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DESIGN AND DEVELOPMENT TESTS OF A FIVE-BLADED HINGELESS HELICOPTER MAIN ROTOR

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DESIGN AND DEVELOPMENT TESTS OF A FIVE-BLADED HINGELESS HELICOPTER MAIN ROTOR

by

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Abstract

To evaluate the effects of a higher number of blades on main rotors, an experimental program was conducted with a five-bladed rotor system. For that, the four-bladed hingeless rotor system of the BO 105 helicopter was fitted with an additional fifth blade resulting in 25 % more blade area. The five-bladed hub design is very similar to that of the four-bladed production version. An essential difference, however, is represented by changing the inclination of the blade pitch axis to 0° which was expected to effect positively the lead-lag/torsion coupling and in-plane damping.

After whirl tower testing, extensive flight tests were performed on a BO 105 LS helicopter. Mainly due to reduced blade loading, power required is lower for the five-bladed rotor, especially at higher thrust levels and in high speed/high altitude ranges. The fifth blade also influenced positively the levels of cockpit vibration and rotor/control loads. The in -plane damping was found to be substantially higher due to the zero pre-cone effect.

In the present paper, a survey of the rotor design rationale, the main characteristics, and the most important results from whirl tower and flight testing in the fields, performance, handling qualities, rotor loads, aeroelastic stability, and vibrations is given.

1. Introduction

Since the late 1950s - early 1960s, when the Bölkow Company, now Messerschmitt-Bölkow-Blohm GmbH, was taking its first steps in becoming a member of the helicopter manufacturer community, R & D work at MBB -amongst others- was always centered around rotor systems technology. The novel idea of the "Bölkow Rigid Rotor System", now more correctly designated as "Hingeless Rotor System" has pioneered the unique application of fiberglass to rotor blades, and became a break-through in rotor systems technology (Ref. 1).

Based on this tradition, active work on new rotor systems continued over the years and today, we can view various rotor designs -hingeless, fiber-elastomeric, bearingless, 2-, 3-, 4-, 5-bladed main/tail rotors- which were manufactured and tested on whirl rigs and in flight.

Fig. 1: 5-Bladed main rotor on BO 105 LS

2. Design goals and objectives

One of the most interesting work conducted recently, was the design and flight test evaluation of a five-bladed hingeless rotor system (Fig. 1). The number of blades -from the physical point of view- is a key parameter in the aerodynamic and dynamic rotor layout: As we know, the number of blades influences the performance -although the experience has not always supported the theory- and particularly rotor loads and aircraft vibrations.

The objective of our five-bladed rotor experimental program was three-fold: First, to examine -as expected- the positive effects of the higher number of blades, secondly, to evaluate the effects of the increased rotor solidity (reduced blade loading) which was introduced by adding the fifth rotor blade, and thirdly, to exemplify some additional hub parameter variations which were expected to be beneficial to the rotor characteristics.

3. Rotor design rationale

3.1 Rotor description

The five-bladed prototype rotor is derived from the well-known BO 105/BK 117 hingeless soft in-plane main rotor system. The rotor hub design is very similar to that of the basis version. The titanium rotor star has five instead of four arms (Fig. 2). Each arm contains two roller bearings for blade pitch setting. In contrast to the BO 105/BK 117 design, the pitch axis is arranged perpendicular to the rotor shaft (0° pre-cone angle; BO 105/BK 117: 2.5°) and a 2.5° pre-droop angle is built-in at the station of the blade attachment device (at 0.06 R). The centrifugal forces

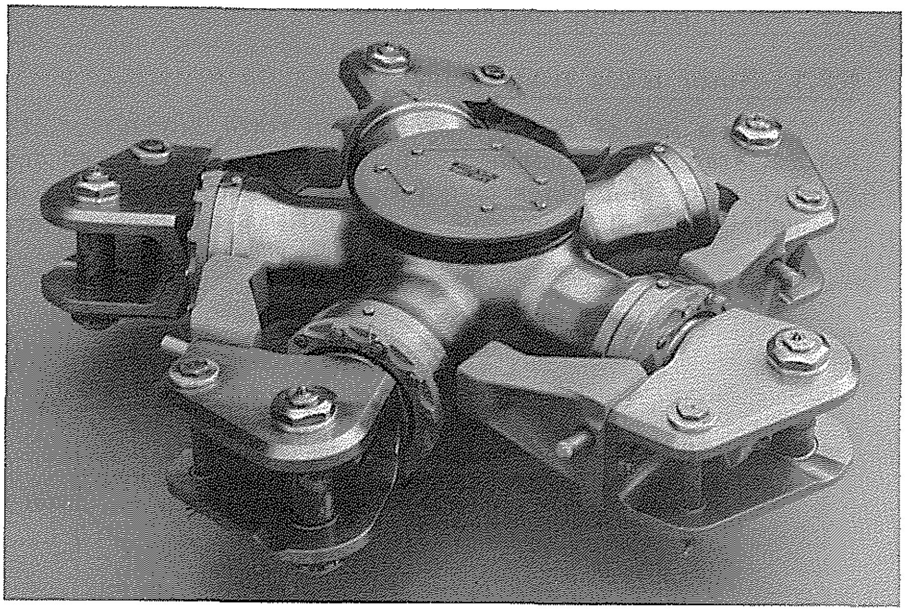

Fig. 2: Rotor hub

are transmitted by Bendix tension-torsion elements. Five original BO 105 composite blades complete the rotor leading to a 25 % increase of blade area. In Fig. 3, the main data of the five-bladed rotor are summarized in comparison to the four-bladed standard rotor version.

