DEVELOPMENT OF BEARINGLESS TAIL ROTORS

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Abstract

Conventional helicopter tail rotors (CTR) represent a highly efficient but complex control concept. They provide uniquely low power requirements and outstanding controllability, to name their main benefits. On the other hand they often imply problems with respect to maintenance efforts and life-time. The key for overcoming such problems is the application of new composite materials which, for several reasons, is particularly attractive for tail rotors. This enables a new design solution in the form of the bearingless tail rotor (BTR).

The paper gives an overview of the development and tests of advanced composite tail rotors since the late 1970's and early 1980's at MBB. After the discussion of general design aspects, the lay out, structural design, and testing of several bearingless prototypes are demonstrated. Emphasis is also laid on the assessment of relevant technological criteria, as weight, manufacturing costs, maintenance effort, reliability and vulnerability. Finally a view is taken of the BTR's potential for further development and its application to MBB's future product range.

1. Introduction

At present, helicopter yaw control concepts are encountering considerable development efforts. Different concepts are available, both in production and under development. They give rise to the question as to which extent they are capable to comply with the technical and economical requirements of tomorrow.

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Due to a number of reasons, tail rotors belong to the helicopter's most delicate components, and it is well known that maintenance and life-time of conventional tail rotors have been a problem for many helicopters in the past. On the other side, the conventional open tail rotor concept - from its inherent physical laws - belongs still to the most effective solutions for low power requirements and manoeuverability. As a consequence, MBB's philosophy in the development of yaw control devices clearly goes into the direction of the conventional concept, whilst improving its inherent problems, as mentioned before.

As it is well known since many years, one governing factor in aeronautical technology at MBB has been composite material design. Based on this substantial background, the development of advanced composite tail rotors has a long tradition, as can be seen from Figure 1.1 and Ref. 1.

The key for these technical developments clearly is the definition of new composite materials and their application to the highly loaded structures. This is particularly attractive for tail rotors, for several reasons.

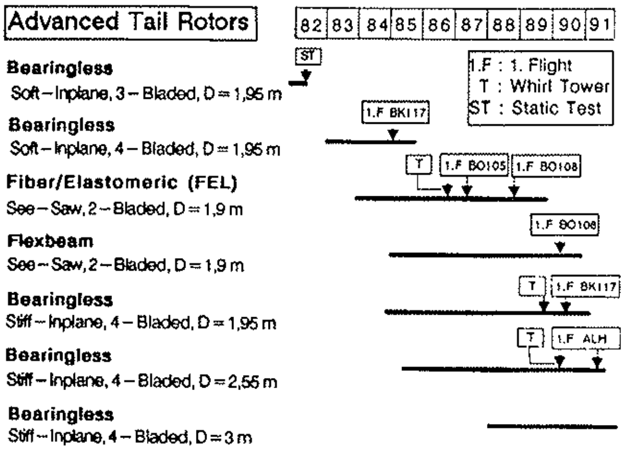


Fig. 1.1 Development and Test of Advanced Composite Tail Rotors at MBB

2. General Design Aspects

The general design of advanced tail rotors has to establish the thrust characteristics which are necessary to provide the required manoeuverability at a reasonable power consumption and moderate noise level.

2.1 Power Efficiency

The conventional tail rotor (CTR) has a high power efficiency as it accelerates a large in-flow mass to a relatively low axial velocity. As an advanced version of the CTR system the BTR can claim additional advantages. So the absence of conventional bearings allows a simple, small, and aerodynamically clean hub which reduces drag in forward flight. In addition, the composite material applied enables an optimized aerodynamic blade shaping.

2.2 Manoeuverability

The maximum turn rate expressed by the yaw angle which is achieved after the first second, is a measure for the helicopter's yaw agility. Here, the BTR demonstrates excellent characteristics due to its optimized blade planform and low stress level (under precession flapping), both enabled by the particular composite design.

In the case of the BK 117 with an increased gross weight (3600 kg), the 4-bladed BTR's (Fig. 1.1) would allow a yaw angle of about 50 degrees after the first second, taking into account fin interferences. Together with a favourable potential to cope with sidewind conditions this represents outstanding manoeuvering capacities.

2.3 External Noise

The noise radiation of helicopters in high velocity fly-over situations is considerably influenced by the T/R system applied. Therefore the design of advanced T/R systems such as the BK 117 (growth) BTR has to tackle the relevant sources of sound creation. So this BTR is driven with the low tip speed of v_T = 207 m/s as the tip speed is a key parameter of noise emission. In addition a low blade loading, providing a high margin with respect to stall onset, and a blade geometry, designed to smooth pressure and velocity distribution have been realized. This sculpturing of complex blade planforms is strongly facilitated by the use of composite materials.

3. Lay Out and Design

3.1 Dynamic Lay Out

The dynamic lay out of a rotor is characterized by the placement of the fundamental bending natural frequencies. It basically affects load and stability requirements. Figure 3.1 shows the normalized inplane frequency versus the normalized out of plane frequency of MBB tail rotor designs.

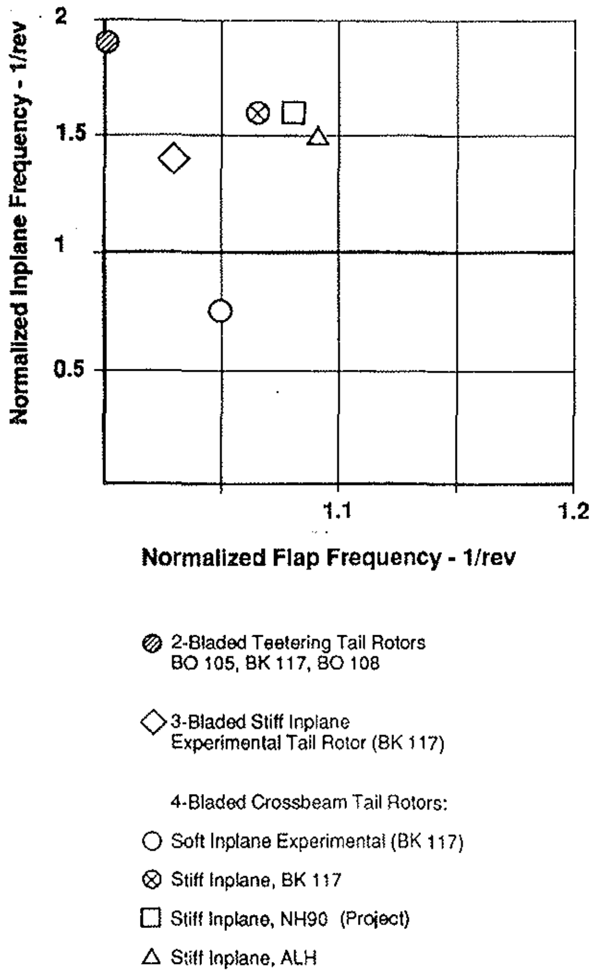
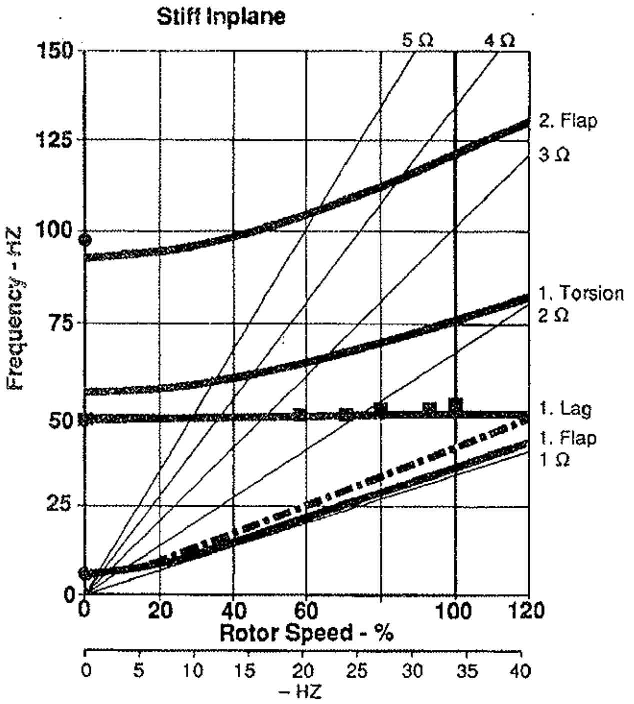


Fig. 3.1 Fundamental Flap and Lead-Lag Frequencies of MBB Tail Rotors

The chordwise stiffness of the flexbeam in conjunction with the mass distribution determines the placement of the first inplane frequency below or above the nominal rotating frequency.
A comparison of the resonance diagrams of Figure 3.2 shows the fundamental frequencies of a soft and a stiff inplane rotor, both experimental BTR-systems developed and tested at MBB.

