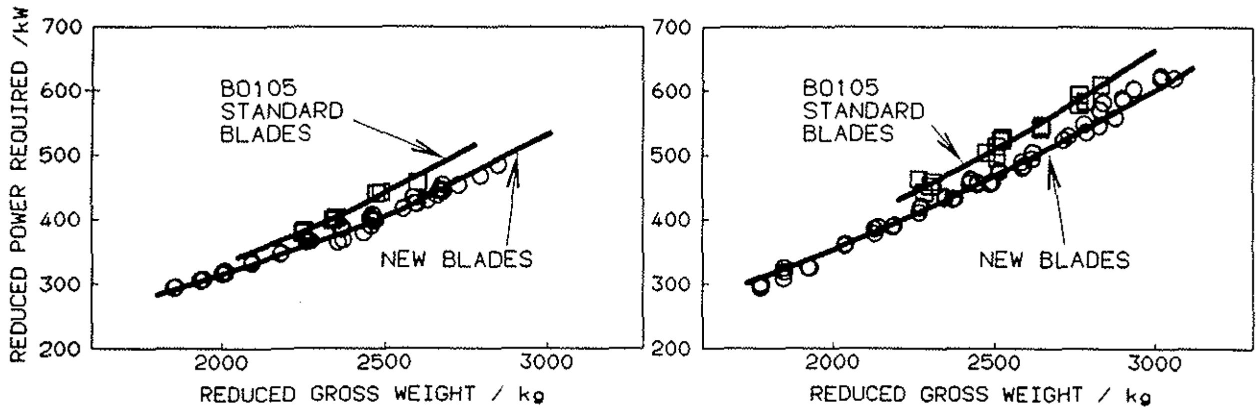
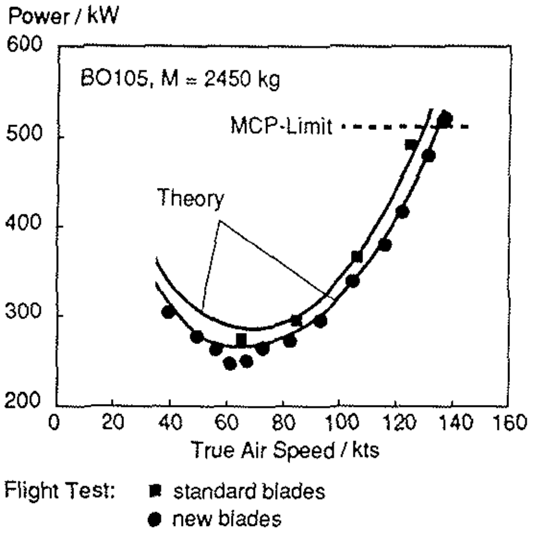


Fig. 12: Hover power required vs gross weight (IGE)

Fig. 13: Hover power required vs gross weight (OGE)

Figures 14 and 15 show the power required versus forward speed at density altitudes of 5000 ft and 10000 ft for gross weights of 2475 kg and 2450 kg respectively in comparison to theoretical results. For the new rotor blades, significant power savings can be detected over the whole forward speed range. In high altitude and at high speed, a power reduction of more than 10 % was measured.

The single engine service ceiling performance was also improved with the new blades. The BO105 CBS-5 is capable to perform a forward flight at v_y with some climb reserve even at its maximum gross weight of 2500 kg up to an altitude of 3000 ft (ISA). For the standard rotor blades, due to the higher power required, the single engine service ceiling performance is limited by the main gearbox torque between S.L. and 2600 ft (ISA) and the maximum gross weight is 2430 kg.



