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FEL – A NEW MAIN ROTOR SYSTEM

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Abstract

A new hingeless main rotor system, the **Fi**bre **El**astomeric Bearing Rotor (FEL) for a 4 to 5 ton helicopter is under development at MBB. Its main features are elastomeric bearings and composite materials for the blades and hub. Flapping and lead lag motions are made in the flexible neck of the blades, pitch change is accomplished by the elastomeric bearings.

The design goals for this new rotor type are low weight, simple and robust construction, low parts count, minimal maintenance, reduced vulnerability, and excellent maneuverability by high control power. Stress calculations, stiffness optimization and component testing have been performed. Following, the new rotor system has been verified on the whirl tower.

1. Introduction

In general, two main trends can be recognized worldwide in design and development of modern rotor systems

- bearingless rotor types with flexible sections in the blade root for all blade motions and
- the use of elastomeric bearings which replace the conventional mechanical hinges and bearings

Furtheron, the application of composite materials with their excellent properties increases continuously not only for blades, but also for hubs.

MBB has both rotor types under development in different sizes and for different projects. Both new MBB rotor types are based on the hingeless rotor system "Bölkow" which is incorporated in BO 105 and BK 117 helicopters.

Subject of this paper is the FEL rotor system (**Fi**bre **El**astomeric Bearing Rotor) using a fibre composite material blade and hub structure and elastomeric bearings for pitch change. The FEL rotor concept is planned for the Franco – German PAH-2/HAP/HAC3G, a combat helicopter of the 5 tons class. A predecessor of this rotor with slightly smaller size is described here. It has been manufactured and tested on a whirl tower test stand at Aérospatiale, our partner firm in the PAH-2/HAP/HAC3G program.

2. Design goals and objectives

The main rotor, as the heart of a helicopter, represents one of its major subsystems. Flight performance and flying qualities of a helicopter are mainly determined by the characteristics of the main rotor. The following objectives have been envisaged through the application of composite material for hub, blades, and their attachments in combination with laminated elastomeric bearings:

- improvement of safety and vulnerability through a robust design, a low number of parts, and the fail safe properties of composite material structures and elastomeric bearings
- reduction of weight through replacement of mechanical bearings and consequent use of composite materials
- reduction of purchase and maintenance costs through simple design, infinite life of structures, maintenance-free elastomeric bearings with minimum life time of 2500 hours, and on-condition maintenance for the total rotor
- improvement of flight performance through low parasite drag, newly developed blade profiles and blade geometry, especially at the tip
- excellent maneuverability through high control power

3. Rotor concept [1]

3.1 Rotor principle

The FEL rotor is a four bladed main rotor with **f**ibre composite structures and **el**astomeric bearings. Fig. 1 shows a schematic comparison between the hingeless main rotor of BO105/BK117 and the FEL rotor. The basic hub houses the pitch change mechanism and transmits the flight loads to the aircraft. The flap and lag motions take place in a flexible neck that transitions into the rotor blade. Graphite plates and elastomeric bearings are used instead of titanium housings, conventional roller bearings and tension torsion straps.

Rotor concept

	BO105/BK117	**FEL**
Hub	Titanium hub	Fiber composite material plates
Blade pitch bearing	2 Roller bearings oil-lubricated	2 Elastomeric bearings maintenance-free
Centrifugal force fitting	Bendix element (tie bar)	Conical elastomeric bearing
Blade	Fiber composite flexible	Fiber composite flexible

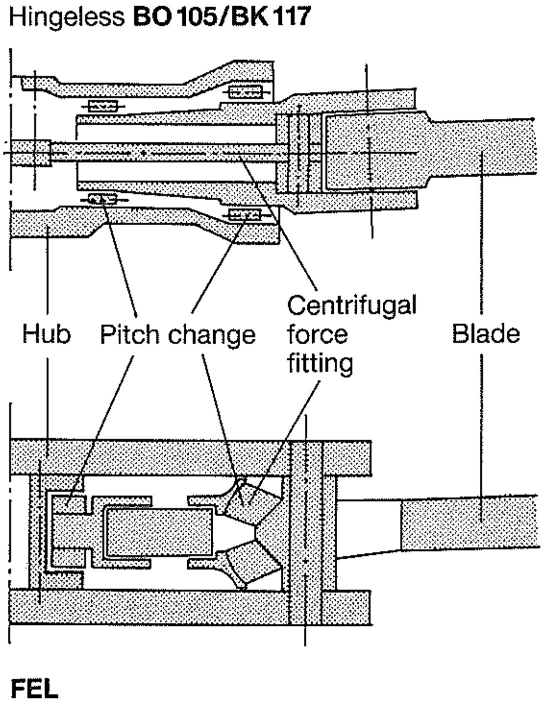


Fig. 1 BO105/FEL rotor concept comparison

3.2 Rotor configuration

Fig. 2 shows the FEL rotor design. One of the greatest advantages of the FEL concept is its simplicity. Besides standard parts such as bolts, nuts, bushings etc., the total rotor counts only 20 main parts.

There are no droop stops, cone stops, flap hinges or lag hinges. There is only one centrifugal-force-terminating joint per blade at the conical elastomeric bearing with only one main blade bolt.

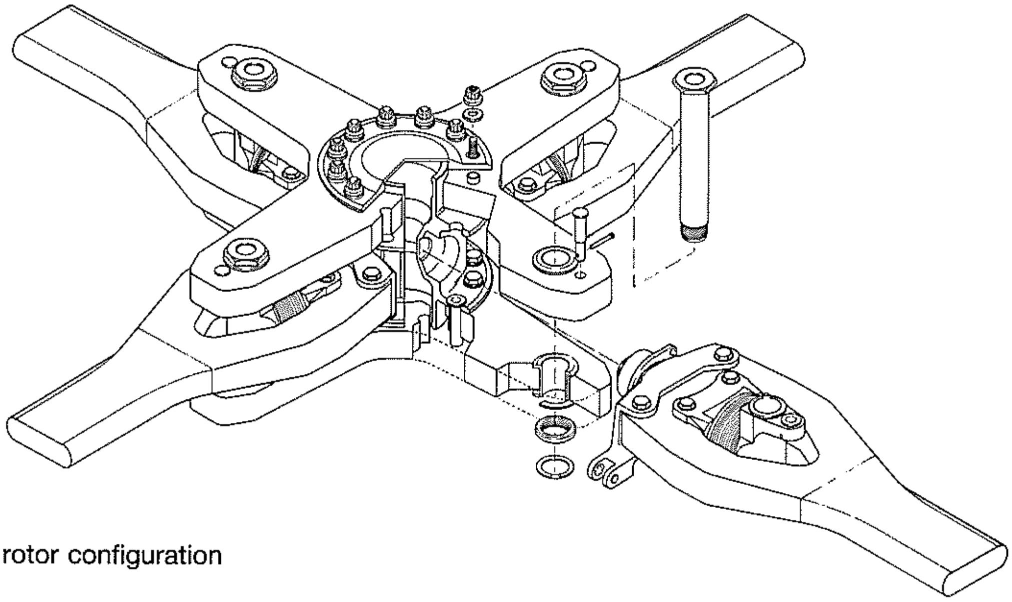
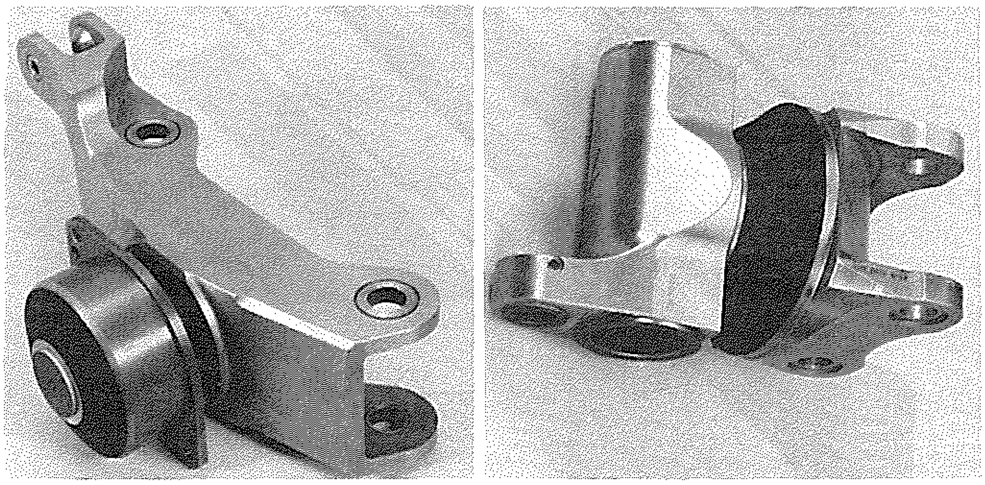


