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A MODEL FOR WIND-TUNNEL ROTORCRAFT RESEARCH
- MODEL DESIGN AND TEST OBJECTIVES -

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Abstract

In a joint program with Dornier, Messerschmitt-Bölkow-Blohm and VFW-Fokker a helicopter test stand for wind-tunnel testing has been assembled at the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V. (DFVLR), Institut für Flugmechanik at Braunschweig under contract to the German Ministry of Defence.

This paper discusses the essential factors which affected the design of the various components of the test stand.

Using the model scaling laws, the transferability of the obtained results to full-scale helicopters is investigated. It is shown that both aerodynamic and dynamic results can be transferred with sufficient accuracy.

The paper presents and discusses some results from hover tests. Finally, a preview of future wind-tunnel test programs is given.

1. Introduction

Today's helicopters are used for an ever increasing number of tasks by both civilian and military users. Particularly for military helicopters there is an continuously increasing need for increased aircraft performance, optimized stability and control behaviour and better noise reduction. To satisfy these requirements, much more fundamental knowledge in the fields of helicopter aerodynamics, aeroelastics, dynamics, acoustics and flight mechanics is essential.

In recent years theoretical work in these areas has been intensified. It is necessary, more now than ever before, to verify and expand theoretical results with proper and sufficient testing. This will help to establish a reliable data base for further development of rotary-wing aircraft. Moreover, extensive configurational studies and tests are required to obtain aerodynamic and flight mechanic improvements for the design of novel helicopter systems.

A helicopter test stand for large wind-tunnels has been assembled in Germany to do this experimental work. Under contract to the German Ministry of Defence, the test equipment was produced in a joint program by DFVLR, Dornier, MBB, and VFW-Fokker, see Figures 1 and 2. The program is managed by DFVLR, Institute for Flight Mechanics at Braunschweig.

2. Design of the Helicopter Test Stand

From the beginning the versatility of the test equipment had to be considered. The test stand must be adaptable to many investigations in different fields. This dictated the following requirements (Ref. 1):

- The test stand should be suitable for many different investigations in the fields of aerodynamics and dynamics with one rotor model. The transferability of test results to full-scale helicopters must be valid for these investigations.

In general it is impossible to accomplish this requirement with one model. Considerations of the similarity principles show conflicting requirements dictated by different model scaling laws.

Because of the many investigations to be conducted in the field of aerodynamics it is necessary to have a "Mach scaled" model. The requirement for Mach scaling plus the requirement for sufficient transferability in other fields dictates that the model be as large as possible. The scaling laws will be discussed in more details in section 3.1.

- The test stand should be suitable for different models.

It must be possible to test both shaft driven and reaction driven rotor systems. It must be possible to vary the number of blades. And, the test stand must be adaptable to different fuselage, tail, and tail rotor configurations.

- The test stand should fit in the large wind-tunnels available.

At this time in Germany there are two wind-tunnels suitable for experiments with large rotor models. One is at the Volkswagen research facility in Wolfsburg. It has a test-section 7.0 meters wide and 5.0 meters high and a 50 m/sec maximum test section wind speed. The other is at the Daimler-Benz facility in Stuttgart. It has a test section 7.4 meters wide and 4.9 meters high and a 80 m/sec maximum test section wind speed.

How the test stand was designed to satisfy the requirements is discussed next.

2.1 Drive System

There are many difficulties in the selection of the power plant for a Mach scaled rotor model. The available electric, hydraulic and air turbine motors are still too heavy to allow proper dynamic scaling (Ref. 2). If the drive system were placed on the "live" side of the load balance, weight taxes with respect to rotor loads would be too large. The only current means to achieve dynamic scaling weight objectives is to mount the drive system external to the rotor model. Figure 3 shows how this was done.

Special flex couplings have been designed and fabricated to have the required torque capability. To allow accurate measurements at the balance, the couplings are "soft" enough so that axial force, lateral force, and moment losses to the test stand are very small compared to the loads measured.