The test data were achieved during whirl tower tests. The dotted lines indicate the shifting of the first out of plane mode caused by the pitch/flap coupling effect. A positive δ_3 coupling is used to reduce excessive cyclic flapping caused by forward speed and yaw/roll rates. This is accomplished by a proper positioning of the pitch arms relative to the equivalent flapping hinge. As is seen from Figure 3.3, both designs have different control devices. The soft inplane rotor was designed with a cantilevered pitch horn, while the stiff inplane design uses a cuff with a snubber bearing.



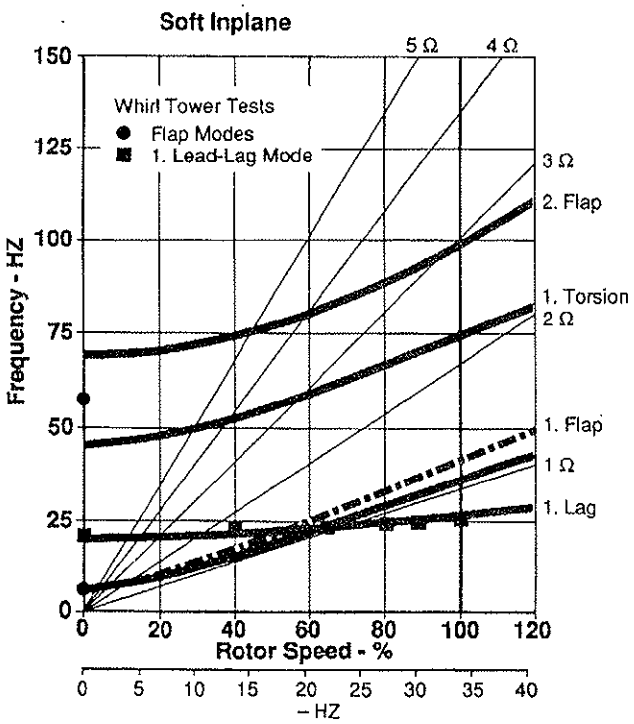
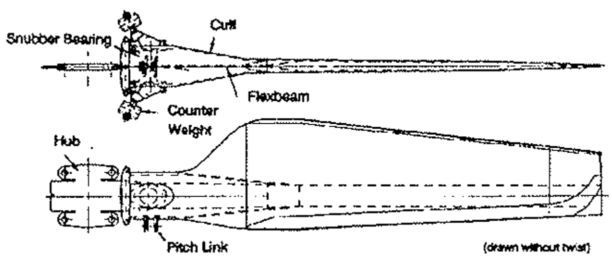


Fig. 3.2 Resonance Diagrams of 4-Bladed BK 117 Experimental BTR's

Soft Inplane Experimental Rotor



Stiff Inplane Experimental Rotor

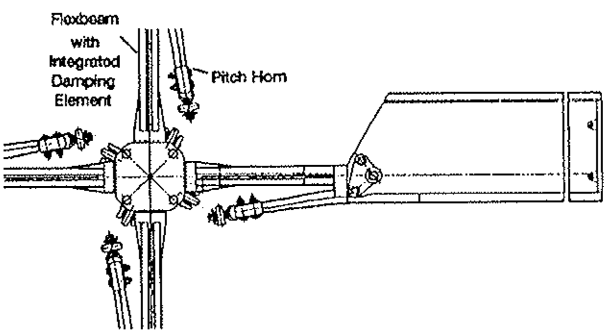


Fig. 3.3 Comparison of Control Devices and Soft and Stiff Inplane Principle

Essential for low hub and shaft moments is a low equivalent flap hinge offset. This can be achieved in the case of non-teetering rotors by a cross beam design of the flexstraps leading to a small and light hub. Tapering the flexbeam in width and thickness forms a quasi flap hinge and separates the maxima of flatwise and edgewise bending stresses.

The torsional stiffness of the flexbeam has to be minimized, to accommodate blade pitch motion with minimum flexbeam length and to keep down control loads caused by structural deformations. Counter weights are used to compensate adverse inertia moments and to obtain pedal forces similar to those of the production see-saw rotor. Figures 3.4, 3.5, and 3.6 give an impression of the stiffness and mass tailoring versus rotor radius of the two 4-bladed BK 117 tail rotors.

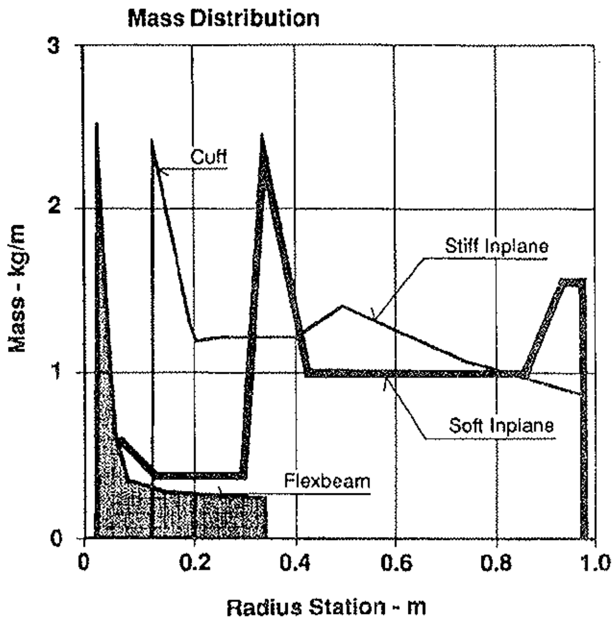


Fig. 3.4 Mass Distribution of the 4-Bladed BK 117 Tail Rotors

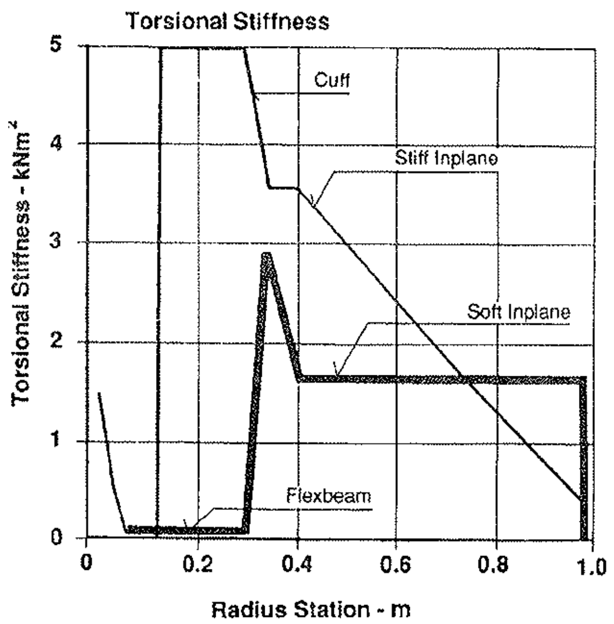
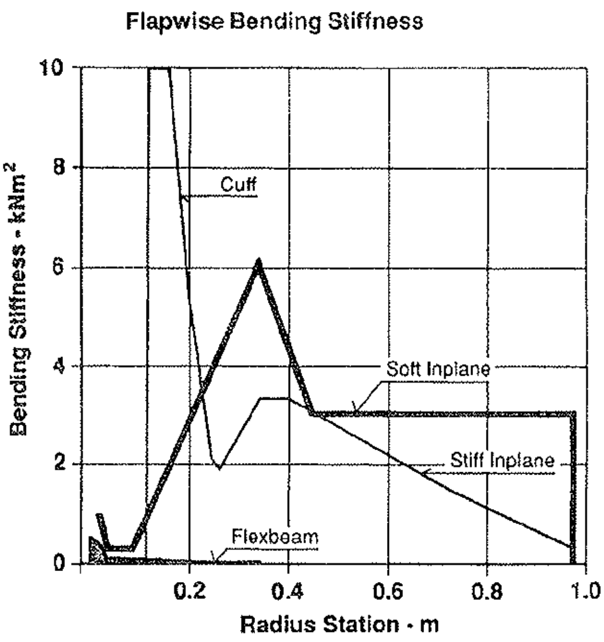