	4 blades (production)	5 blades (prototype)
Radius	4.912 m	4.912 m
Solidity	0.07	0.087
Pitch axis pre-cone angle	2.5°	0°
Blade pre-droop angle	0°	2.5°
Equivalent flapping hinge offset	~ 14.5 %	~14.5 %
Lead-lag frequency	0.66	0.66
Blade planform	rectangular	rectangular
Airfoil	NACA 23012	NACA 23012
Blade twist	−8° (linear)	−8° (linear)
MCP gearbox limit (BO 105 LS)	588 kW	588 kW
C_T/σ (G = 2600 kg, S. L. ISA)	0.082	0.066
(G = 2700 kg, S. L. ISA)		0.068
Mast moment per degree cyclic control input	~ 2600 Nm	~ 3200 Nm

Fig. 3: Comparison 5-/4-bladed rotor - main data

3.2 Rotor dynamic characteristics

3.2.1 Rotor blade frequencies

The use of BO 105 production rotor blades results in the same rotor natural frequency placement. In Fig. 4, the calculated frequency diagram for the rotor blade is shown (uncoupled calculation). In addition, measured frequencies for 0 % and 100 % rotor RPM are plotted into the diagram.

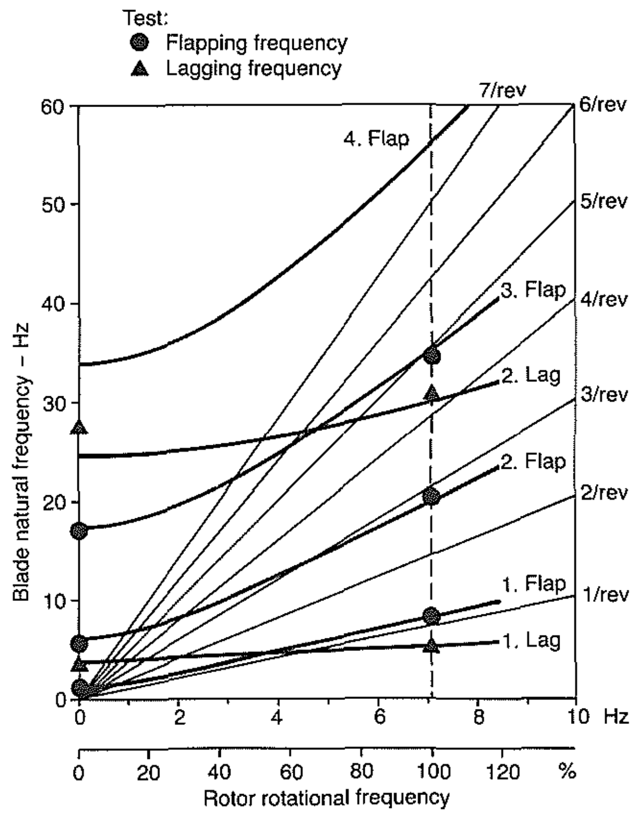

Fig. 4: Frequency diagram of rotor blade (uncoupled calculation)

The positions of the fundamental natural bending frequencies are of interest for the flight mechanical (flapping) and aero-mechanical (lagging) system behaviour wereas the positions of the higher natural bending frequencies in flap and lead-lag direction are important for the vibratory behaviour of the rotor system.

Due to the fact that the blade airloads have a generally decreasing trend with increasing harmonic order and due to the different "filtering" properties of four- and five-bladed rotors for in-plane and out-of-plane rotating system loads, a decrease of the aircraft vibration levels could be expected (Ref. 2). This mechanism is qualitatively explained in Fig. 5. The harmonic spectrum of typical generalized out-of-plane airloads on the rotor blade is shown in the upper half of Fig. 5. In the lower half, the modal blade amplification is plotted versus the rotor harmonics.

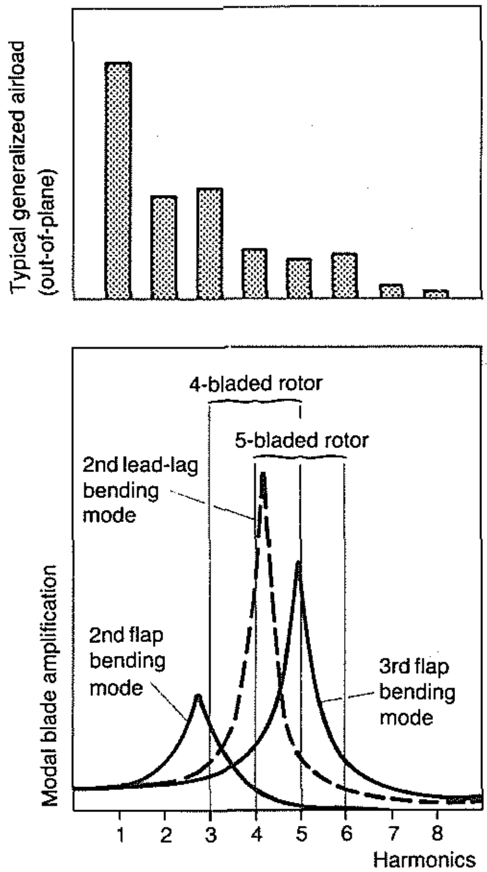

Fig. 5: Airload response behaviour for 5-/4-bladed rotor

It can be seen that 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 mainly influenced by the 2nd and 3rd flap bending modes (cyclic rotor modes). In case of the five-bladed rotor, the 2nd flap bending mode is of minor importance. Here, the dominant rotor excitations in the non-rotating system are 5/rev vertical and in-plane forces which are mainly influenced by the 3rd flap bending mode (collective rotor mode) and the 2nd lead-lag bending mode (cyclic rotor mode). In addition, due to the fact that the higher blade passage frequency of the five-bladed rotor (35 Hz vs 28 Hz) has shifted outside of a region of vibration critical airframe torsional/wharping natural modes, it could be exepcted that the reaction to the excitation forces and especially moments would be less sensitive.