Fig. 2 FEL rotor configuration

3.2.1 Rotor hub

Two star shaped graphite plates form the main structure of the hub. They are supported by a central titanium part which also serves for the housing of the inner (cylindrical) elastomeric bearings. The blade root section features an oval hole for the incorporation of the outer (conical) bearing, which is attached to the hub plates by a bolt. The hub plates are stiffness-designed and therefore made of graphite/epoxy fabric prepregs with fibre orientation in alternating sequence. This renders a quasi-isotropic structure which can carry the same loads in all directions.



Radial Bearing (inboard)

Conical Bearing (outboard)

Fig. 3 Elastomeric bearings

Fig. 3 shows the elastomeric bearings which are vulcanized to the attachment fittings, the pitch horn is integrated in the cylindrical bearing. The elastomeric layers and the shims can have simple geometries because these bearings must only accomodate the pitch change motions and no combined motions in different directions. They are designed for a life time of 2500 hours.

3.2.2 Rotor blade

The cross section of the blade airfoil section shows a rectangular spar consisting of two beams and two shear webs made of glass fibre prepregs, a carbon fibre composite skin and 3 cores of foam or honeycomb (Fig. 4). A lead trim weight and a steel cap for erosion protection are incorporated in the nose.

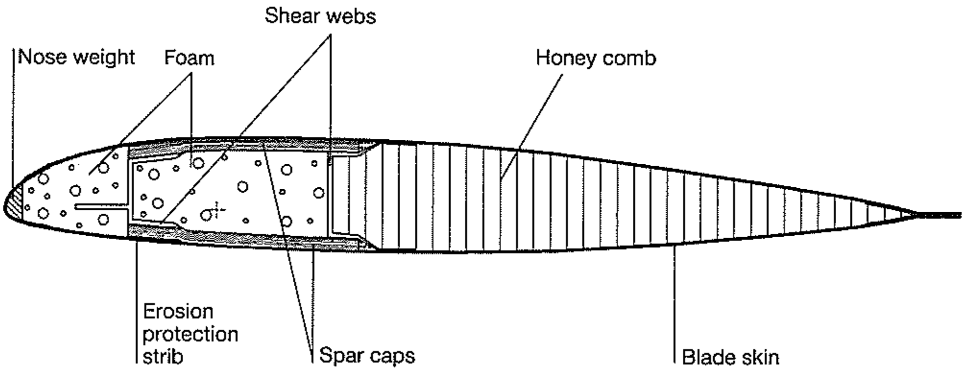


Fig. 4 Blade cross section

The blade root is made of quasi-isotropic composite material using the unidirectional glass fibre prepregs of the spar and of carbon fibre prepregs with fibre orientation in alternating sequence (Fig. 5). With this construction, no lugs are necessary, all blade loads can be transferred from the root to the hub by bearing stress and face pressure.

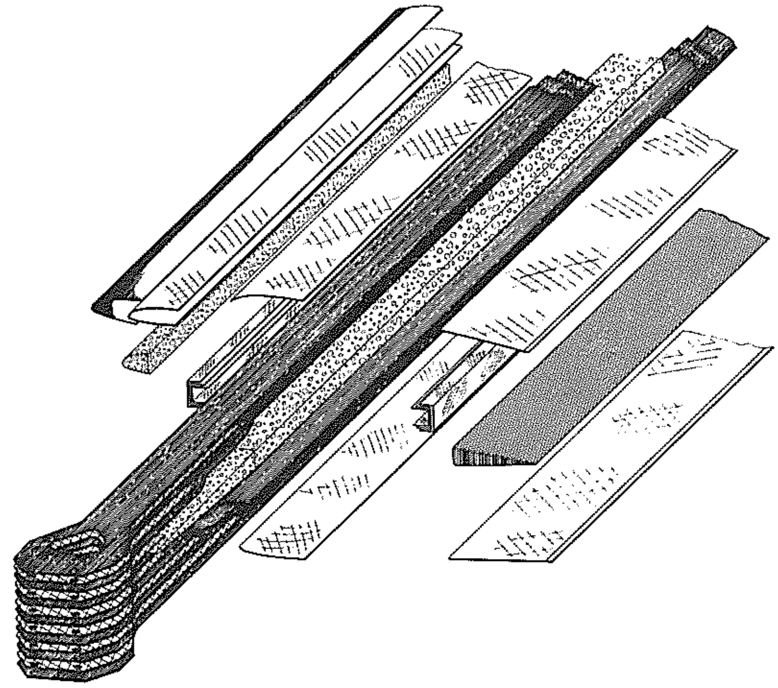


Fig. 5 Blade structural arrangement

4. Basic layout consideration [1]

4.1 System layout

The layout of the FEL main rotor system is essentially determined by the hingeless, soft in-plane rotor concept, i. e. flap and lead-lag motions of the blade are allowed by elastic bending of the inboard blade section, the natural frequency for the fundamental lead-lag mode lies at nominal speed below the rotor RPM. The design goal for the 1st in-plane frequency was 0.7 Ω.

The equivalent flap hinge offset which is a clear measure for the moment capacity of the rotor system, is fixed by the tuning of the 1st flap bending natural frequency. For the FEL rotor, a hinge offset of 10 % has been chosen. This value was derived from the BO105/PAH-1 experience where high agility and maneuverability characteristics were considered important in particular for a military helicopter. The main advantages of the 10 %-hinge-offset rotor are high control power, high natural damping, and acceptable rate response with short time delay for both, pitch and roll axis. The high control moment ability also provides good control power for negative and low g flight maneuvers. The high and nearly constant level of control power (and damping) independent of rotor thrust changes results in minimal variations in flying qualities with speed, altitude, gross weight, and load factor changes. Of course, a low hinge offset rotor with similar characteristics can also be realized by artificially increasing damping and control sensitivity by use of a complex CSAS. However, high gain augmentation and a larger control range due to the "overshooting" from the control "quickener" in combination with larger control and flapping angles have to be accepted.

The flap and lead-lag bending stiffness distributions for the FEL rotor blades which lead to the required rotor characteristics are shown in Fig. 6.