Fig. 3.5 Torsional Stiffness Distribution of the 4-Bladed BK 117 Tail Rotors



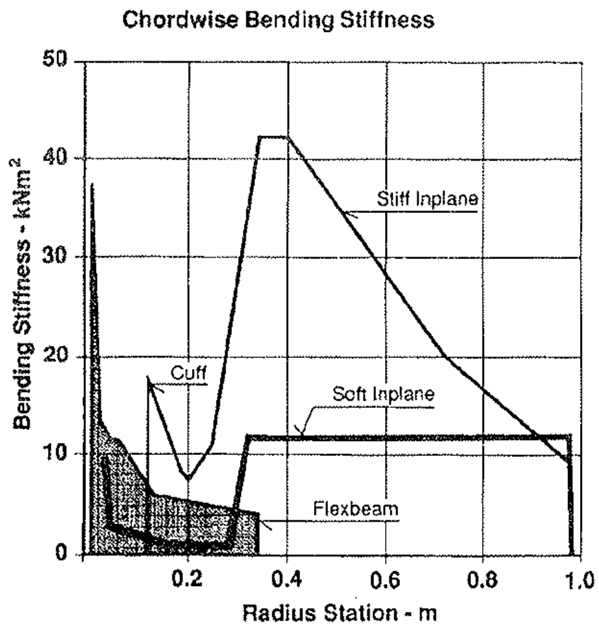


Fig. 3.6 Bending Stiffness Distribution of the 4-Bladed BK 117 Tail Rotors

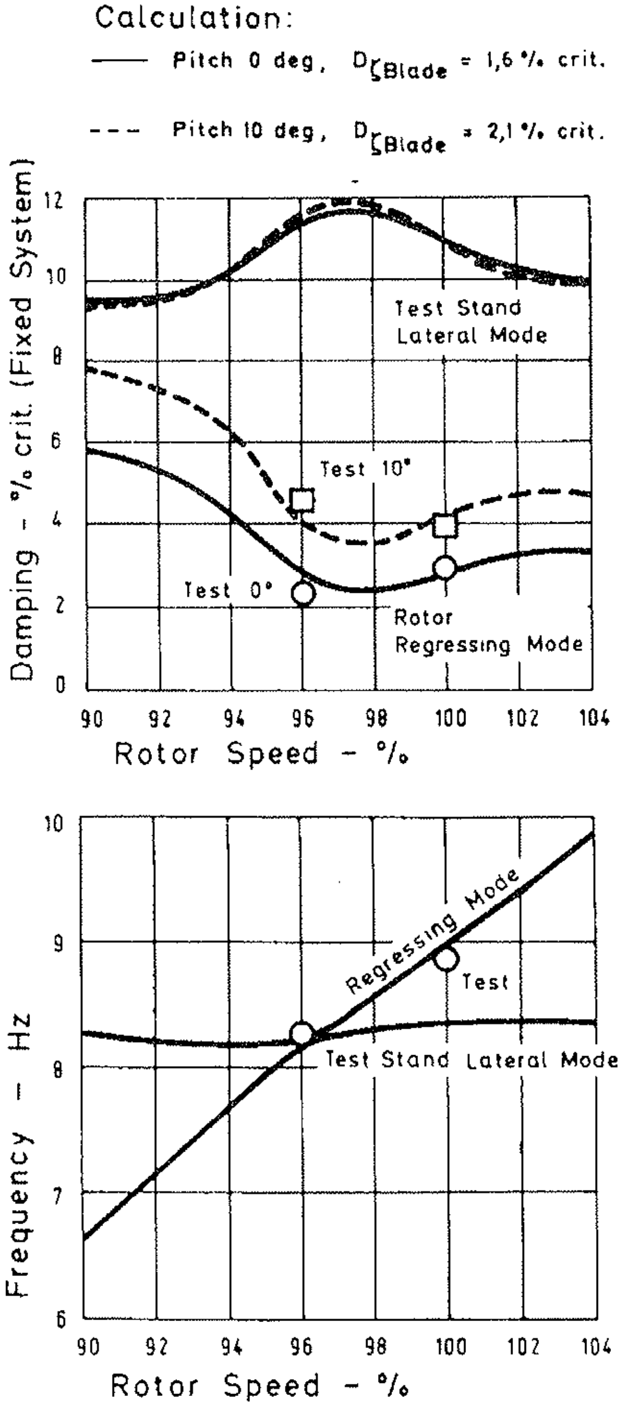


Fig. 3.7 Ground Resonance Simulation of the Soft Inplane Rotor on Whirl Tower

A soft inplane lay out will be preferred, when minimum oscillating chordwise loads of the flexbeam and low control forces should be achieved. But the lead-lag motion coupled with body modes could cause aeromechanical stability problems. Therefore a proper tuning of the fuselage/tail boom modes is required and adequate lead-lag damping sources have to be incorporated in the design. Figure 3.7 shows whirl tower test results at two different pitch settings of the rotor under simulated ground resonance conditions. The pretest damping and frequency calculations were well confirmed by the measurements.