3.2.2 Pitch-lag coupling and in-plane damping

As mentioned above, the five-bladed rotor hub -in contrast to the four-bladed standard version- was provided with a "zero pre-cone" pitch axis location (Fig. 6). Work on aeroelastic coupling effects which was carried out in the early 1970s (Ref. 3), had indicated that on hingeless rotors powerful influences on flap-lag-torsion coupling could be introduced by a few important hub design parameters. Amongst them, the pitch axis pre-cone angle was shown to be particularly active in producing beneficial pitch-lag coupling effects which could be used to increase blade lead-lag damping and improve substantially ground/air resonance stability.

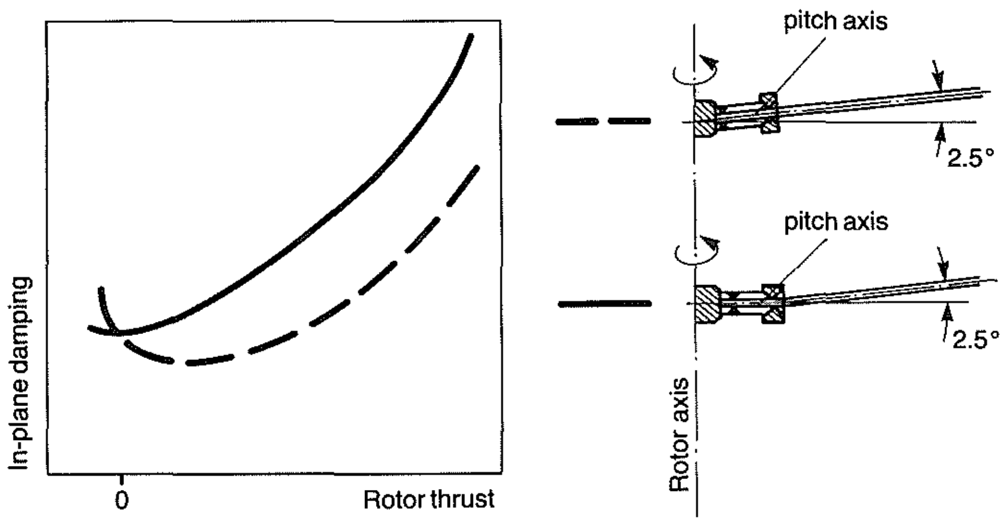

Fig. 6: In-plane damping vs rotor thrust - influence of pre-cone/pre-droop angle (calculated data)

This effect is qualitatively shown in Fig. 6, indicating that for the five-bladed rotor (zero pre-cone), a substantial increase of in-plane damping could be expected.

3.3 Noise

Reduced blade loading and lower levels of harmonic airloads on the individual blades in case of the five-bladed rotor could be expected to influence positively the rotor noise generation. Calculated results for the fly-over noise are represented in Fig. 7. The tone corrected overall

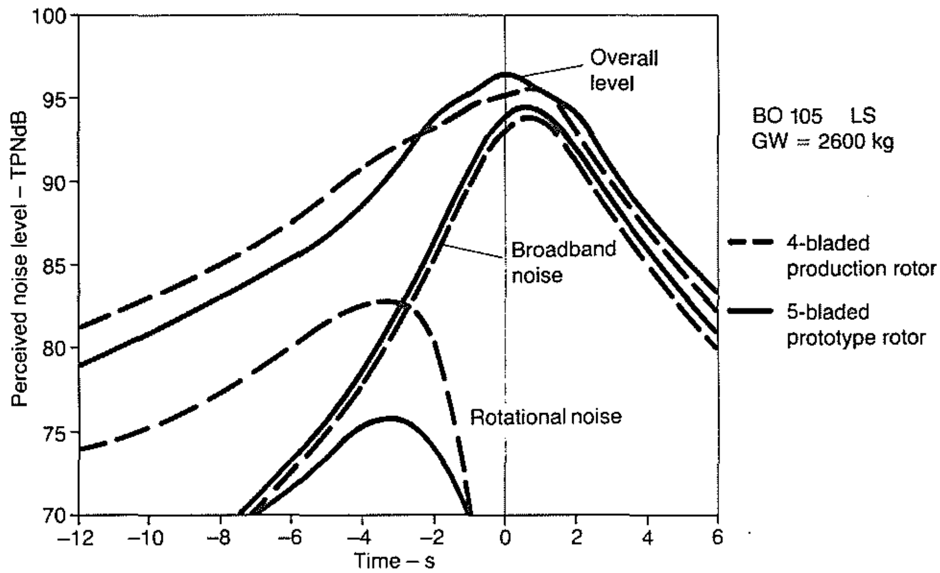

Fig. 7: Calculated fly-over noise

perceived noise levels for both rotor systems are plotted together with their most important contributors versus the fly-over time. The so-called broadband noise is mainly caused by boundary layers and free shear layers and is largely independent of the blade pitch setting. Due to the additional blade, the broadband noise is for the whole fly-over time slightly higher in case of the five-bladed rotor and leads to a higher maximum fly-over level. The rotational noise resulting from the blade air loading and its harmonics, is mainly emitted in the forward direction. It is lower for the five-bladed rotor and reduces the fly-over noise exposure time (10 dB downtime) by about 2 s in comparison to the reference rotor. This value strongly influences the effective perceived noise level (EPNdB) used for ICAO noise certification.

4. Test results

At first, the five-bladed prototype rotor was tested on the whirl tower, mainly with regard to the following items:

- measurement of the thrust-power polars
- investigation of the lead-lag damping
- verification of the blade natural frequencies
- measurement of rotor and control loads.