The drive system package used on the DFVLR helicopter test stand is a hydraulic system driven by an electric motor. The two components of the hydraulic system, the pump and the motor, are connected with high pressure hoses. The rpm of the hydraulic motor is continuously variable. The result is a high power (90 KW at 1050 rpm) compact drive system on the test stand. The bulky primary power unit, that is the electric motor and hydraulic pump, can be easily positioned as required for set up in various wind-tunnels.

2.2 Data Acquisition and Presentation

The most important factors in the design of the measurement equipment were

- on-line presentation of all critical data to ensure safety of flight monitoring
- high reliability and accuracy of the data
- flexibility and adaptability of the equipment to different measurement problems.

For measuring the forces and moments at the rotor hub and at the fuselage, two six-component strain gage balances have been installed. These strain gage balances measure the steady-state loads with high accuracy (error < 2% of maximum load). They also provide good dynamic load data up to 4 per revolution.

Because the forces and moments of the rotor are measured independently of the fuselage loads, interference effects between rotor and fuselage can be established. Rpm, torque, and rotor power are obtained from a measurement package fitted in the drive shaft.

For many investigations it is necessary to obtain data from the rotor concerning blade motion, blade loads and other variables. Data from the rotor is transmitted to stationary test stand by PCM telemetry. The telemetry transmitter and antenna is located on top of the rotor hub and rotates with the rotor. Thirty-two data channels are provided, each with a frequency response of 100 Hz. By reducing the number of data channels the available frequency response can be increased. Since the data is transmitted in digital form there is no possibility of bias errors common to analog systems.

The DFVLR data acquisition and presentation system consists of two elements

- Quick-Look Data System
- Dynamic Data System

The Quick-Look Data System, see Figure 4, allows monitoring of analog data from the six-component balances, the measurement shaft, and the strain gage bridges on the rotor. Selected parameters are presented in engineering units on an oscilloscope, an oscillograph, and a monitor display which has both digital and analog readouts. This allows timely decisions to be made while experiments are being run. Also flight safety can be continuously monitored.

In the Dynamic Data System, see Figure 5, analog data from the balances and the measurement shaft is digitized. This data together with the digital data from the rotor is recorded on magnetic tape. Detailed off-line analysis of the experiments will be accomplished with the help of the DFVLR computer facility at Braunschweig.

2.3 Control System

A conventional swashplate system is used for rotor control. The non rotating swashplate is adjusted by three electrical servomotors, see Figure 6. Both collective and cyclic blade pitch angles can be adjusted. The servomotors are remotely controlled from a central control unit. In the design of the swashplate, provisions were made to allow the use of various rotors with different blade numbers. The rod end bearings are lined with Teflon fiber to avoid the problems often encountered when metal-on-metal rod end bearings are used in a Mach scaled model (Ref. 2).

The rotor shaft angle is controlled by tilting the upper part of the test stand while the lower test stand remains stationary. The upper test stand is tilted by a hydraulic jack which is remotely controlled from a central control unit. The rotor shaft angle can be varied through a range of ± 15 degrees.

The ability to remotely control both collective and cyclic blade angles and rotor shaft angle allows rapid changes in test conditions without shutting down the model or the wind-tunnel.

2.4 Rotor Model

Presently in Germany, work is being concentrated on helicopters of up to eight tons gross weight. The corresponding rotor diameter is approximately sixteen meters. To maximize transferability, model rotor diameter was made as big as possible while still allowing use in the available wind-tunnels. Maximum rotor diameter is four meters.

The first rotor fitted to the model is a hingeless four blade, Mach scaled unit, see Figure 7. The scaled rotor was designed to model the dynamic and geometric characteristics of the MBB BO 105 main rotor. The linear scale

factor is 2.5. The rotor blades are soft flapwise and inplane; the hub is stiff flapwise and inplane. In the design of the scaled rotor care was taken to accurately model the stiffness and mass distribution of the BO 105 rotor (Ref. 3). With only a few exceptions, all dimensions and wall thickness were scaled linearly. The blades are fiberglass plastics and the hub is steel. This design resulted in a rotor system which is sufficiently strong to allow operations over the entire flight regime of the full-scale rotor system. This design plus tuning of the test stand natural frequencies has eliminated the danger of ground resonance. The test stand natural frequencies were analysed based on test runs augmented by theoretical calculations (Ref. 4). The following table gives the important characteristics of the rotor.