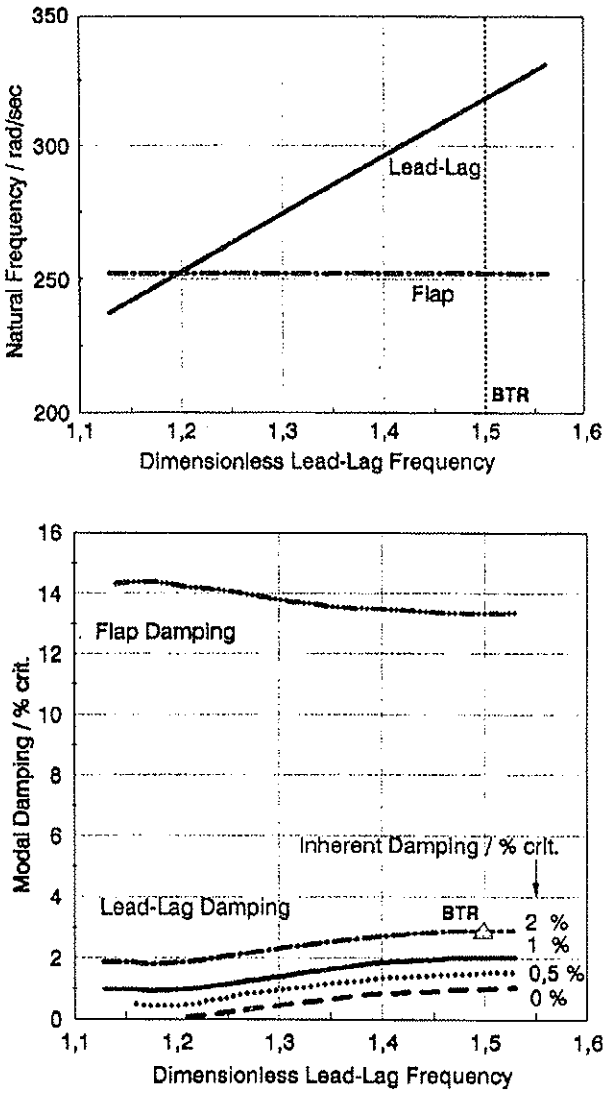
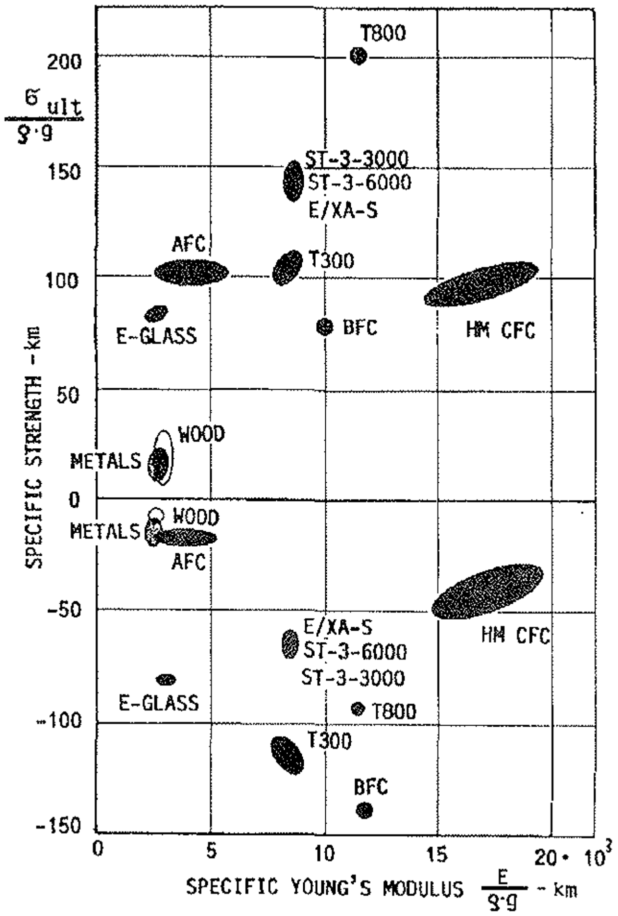


Fig. 3.8 Flap Lag Stability of the Stiff Inplane BK 117 (Growth) BTR - Theory
D_{6}= 21,3°, Ω= 212,2 rad/s

The stiff inplane rotor concept is free from aeromechanical stability restrictions . But aeroelastic stability problems due to the proximity of the fundamental bending frequencies can occur. Figure 3.8 shows the calculated system stability of a stiff inplane rotor versus the first lead-lag frequency placement. With low structural inplane damping the system was found stable, even with coincident first flap and first lead-lag frequencies. Test results on a rig (see Figure 4.4) showed a high lead lag stability and a large offset between lead lag and flapping frequency even at high thrust values.

3.2 Structural Design

During the past years new composites with high-strain carbon fibers have been developed. These improved materials are beneficial for the design of high loaded structures such as bearingless tail rotors. Figure 3.9 shows the specific strength and stiffness characteristics of unidirectional composites with 60 % fiber volume content. The high-strain carbon fiber composites have the highest specific strengths of all materials available, with T 800 representing the outstanding potential (see Ref. 2,3). This material was selected for the flexbeam of the stiff inplane tail rotors allowing a simple rectangular cross section.



GFC glass fiber composite
AFC aramid fiber composite
BFC boron fiber composite
HM CFC high modulus carbon fiber composite

Fig. 3.9 Specific Young's Moduli and Strengths

A strain optimization of the flexbeam was conducted using uncoupled beam theory in the preliminary design phase as well as 3D NASTRAN calculations for the final design. Figure 3.10 shows the result of a stress calculation for a load case with simultaneous flap and lag deflections under centrifugal forces.

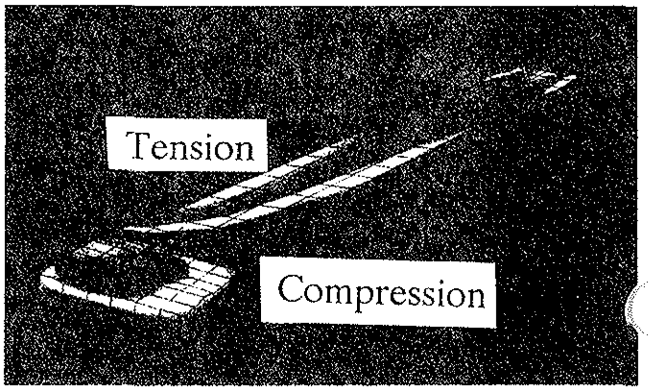


Fig. 3.10 Calculated Stress Distribution of the Stiff Inplane BK 117 (Growth) Tail Rotor

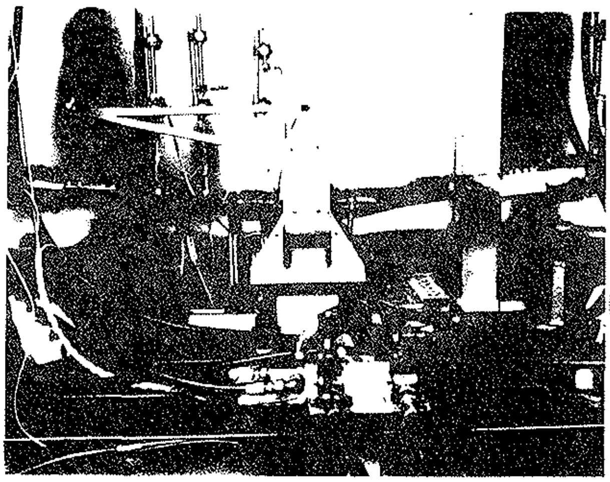


Fig. 3.11 Structural Dynamic Components Test

Tests were conducted to determine the fatigue characteristics of composite structures subjected to large stresses due to torsion. Of particular interest were fatigue strength and failure mode characteristics under combined bending, torsional and tension loads. Figure 3.11 shows a bench test setup with a completely assembled blade pair during a symmetrical flapwise load.

3.3 Conceptual Designs

Two new see-saw tail rotor concepts are shown in Figure 3.12. Concept (a) consists of two single composite blades and a composite hub with elastomeric bearings. The rotor was successfully flight tested on a BO 105 and is now on the BO 108 prototype aircraft. The second concept features a pair of blades with an integrated flexbeam element in between. Control inputs to the blade are transferred by a composite cuff directly bonded to the blade. This system represents an alternative solution for the BO 108. It is just tested on a rig and will also be flight tested this year.