Subsequently, the rotor was installed on a BO 105 LS test vehicle (Fig. 1). The BO 105 LS helicopter is a stretched BO 105 version with more powerful Allison C28 engines. It is specifically designed for operation at high altitudes and extreme temperature conditions. The maximum gross weight is 2600 kg (Ref. 4). For the adaption of the five-bladed rotor to the test vehicle, the rotating part of the swash plate had to be modified correspondingly. The rotor was tested in a speed range from hover to v_{NE} and in a load factor range from 1 g to 2.3 g. The flight envelope flown is shown in Fig. 8.

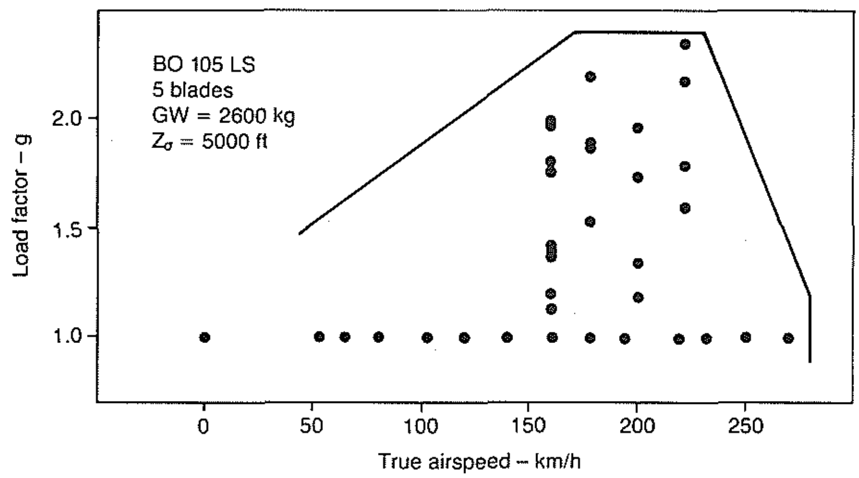

Fig. 8: Flight envelope flown

For reference, the four-bladed production rotor was tested on the same aircraft. The focal points of the in-flight measurements were:

- power required
- handling qualities
- in-plane damping
- rotor/control loads
- vibration.

In the following paragraphs, the most important test results are discussed.

4.1 Power required

The power required was measured in hover for gross weights from 2000 kg up to 2600 kg and in forward flight for a gross weight of 2600 kg at two different altitudes. In Fig. 9, hover power (out of ground effect) is plotted versus gross weight for the four- and five-bladed rotors. In addition,

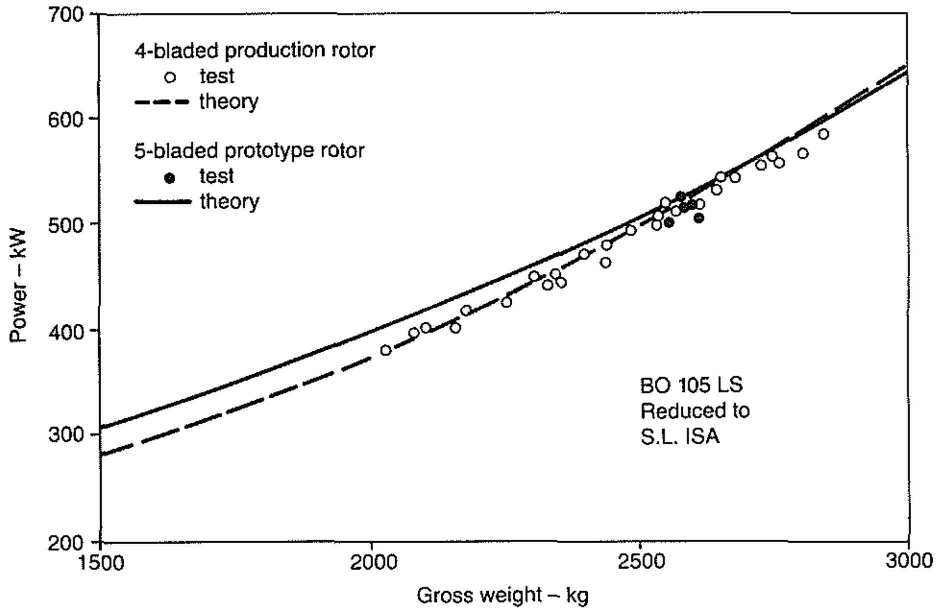

Fig. 9: Power required vs gross weight (HOGE)

theoretical curves are shown. All results are reduced to S.L. ISA condition. Theory for both rotors is in good agreement with flight test results. The five-bladed rotor requires more power at lower gross weights due to higher profile power. For weight levels higher than $G/\ (\rho/\rho_o)$ = 2700 kg, the five-bladed rotor becomes superior due to the lower blade loading. This is particularly important for hover conditions at higher altitudes.

Figs. 10 and 11 show the power required versus forward speed at density altitudes of 5000 ft and 10000 ft for both rotors in comparison to theoretical results. Due to the reduced blade loading (c_T/σ = 0.112/0.090 for 4-/5-bladed rotor at 2600 kg, 10000 ft), power required is lower for the five-bladed rotor, especially in the high speed/high altitude range. Power savings of the five-bladed rotor seem to be even slightly higher than predicted by the theory. From the test results, power reductions of 7 % (at 5000 ft) and 12 % (at 10000 ft) are seen at the higher flight speeds.