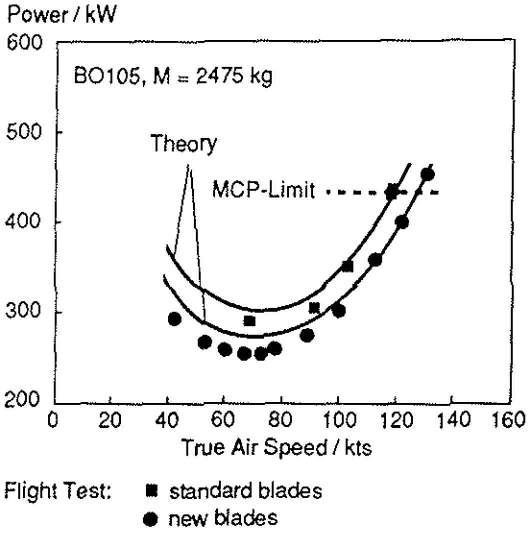
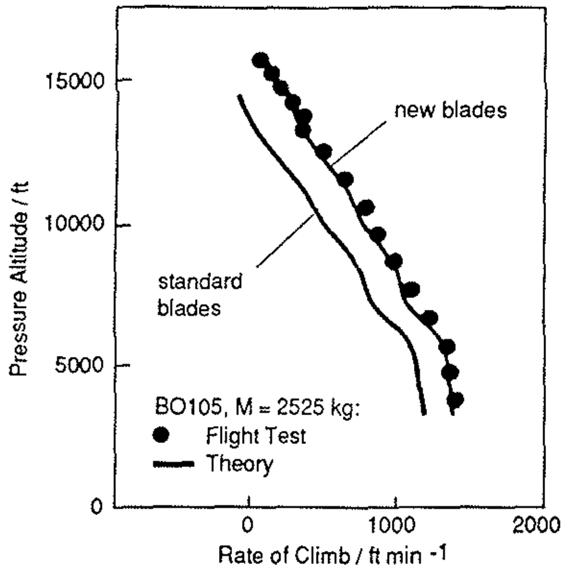


Fig. 14: Power required vs fwd speed ($z_\sigma = 5000$ ft)

Fig. 15: Power required vs fwd speed ($z_\sigma = 10000$ ft)

In Figure 16, the benefit of the new rotor blades with regard to climb performance is demonstrated. The pressure altitude versus rate of climb at v_y is compared with theoretical curves for both blade versions (all engines operative; maximum continuous power; 2525 kg). Theory is in good agreement with measured values. The climb potential of the BO105 CBS with new blades is increased between 200 and 350 ft/min according to the actual altitude. An important advantage of the improved climb ability is the possibility to perform quicker takeoffs resulting in a shorter noise intrusion time at the ground.

Figure 17 shows the calculated maximum cruise speed as a function of pressure altitude at ISA condition for the BO105 with new and with standard rotor blades. In addition, CBS-5 flight test data are plotted into the diagram. In higher altitudes where the helicopter performance is limited by the engines, the test results indicate a higher achievable cruise speed than predicted by theory. It should be mentioned that the theoretical curves shown are based on guaranteed minimum engine performances. In general, a substantial increase of the maximum cruise speed is provided by the new rotor blades. They allow to operate the helicopter in higher altitudes and at higher temperatures.



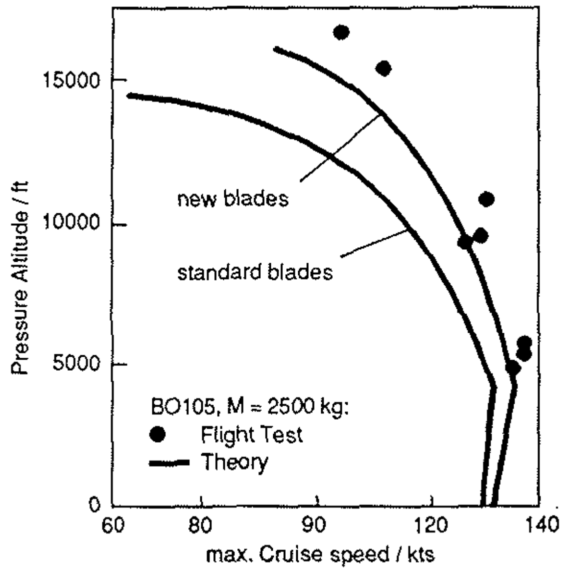


Fig. 16: Rate of climb at v_y as a function of pressure altitude

Fig. 17: Maximum cruise speed as a function of pressure altitude

3.3 Vibration

The dynamic optimisation measures applied (see Chapter 2.3) promise a reduction of airframe vibration which is confirmed by flight test. The frequencies of the relevant blade bending modes which were measured on whirl tower at 0 % and 100 % rotor RPM, are plotted into the calculated frequency diagram (Figure 18). On the whole, the predicted values were confirmed by the test results.