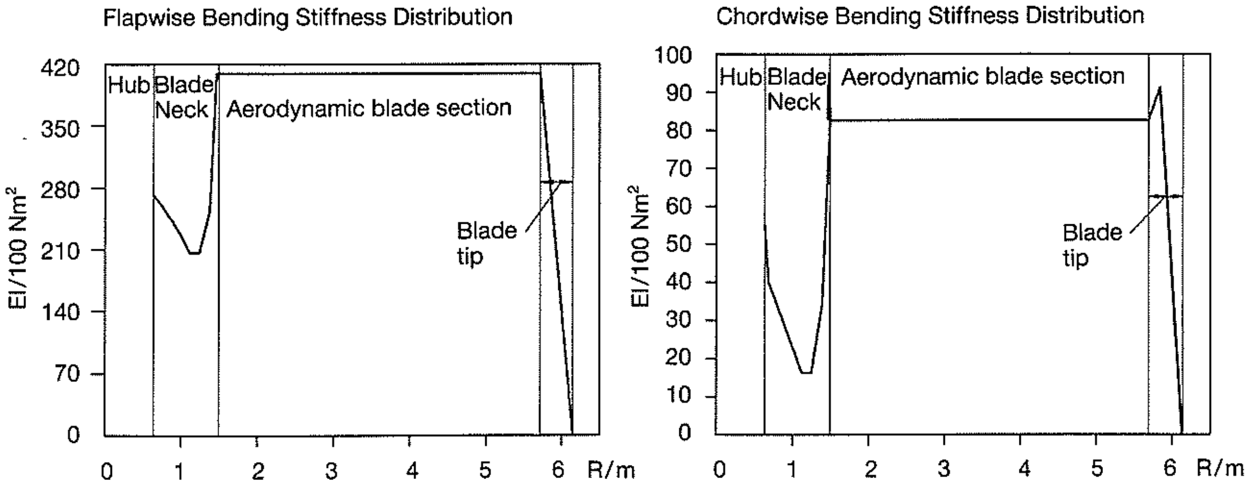


Fig. 6 FEL rotor blade stiffness distributions

The 2nd flap bending natural mode has been tuned by a concentrated mass at 0.5 R to 2.75 Ω to reduce the 3/rev moment excitation in the rotating system. Main dimensions and characteristic data of the FEL rotor concept in comparison to the corresponding BO105 and BK117 main rotor values are summarized in Fig. 7.

	BO105	**BK117**	**FEL**
Rotor diameter	9.82 m	11.0 m	12.3 m
Number of blades	4	4	4
Airfoils	NACA 23012	NACA 23012	DM-H4/DM-H3
Chord	0.27 m	0.32 m	0.45 m
Twist (lin.)	−8°	−8°	−10°
Beginning of aerodyn. blade section	22.5 %	20 %	24 %
Tip speed	218 m/s	220 m/s	215 m/s
Precone angle	2.5°	2.5°	0°
Preflap angle	0°	0°	2.5°
1. flap frequency	1.12 Ω	1.10 Ω	1.08 Ω
equiv. flap hinge offset	~14 %	~12 %	~10 %
2. flap frequency	2.75 Ω	2.55 Ω	2.75 Ω
1. lead-lag frequency	0.66 Ω	0.67 Ω	0.7 Ω
rotor weight	210 kg	258 kg	366 kg
Helicopter gross weight	2500 kg	3200 kg	4200 kg

Fig. 7 Basis rotor data

4.2 Stress analysis [2]

Comprehensive stress calculations for the hub and blade have been performed. In particular, the blade attachment area represents a very high loaded component. Because of the complexity of the combined loading by centrifugal force, flap and lead-lag moments and the indefinite load paths due to the special shaping, a three-dimensional FE model was generated for this element. The corresponding FEM idealization is shown in Fig. 8. From symmetry reasons, these considerations could be limited to a half-model.

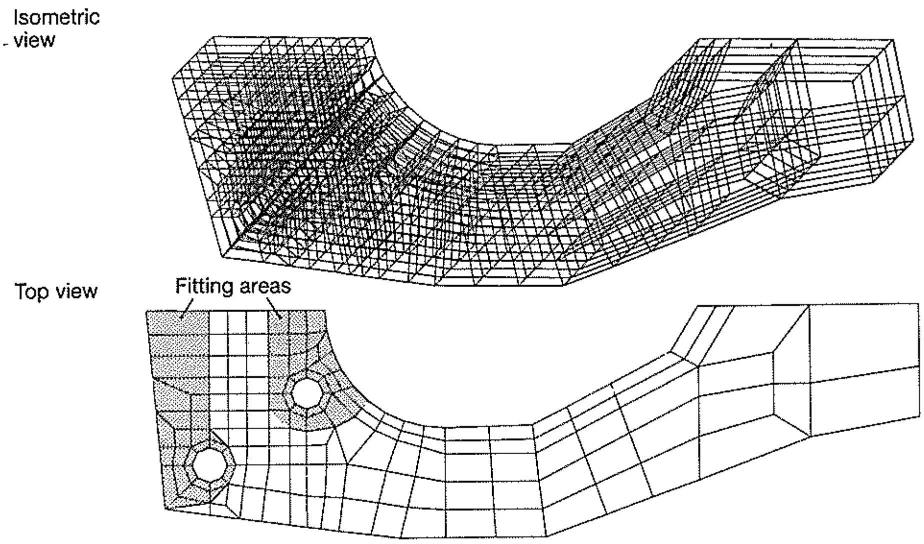


Fig. 8 FEM idealization of the blade attachment area

As a representative result of these structural calculations, the distribution of the maximum stresses at the surface is shown in Fig. 9 for a pure moment loading in the flapping direction. In addition, the distributions of the principle stresses and of the maximum shear stress are plotted for a typical cross section. A stress concentration (compression) appears in the vicinity of the fastening bolt for the conical bearing. To deload this area, constructional modifications (e. g. shifting the bolt more outboard, enlargement of the supporting area of the bearing fitting etc.) were introduced.

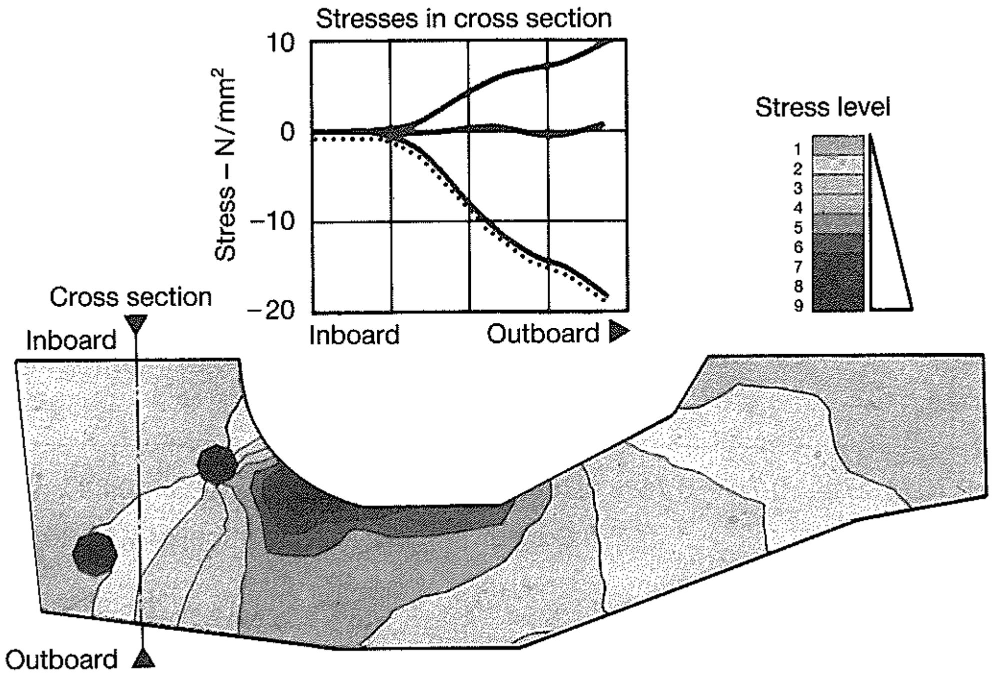


Fig. 9 Stress distribution in the blade attachment area due to flap bending

4.3 Aerodynamic layout

The aerodynamic layout of a helicopter rotor implies, apart from the dimensioning parameters such as rotor diameter, blade tip speed, number of blades, basic blade chord in particular, the geometrical shaping (airfoils, twist, planform) of the rotor blades.