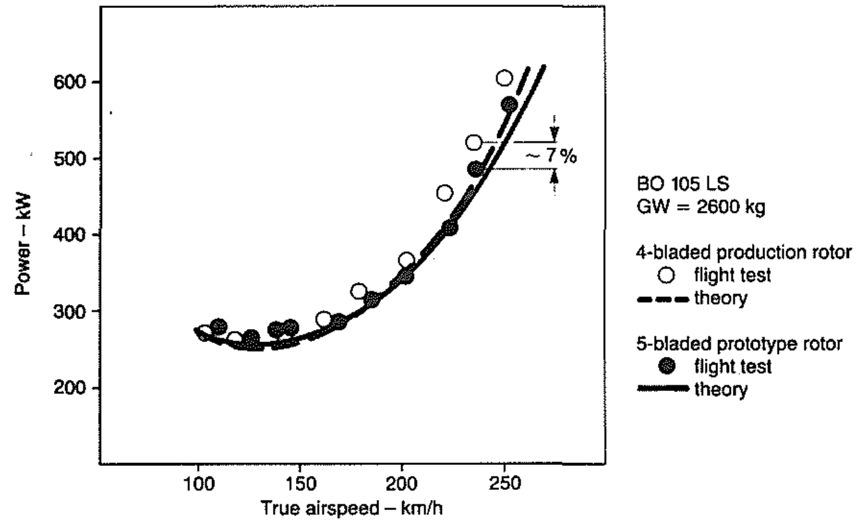

Fig. 10: Power required vs fwd speed (z_σ = 5000 ft)

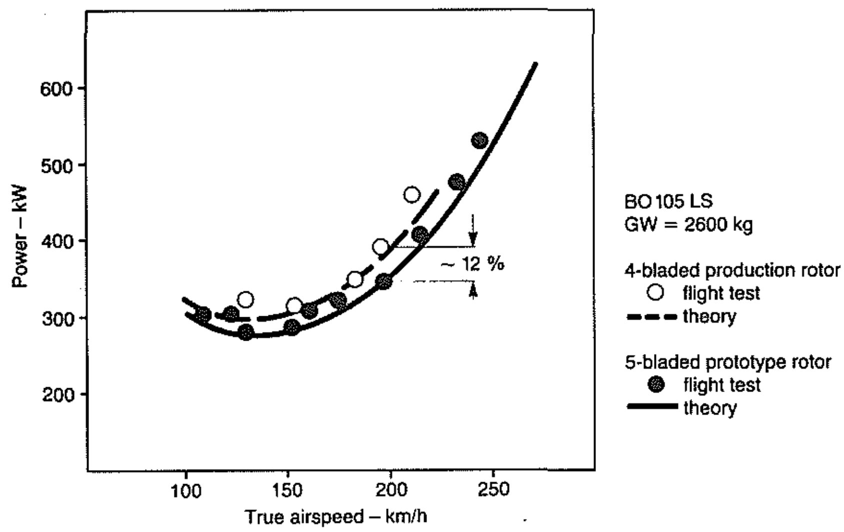

Fig. 11: Power required vs fwd speed (z_σ = 10000 ft)

This is obviously a clear demonstration of the beneficial effects of the reduced blade loading.

4.2 In-plane damping

For damping measurements of the critical regressive lead-lag mode, the rotating system was excited by a sinusoidal ($\Omega-\omega_\zeta$) input into the cyclic control. The lead-lag damping values were then evaluated from the in-plane bending moment decay curves treated by a band pass filter after stopping the excitation. In Fig. 12, the dependence of damping for the fundamental lead-lag mode of the individual blade on the collective pitch angle is shown (whirl tower results). The diagram shows that a substantial increase in

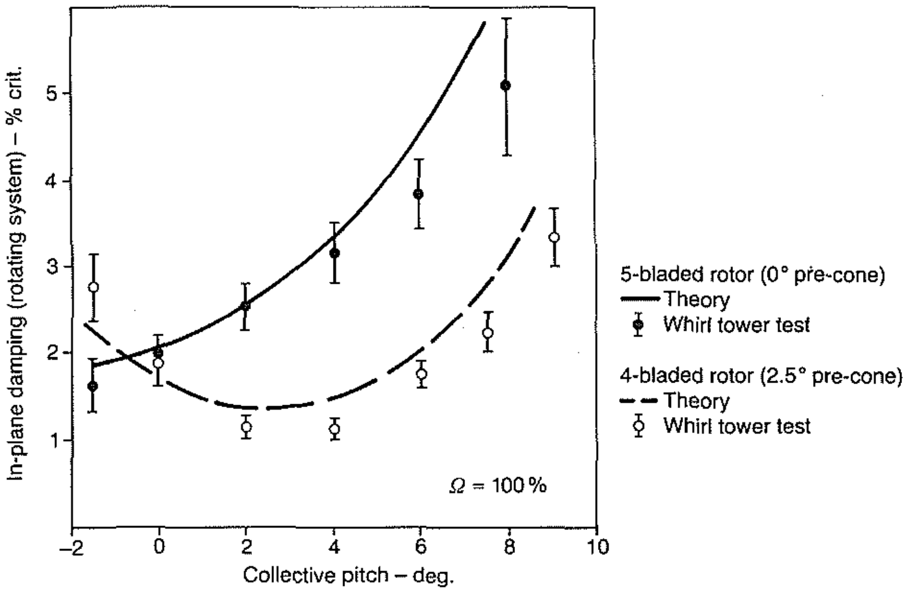

Fig. 12: Lead-lag damping vs collective pitch

lead-lag damping is achieved at higher thrust conditions. At a 1 g hover condition (coll. pitch ≈ 8 deg.), the damping level is nearly doubled. Hence, the favourable couplings of the zero pre-cone five-bladed rotor, as expected from theory, were clearly demonstrated.