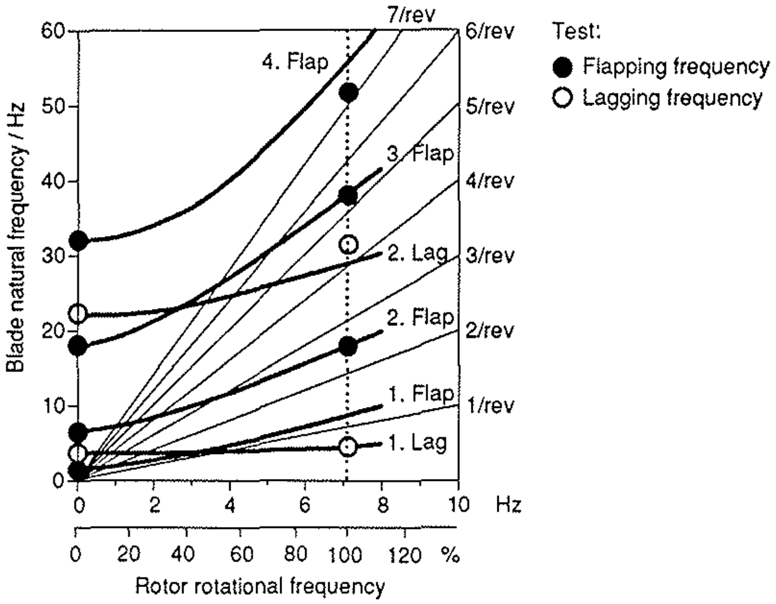


Fig. 18: Frequency diagram of new geometry rotor blade

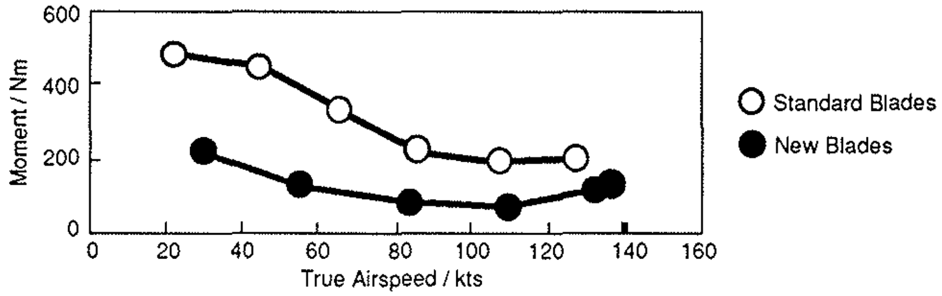


Fig. 19: 3/rev rotor shaft bending moment vs fwd speed

In Figure 19, the 3/rev rotor shaft bending moments which are the most important contributor to the 4/rev vibration excitation, are plotted versus forward speed in comparison to the standard version. Due to the reduction of the 2nd flap bending frequency and due to the optimisation of the 3/rev centrifugal force pendulum absorbers, the BO105 CBS-5 moment is significantly lower over the total speed range. In Figure 20, the longitudinal, lateral, and vertical 4/rev cockpit accelerations are shown as a function of forward speed. The CBS-5 vibration level is in particular in case of the longitudinal and the lateral axis considerably lower compared to the BO105 with standard blades. The measurements are confirmed by the crew reporting a comfortably low cockpit vibration level over the whole flight range.

Of course, the overall subjective feeling of crew and passengers in a vibrating helicopter environment can not completely be described by the 4/rev acceleration values. A more comprehensive measure of whole body vibration is the so-called Intrusion Index according to ADS-27 (Reference 4). In Figure 21, the Intrusion Index is shown as a function of speed for both helicopter versions. The BO105 CBS-5 values are in particular in the low and medium speed range well below the standard BO105 levels.

