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MBB BO 108 HELICOPTER GROUND AND FLIGHT TEST EVALUATION

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Abstract

The BO 108 light twin engine helicopter was designed for integrating new technologies into the next generation of helicopters. Technology innovations include the composite bearingless main rotor system, new aerodynamic blade design, tail rotor with elastomeric bearings, composite structures, anti-resonance vibration isolation system, electrical and avionic systems, new gearbox design, and engine integration. These components were tested and evaluated separately and mounted in the prototype.

The ground test evaluation contained aeroelastic stability on the whirl tower, shake tests of the fuselage, and ground resonance tests. The main items of the flight test were air resonance stability, loads, flight performance, handling qualities, and the flight envelope survey.

Besides verifying the new technologies, the flight behaviour of the new helicopter was rated as excellent by the pilots and flight test analysis confirmed the expected performances. This paper describes the particular design features and gives an overview of the successful ground and flight testing.

1. Introduction

For several years, MBB has been engaged in development programs for advanced helicopter systems. Some of these systems, such as the bearingless main rotor (Ref. /1/, /2/) and new rotor blades were already tested on ground and in flight on a BO 105 helicopter.

The BO 108 was planned as a "new generation helicopter" with ambitious design objectives, such as superior performance and handling qualities, and significantly reduced operational costs. To provide its desired characteristics, all the new systems were integrated in the BO 108.

The first flight of the BO 108 took place on October 17th, 1988 at Ottobrunn (Figure 1). In the first test campaign, 75 flights with a total of 54 flight hours were accomplished, primarily for the investigation of systems function, dynamics, performance, handling qualities, and loads. Up to now, all flight tests were performed without SAS and vibration isolation system (ARIS) (Ref. /3/).

Figure 1 BO 108 – Prototype 1

2. Design Objectives

The BO 108 was designed as a five-seater with a design gross weight of 2350 kg. It was planned as a completely new aircraft with a number of advantages compared to the present production helicopters.

The design objectives were:

- increase of the payload/empty weight ratio by use of new subsystems and composite structures
- improved maintainability by high life-time of dynamically loaded components (3000 h MTBR)
- improvement of performance by use of new rotor blades with advanced aerodynamics and a low-drag fuselage
- comfortable pitch attitude for cruise flight
- optimized handling qualities (improved inherent stability and matched controllability)
- low vibration level by dynamic tuning and use of a vibration isolation system (ARIS)
- development following “design to cost” guidelines
- 25 % DOC reduction compared to BO 105
- certification according to FAR part 29 under IFR condition with a cost effective SAS unit

3. Helicopter Description

The result of the development work was an ambitious helicopter design with the following components (Figure 2, Ref. /4/):

- Bearingless, all-composite main rotor system with newly designed rotor blades and an optimized blade geometry
- New flat-design, two-stage main rotor transmission
- Fully integrated passive rotor isolation system
- New main hydraulic system attached to the main rotor transmission with integrated SAS input
- New tail rotor system with elastomeric bearings
- Redundant engine system
- Aerodynamically optimized airframe assembly with a high percentage of fibre components and increased interior width, cargo compartement, and fuel tank capacity.

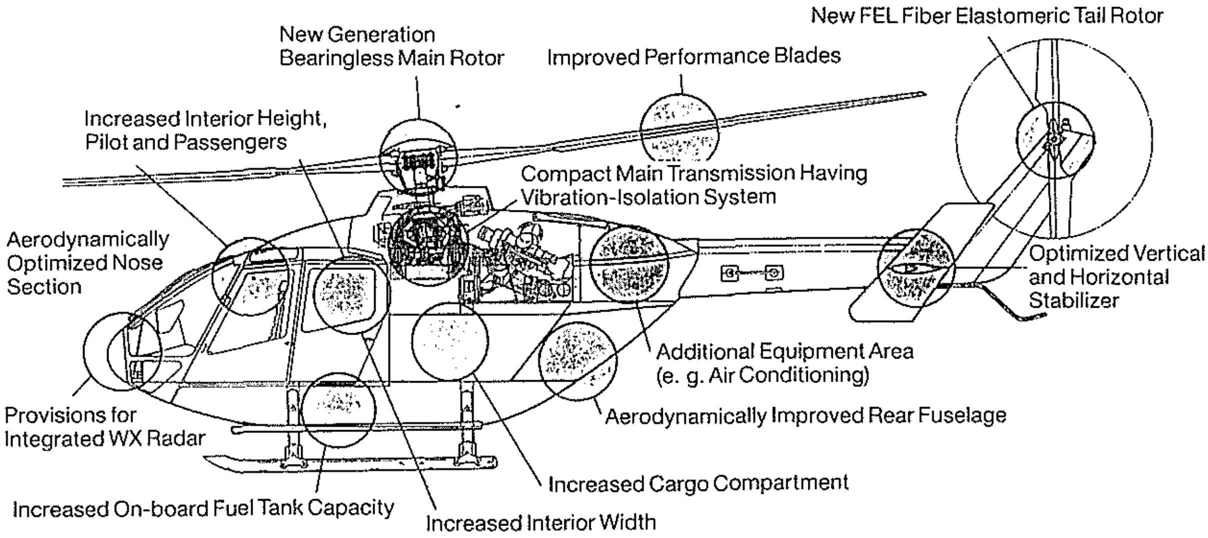

Figure 2 Improvements of the BO 108 Compared to the BO 105

The main dimensions and data are given in Figure 3 and the following Table:

Gross Weight	2350 kg
Bearingless Main Rotor	
Radius	5 m
Number of blades	4
Airfoils	DM-H4/DM-H3
Solidity	7 %
Blade planform	tapered
Equ. flapping hinge offset	9.5 %
In-plane frequency ratio	0.7
Shaft tilt (FWD)	5 deg
Engines (SL. STD)	
Standard	Allison C 20R
MCP	2 × 250 kW
TOP	2 × 311 kW
Option A	Pratt & Whitney PW 205-B/1
MCD	2 × 233 kW
TOP	2 × 288 kW
Option B	*Turbomeca TM 319*
MCP	2 × 263 kW
TOP	2 × 300 kW

Tail Rotor (see-saw)	
Radius	0.95 m
Pitch-flap coupling	45 deg
Tip speed	210 m/s
Airfoil	S 102 E
Horizontal Stabilizer	
Area	1.1 m^2
Span	2.2 m
Airfoil	GAW-1
Incidence (nose down)	1 deg
Vertical Stabilizer	
Area	0.84 m^2
Incidence	5 deg
Airfoil	V 162080
End Plate	
Area	2 × 0.65 m^2
Incidence	4 deg

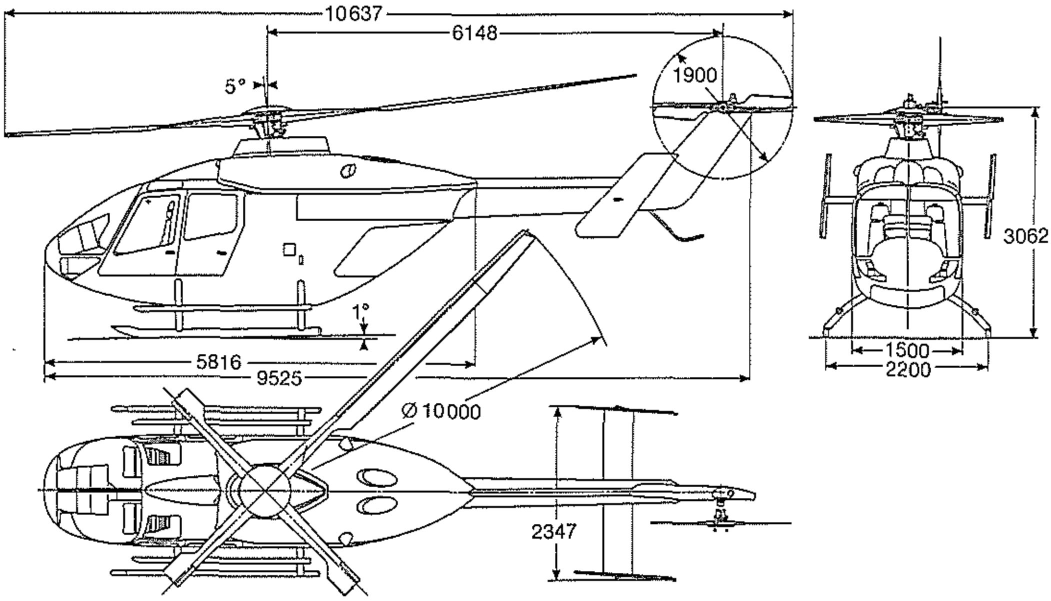

Figure 3 Three View Drawing of the BO 108

4. Dynamic and Structural Development Tests

4.1 Main Rotor Tests

The dynamic characteristics of the main rotor fundamentally influence the aeroelastic stability, loads, and vibrations as well as the handling qualities of the helicopter (Ref. /5/). Therefore, a thorough validation of the design objectives by component tests, whirl tower, and flight tests was an important step.