In Fig. 13, the in-flight lead-lag damping (rotating system) is plotted versus forward speed in comparison to calculated results. The system damping of the critical regressive lead-lag natural mode is ≥ 5 % for the five-bladed rotor. The corresponding value for the four-bladed reference rotor amounts to about 3 %.

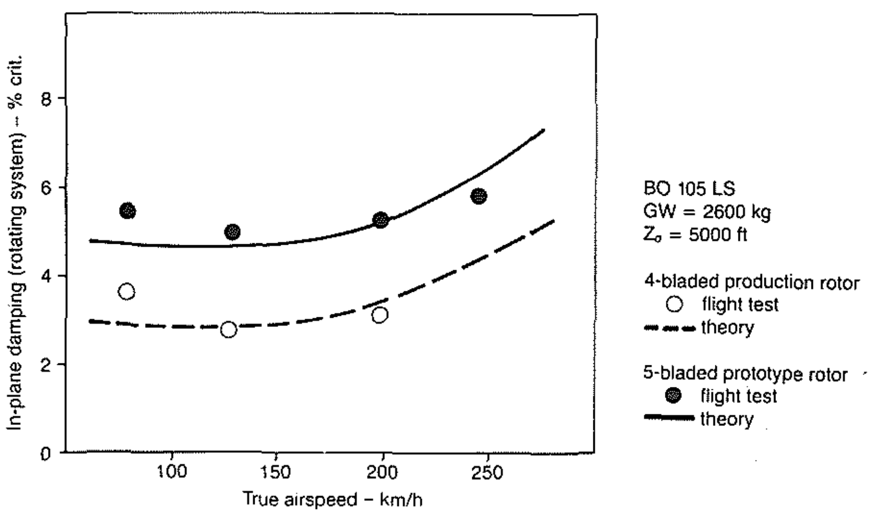

Fig. 13: Lead-lag damping vs fwd speed

4.3 Handling qualities

Substantial effects by adding a fifth blade to the rotor could be expected in the field of handling qualities: With the individual blades being identical, a higher number of blades leads to a higher rotor inertia, higher load factor capability, and higher control power and also influences major stability parameters. Some flight test results are shown in the following figures.

In Fig. 14, a comparison of the control characteristics for the roll axis is given. The data for damping and control power were gained from ramp control inputs in flight. Damping and control sensitivity are, as

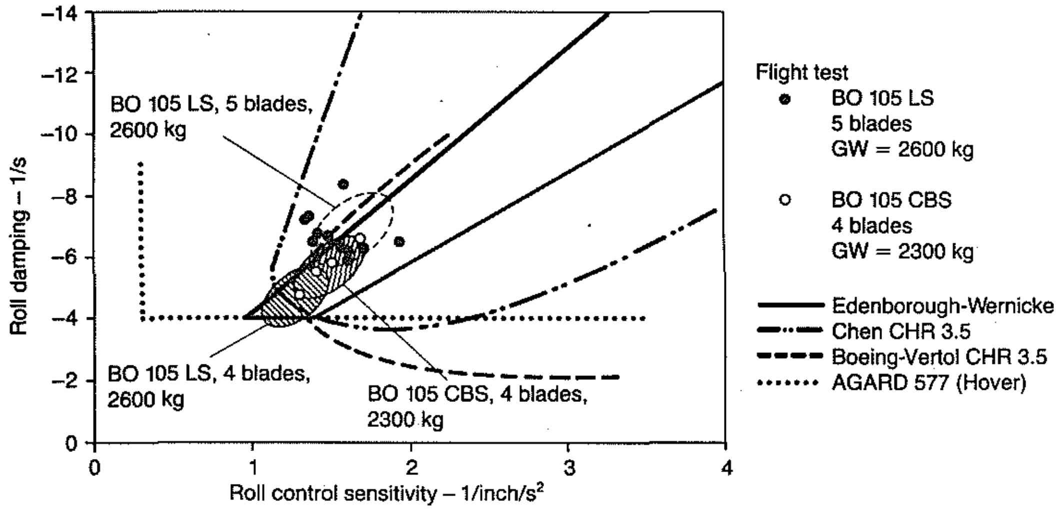

Fig. 14: Controllability about roll axis

expected, higher for the five-bladed rotor. As a result, lateral and longitudinal cyclic control angles in trimmed flight were lower allowing more control margin in the extreme flight conditions.

The effect of the number of blades on the stability behaviour is more complex since the number of blades influences several stability derivatives, like the rotational damping, angle-of-attack stability, and vertical damping. All these parameters again depend on flight speed. Analytical results and flight test results for the longitudinal dynamic stability are collected in Fig. 15. High speed results were as expected from the theory. However, at lower speeds (below 150 km/h), test results indicated a better longitudinal dynamic stability with the five-bladed rotor compared to the four-bladed version.