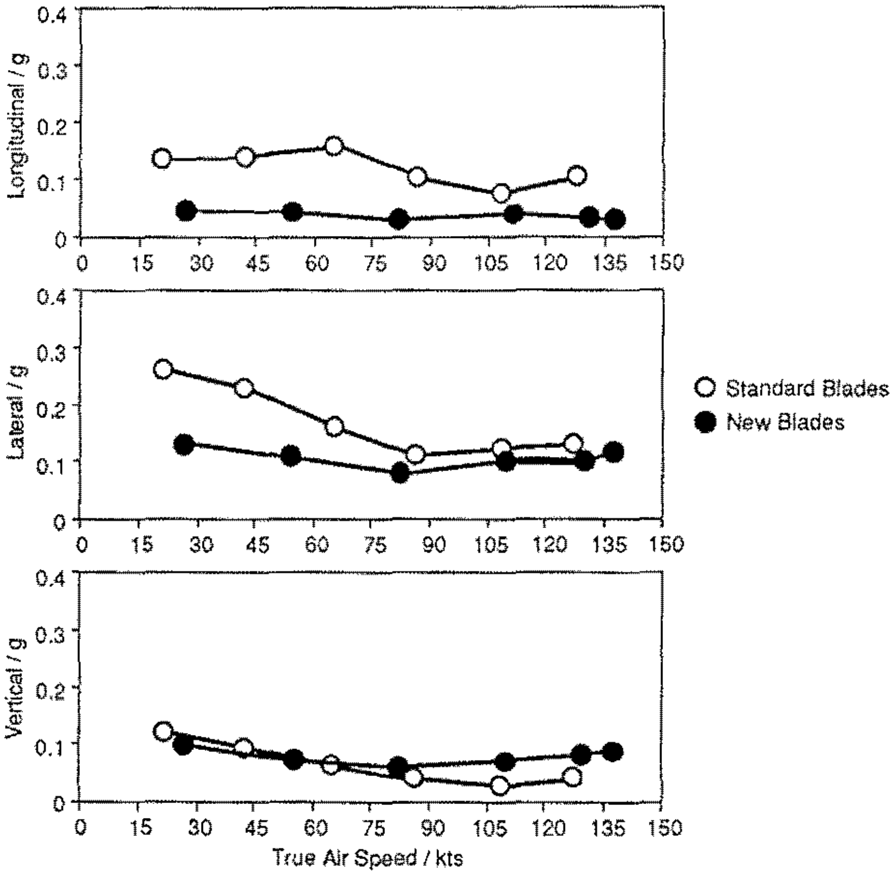


Fig. 20: 4/rev cockpit accelerations vs fwd speed

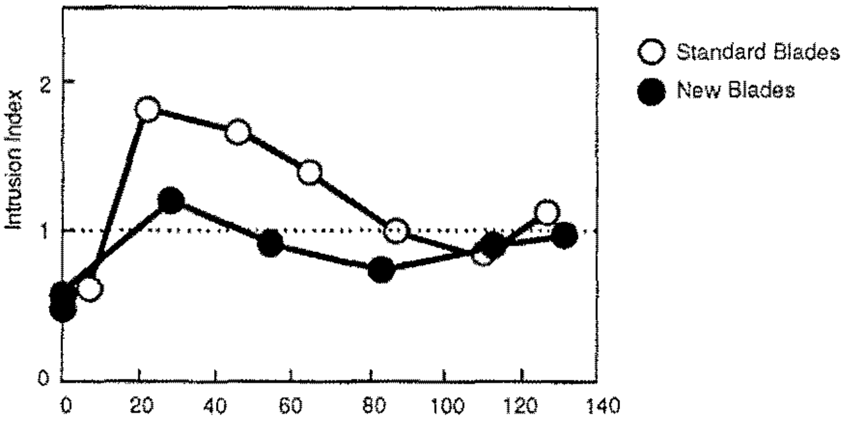


Fig. 21: Cockpit vibration level in fwd flight (Intrusion Index)

3.4 External Noise

To verify the noise characteristics of the new rotor blades, the noise emission of a 40 % Mach scaled model rotor was measured in the German-Dutch Wind Tunnel (DNW). These tests were performed by DLR Braunschweig (Reference 5). Similar measurements exist for the rectangular standard rotor blades with NACA 23012 airfoil and are used as a reference.

Figure 22 shows the PNL (Perceived Noise Level) contours of both rotors in horizontal flight condition at 60 m/s. The results indicate clearly the noise reduction benefit as expected. In particular on the upstream advancing blade side, the most important noise reduction can be noticed. Even more impressive is the comparison of the sound pressure time histories coming from the most

2 PNdB can be observed in relation to the standard blades. At the downstream retreating blade side, mainly the tail rotor noise contribution is reduced, while at the upstream advancing blade side, the main rotor thickness noise is decreased. Even more impressive is the comparison of the sound pressure time histories coming from the most upstream microphone position which are also included in Figure 22. Contrary to the expectation, no significant noise reduction could be measured in descent flight condition where most BVI noise is generated.