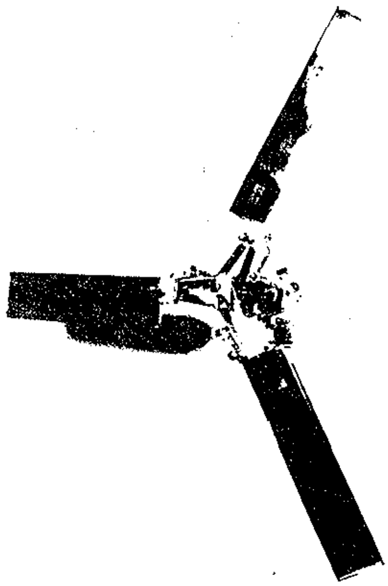
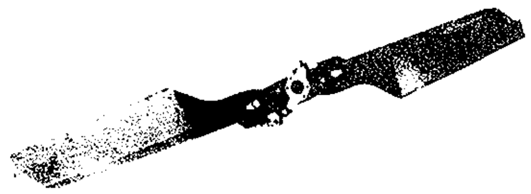


Fig. 3.13 Experimental 3-Bladed Bearingless Stiff Inplane Design

(a)



(b)

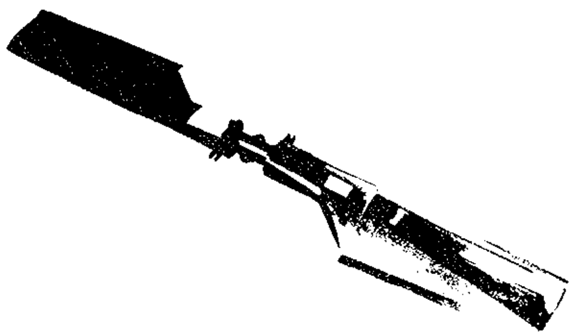


Fig. 3.12 2-Bladed BO 108 Teetering Rotors with
(a) Elastomeric Flap and Pitch Bearings
(b) Elastomeric Flap Bearings, Flexbeam

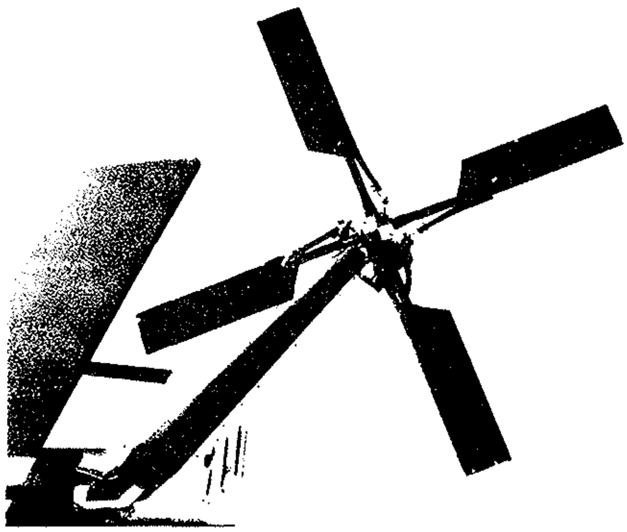


Fig. 3.14 Experimental 4-Bladed Bearingless Soft Inplane Design

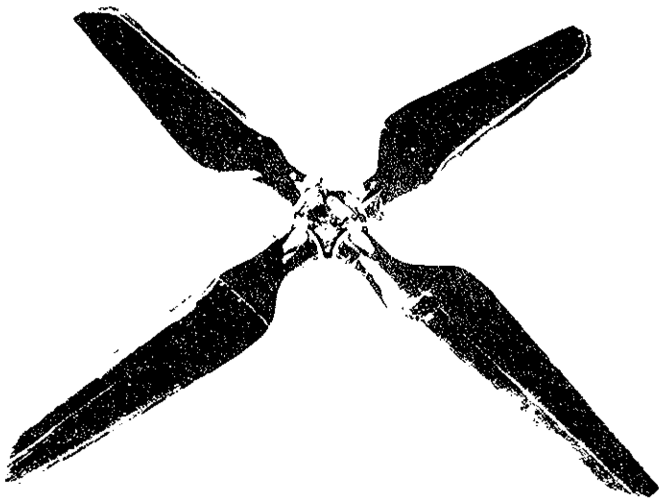


Fig. 3.15 4-Bladed BK 117 Bearingless Stiff Inplane Rotor

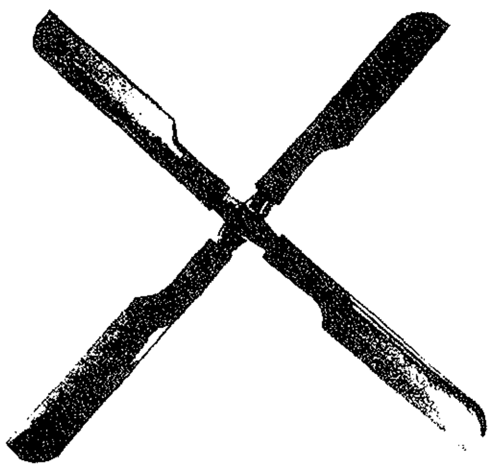


Fig. 3.16 4-Bladed ALH Bearingless Stiff Inplane Rotor

Two experimental BK 117 tail rotors are illustrated in Figures 3.13 and 3.14. Among the two designs the four-bladed soft inplane version was favoured and successfully flight tested on a BK 117 helicopter (Ref. 4). An integrated damping element is applied to the chordwise flexible part, consisting of a "bridge" type construction of carbon-fiber composite plates. Due to cost reasons the rotors were manufactured using BO 105 standard tail rotor blades (rectangular shape, NACA 0012 cross section).

Figures 3.15 and 3.16 show prototype rotors of the stiff inplane type. The first one is intended for application to a BK 117 growth version aircraft (3.6 t), while the blade shown in Figure 3.16 belongs to the BTR-version for the ALH (Advanced Light Helicopter), a cooperation program with the Indian Government. Both types are currently tested on the whirl towers at Ottobrunn, and Bangalore/India.

4. Full Scale Test Substantiation

Advanced tail rotor development at MBB has been supported by intensive full-scale test substantiation. The investigations allowed a validation of the technical potential and included component, whirl tower, and flight tests. They cover the areas of loads, stresses, aerodynamics, dynamics, aeroelastics, and aeromechanical stability.

4.1 Whirl Tower Test

An advanced test rig for the evaluation of full-scale tail rotors is depicted in Figure 4.1. It is driven by a 250 kW hydraulic engine and has the ability to rotate up to 20 rpm around its vertical axis in order to excite blade motions under simulated yaw turns (120 deg/sec). The rig's support stiffness and damping is adjustable to allow a realistic simulation of ground resonance conditions.