Structural Tests

The basic element of the bearingless rotor concept is the so-called flexbeam. Is has to carry the centrifugal loads as well as the static and dynamic bending and torsional moments. In addition, it is responsible for the tuning of the fundamental bending modes which strongly influence stability, loads, and handling qualities. Its structural design is determined by the demand for high torsional flexibility keeping the flexing element short and the structural control loads low (Ref. /6/, /7/). Figure 4 shows a picture of the flexbeam, torque tube, and damper assembly. The verification of the calculated torsional flexibility by a static component test is given in the diagram. Comprehensive bench tests of the whole blade were conducted to determine stiffness and fatigue characteristics under combined tension, bending, and torsion loads. Figure 5 gives two examples of component test arrangements.

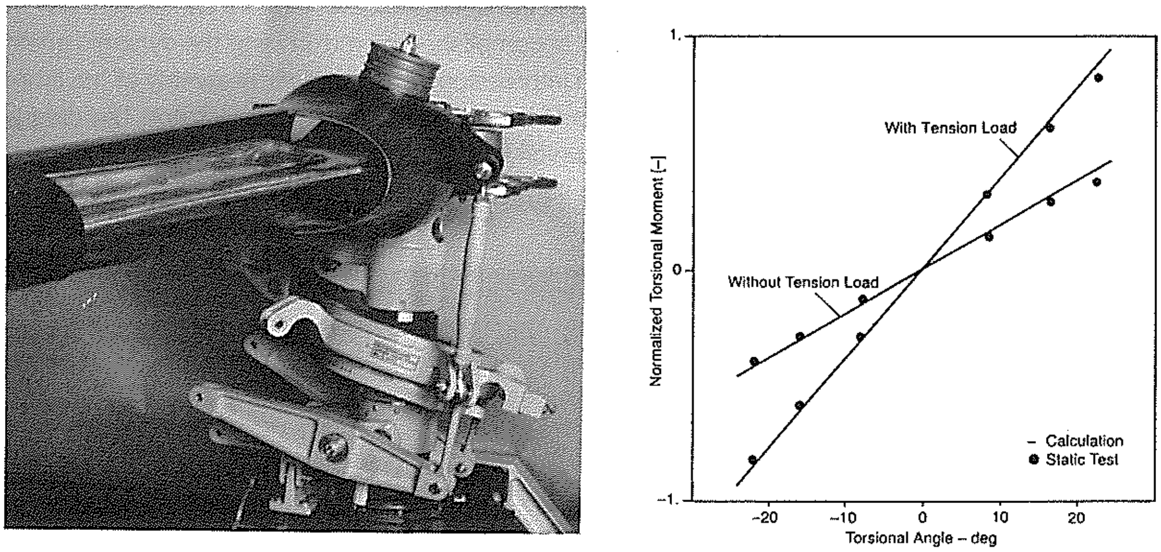

Figure 4 Flexbeam, Torque Tube, and Damper Assembly and Torsional Flexibility of the Flexbeam

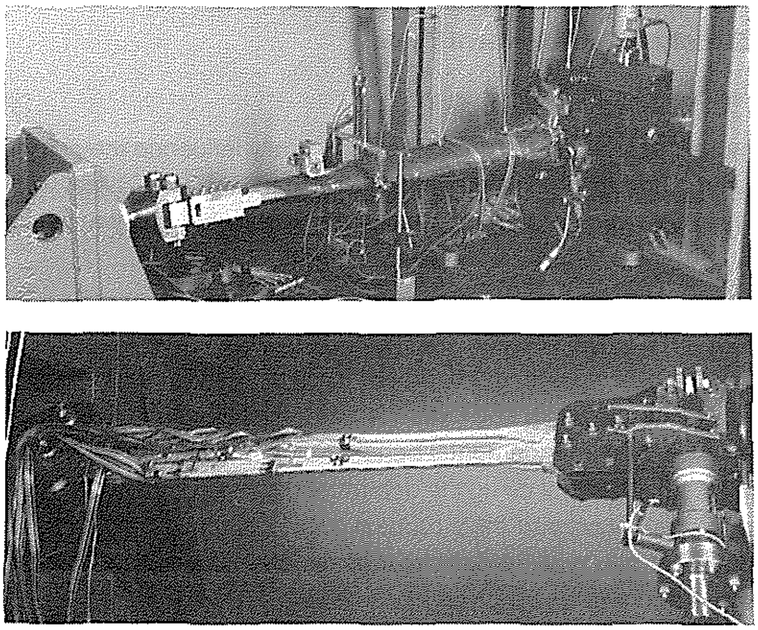

Figure 5 Torque Tube and Flexbeam Fatigue Test Setup

Elastomeric Damper Tests

A fundamental goal in the design of bearingless rotors is the optimization of inplane damping, thus avoiding aeromechanical stability problems. This was accomplished by maximizing the dynamic shear deflections of the damper elements. Figure 6 gives an impression of the damper assembly at the inboard end of the cuff and the integrated shear travel pick-up of the instrumented prototype rotor. The diagram indicates the modal damping capacity for one blade which is a highly nonlinear function of the lead-lag amplitude (see Ref. /8/).

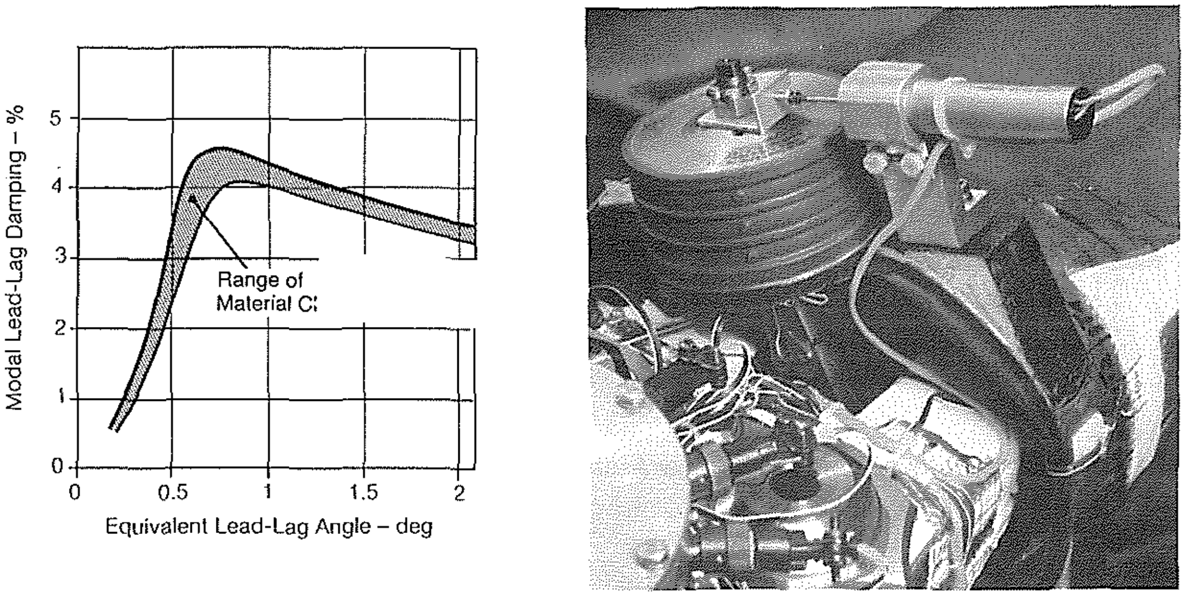

Figure 6 Modal Damping Capacity of the Elastomeric Dampers and Damper Assembly at the Cuff

4.2 Rotor System Aeroelastic Whirl Tests

Full scale rotor system whirl tests were conducted on the whirl tower as shown in Figure 7. The objectives of these tests were to verify the inplane damping and to measure the rotating blade natural frequencies as well as rotor and control loads. Two sets of dampers were selected for testing on the whirl tower. The first was an optimized damper with regard to structural damping capacity. The stiffness of the second one was higher, giving a compromise between steady damper deflection and damping efficiency. For normal operating conditions, these tests showed at least 2 percent modal damping for the most critical collective range.