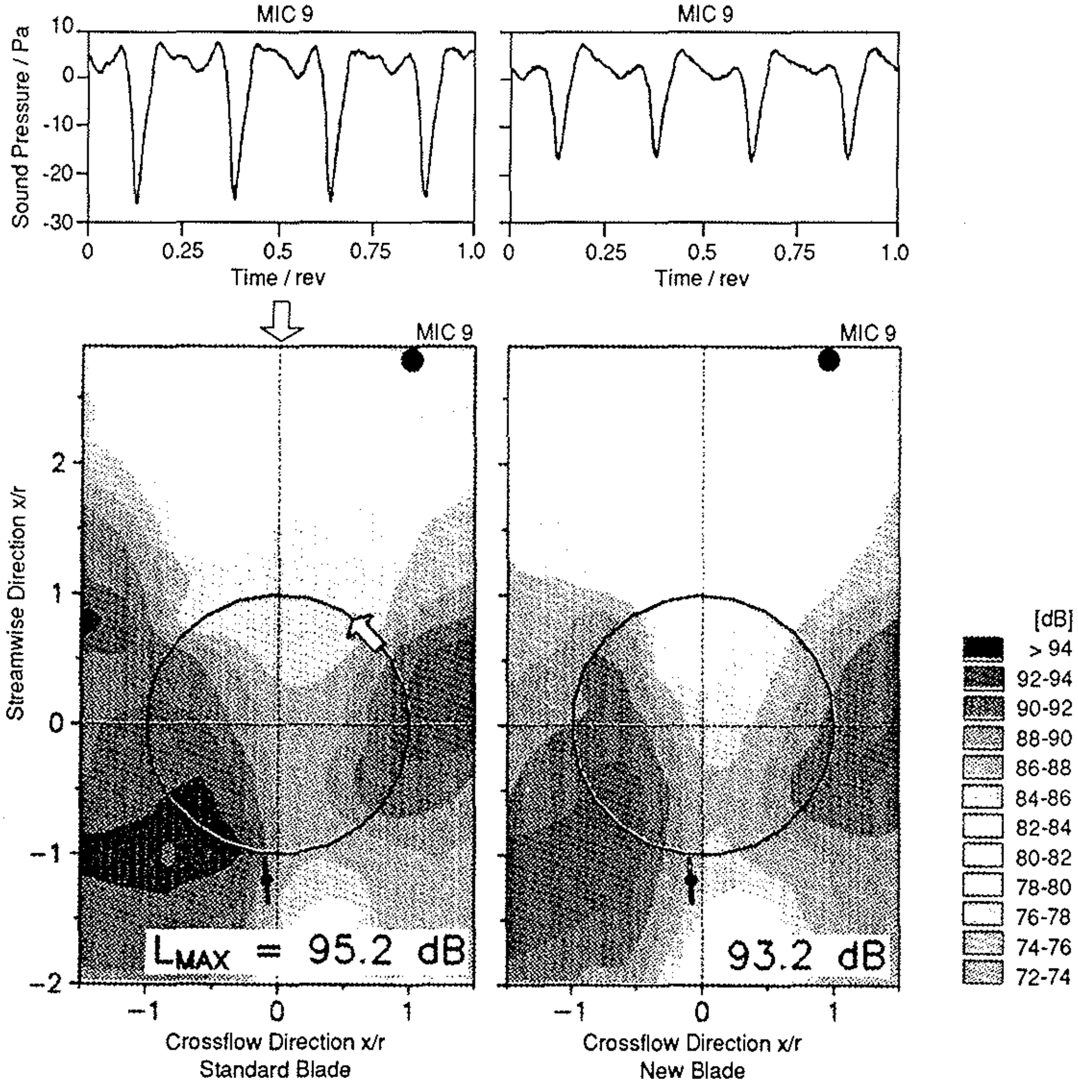


Fig. 22: DNW model rotor tests: Low frequency noise contours (PNL) at 60 m/s level flight