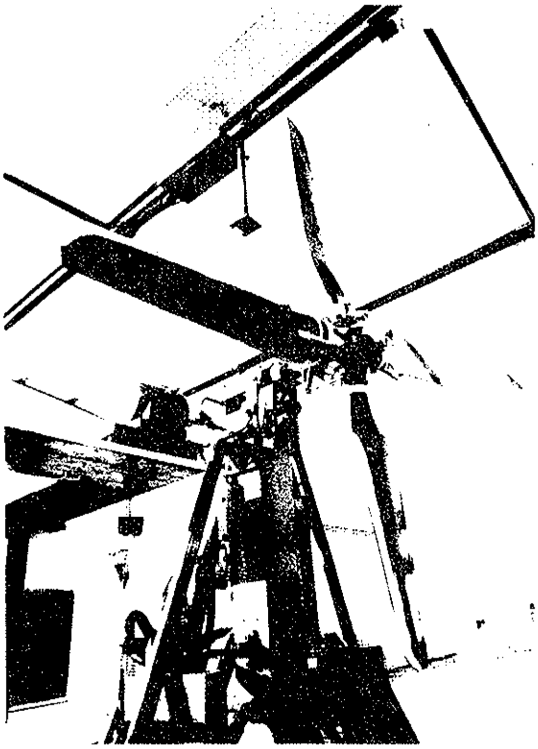


Fig. 4.1 Bearingless Tail Rotor on the Whirl Tower

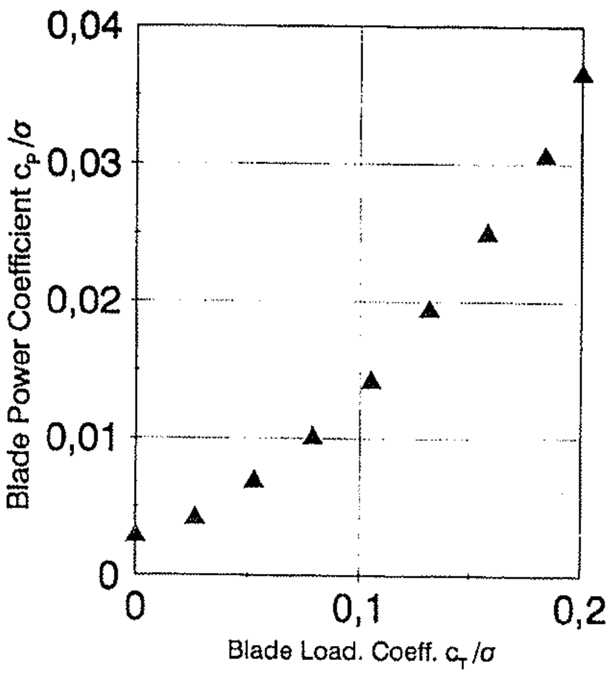
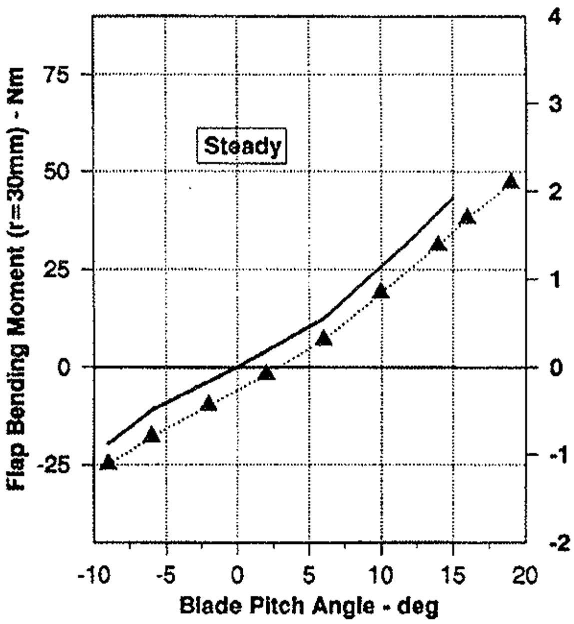


Fig. 4.2 Thrust/Power Characteristics of the Four-Bladed 1,95 m Diameter BK 117 (Growth) BTR (experimental version)

The thrust/power characteristic of an experimental version of the stiff inplane four-bladed BTR for the BK 117 growth version, measured on the test rig, is depicted in Figure 4.2. Due to power supply restrictions, the maximum thrust of about 6000 N could not be achieved.

Some typical examples of root flap bending moments, excited by rig rotation, are shown in Figure 4.3. It can be seen that a maximum dynamic flapping angle of $\Delta\beta$= 4,5° was reached, the maximum allowable flapping angle being β_{max}= 6°.



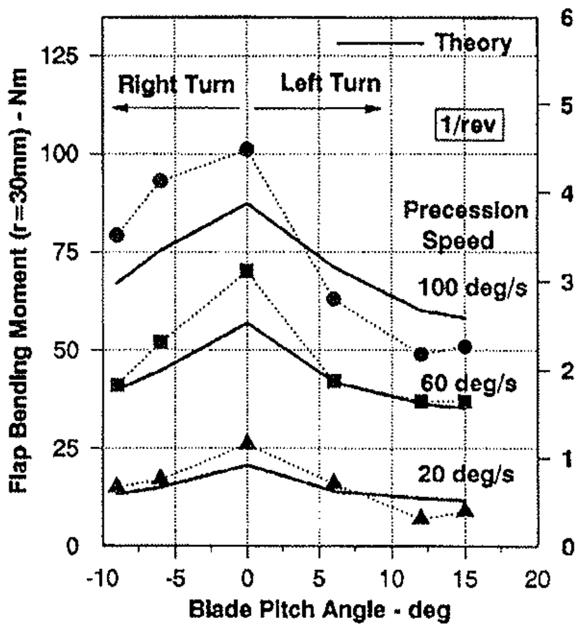


Fig. 4.3 Flap Bending Moment during Precession Tests on the Whirl Tower of the 4-Bladed Stiff Inplane BK 117 BTR

The excitation of the cyclic lead-lag rotor mode was performed by shaking the softly supported test stand in the lateral direction. The natural frequency and the appropriate modal damping were measured from the decaying chordwise bending moment after stopping the excitation. The frequency placement well above the fundamental flap mode (see Figure 3.2) and the damping ratio, which are shown in Figure 4.4 versus blade pitch angle, give an indication of the rotor system's flap-lag stability margin.

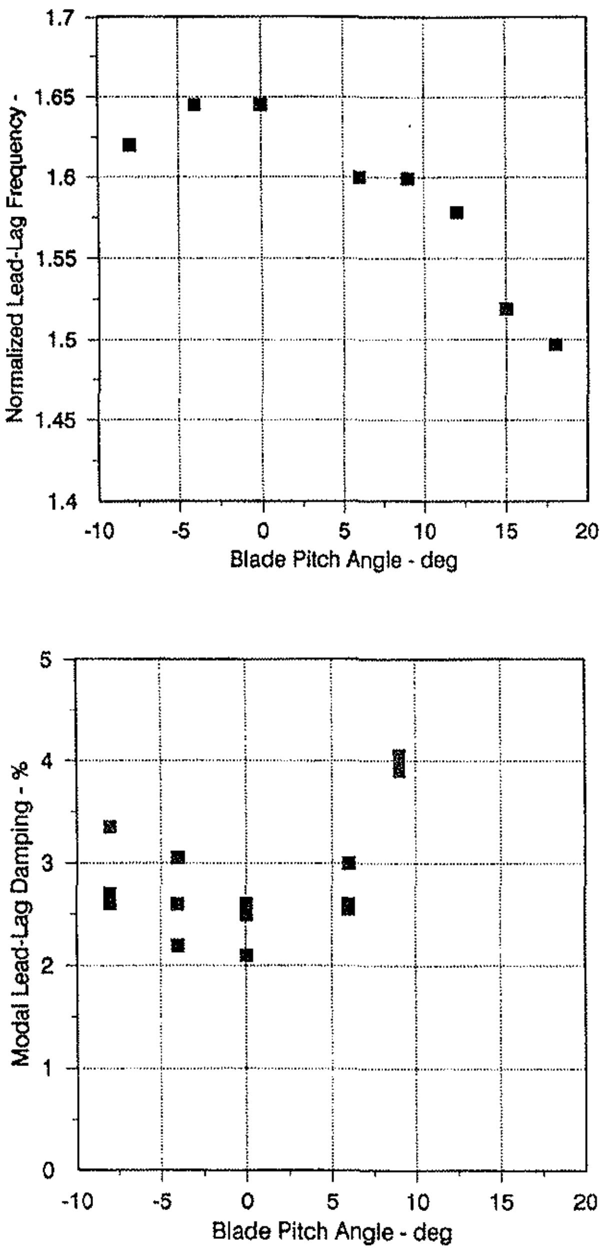


Fig. 4.4 Lead-Lag Mode Frequency and Damping of the 4-Bladed Stiff Inplane BK 117 (Growth) BTR at Nominal Rotor Speed

4.2 Flight Test

The soft inplane system shown in Figure 3.14 has been demonstrated on a BK 117 aircraft. The dynamic flap and lead-lag bending moments, measured during the flight tests, led to acceptable loads and strain levels. This is demonstrated with respect to the blade root in Figure 4.5 for horizontal flight conditions. Figure 4.6 summarizes the maximum loads and strains in the flapping flexure for different test conditions.

Component testing, whirl tower evaluation, and flight test demonstration provided a comprehensive data base for the design of all subsequent BTR systems.