diameter	$D = 4 \text{ m}$
number of blades	$z = 4$
solidity	$\delta_{0.7} = 7.73 \%$
blade planform	rectangular
blade profile	NACA 23012
twist	$\Delta\theta = -6^{\circ}14'$
flapping frequency ratio	$\omega_{\beta}/\Omega = 1.12$
lagging frequency ratio	$\omega_{\zeta}/\Omega = 0.71$
rotor speed	$n = 1050 \text{ rpm}$
tip speed	$U = 220 \text{ m/sec}$
design thrust	$T = 3630 \text{ N}$
disc area loading	$T/A = 290 \text{ N/m}^2$
maximum thrust	$T_{\text{max}} = 4400 \text{ N}$

2.5 Fuselage Model

The fuselage consists of a supporting structure and outer shell. The fiberglass outer shell can be changed for various experiments. A representative fuselage for a medium weight transport helicopter is presently on the test stand, see Figure 8.

The fuselage is mounted on the test stand using a six-component balance. By mounting the fuselage shell in various positions it is possible to change the position of the fuselage relative to the rotor hub and/or the fuselage's longitudinal flight angle. Auxiliary wings are mounted on the fuselage. Provisions have also been included for a tail rotor drive system.

3. Transferability of Test Data to Full-Scale Helicopters

The transferability of test data is dependent on the proper useage of the model scaling laws. Additionally other factors such as wind-tunnel interference effects must be considered.

3.1 Model Scaling Laws

To assure transferability, the scaling laws must be used. Unfortunately difficulties in model design, construction, and fabrication arise when the scaling laws are applied.

"Buckingham's Π -Theory" (Ref. 5) provides a technique to obtain the minimum number of independent dimensionless ratios required. When this dimensional analysis technique is used; there is no need to know in detail the physical equations governing the phenomena in question. However, given sufficient knowledge of the phenomena, the same scaling laws can usually be found without resorting to dimensional analysis.

For a complete simulation which takes into account a flexible rotor in a viscous, compressible flow in a gravity field, the following parameters must be correct, see Figure 9

- ratio of linear dimensions
- Mach number
- Reynold's number
- Froude number
- density ratio
- elasticity ratio.

With the limitation that only wind-tunnels utilising air at atmospheric pressure are available, the relevance of these parameters to the DFVLR Helicopter Test Stand will be discussed.

3.1.1 Ratio of Linear Dimensions

The "geometrically scaling" approach is popular because of a number of factors. For instance, if everything is geometrically scaled, then both the material mass density and structural moduli can be the same as in the full-scale helicopter.

Another advantage of geometrical scaling is that if the aerodynamically important portions of the rotor - especially the blades - are geometrically scaled, the model rotor has the same incompressible, non-viscous aerodynamic characteristics as the full-scale rotor.

It is usually possible to reduce the external shape of a helicopter by applying the same scale factor. Unfortunately the reduction of all full-scale dimensions by the same scale factor often brings fabrication and handling problems because of the decreased absolute thickness of many parts and the small absolute size of others.

Because of the large size of the DFVLR model rotor it is practicable to use geometrical scaling.

3.1.2 Mach Number

Aerodynamic data, for instance blade loads due to air loads, can only be accurately obtained if Mach scaling is used. Most model rotors including the DFVLR model are Mach scaled. The model rotor tip speed is 220 m/sec which is the same as full-scale.

3.1.3 Reynold's Number

The use of a Mach scaled model rotor makes impossible the correct simulation of Reynold's number in wind-tunnels using air only.

The two-dimensional characteristics of an airfoil section show the well known reduction in the maximum lift coefficient as Reynold's number is reduced. Associated with this reduced $c_{L,max}$ is a decrease in the angle of attack at which the airfoil stalls and at which the moment curve breaks.