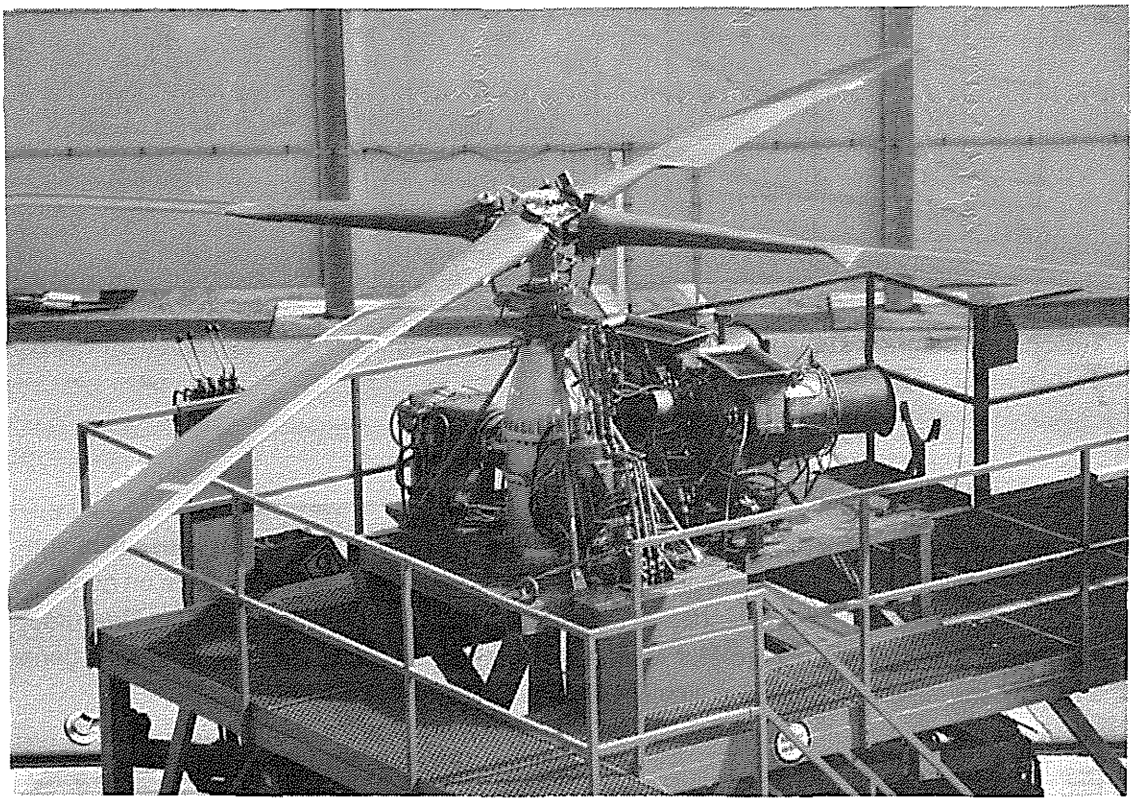

Figure 7 Full Scale Whirl Tower

High frequency cyclic booster excitation permitted the measurement of the natural bending frequencies. The resonance diagram of Figure 8 compares the test results at a collective setting of 4 degrees with a coupled calculation. There is good correlation between test and calculation.

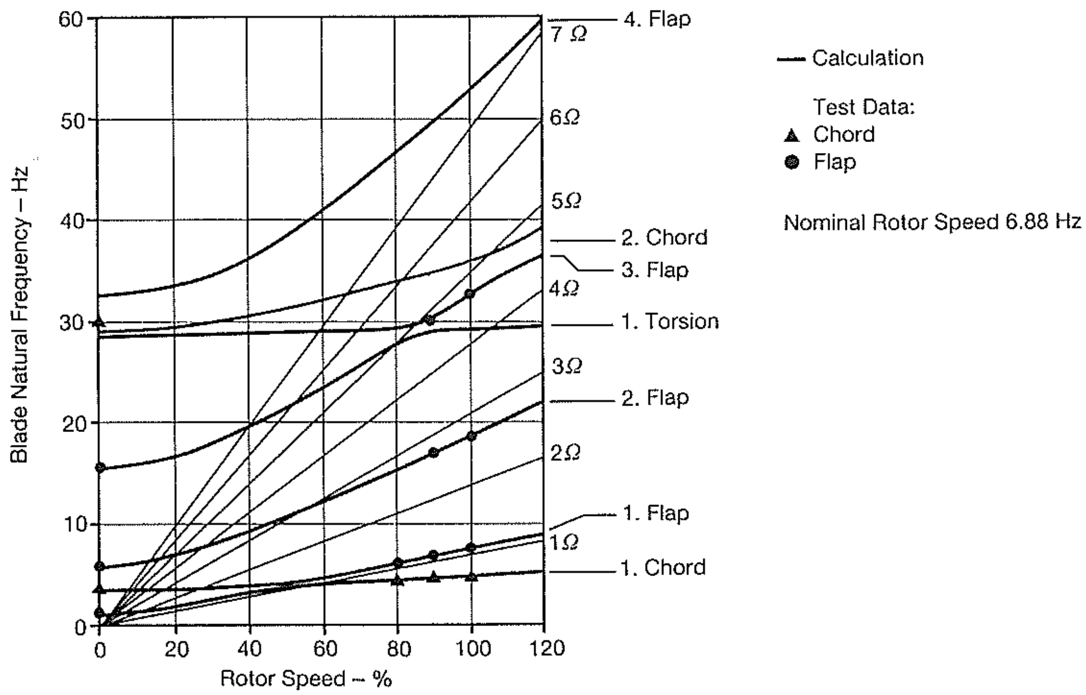

Figure 8 Resonance Diagram of the Main Rotor Blade. Coupled Calculation and Validation on the Whirl Tower.

4.3 Airframe Modal Survey Tests

Two different test configurations were used for the airframe modal survey test. At first, those fuselage modes which are relevant for ground resonance considerations were measured with skids on concrete. In a second test, the helicopter was suspended at the hub via a soft air spring, simulating a "free-free" condition. Figure 9 is a comparison of pre-test to measured natural frequencies of the aircraft. In general, most of the modes correlate well with finite element MSC NASTRAN calculations.

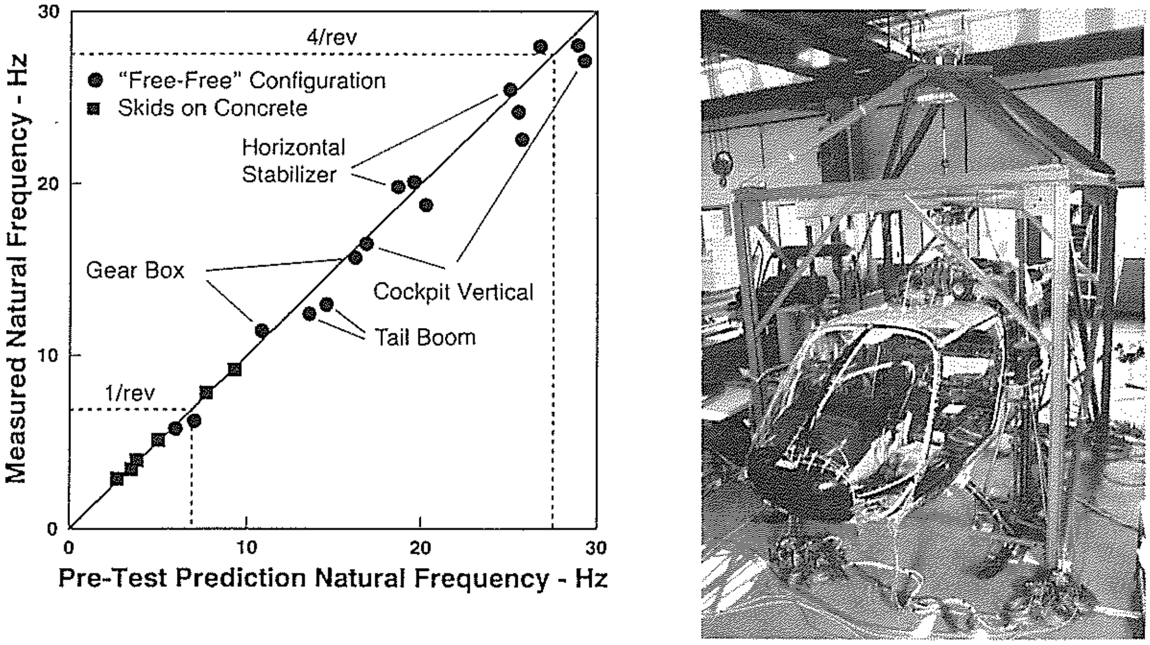

Figure 9 Modal Survey Test of the Airframe in the "Free-Free" Configuration

4.4 Validation of Ground and Air Resonance Stability

Initial pre-flight tests of the aircraft were ground resonance tests with landing gear on concrete and turf. Frequency and damping was found by analyzing the decaying lead-lag bending moment after a cyclic resonance excitation of the rotor by stick whirling. The tests were conducted up to nominal rotor speed and collective pitch settings shortly before the aircraft became airborne. Figure 10 shows the essential test results. The inherent stability of the soft-inplane rotor was verified by these tests which showed a system damping of at least 2 percent critical damping at medium lead-lag amplitude measured in the rotating frame.