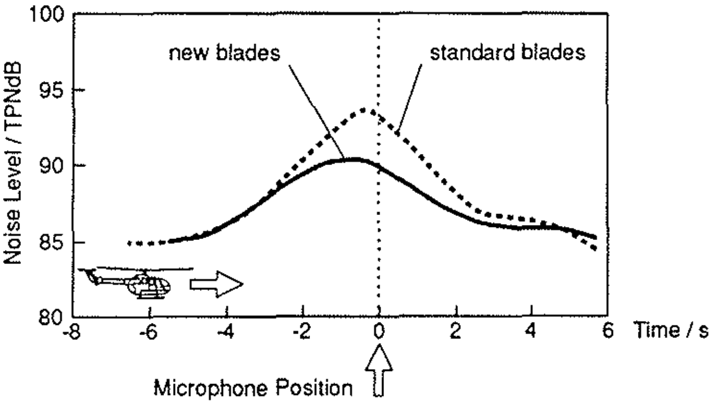


Fig. 23: Flyover noise level vs time for BO105 CBS with new and standard blades

The noise reduction potential of the advanced rotor blades was also proved in flight. The measurements were performed during flyover at 100 ft and 500 ft over ground. In Figure 23, the tone corrected perceived noise levels (PNLT) are presented as a function of flyover time for both, the new and the standard blades at 500 ft and 100 kts. A reduction of about 3 dB can be seen. In the certification relevant EPNL (Effective PNL) values, the BO105 CBS-5 was measured 1.3 dB lower in flyover condition than the standard version.

3.5 Further Benefits

One of the design goals for the new rotor blades was to improve or at least to maintain the flying characteristics of the BO105 helicopter. The static longitudinal BO105 stick stability with new rotor blades was improved mainly due to the more nose-up moment characteristic and the higher Mach tuck boundary of the DM-H3Tb tip airfoil in combination with a higher torsional stiffness of the new blade. This advancing blade tip effect is clearly shown in Figure 24 where the longitudinal cyclic stick position is plotted versus tip Mach number for the new and the standard version.

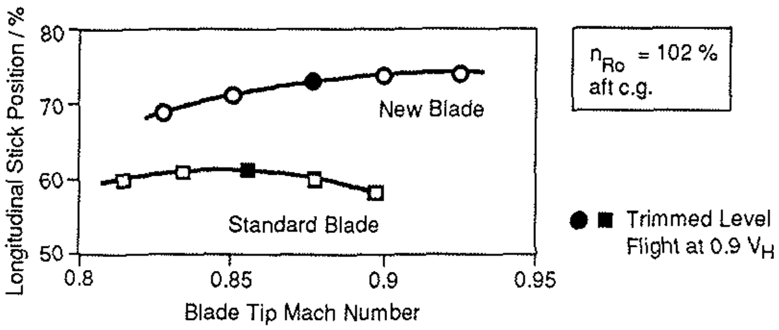


Fig. 24: Longitudinal cyclic stick position vs tip Mach number

As a result of the heavier blades, the rotor inertia increased by about 10 % leading in combination with the reduced hover power required to improved autorotation characteristics. According to Reference 6, a convenient measure to evaluate the autorotation capabilities of a helicopter, is the time a touchdown may be delayed after a power failure during hover. This time delay index takes into account the rotor energy, the hover power required, and also the blade stall characteristics. By inserting the corresponding data for the BO105 rotor with new and standard blades, the autorotation index yields a value of 1.2 s in case of the new rotor compared to 1.0 s for the standard rotor. Expressed in pilot ratings, the autorotational landing ability is improved from "acceptable" to "good".

4. Operational Aspects

Basis for operational requirements are the JAR-OPS 3 and ICAO Annex 6 regulations. For large rotorcraft and also for smaller rotorcaft if used for commercial passenger transport and VTOL operation respectively, JAR Part 29 requires a certification according to Category A. In this regulation, the case of an engine failure during takeoff and landing is considered. The less severe Category B certification is required for all rotorcraft.

With regard to performances, the BO105 CBS-5 will be certified according to both, JAR 29 Cat. A and Cat. B. The Cat. A version includes a kit that offers the use of an increased one-engine gearbox torque.

4.1 OEI Rate of Climb

The OEI climb performance is the most decisive characteristic for the maximum allowable payload under Cat. A takeoff and landing conditions. Figure 25 shows the OEI climb performance at the best-rate-of-climb speed at ISA condition with 30 min. engine power rating for both types of main rotor blades.