For rotary wing aerodynamics a number of recent papers (Ref. 6, 7, 8) have shown that the trends in $c_{L,max}$, Reynold's number, and Mach number produce a considerably more favourable model/full-scale relationship than for fixed-wing aircraft. In analyzing the influence of Reynold's number one must consider both the effect of c_L on lift and the effect of c_M on lift. The effect of c_M on lift is a function of both Reynold's number and the structural properties of the blades.

Although Reynold's number considerations are important, particularly for higher advance ratios ($\mu > 0.5$), it is much more important to properly simulate Mach number. Of course, this approach is a correct one for a rotor model having a scale factor of 2.5.

3.1.4 Froude Number

The Froude number also cannot be simulated correctly with a "Mach scaled" model rotor. Generally the Froude number is too large.

For rotors with a substantially horizontal disc plane, the gravitational forces on a rotating blade have a constant value in the flapwise direction. Since the flapwise aerodynamic, centrifugal, and inertia forces are usually large compared to the blade weight, the gravitational forces can be ignored.

Froude number is important for "off-loaded" rotors at high tip-speeds and particularly for rotors with a vertical disc plane. In this case the blade weight is a once-per-revolution excitation force in the blade lagwise direction. Some instabilities such as air and ground resonance and whirl flutter are dependent on the lagwise behaviour of rotor blades.

In the DFVLR test stand the consequences of the incorrect Froude number are acceptable because of substantially horizontal disc plane, the high centrifugal forces resulting from Mach scaling, and the low blade weight resulting from the fiberglass epoxy fabrication.

3.1.5 Density Ratio and Elasticity Ratio

In order to ensure similar dynamic characteristics with a Mach scaled model rotor, the structural density and the modulus of elasticity should be identical to the full-scale values. Geometrically scaling using the same materials is an obvious method of ensuring dynamic similarity. In this case the rotor blade natural frequencies and the stresses in the rotor system are the same as full-scale.

Because of the relatively large size of the DFVLR model rotor, this method of model fabrication was practicable. It is expected that useful and quite accurate dynamic test data will be obtained.

3.2 Wind-Tunnel Interference

In choosing model dimensions to be used in a particular wind-tunnel, it is necessary to consider wind-tunnel interference effects.

H.H. Heyson (Ref. 9) has considered this problem in detail. He discusses eight constraints that apply to wind-tunnel tests. Depending upon the type of wind-tunnel model, type of data desired, and test conditions one of these eight factors will limit the test. Generally the most limiting factor tends to be flow breakdown.

As a rule of thumb a flow angle error ($\Delta\alpha$) of 5 degrees at the centre of the rotor is the interference limit. Figure 10 shows disc loading (T/A) plotted against the ratio of rotor diameter to tunnel breadth (D/b) for a tunnel height/breadth ratio of 2/3 with the interference limit criterion at $\Delta\alpha = 5^\circ$. This figure shows that the permissible diameter to breadth ratio is primarily determined by the lowest velocity and moreover by the disc loading at which rotor testing is desired.

For the VW wind-tunnel and the DFVLR model, the ratio of rotor diameter to wind-tunnel breadth is 0.57. This value seems sufficient for doing measurements with good accuracy in the transition flight region.

4. Wind and Hover Tests

The test stand was run for the first time in May 1976. A number of tests were necessary to assure flight safety and to check the basic properties of the model. This data is essential for all research work in the future. Up to now the following investigations have been accomplished.

Static and dynamic tests and calculations prior to first run:

- elastomechanical properties of the test stand and blades were determined,

- control elasticity and clearance were measured,
- ground resonance was calculated.

Hover tests:

- rotor was balanced and tracked,
- resonance diagram of the blades was confirmed,
- rotor characteristics were determined,
- limits for regions of flight safety were established.

The test data obtained was in good agreement with calculated data.

Figure 11 shows the resonance diagram of the rotor with computed and measured data. The ground resonance investigations are discussed in Ref. 4.

5. Wind-Tunnel Test Program

The first wind-tunnel tests took place in the VW wind-tunnel at Wolfsburg between 13. and 18. of September. The following test program was accomplished:

- rotor characteristics were measured,
- regions of flight safety were defined,
- aerodynamic interference effects between rotor, fuselage, and auxiliary wings were investigated,
- downwash at selected field points was measured.