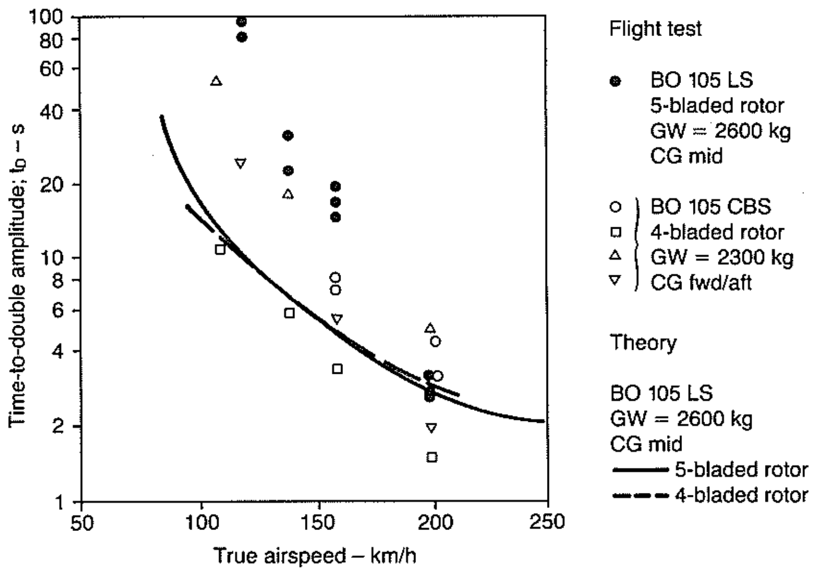

Fig. 15: Longitudinal dynamic stability

4.4 Rotor loads

Due to the fact that the five-bladed rotor is derived from the four-bladed BO 105 production rotor by adding a fifth blade (25 % blade area increase), the rotor loads are expected to be on the whole equal or lower for comparable flight conditions. Two representative flight test results are shown in Figs. 16 and 17. In Fig. 16, the mean value of the collective booster load is plotted versus forward speed for both rotor systems.

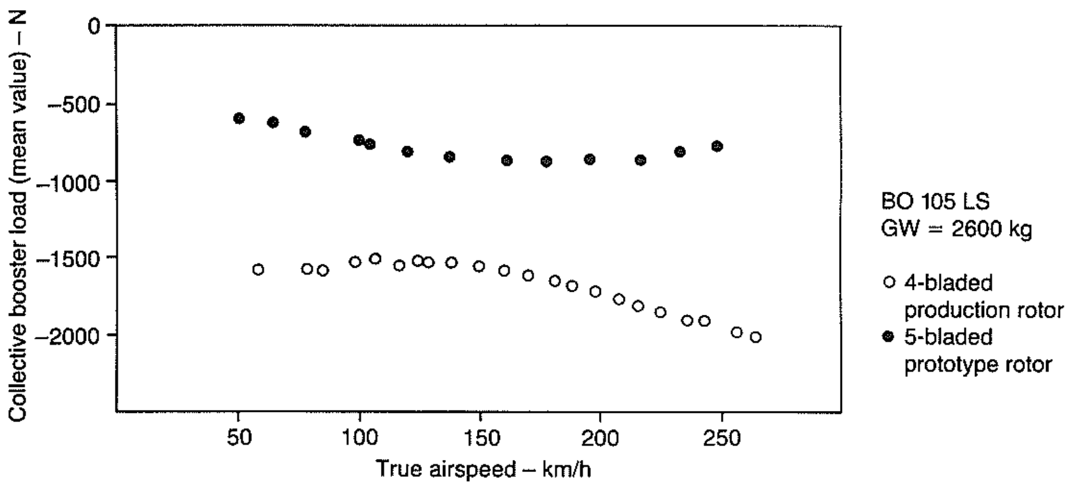

Fig. 16: Collective booster load vs fwd speed

The loads for the five-bladed rotor reach half the values of the reference rotor. This mainly reflects the effect of the zero pre-cone design of the five-bladed rotor which causes a substantial reduction of the mean control load of the rotor blades.

In Fig. 17, the 1/rev flap bending moment (at 0.11 R) is plotted versus forward speed. Again as a result of the reduced airload per blade and due to the higher moment capacity, the values for the five-bladed rotor are essentially lower.

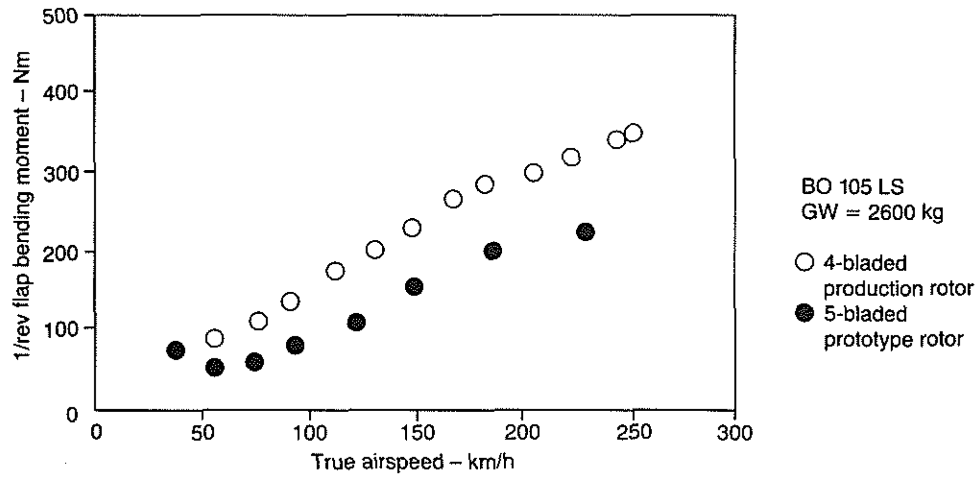

Fig. 17: Flap bending moment vs fwd speed

4.5 Helicopter vibration

One of the important parameters in evaluating the success of a helicopter design is the vibration characteristics. Increasingly stringent demands are being made especially by military customers for helicopters with good ride qualities throughout the flight envelope. The rotor excitation loads in combination with the vibratory airframe modes are determining for the cabin vibration level. As indicated in chapter 3.2, the five-bladed rotor promises a reduction of airframe vibration which is confirmed by flight test. In Fig. 18, vertical n/rev cockpit accelerations (n: number of blades) are plotted versus forward speed. The 5/rev vibration level for the five-bladed