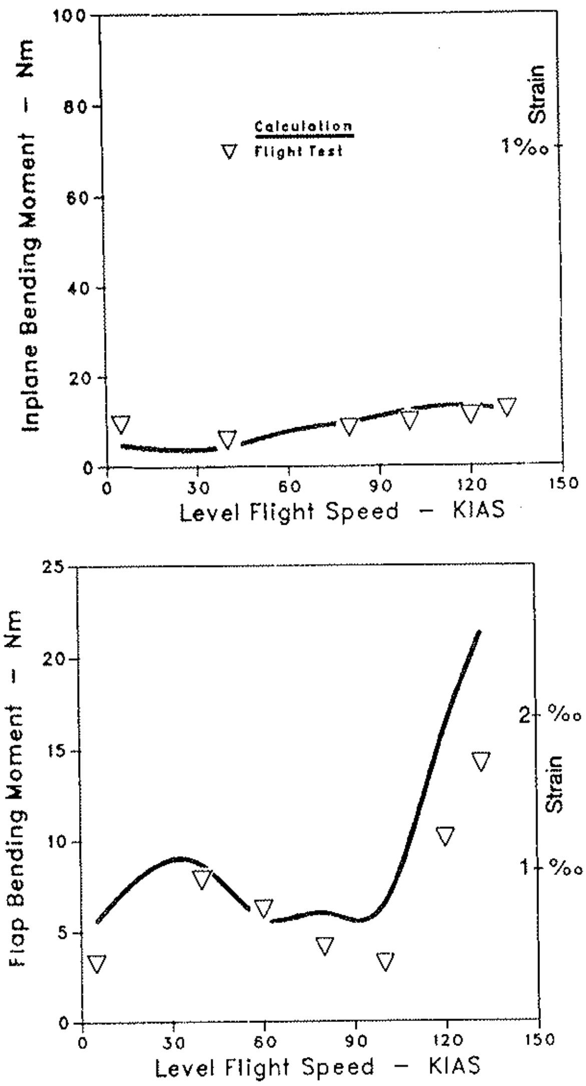


Fig. 4.5 Dynamic Flap and Lead Lag Bending Moment at the Blade Root of the 4-Bladed Soft Inplane BK 117 BTR

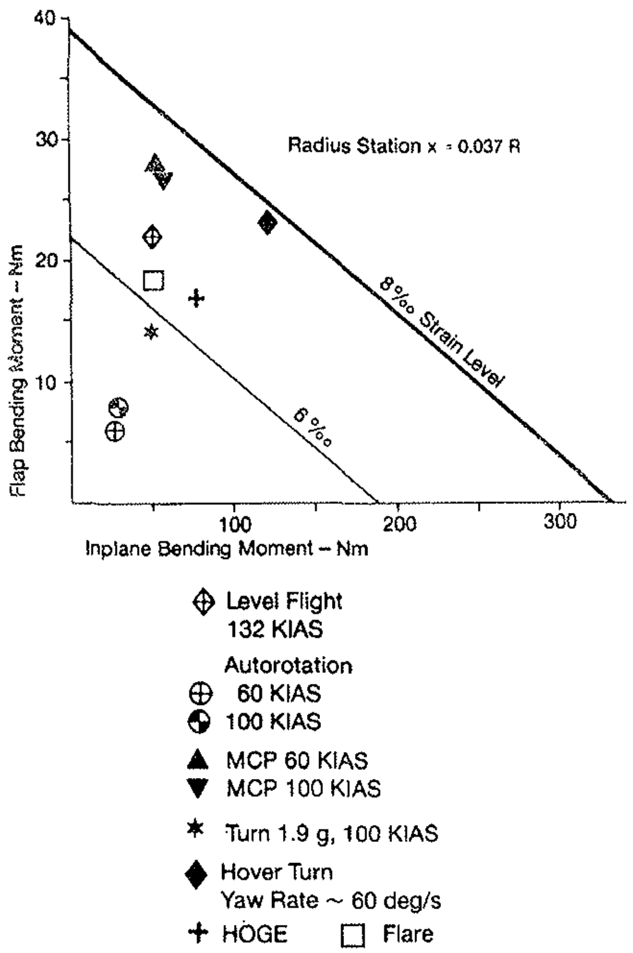


Fig. 4.6 Strain Level in the Flapping Flexure of the 4-Bladed Soft Inplane BK 117 BTR

5. Technological Criteria

Technological criteria as weight, cost, maintenance, reliability, vulnerability, and damage aspects play an important role in the assessment of the applicability of a T/R system as they strongly influence economic and safety areas.

5.1 Weight

The application of advanced composite materials having higher ratios between endurable strains and specific mass leads in principle to substantial weight savings. This has been demonstrated at MBB through all bearingless tail rotor developments during the past years. A statistic tail rotor weight comparison versus the helicopter's take-off mass is illustrated in Figure 5.1. As it can be seen in this figure, BTR systems show weight savings up to 30 to 50 % when compared to conventional articulated systems. As a further beneficial effect, weight reduction on a tail rotor - due to its far aft position - also influences the helicopter's C.G. situation quite substantially. Since "aft - C.G." problems have been encountered during the development of nearly all helicopters (and will continue to do so!), weight saving at the tail is of twofold advantage.

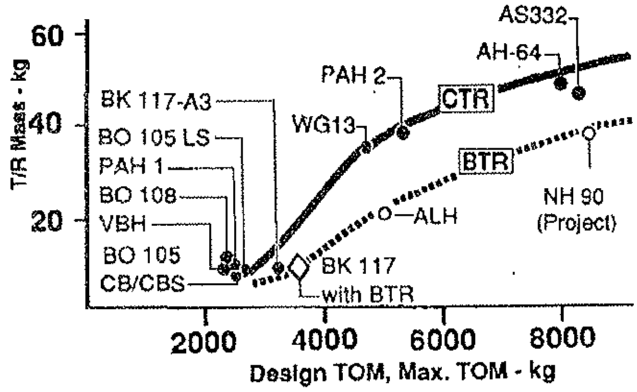


Fig. 5.1 Tail Rotor Weight Trends

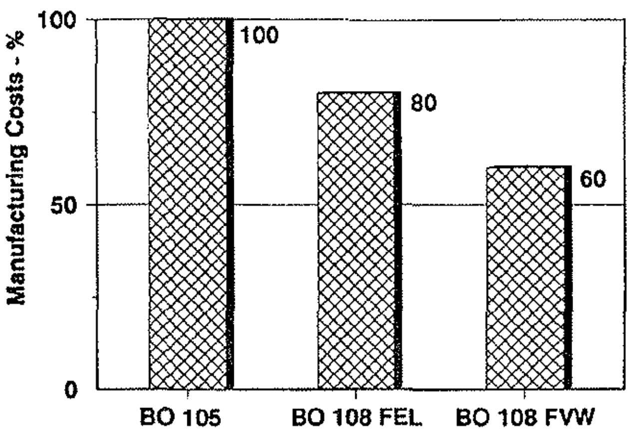


Fig. 5.2 Manufacturing Costs of MBB's 2-Bladed T/R's
FEL: With elastomeric flap and pitch bearings
FVW: With elastomeric flap bearings and flexbeam

5.2 Manufacturing Costs

Compared to metal designs, composite systems allow for larger sub-structures with fewer parts and lower tolerance requirements which reduce the manufacturing costs considerably. The composite structures are simple designs and nearly all parts can be manufactured in house. The number of connection parts and fits is low. The materials applied warrant good availability. A comparison of the manufacturing costs of three different 2-bladed T/R's (see Figure 5.2) illustrates the advantage of the bearingless version.

5.3 Maintenance and Operating Costs

The relevant drivers with respect to maintenance efforts and operating costs are wearing parts as bearings and joints and all life time critical components. Replacing time change items by parts, designed to infinite life and on-condition maintenance, reduces the operation costs considerably. Maintenance can be carried out everywhere through a comfortable access to all relevant components, and the modal architecture allows an easy exchange of components.