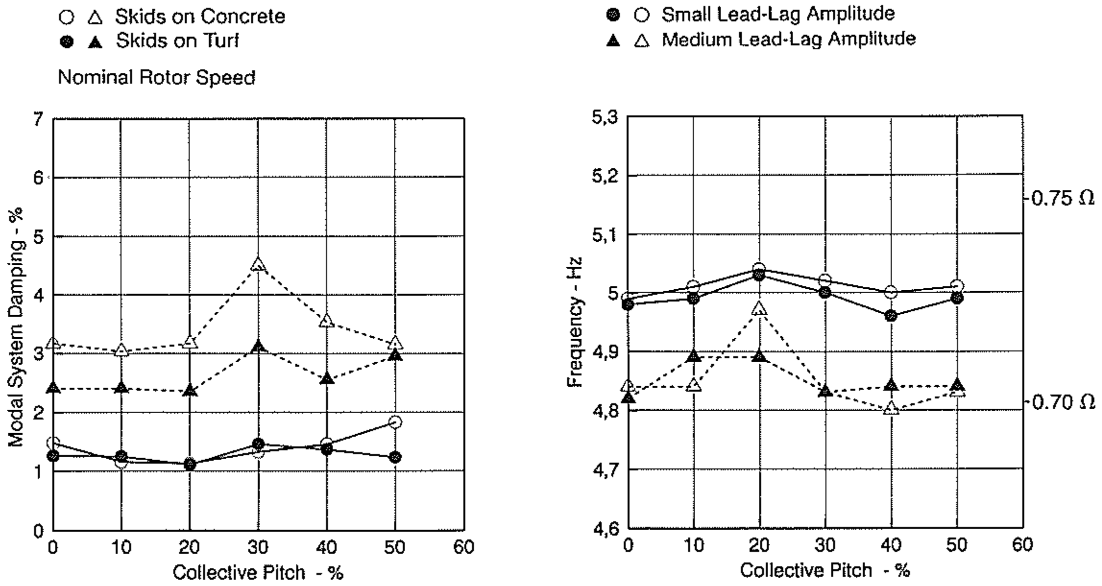

Figure 10 Ground Resonance Test Results. System Damping and Frequency Measured in the Rotating Frame.

The aeromechanical stability in the air was proven with the same method. Figure 11 shows the test results during level flight up to 130 kts (IAS). Again, no indications of resonance problems were found. The system damping was as high as on the ground (Ref. /9/).

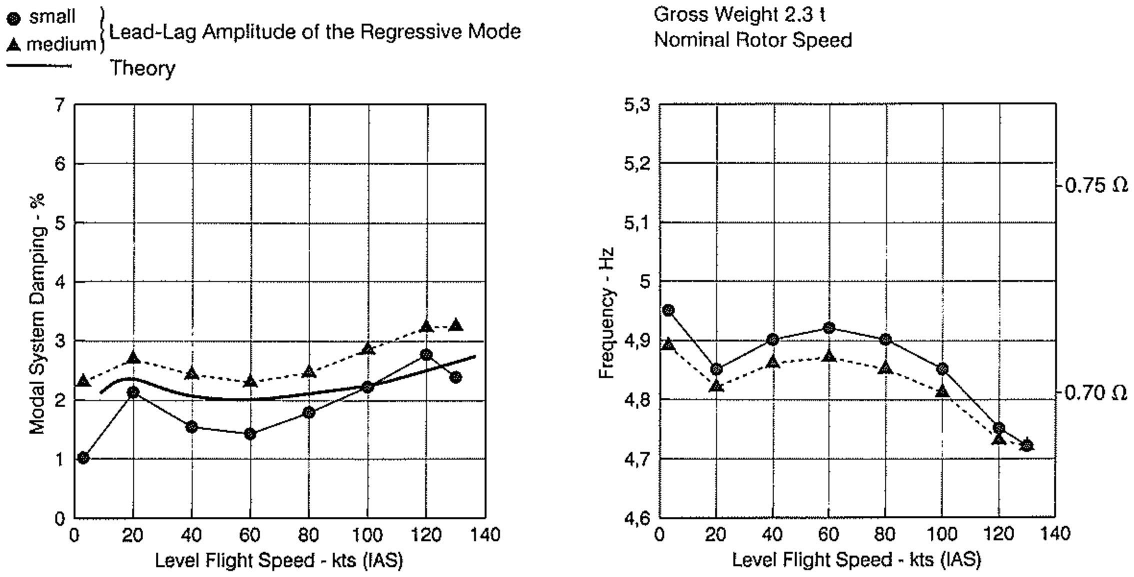

Figure 11 Air Resonance Stability Test Results. System Damping and Frequency Measured in the Rotating Frame.

5. Aerodynamics and Performance

5.1 Aerodynamics

Rotor Aerodynamics

New airfoils for the blade tip and the inner blade section, designated DM-H3Tb and DM-H4Tb, were developed in cooperation with the DLR (Ref. /10/, /11/). These airfoils provided a general improvement of the transonic characteristics and a significant drag reduction in comparison to the NACA 23012. With the 9 % thick DM-H3Tb, the Mach tuck boundary could be shifted forward by about 50 km/h (Ref. /10/, /11/, /12/, /13/).

Further improvements in power required and general aerodynamic behaviour of the rotor were obtained due to the trapezoidal planform of the outer blade section (from 80 % radius) and the blade tip shape.

Model rotor tests – For verification of the predicted aerodynamic and dynamic characteristics of the new rotor blade design, a model rotor of 4 m diameter, fitted with BO 105 hub, was built and tested in the 8 x 6 m test section of the Dutch German Wind Tunnel (DNW) (Figure 12, left hand side). For comparison, test data from a 4 m model of the standard BO 105 rotor were available (Ref. /12/).

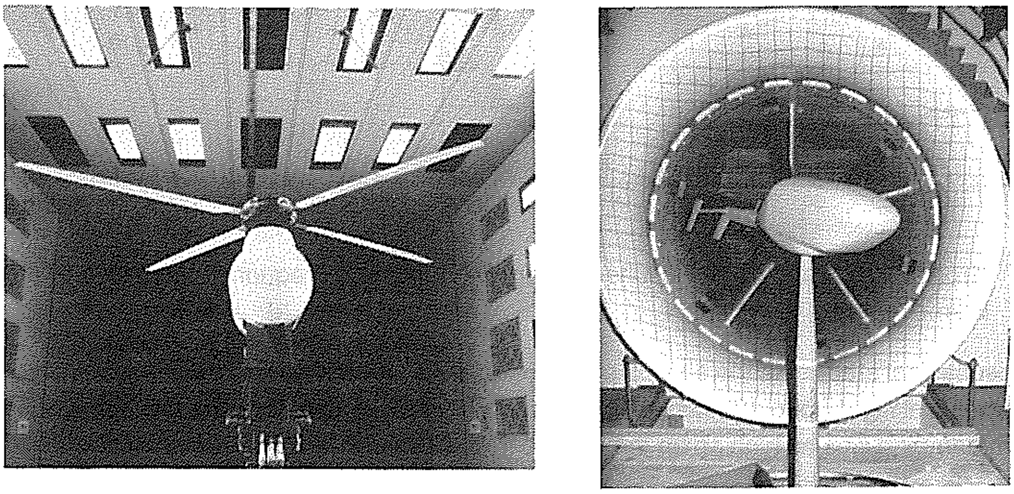

Figure 12 Model Rotor in the DNW Wind Tunnel and Optimization of Fuselage Shape

Whirl tower tests – Full scale tests were performed with the advanced rotor blades in combination with a BO 105 hub and with the BO 108 system on the MBB whirl tower (see Figure 7), showing similar performance results as achieved during the model rotor tests.