One of the first objectives of data analysis will be to establish the degree of correlations between full-scale, model, and theoretical results. Additionally, attempts will be made to verify and expand theoretical work done in recent years concerning rotor downwash and interference effects.

Future plans include wind-tunnel tests by various DFVLR Institutes and German aircraft manufacturers in the following areas:

- rotor downwash
- rotor stall limits
- aerodynamic interference effects
- pressure distribution on rotor blades
- dynamic response of the rotor
- offset-lift rotor
- aeroacoustical effects
- novel rotor control systems
- fuselage, tail unit and tail rotor aerodynamics.

This work will be done with both the existing model and new models. A two blade rotor model which can be either shaft or reaction driven already is designed.

6. Conclusions and Future Aspects

The Helicopter Test Stand assembled at DFVLR is of great importance for further rotary-wing research and development in Germany.

Improvements in the data base will contribute to future designs of novel rotary-wing aircraft. Especially important will be configurational investigations.

The close cooperation between helicopter users, research institutes and manufacturers in the design and assembly of the helicopter test stand has been gratifying. It is hoped that this will prove to be only the beginning of a successful test series.

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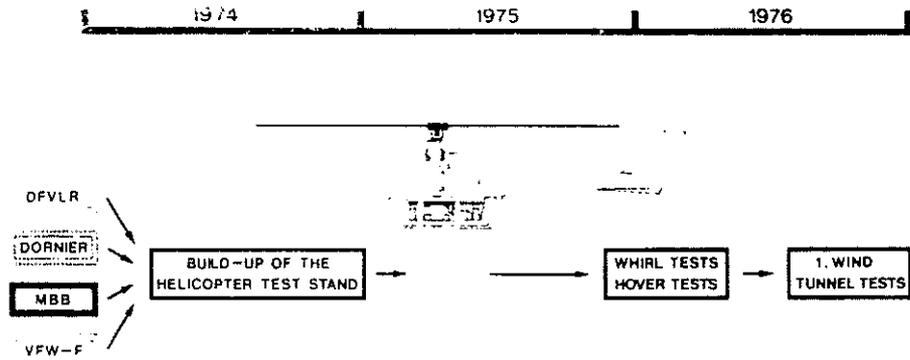