At present, the widely-used helicopter airfoils NACA 0012 and NACA 23012 are globally replaced by newly-developed airfoils with improved characteristics. The French OA series, the American VR series, and also the German DM-H series [3] belong to this new generation of helicopter airfoils which have the following benefits in comparison to the conventional NACA airfoils

- lower drag at low to medium Mach numbers
- suitable for higher transonic Mach numbers
- higher maximum lift coefficient at same profile thickness

In Fig. 10, the maximum lift coefficient at Ma = 0.4 is plotted versus the drag divergence Mach number for different airfoils.

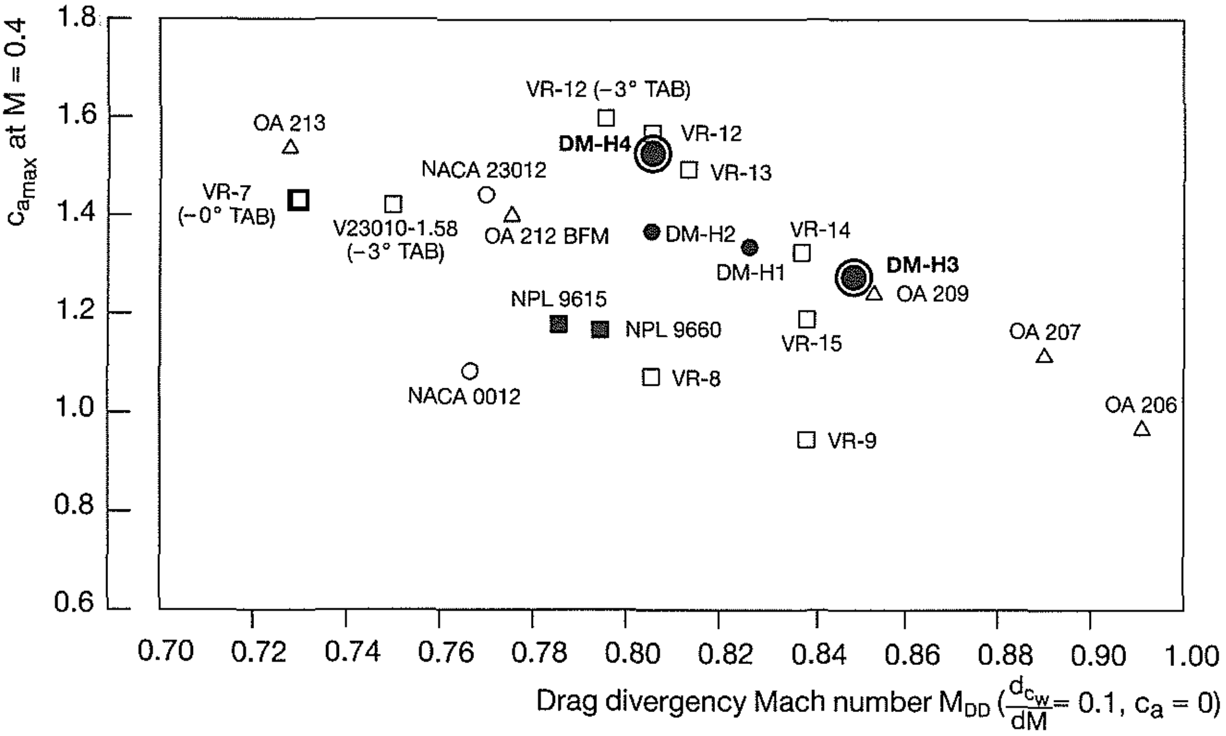


Fig. 10 Comparison of airfoil data

The DM-H4 airfoil with 12 % thickness for the inboard blade section to 80 % radius and the DM-H3 airfoil with 9 % thickness for the outboard blade section from 95 % radius have been selected for the FEL rotor. In between, the thicker airfoil passes linearly into the thinner one. With this airfoil combination, a power saving of 5 to 8 % (according to the flight conditions) and a speed limit shifting due to Mach number effects of about 50 km/h upwards can be achieved. A proper shaping in particular of the blade tip section can contribute to a considerable drag and noise reduction. A swept leading edge between 95 and 100 % radius of the FEL rotor blade is expected to provide an additional 3 to 5 % power saving. The planform of the FEL rotor blade is shown in Fig. 11.

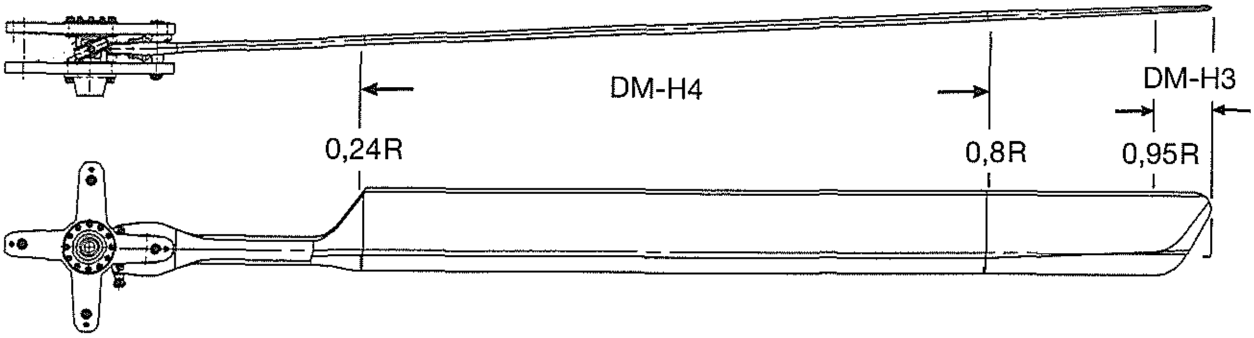


Fig. 11 FEL rotor blade planform

5. Manufacturing Concept

The hub plates and rotor blades are designed specifically for mechanized manufacturing. Both consist of fibre composite prepregs with interchanging fibre orientations. Fig. 12 shows a hub plate in the curing mold. The manufacturing process starts with prepressing and precuring of 11 prepreg layers. After precuring, the package is punched in a tool with a cutter which has the star shape of the plates. Several of these precured packages are cured in a mold to achieve the final contour of the plate. The holes for the bolts are machined after curing using diamond tools.

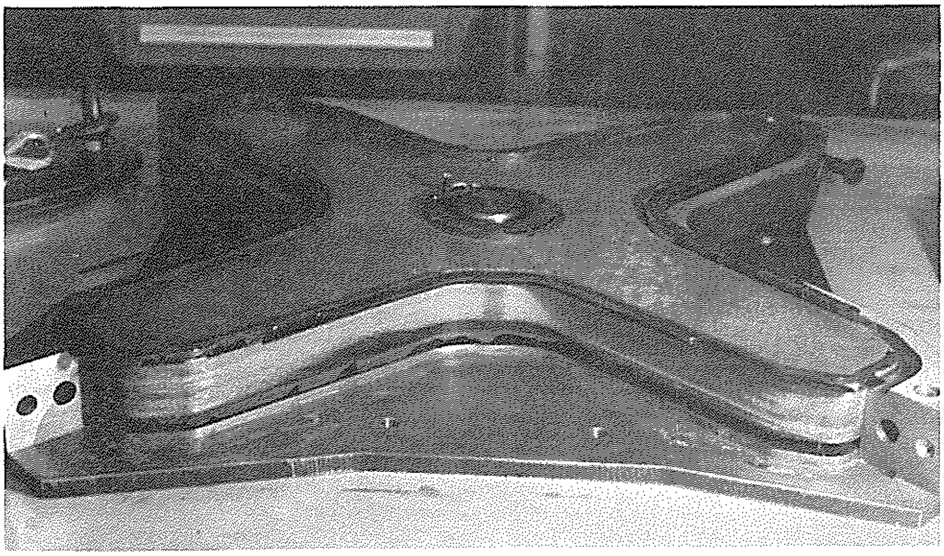


Fig. 12 Hub plate in mold after curing

The rotorblade is manufactured in 2 sections as seen in Fig. 13:

- the main section with blade attachment, neck, skin and 2 cores
- the nose section including skin, nose weight and erosion protection

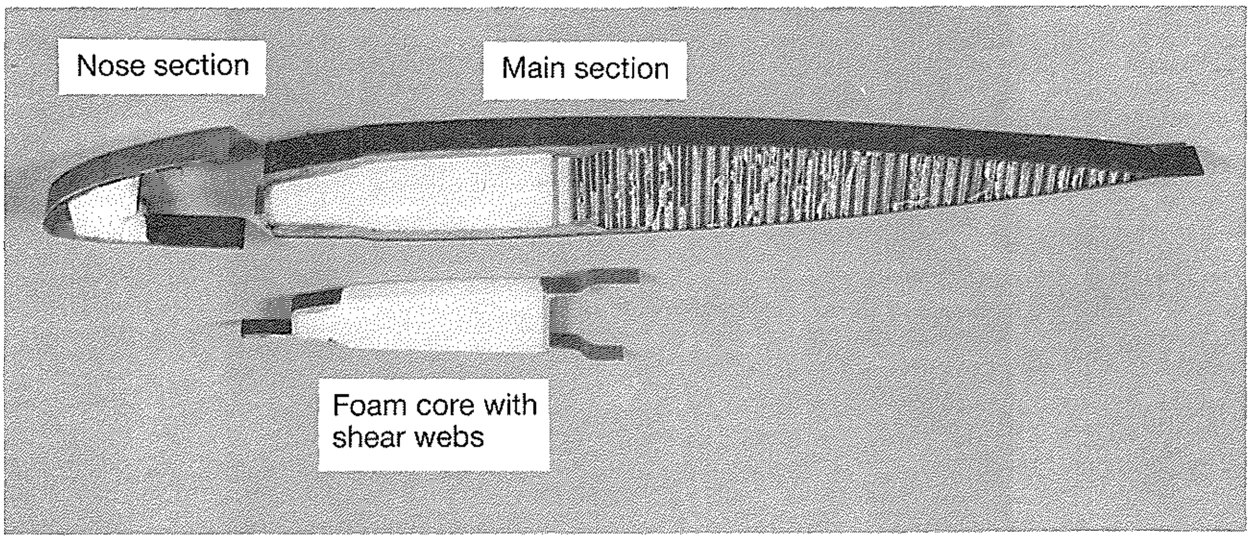


Fig. 13 Manufacturing details of the blade

Fig. 14 shows the main section in the mold before curing. Blade attachment and neck are also made of prepressed and precured fibre composite prepreg packages with interchanging fibre orientation. The unidirectional fibre composite prepregs of the spar beams run from the blade tip to the root. The cured nose section is bonded to the cured main section in an additional mold.

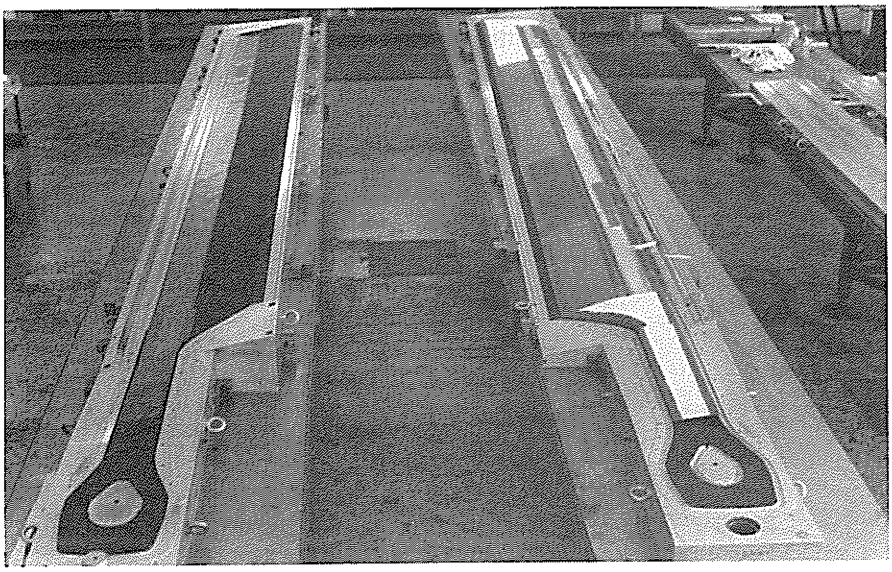


Fig. 14 Main blade section in the mold

6. Component Testing

Static and endurance tests have been conducted with all main components to confirm mathematic modelling and calculated structural properties, to check fatigue life under relevant loads, and to obtain additional data. Fig. 15 shows the test rig with the FEL hub fixed to the ground.

All static and oscillating in-plane and flapping loads with a constant centrifugal force have been applied to all four arms. In addition, a start-stop-cycle test with 25 percent overload in radial direction was run. The expected load cycles without damages were realized in both tests.

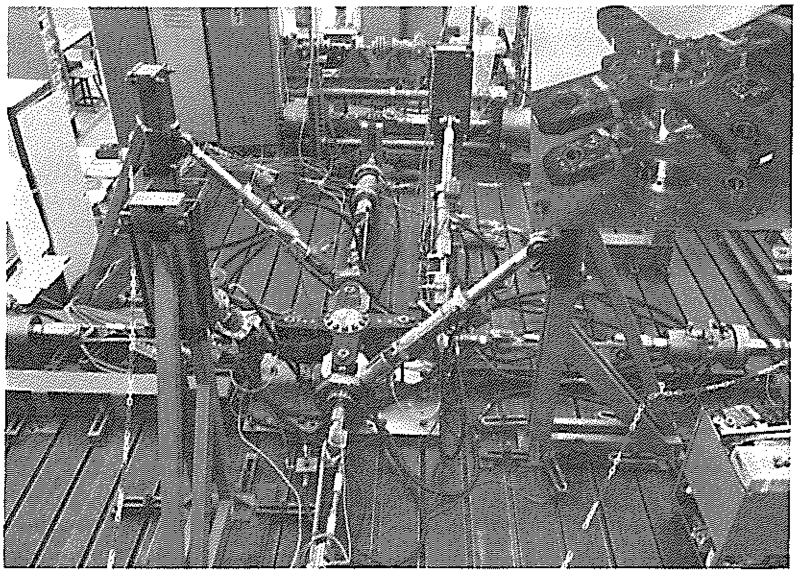


Fig. 15 FEL hub in test rig

A series of blade attachment and blade neck specimens were treated with similar loading. Fig. 16 shows the current FEL design. This specimen was tested for more than 10^6 cycles without any change in the load transfer behaviour. The manufacturing quality of the specimen as well as its condition during the test were controlled by "Computer Tomography", a method which is normally applied in radiographic diagnostics in hospitals.