Airframe Aerodynamics

During the BO 108 aerodynamic layout, specific attention was payed to minimize the parasite drag and to reduce adverse interference effects. Fuselage shape and tail surfaces were optimized by wind tunnel testing with a ⅕ scale model (Figure 12, right hand side).

A significant drag reduction, compared to the BO 105, was achieved by the new aft-body shape. Large effort was also made to optimize the "upper cowling area", (i. e. engine cowling, air intakes, exhaust ducts, mast fairing, hub cap, and rotor blade inboard section (Figure 13). Low drag as well as good flow quality behind these parts was obtained, leading also to high efficiency of the tail surfaces. The low level of flow disturbance is one reason for the absence of tail shake or other adverse interference effects, as notified from the very beginning of the BO 108 flight testing.

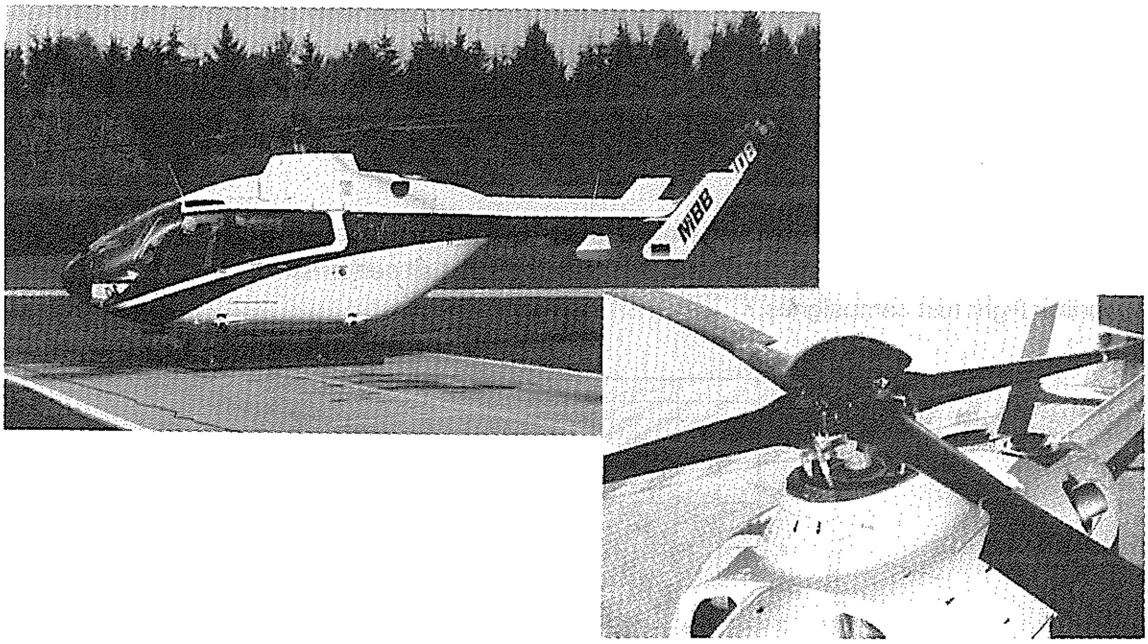

Figure 13 Aerodynamically Optimized Airframe and Upper Cowling Area

5.2 Performance

Hover in and out of ground effect – A significant improvement of the HOGE power required was determined during the flight tests in comparison to the BO 105 (Figure 14). The normalized power vs mass curve shows a power reduction between 8 % and 9 %, which corresponds to the design targets. For HIGE condition, the reduction in power required is slightly less (between 7 % and 8 %) than for HOGE. This is due to an aerodynamic effect of the tapered blade in ground effect (Ref. /12/).

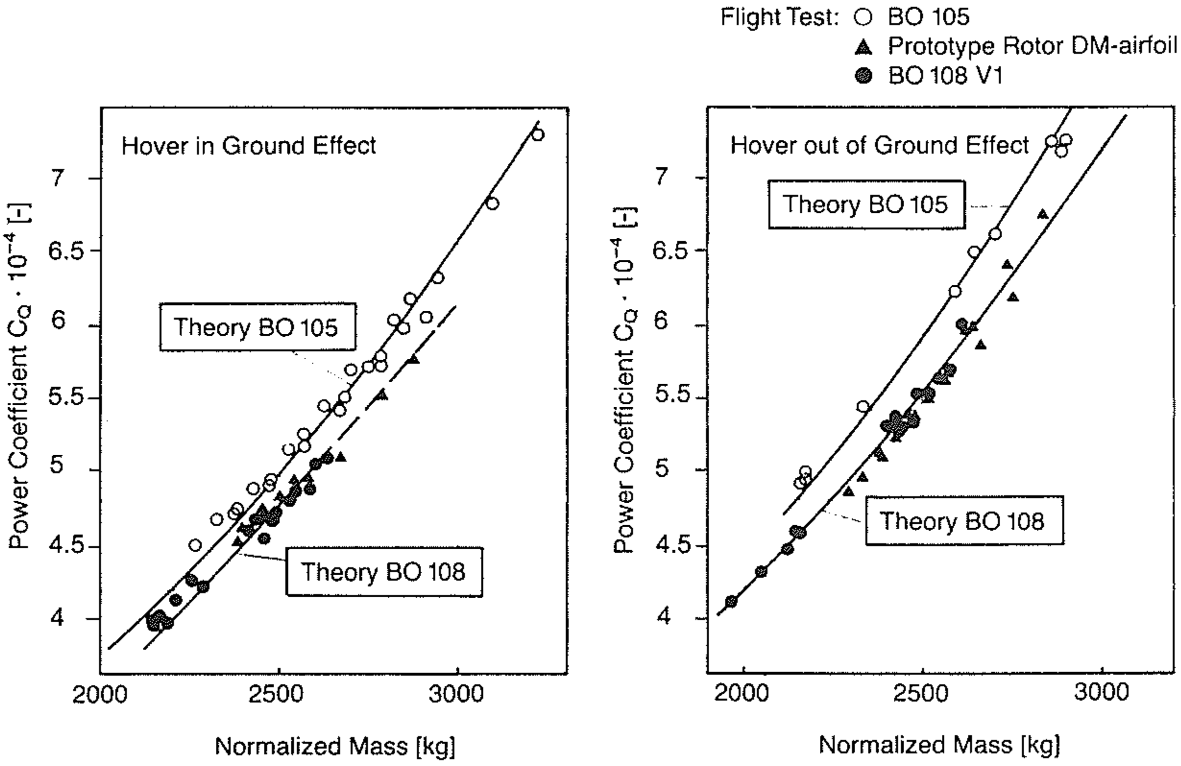

Figure 14 Hover Performance

Forward flight – The BO 108 power required in forward flight is reasonably low due to the improved rotor aerodynamics and the reduction in parasite drag. The maximum horizontal flight speed of 274 km/h at 5000 ft altitude, achieved up to now, is in good agreement with the predictions (Figure 15). At the power minimum, which indicates the capabilities of maximum rate of climb and endurance, the measured power required is less than predicted.

For the time being, the full performance envelope of the BO 108 is not yet investigated. However, on the basis of the flight tests conducted up to now, it is expected that all performance objectives will be met during further flight test campaignes.

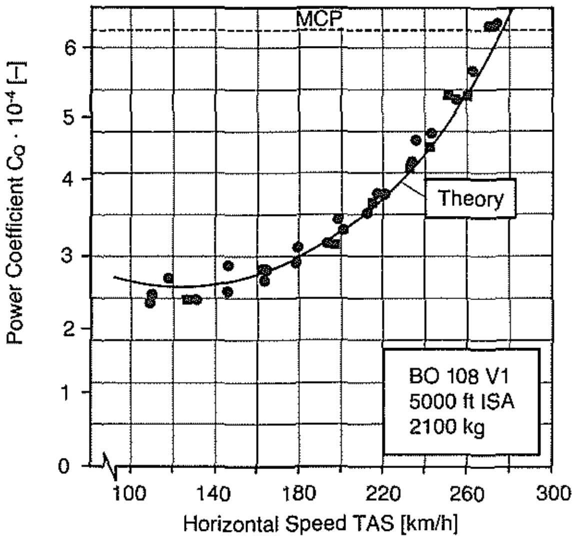

Figure 15 Power Required in Level Flight

5.3 Flight Envelope Tested

An n_z-v envelope was tested within a preliminary defined boundary as shown in Figure 16.