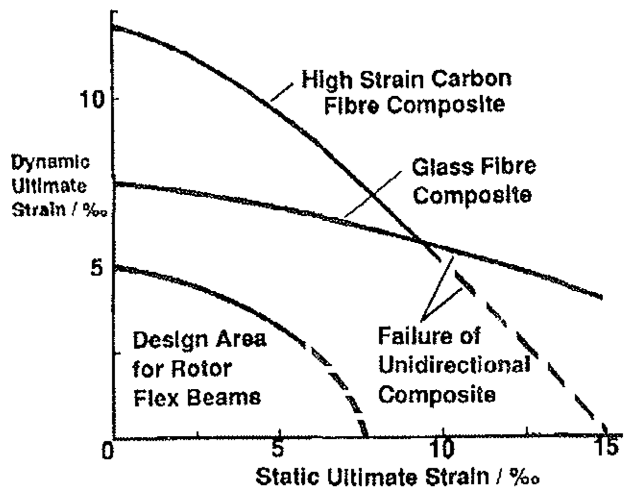


Fig. 5.3 Margin Between Design Area and Failure Limits of Rotor Flexbeams

5.4 Reliability

Apart from the improvements in maintenance costs, composite designs, significantly contribute to the systems' reliability due to their higher margins between design values and failure limits (Figure 5.3).

This is further amplified by several beneficial particularities: The composite materials imply positive damage tolerance characteristics, allowing for a safe crack growth. Relevant components are fail safe constructions, realized by redundant structures. Due to the material's low susceptibility to corrosion in general, and to fretting corrosion in particular, a high resistance against humid, saliferous and dusty atmosphere has been achieved.

5.5 Vulnerability

When considering the BTR's vulnerability with respect to damages by exterior objects, one has to distinguish between its different components as the aerodynamic section of the blades, the areas of load transmission with shaft, flexbeam, and hub, and the control system with control rods and cuff.

The composite parts blades and cuff are uncritical as the dimensions of the load-carrying structures are relatively large and even in the flexbeam the stresses are low, and the growth tendency of potential cracks is marginal. In addition, blade and cuff are designed in a way that the torsional moment can be transmitted even after larger damages.

6.Technical Potential for further Development

The BTR concepts and experimental versions which are discussed in this paper, imply pronounced potential for further development. This relates both to the pure structural part and to the aerodynamic blade section. As an example for structural improvements, reducing the BTR's life cycle costs, Figure 6.1 shows a design study of a full composite cuff support structure of infinite life, replacing the common elastomeric snubber bearings. For series production tail rotors a further important step towards the reduction of manufacturing costs will be the mechanization of manufacturing processes for relevant T/R components.

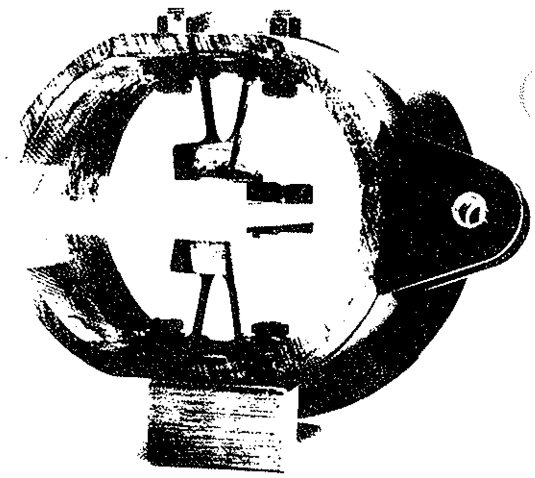


Fig. 6.1 Composite Cuff Support Structure

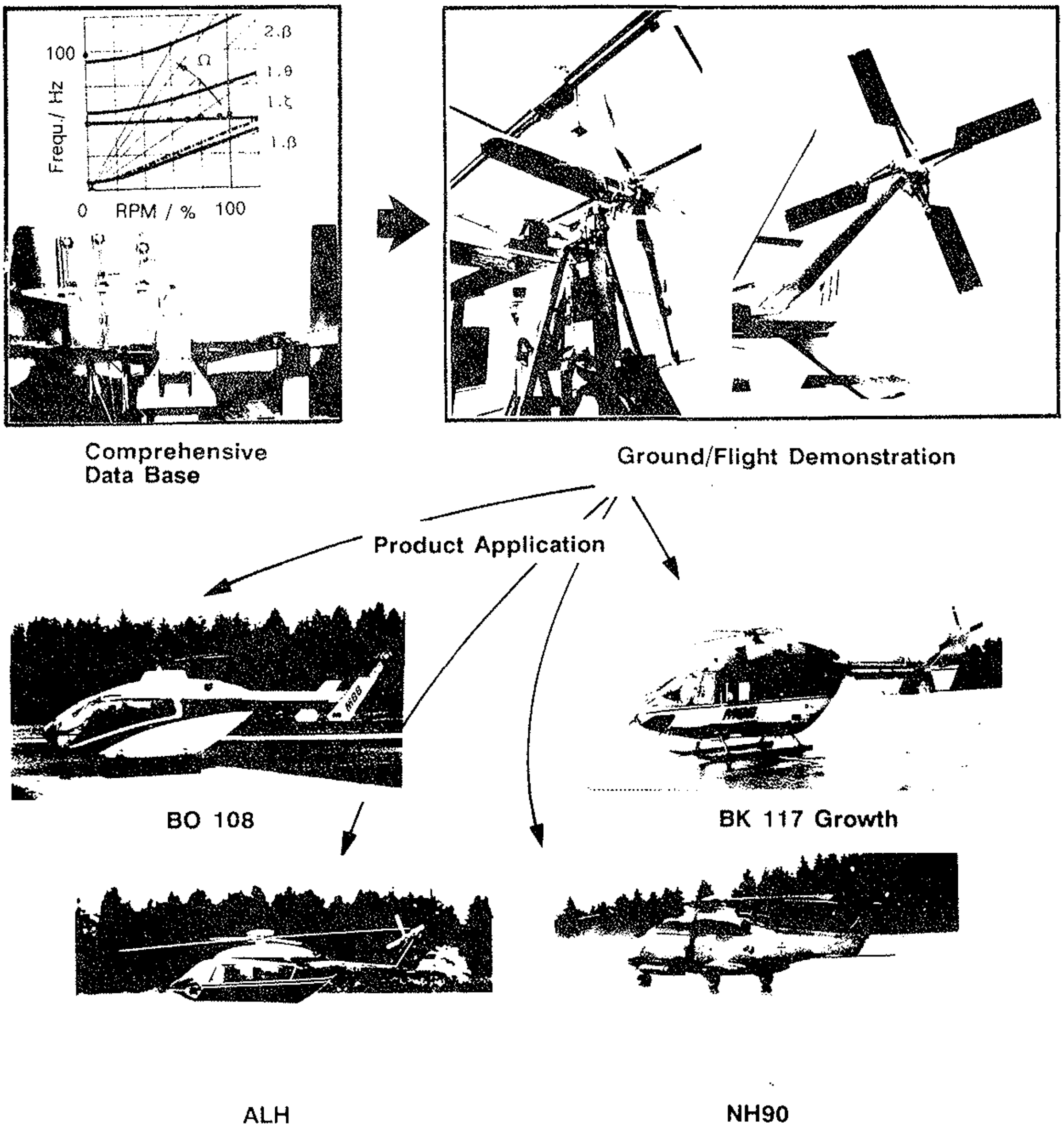


Fig. 6.2 Advanced Tail Rotor Technology - Ready for Application

The future application spectrum of the BTR supported by a comprehensive data base and an extensive ground/flight test demonstration is illustrated in Figure 6.2.

7. Conclusion

- The conventional T/R represents a highly effective concept with respect to power requirement and manoeuverability.

- The inherent problems of many conventional designs (e. g. maintenance and life time) can be overcome by introducing composite material designs.

- The BTR has significant advantages in weight, manufacturing costs, maintenance expenses, reliability, and vulnerability.

- MBB has established the data base for the BTR technology during several experimental and production programs and the technology is in hand today. It is ready for application to future products.

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