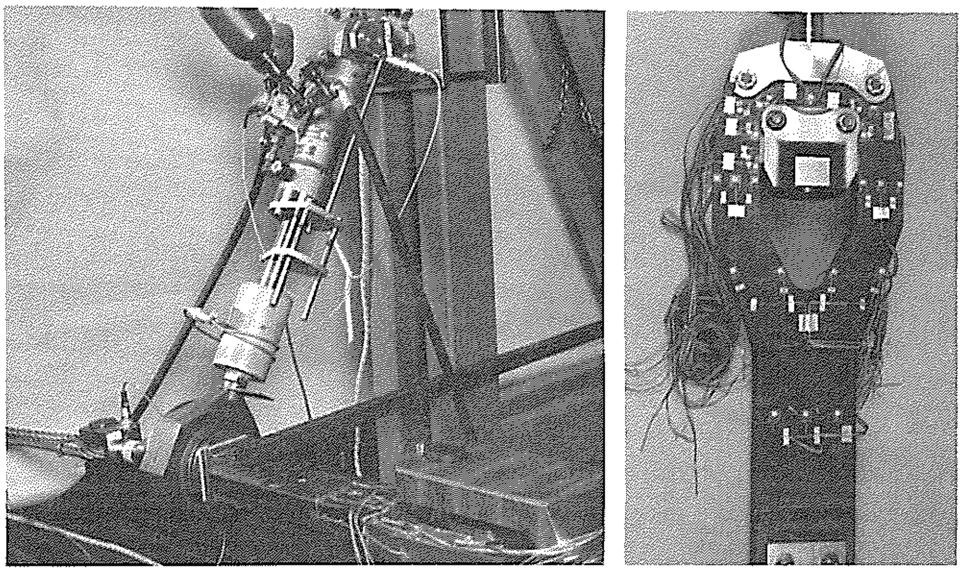


Fig. 16 Blade attachment test specimen

7. Rotor verification on whirl tower

After successfully finishing the most important laboratory tests and proving the static and dynamic strength of the critical components, the verification of the rotating FEL rotor system began. These functional tests at realistic operation conditions were conducted to obtain information and data regarding the following:

- substantiation of the theoretical rotor model
- verification of the load and stiffness assumptions
- verification of the bearing properties
- verification of the blade natural frequencies
- investigation of the damping capability
- check of the control kinematics
- measurement of the thrust-power potential

7.1 Description of test rig

Because of the lack of a whirl tower in the suitable size at MBB, the rotor was mounted on an existing test rig at Aérospatiale's Marignane plant (see Fig. 17). This rig had been used for endurance tests of the AS 365 main rotor. The drive system consists of an original 365 N main gearbox including swash plate and control boosters and two Turbomeca Turmo engines with special reduction gearboxes. The main gearbox is mounted to the rig by four diagonal struts. Like in the aircraft, the rotor shaft is inclined 4° forward. For the adaption of the FEL rotor to the whirl tower, the rotor shaft and rotating control rods had to be redesigned. Since the test rig was not equipped with a thrust balance accurate thrust measurements were not possible. As a compromise, each of the four gearbox struts had been furnished with strain gages to obtain an approximate measurement.

The three hydraulic boosters are linked mechanically to control handles at the operator's station. In order to investigate the dynamic behaviour of the rotor system, a special actuator with a limited authority and an electrical control input had been designed. It could be used instead of the longitudinal cyclic booster to introduce a sinusoidal excitation into the rotating system.

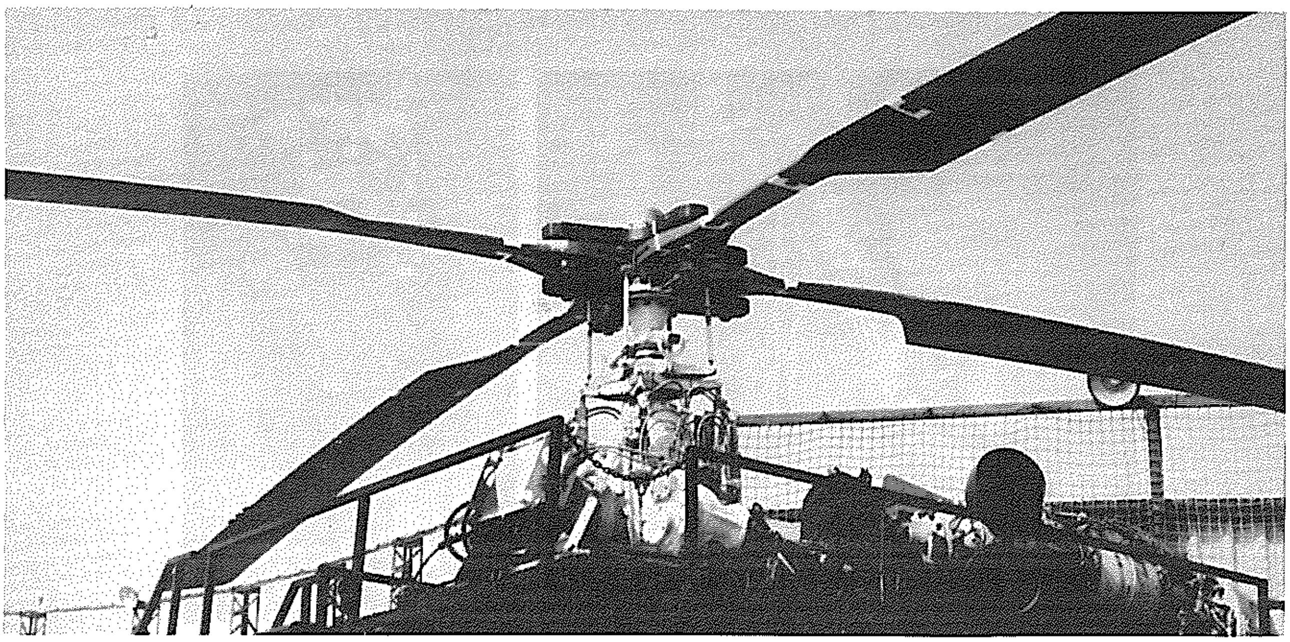


Fig. 17 FEL rotor on whirl tower

7.2 Test results

Some of the main results of the FEL rotor verification in the centrifugal force field are presented in the following paragraphs.

Thrust-power polar

Though it was not a primary target of the whirl tower test – as mentioned above, the test rig was not equipped with a real thrust balance – rotor thrust and the corresponding rotor torque have been measured for collective angles between −1.5° and +12°.

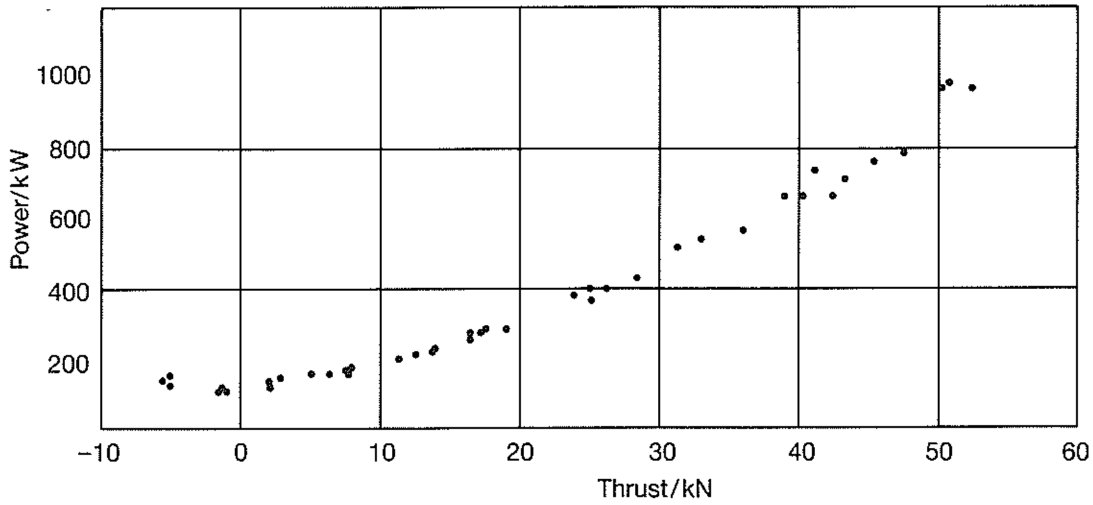


Fig. 18 FEL rotor power vs thrust

In Fig. 18, rotor power is shown as a function of rotor thrust. The measuring points come from five different test runs with 100 % and 90 % (corrected to 100 %) rotor RPM. It should be mentioned that the theoretically predicted power saving due to the new airfoils and tip geometry could not be completely verified because of several reasons:

- deficient thrust measurements
- unfavourable test conditions (wind in combination with shaft inclination)
- obstacles (buildings, protective fence,...) near to the rig

Rotor loads

The measurement of rotor loads has been performed in a thrust range of −5000 to 40000 N at cyclic control inputs up to 2°. Because of the high moment capacity of the FEL rotor, the cyclic control input was limited to this value due to stress problems of the AS 365 rotor shaft which is designed for a 5 % hinge offset rotor. The maximum rotor shaft bending moment was limited to about 8000 Nm.