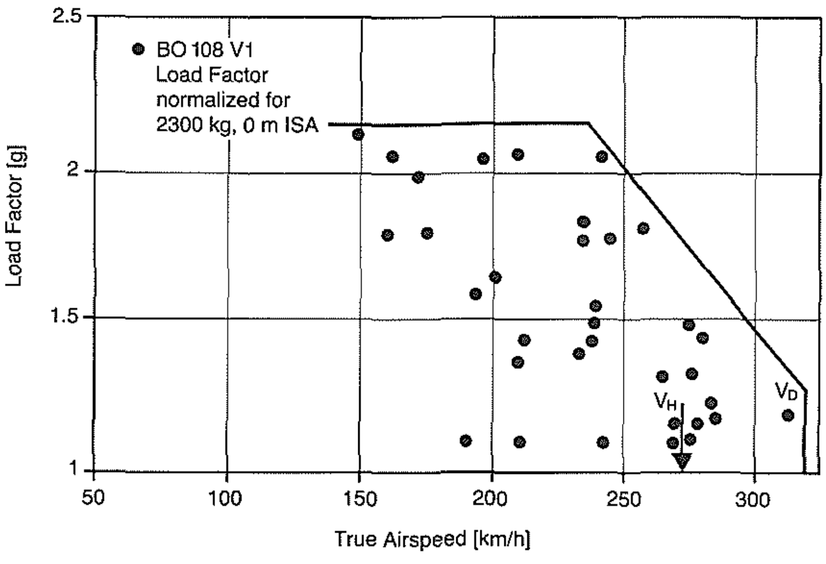

Figure 16 Flight Envelope Tested

Horizontal flight speeds up to 274 km/h and maximum flight speeds of 310 km/h in dive were flown. Bank turns up to 2 g's normal load factor were achieved. The flight tests included also maximum climb tests, autorotation flights, sideward and rearward flights, and maximum yaw turns. High altitude flights were conducted up to 20.000 ft.

The general flight behaviour was assessed by the pilots and no degraded handling qualities were noticed within this flight envelope. An investigation of the maximum achievable flight envelope will be done during the next flight test phase.

6. Handling Qualities

6.1 Control Positions

Flight tests were performed up to v_H. Within the preliminary v_{ne} boundary, maximum speeds up to 168 kts were reached in dive. During the hover and low speed tests, quartering flights in any direction up to 30 kts were performed. The theoretical extrapolation of the flight test results for high altitude and extreme c.g. positions showed the required cyclic trim positions well within the designed control range.

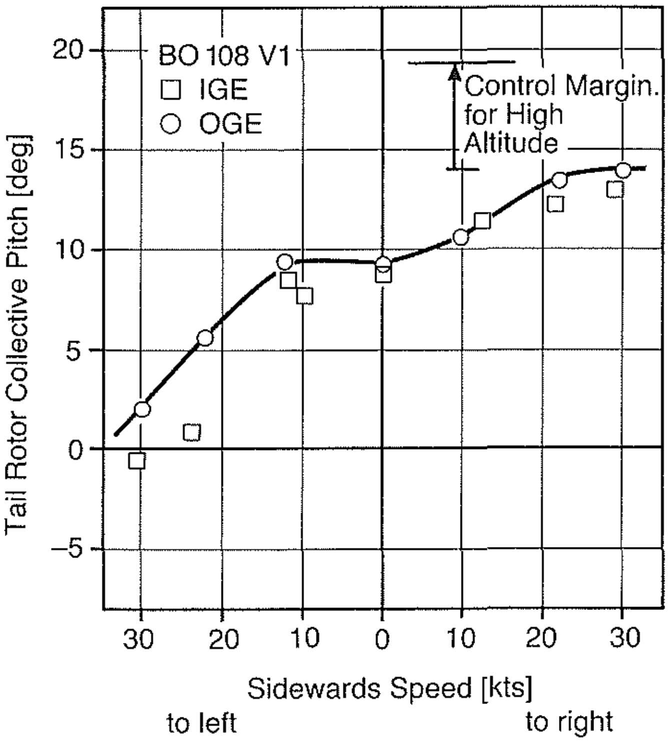

Figure 17 Tail Rotor Control Positions

The tail rotor pitch range was also evaluated during sideward flights, maximum climb, and autorotational flight conditions. Figure 17 shows that up to 30 kts sideward flight in both directions, sufficient tail rotor control margin exists.

6.2 Pitch Attitude in Level Flight

One of the design objectives for the BO 108 was an optimized fuselage attitude for a comfortable cruise flight. As shown in Figure 18 at cruise and v_H speeds, the fuselage stays almost at level attitude. The objective was achieved by tilting the rotor shaft 5° forward, minimized airframe drag, and reduced rotor stiffness.

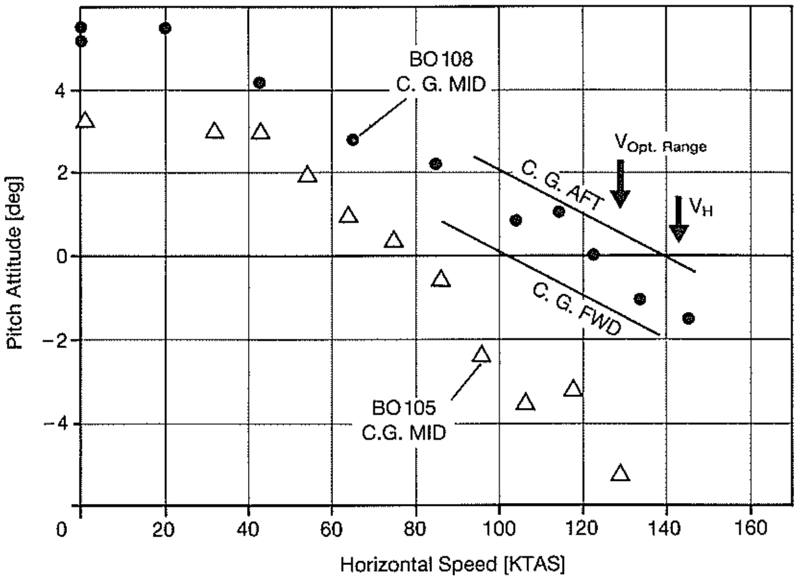

Figure 18 Pitch Attitude in Level Flight

6.3 Static Longitudinal Stability

In the FAR requirements, a positive slope for longitudinal stick position vs speed is demanded up to 1.1 v_H. Airfoil design parameters (low pitching moments, high Mach tuck boundaries) and increased torsional blade stiffness were applied in the rotor design to improve static stability up to high advancing blade tip Mach numbers. A more detailed description of the design parameters and the development of the DM-H-airfoils may be found in References /10/, /11/, /12/.

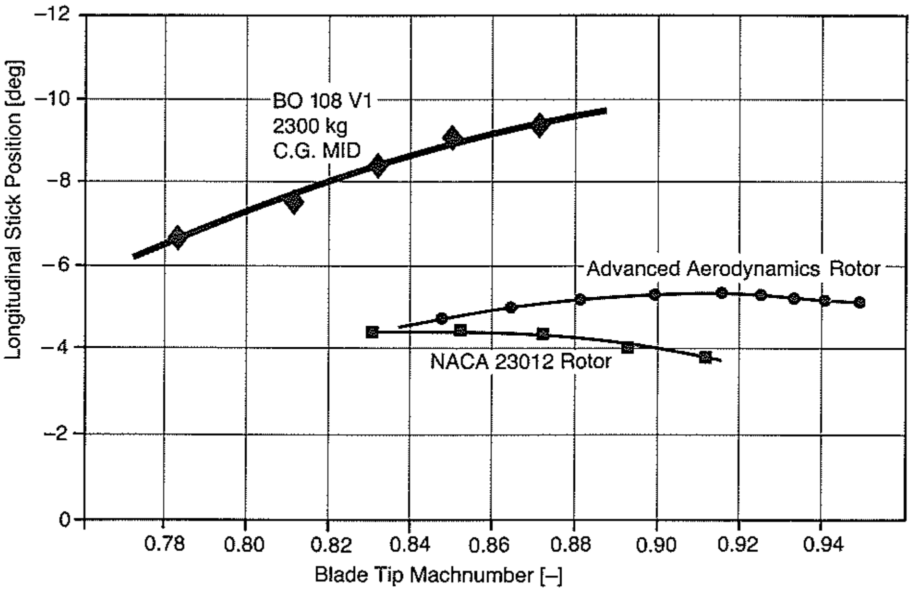

Figure 19 Static Longitudinal Stability

In Figure 19, flight test results of the different development phases are presented. The improvements of the new aerodynamic blade design was demonstrated both on an advanced prototype rotor and on the BO 108. Satisfactory stick stability is seen up to advancing blade tip Mach numbers of 0.95.