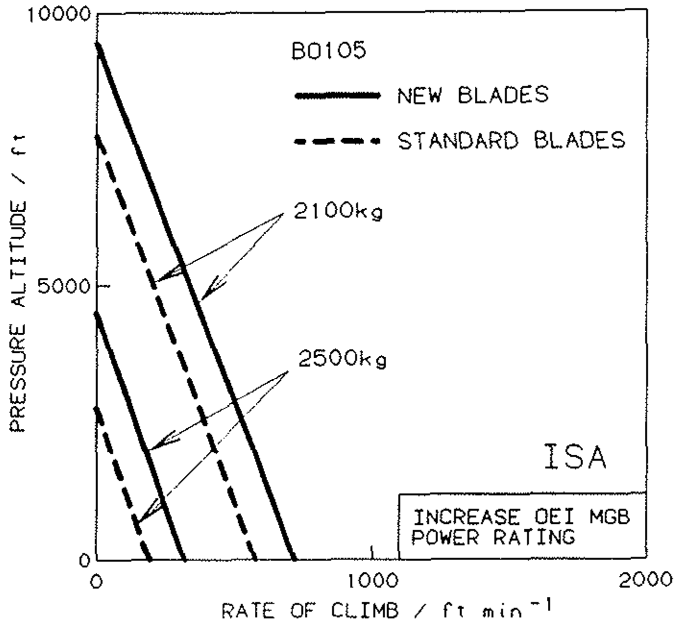


Fig. 25: OEI climb performance at v_y

4.2 Category A Takeoff

The Cat. A takeoff assures that in case of an one-engine failure, the helicopter can return and safely land on the takeoff area or continue the climb and pass over to single engine forward flight according as the failure occurs before or after the Takeoff Decision Point (TDP). Similar procedures exist for a Cat. A landing.

For the BO105 helicopter, the performance to attain single engine forward flight *after* the TDP defines the maximum takeoff and landing gross weight. Therefore, the Cat. A takeoff for two procedures, Clear Heliport and VTOL, is discussed in the following.

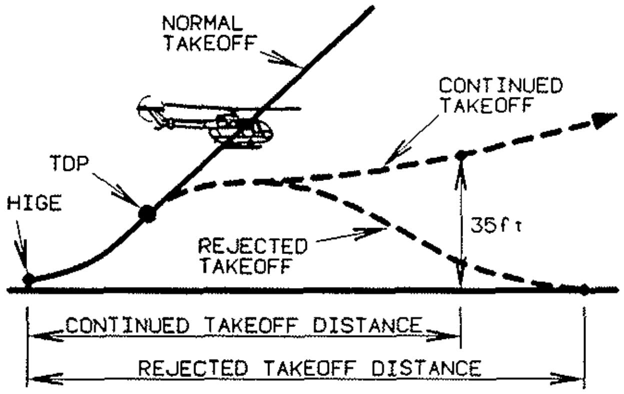


Fig. 26: Cat. A Clear Heliport takeoff procedure

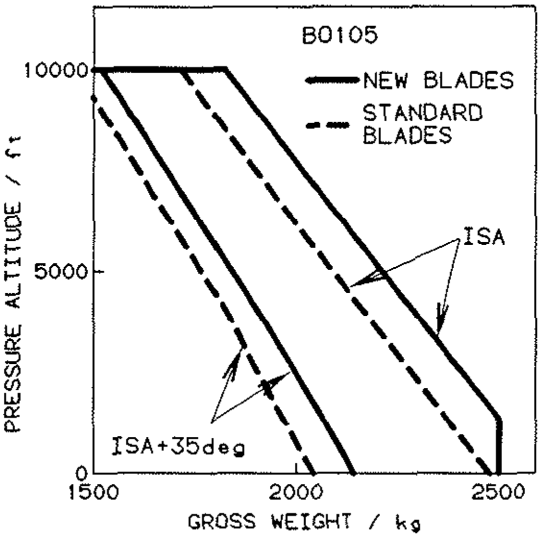


Fig. 27: Maximum takeoff gross weight for Cat. A Clear Heliport procedure

The Cat. A Clear Heliport procedure allows a high takeoff and landing gross weight but requires a spacious continued/rejected takeoff distance area. Figure 26 explains the Clear Heliport procedure as defined in the Aviation Regulations. The takeoff distance required is the horizontal distance necessary to achieve a takeoff flight path in 35 feet or higher with a positive climb rate at takeoff safety speed or, to safely land the helicopter depending on the time of the engine failure. Figure 27 shows an increase of up to 130 kg for the maximum takeoff and landing gross weight (Clear Heliport) for the BO105 CBS-5 compared to the BO105 version with standard rotor blades.