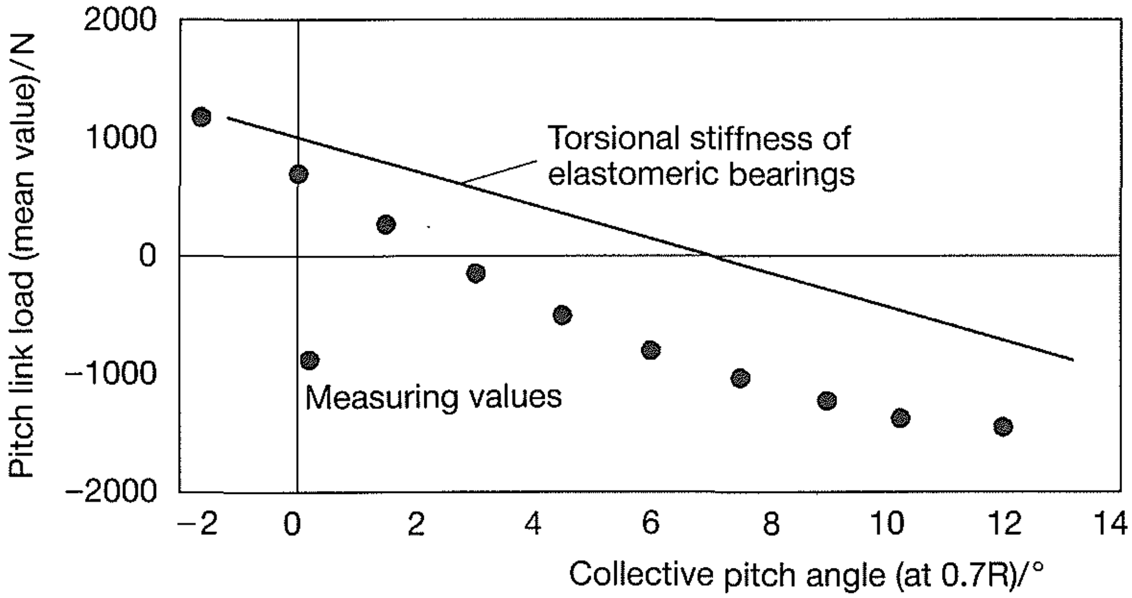


Fig. 19 FEL rotor pitch link load vs collective angle

In Fig. 19, the mean values of the loads in the rotating control rods are plotted versus the collective pitch angle. It is evident that the slope of the pitch link load is determined largely by the contribution of the torsional stiffness of both, the conical and the radial elastomeric rotor hub bearing.

Rotor blade frequencies

The rotor blade natural frequencies have been measured for 0 %, 90 %, and 100 % rotor RPM by a sinusoidal excitation of the longitudinal cyclic control in the frequency range up to 35 Hz. The verification of the fundamental bending natural frequencies is of a great interest for the flight mechanical (flapping frequency) and for the aero-mechanical (lagging frequency) system behaviour. The position of the higher natural bending modes in flap and lead-lag direction are important for the vibratory behaviour of the rotor system. In Fig. 20, the measured natural frequencies are plotted into the calculated frequency diagram. The experimental results correspond well with the theory.

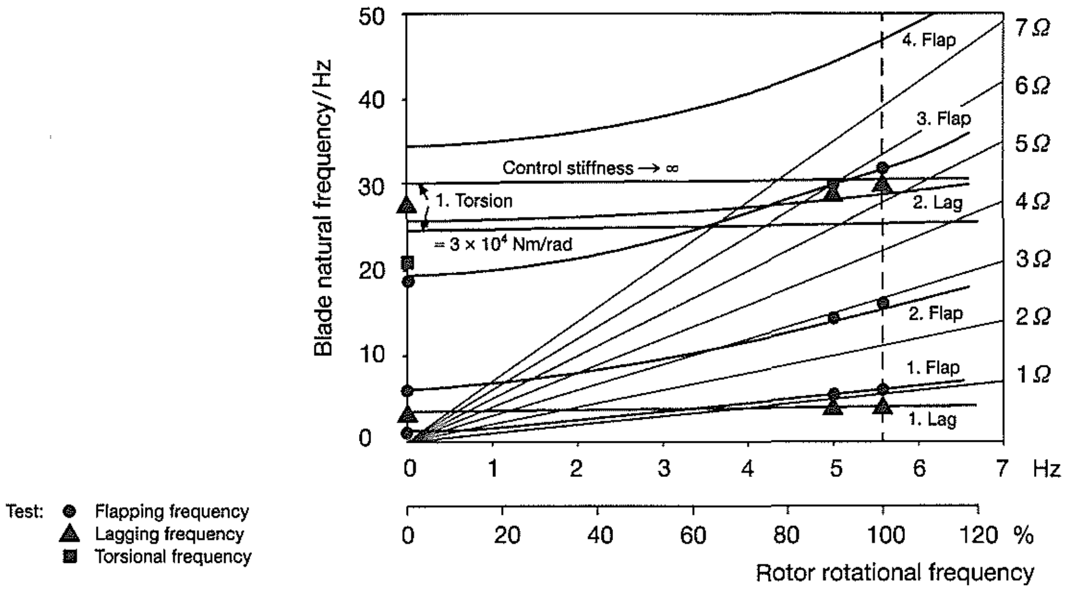


Fig. 20 FEL rotor frequency diagram (uncoupled calculation)

Lead-lag damping

The most important task for the whirl tower test was the investigation of the lead-lag damping characteristics of the FEL rotor in the total collective angle range. For damping measurements, the rotating system was excited by a sinusoidal (Ω-ω_ζ) input into the special actuator which replaced the longitudinal booster for these tests. The lead-lag damping values were evaluated from the in-plane bending moment decay curves treated by a band pass filter after stopping the excitation. In Fig. 21, the dependence of frequency and damping for the fundamental lead-lag mode on the rotor thrust is shown. The minimum modal damping which is critical for ground resonance stability, is about 0.8 % for a slightly positive thrust (blades within tip plane, i. e. no additional damping due to coupling effects in combination with low aerodynamic damping at low thrust). In this case, the lead-lag natural frequency in the rotating system has its maximum value of about 4 Hz at 100 % rotor RPM.

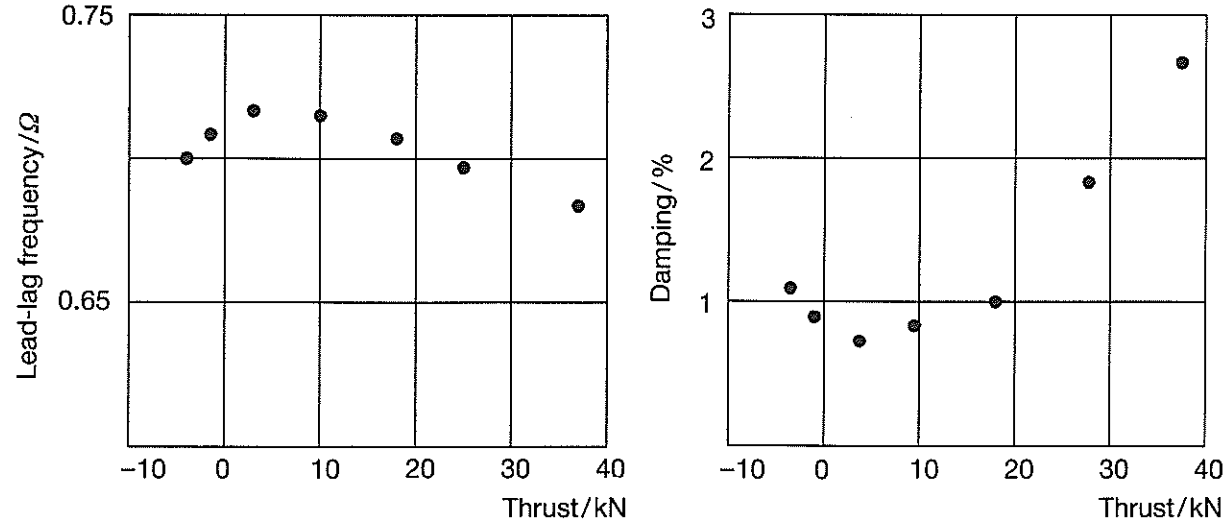


Fig. 21 FEL rotor lead-lag frequency/damping vs thrust

To guarantee an adequate ground resonance stability especially in case of a wheel landing gear, several possibilities for increasing lead-lag damping have been considered. Both visco-elastic as well as pure viscous damping elements, which take advantage of the in-plane bending deformation of the neck, have been tested in the laboratory.