6.4 Dynamic Stability and IFR Requirements

The improvement of the inherent dynamic stability compared to the BO 105 was one of the design goals. The reduction of the hinge offset and the increase of the horizontal stabilizer area improved the stability noticeably (Figure 20).

Figure 20 shows the phugoid and dutch roll eigenvalues of the BO 108 from flight test data. Early in the design effort, it was aspired to fulfil dual pilot IFR requirements of FAR part 29 for a limited flight envelope without SAS. However, the requirements were tightened during the development phase as shown in Figure 20. With the inherent unstable phugoid mode of a helicopter, this new boundary necessitates an SAS about the pitch axis anyhow. But also for the dutch roll mode, the fulfilment of the new requirement by an aerodynamic solution would have imposed too many compromises on the overall design.

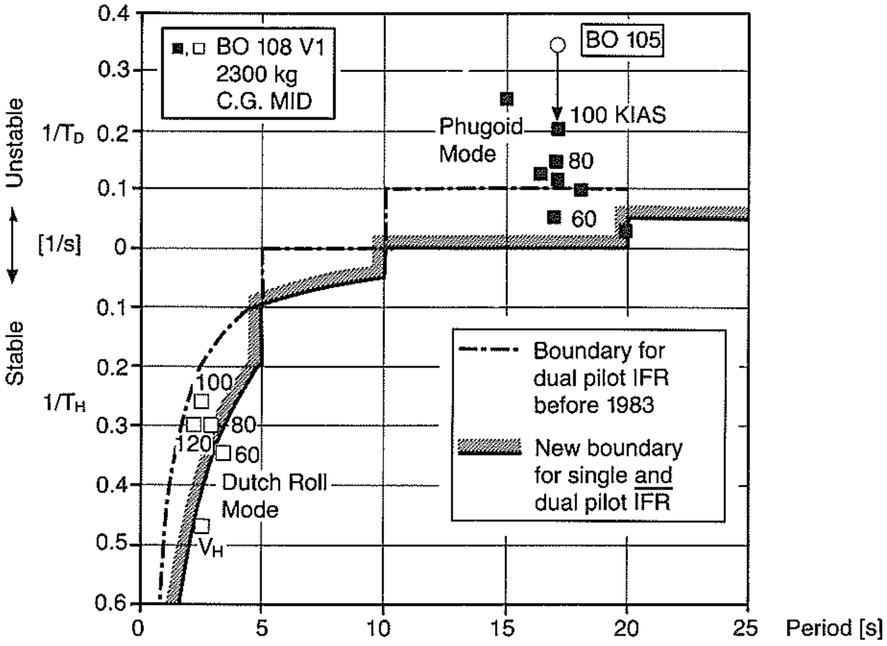

Figure 20 Dynamic Stability and IFR Requirements

The present stability level of the BO 108 was assessed to be excellent for VFR condition. For IFR condition a cost effective SAS solution is expected.

6.5 Control Response

Control response characteristics are fundamental in helicopter handling qualities design (Ref. /14/, /15/, /16/, /17/). By lowering the equivalent hinge offset of the BO 108 bearingless main rotor (≈ 9.5 %) in comparison to the BO 105 production helicopter, a slight reduction in control power and damping was achieved. However, by increasing the control gearing in the longitudinal and lateral direction, control power was held at a level similar to the BO 105, with a slightly higher rate response per stick input (Figure 21). During the flight tests, this type of control response was rated excellent by all the pilots. It is obvious from these results that the control characteristics of the BO 108 are well tailored allowing also any tuning of damping by a rate feedback system even up to extreme agility demands.

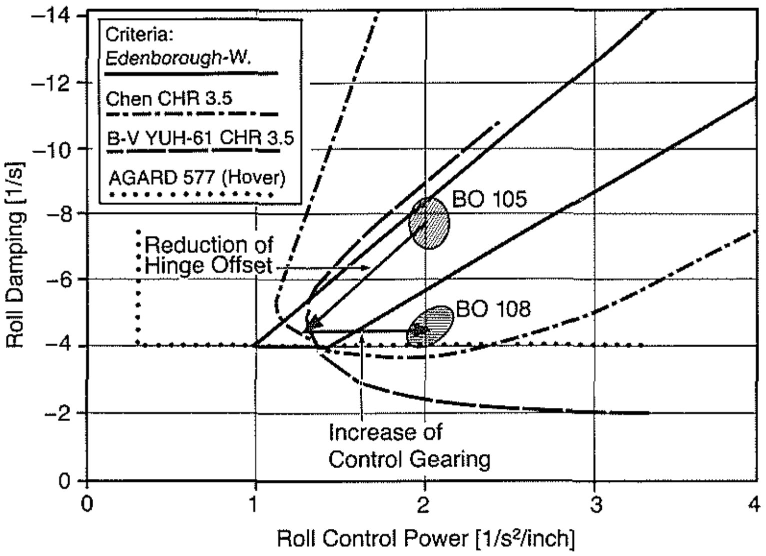

Figure 21 Controllability Diagram

The control characteristics were further validated by a simplified method determining equivalent bandwidth and time delay parameters, as suggested by References /18/, /19/. Figure 22 (left hand side) exemplarily shows a step response about the roll axis at 60 kts (Point A). The results from various other flight cases (hover to 100 kts) in terms of equivalent time delay and bandwidth, as extracted from flight tests, are collected in Figure 22 (right hand side). All cases clearly fulfil the level 1 requirement.

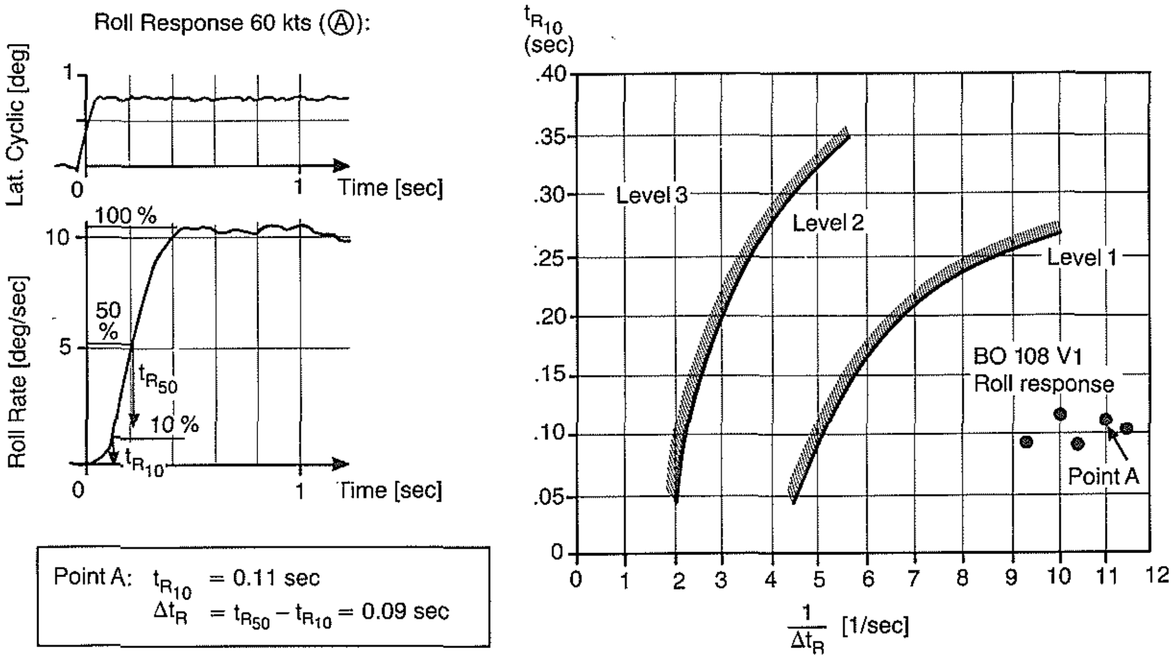

Figure 22 Approximation for Bandwidth from Time Response

7. Loads

7.1 Booster Loads

Figure 23 shows the mean values of the booster loads in level flight condition. These rather low cyclic booster loads result mainly from the torsional soft flexbeam design.