The Cat. A VTOL procedure allows the operation from elevated and ground level helipads with dimensions of 20 x 20 m and 15 x 15 m respectively. This procedure is explained in Figure 28. The maximum takeoff and landing gross weight for safe operation of the helicopter is determined by a combination of weight, altitude, and temperature. Sample curves for the BO105 with new and standard rotor blades are given in Figure 29 at S.L. condition. The increase of the allowable gross weight for VTOL operation offers a substantial payload gain to operators serving for instance, medical centres and oil platforms with small helipads.

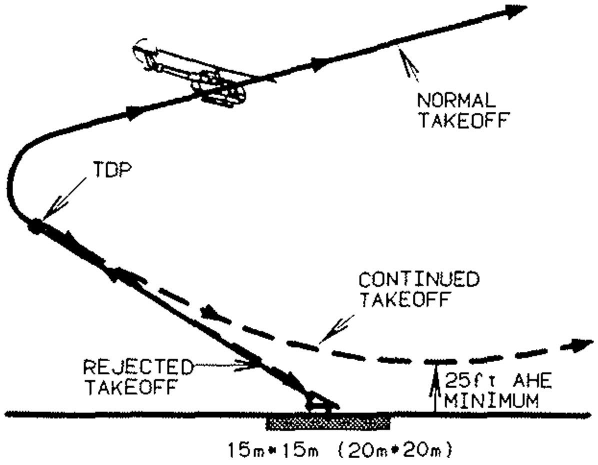


Fig. 28: Cat. A VTOL procedure

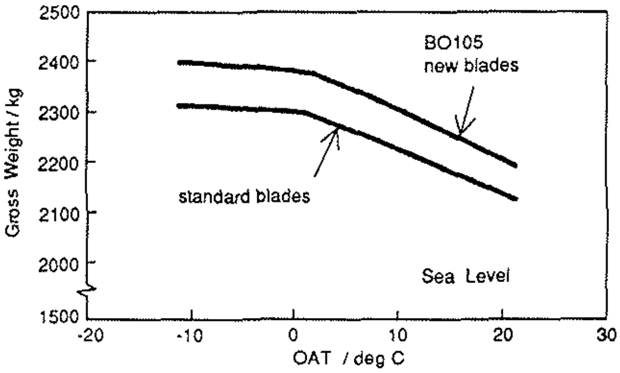


Fig. 29: Maximum gross weight for Cat. A VTOL operation

5. Programme Status

At the date of printing the present paper, the certification flight tests were completed. The German LBA certification as well as the British CAA certification are expected for August 1993, the American FAA certification for October 1993.

6. Conclusions

New blades have been developed for the well-known BO105 hingeless rotor system. The main objectives for the new design were:

- to reduce the power required,
- to improve the manufacturing process and the contour quality,
- to reduce the cabin vibration level,
- to reduce the exterior noise emission,
- to maintain or improve the well-accepted BO105 handling qualities.

The characteristics of the new blades in relation to the BO105 standard rotor were verified in extensive ground and flight tests. Globally, the objectives have been met. The test results can be summarised as follows:

- The new aerodynamic blade layout led to a higher thrust capacity and to an essential reduction of power required.
- The power savings improved the overall performances of the BO105 helicopter with regard to payload, climb, cruise speed, and one-engine operation.
- The cabin vibration level could be considerably reduced due to an improvement of the rotor dynamics.
- The noise emission could be decreased mainly in flyover condition as a result of a thickness noise reduction.
- The longitudinal static stick stability was improved due to the characteristics of the new tip airfoil.

- The autorotational landing ability was improved due to both, the reduction of hover power required and the increase of the rotor inertia.
- The reduction of power required in combination with a higher one-engine power rating for the main gearbox led to a significant increase of the allowable gross weight for Cat. A takeoff procedures

The experimental programme has shown that the new rotor blades have several clear advantages compared to the rectangular standard blades and have together with an improved manufacturing quality the potential to guarantee the attractiveness of the BO105 helicopter for further years.

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