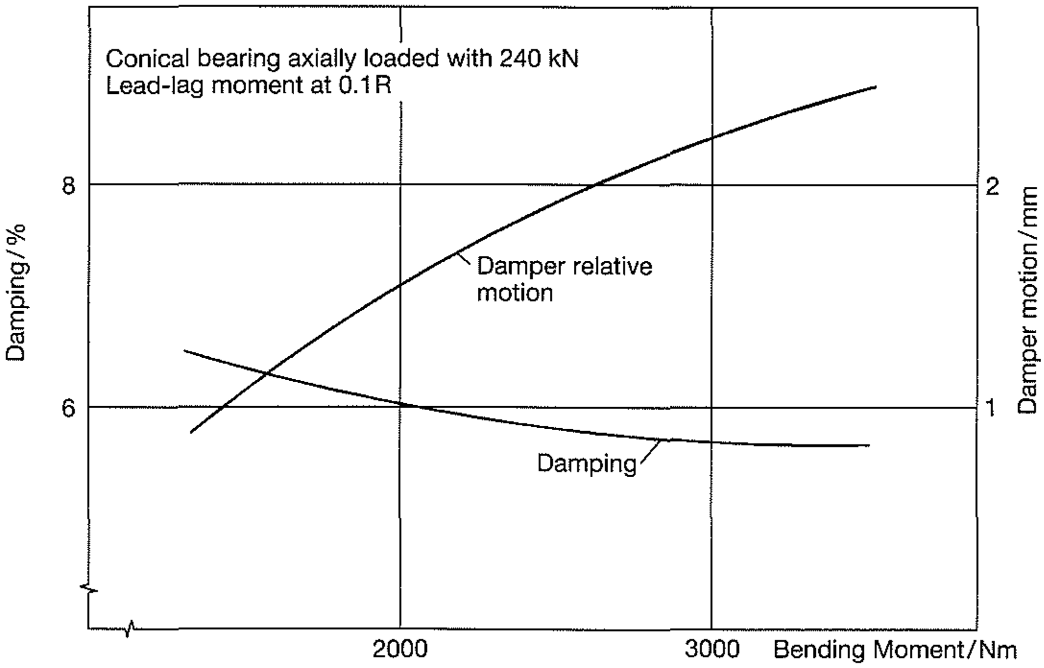


Fig. 22 Additional damping vs lead-lag moment (laboratory test)

A typical test result is shown in Fig. 22. Without centrifugal force but with frequency correction due to the lower natural in-plane frequency, a damping increase of about 6 % has been achieved. Even if the additional damping will be slightly reduced because of the different mode shape of the blade in the rotating system, there should be sufficient damping to prevent any instabilities. Further provisions to increase the damping in the non-rotating system (e. g. at the landing gear) are not necessary.

8. Concluding remarks

A new concept of a practically maintenance-free helicopter main rotor has been presented. The flap and lag motions are performed by elastic deformation of the composite blade neck which result in an on-condition design for the blade. The blade pitch motion is provided by shear deflection of laminated elastomeric bearings which are designed for long life with low maintenance (inspection only). The main features of the FEL rotor are its compact dimensions, its low number of parts, its high control power for excellent agility and maneuverability even at negative load factors, and last but not least its fail-safe design. Laboratory tests for the most critical components and the rotor verification on the whirl tower have shown that the development risk is low due to the close system relationship to the widely-approved BO105 rotor system.

The FEL rotor system is in line with the development trend from the fully articulated over the so-called hingeless to the "bearingless" rotor. It represents the proper design in particular for modern military helicopters (Fig. 23).

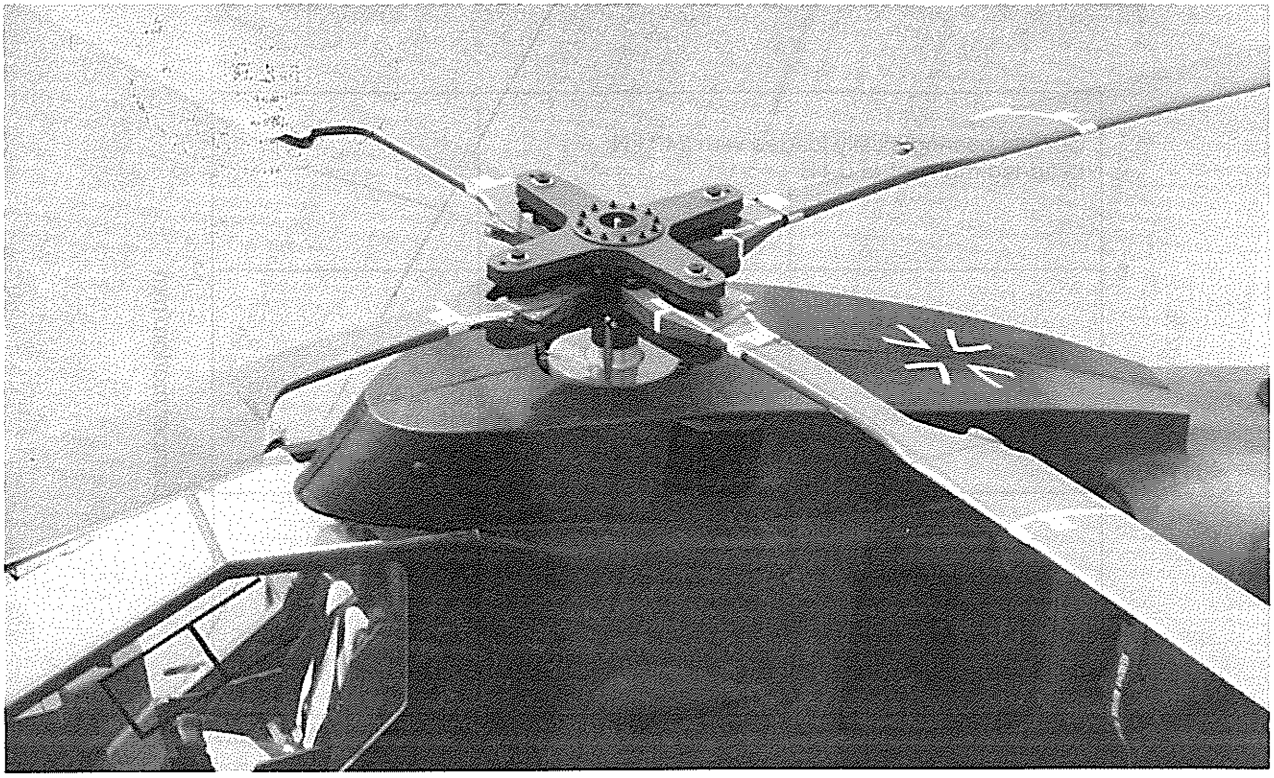


Fig. 23 FEL rotor on PAH-2 mock-up

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