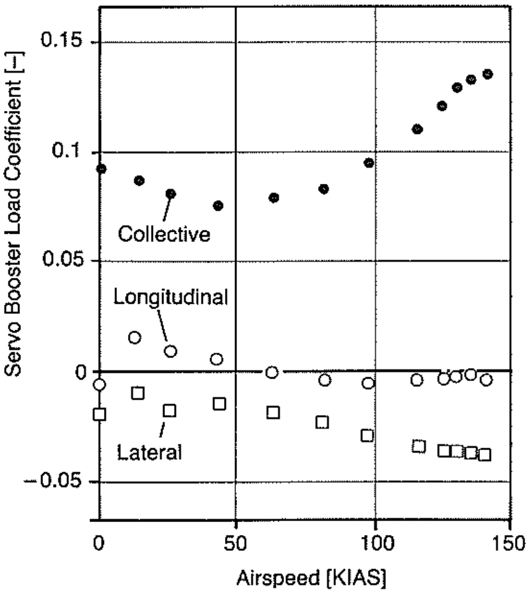

Figure 23 Booster Loads in Level Flight Condition

7.2 Rotor Loads

The inplane bending moment is one of the most important load characteristic in the rotating frame. Figure 24 presents the mean values and the amplitudes of the chordwise bending moment during level flight and turns at 120 KIAS up to 1.6 g. The strain gauges are positioned on the flexbeam at radius station 0.09R (0.45 m). The load level is far below the endurance limits of the prototype rotor, confirming the proper tuning of the fundamental inplane bending mode.

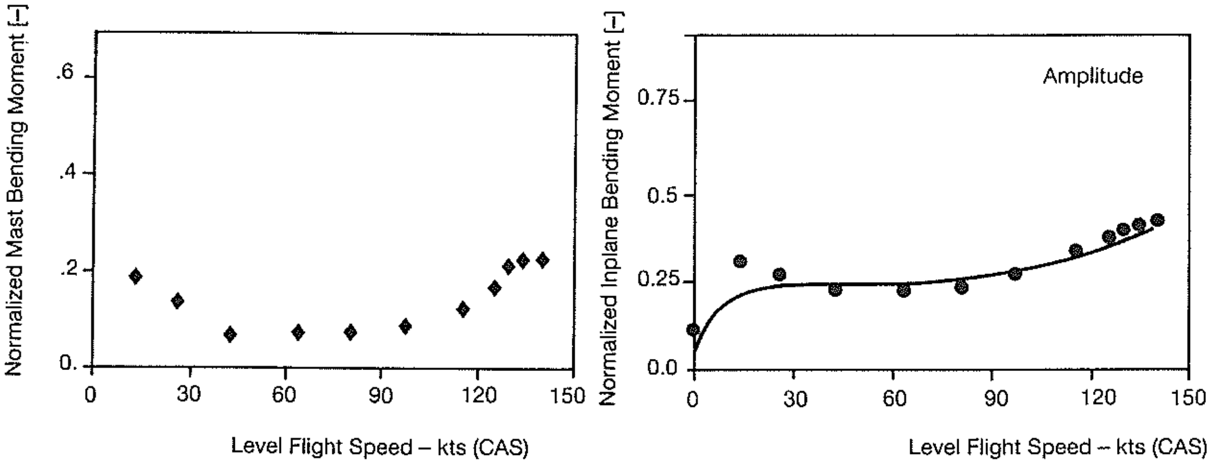

Figure 24 Mast Bending and Implane Bending Moment in Level Flight

8. Vibrations

The vibration characteristics throughout the flight envelope are increasingly important for a new helicopter. Therefore, from the very beginning of the project a multi-axes antiresonance rotor isolation system (ARIS) was provided for the BO 108. It uses hydraulic isolator elements for the reduction of the 4/rev airframe excitation. The high efficiency of the advanced isolator elements was proven by tests described in Ref. /3/.

The first flight phase took place without the vibration isolation system installed. In a second step, the system has been installed. Shake tests with hub force and moment excitation were performed to adjust the final tuning and to measure the isolator transmissibilities as well as the airframe response (Figure 10).

This configuration will be flight tested in the next phase which is scheduled for October '89. The basic configuration consists of four vertical isolators (see Figure 25); if required, an additional isolator in the lateral direction can be installed.

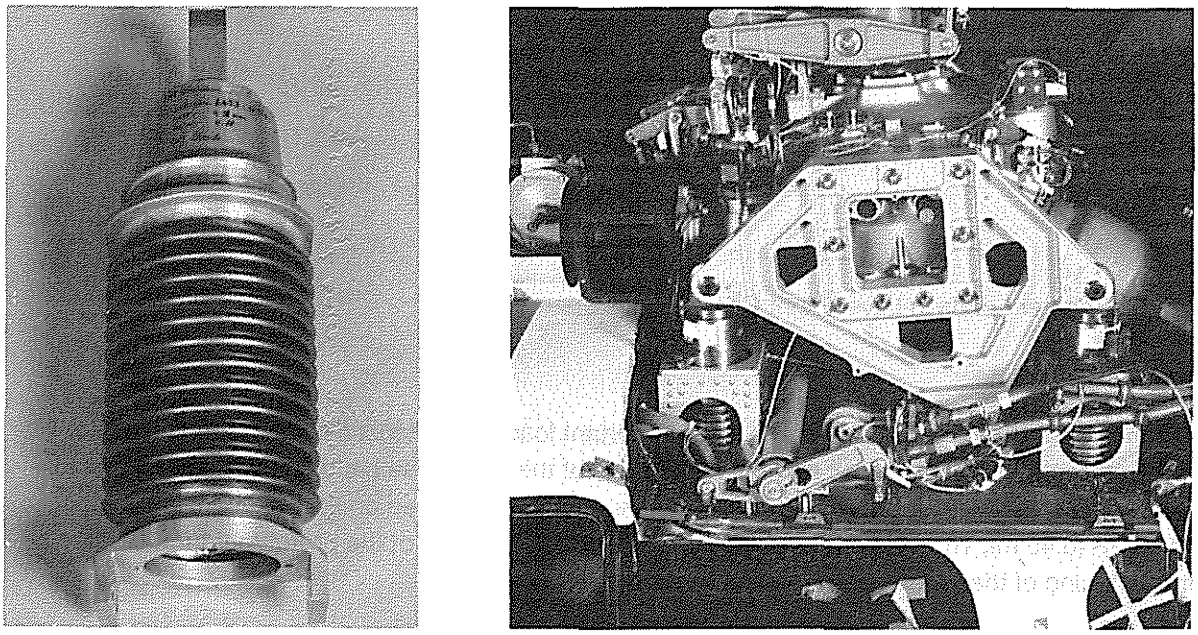

Figure 25 Anti-Resonance Isolation System (ARIS)

9. Noise

Exterior low noise levels were an important design goal for the BO 108. The new airfoils, the blade tip geometry with reduced relative thickness, the reduced blade tip speed, and the drag optimized fuselage lead to a more constant distribution of the local blade loading, and therefore to lower harmonic noise. An average reduction of the exterior noise levels of about 2 EPNdB compared to the BO 105 is expected with respect to ICAO-certification procedures. Measurements will be done during the next flight phase.

To reach a comfortable cabin environment, measurements for low interior noise levels were considered already during the design phase. The objective is 89 dBA for the standard version of the BO 108 and lower than 85 dBA for SAR- and VIP-versions. These goals will be reached by an advanced acoustic treatment of the cabin and by use of components designed to low noise emission such as main gearbox, cooling fan, interior heating, and ventilation system.

10. Summary

The BO 108 is an advanced technology helicopter developed using modern design methodology and the latest component technologies. Extensive theoretical studies coupled with component testing was employed from the onset of the program. The experimental testing of the prototype rotors and finally the flight testing of the BO 108 demonstrate the targeted performance particularly in the field of aerodynamics, power required, dynamics, structural design, and handling qualities.

The dynamic design of the bearingless main rotor demonstrated in particular a well-damped lead-lag motion, as expected. The aeromechanical system tests confirmed ground and air resonance stability. Within the flight envelope tested up to now, the loading of the most critical components was well below the endurance limits.

The design objectives of the new airfoil family and the advanced planform rotor blades were met with a significant saving in power requirements. The transonic blade tip design provided better than expected behaviour at critical high blade tip Mach numbers.

The handling qualities objectives were achieved with the BO 108 demonstrating good static longitudinal stability up to high blade tip Mach numbers, inherent dynamic stability characteristics near to the IFR-requirements, and excellent control response behaviour.

The initial flight and ground test results of the BO 108 let expect that the design goals will be even exceeded. The test program will be continued to explore the aircraft behaviour within the total flight envelope including test flights with the rotor isolation system installed.

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