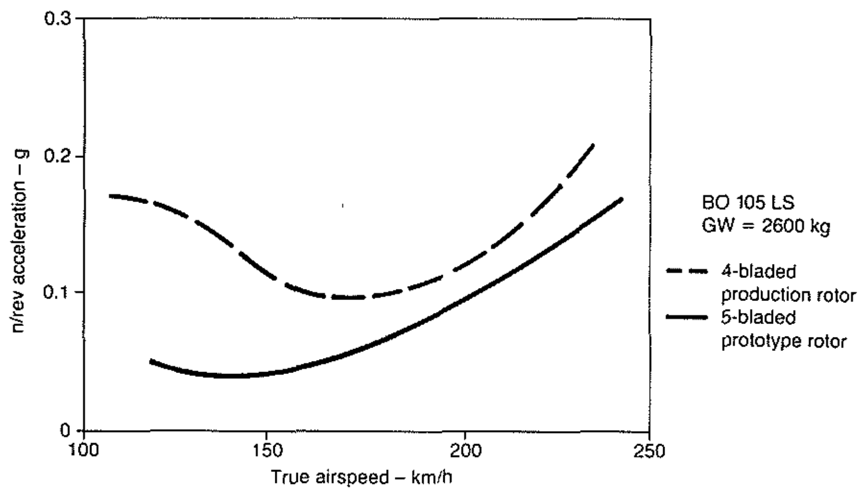

Fig. 18: Cockpit vibration (vertical) vs fwd speed

rotor is considerably lower than the 4/rev vibration level for the four-bladed rotor. It should be mentioned that the BO 105 LS production helicopter (four-bladed rotor) is normally equipped with blade neck mounted centrifugal force pendulum absorbers tuned to 3/rev for vibration reduction. For better comparison, the reference rotor was tested as the five-bladed rotor without pendulum absorbers.

Of course, the subjective feeling of crew and passengers in a vibrating helicopter fuselage is not only determined by the n/rev vertical accelerations. A more comprehensive measure of whole body vibration is the so-called Intrusion Index according to ADS-27 (Ref. 5). This index is a single scalar quantity which has the following features:

- It takes into account the four largest spectral peaks of the relevant frequency range in each direction.
- It weighs vertical vibrations most heavily.
- It weighs low frequency components more heavily than higher frequency components.

ADS-27 (ADS: Aeronautical Design Standard) was officially released by AVSCOM in November 1986 and at the first time applied in the LHX program. It could become a useful tool within the scope of future helicopter vibration specification and qualification.

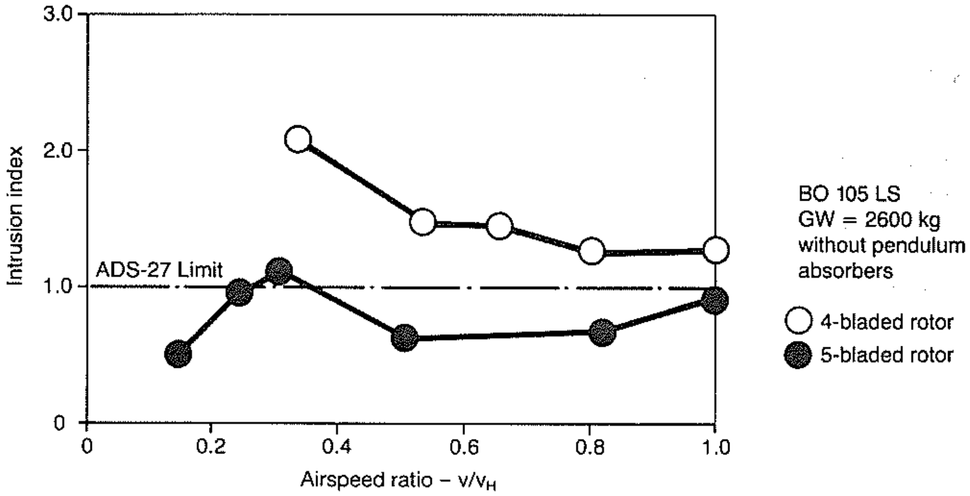

Fig. 19: Cockpit vibration level in fwd flight (Intrusion Index)

In Fig. 19, the Intrusion Index is shown as a function of the airspeed ratio for both rotor systems. With the five-bladed rotor, the ADS-27 limit of 1 is met over the entire speed range, indicating that the five-bladed rotor is particularly attractive from the vibration point of view.

5. Conclusions

A five-bladed hingeless soft in-plane helicopter main rotor has been designed, manufactured, and tested. It was developed from the well-known BO 105 rotor by adding a fifth blade. This procedure represents a cost and time saving way to increase the blade area of an existing helicopter.

The main goals of the experimental program were:

- to examine the effects of a higher number of blades (5 vs 4),
- to evaluate the effects of an increased rotor solidity,
- to exemplify some additional hub parameter variations (zero pre-cone).

The ground and flight test results can be summarized as follows:

- The reduction of blade loading led to improved performance in hover (at higher gross weights) and in forward flight.
- The rotor lead-lag damping of the five-bladed rotor system was substantially increased due to aeroelastic coupling resulting from the zero pre-cone design.
- In the field of handling qualities, a 20 % increase of control power and damping as well as a moderate improvement of the longitudinal dynamic stability were observed.
- Control loads (mean values) of the five-bladed system were lower than for the reference rotor, caused by the zero pre-cone axis location. Flap and lead-lag bending moments per blade were also lower for the same trim conditions.
- Helicopter vibrations were substantially reduced due to cumulative effects of a lower blade loading, better "filtering" properties of the five-bladed rotor, and a more favourable excitation frequency placement (5/rev) with regard to the relevant airframe modes.

The experimental program has shown that the five-bladed rotor has several clear advantages and could be an attractive solution to improve high altitude and high speed characteristics, thus providing a substantial growth potential for the existing BO 105/BO 105 LS and BK 117 versions. Five-bladed rotor designs should also be considered for future new helicopters.

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