Fig.1: Helicopter Test Stand Program

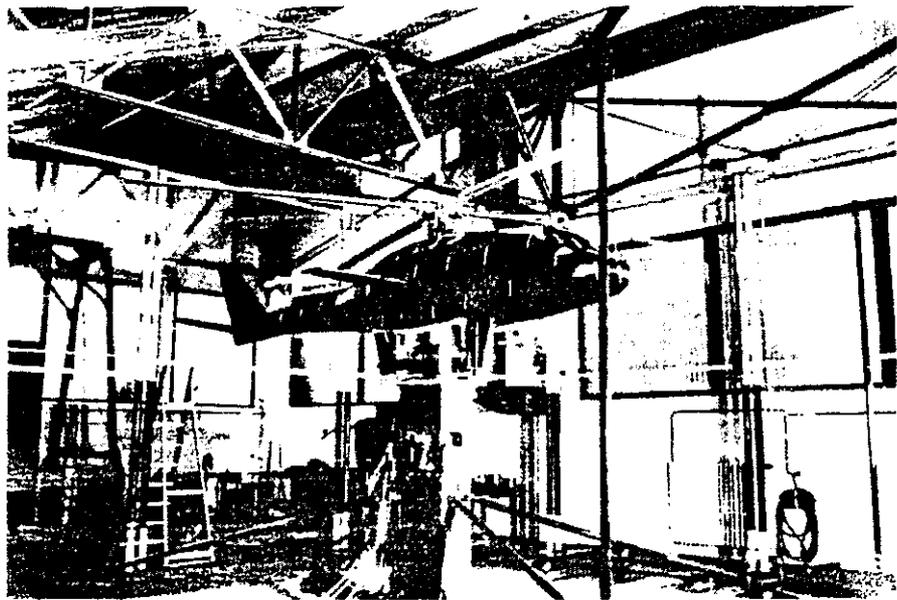


Fig.2: Helicopter Test Stand

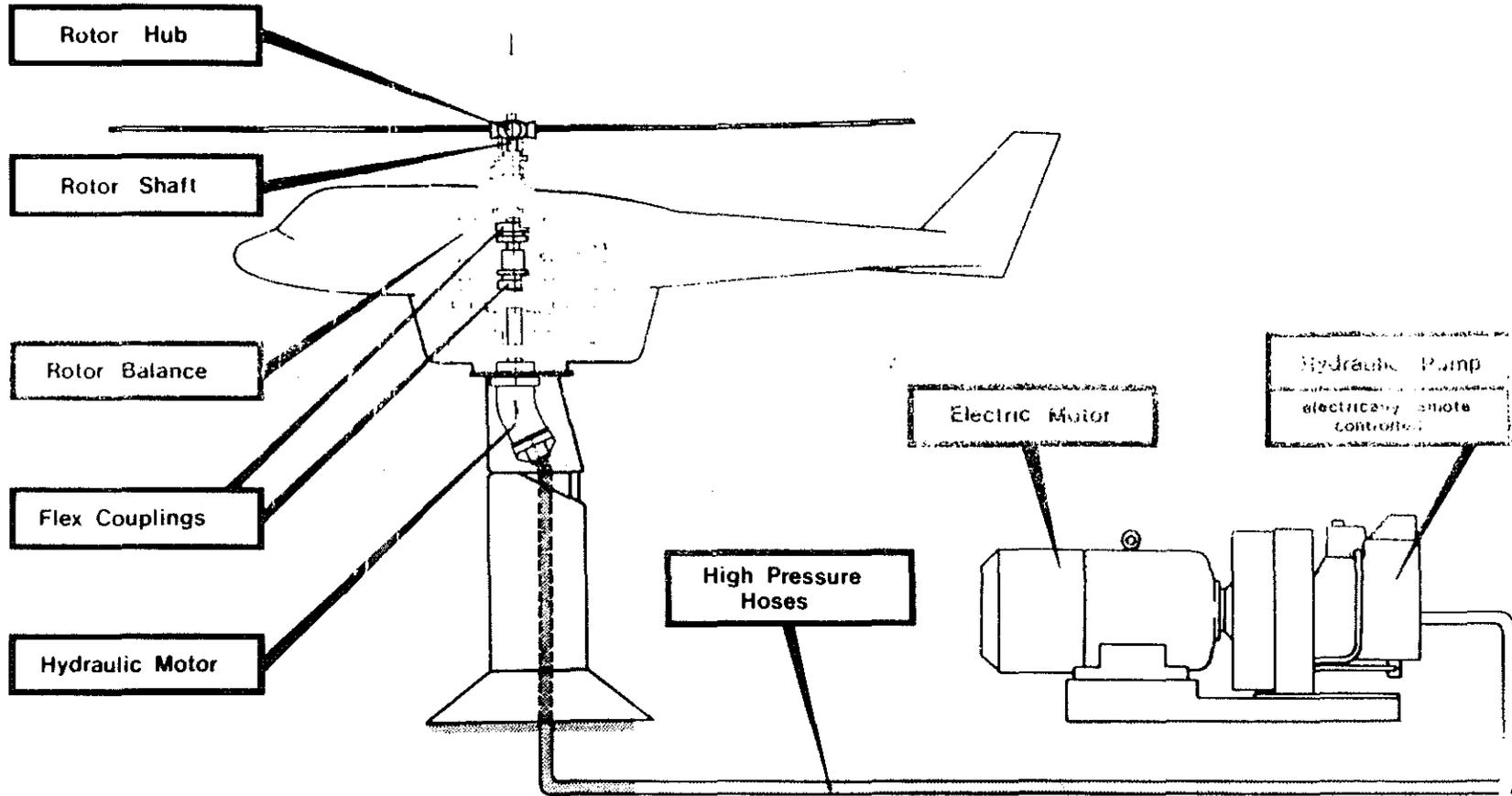


Fig.3: Drive System

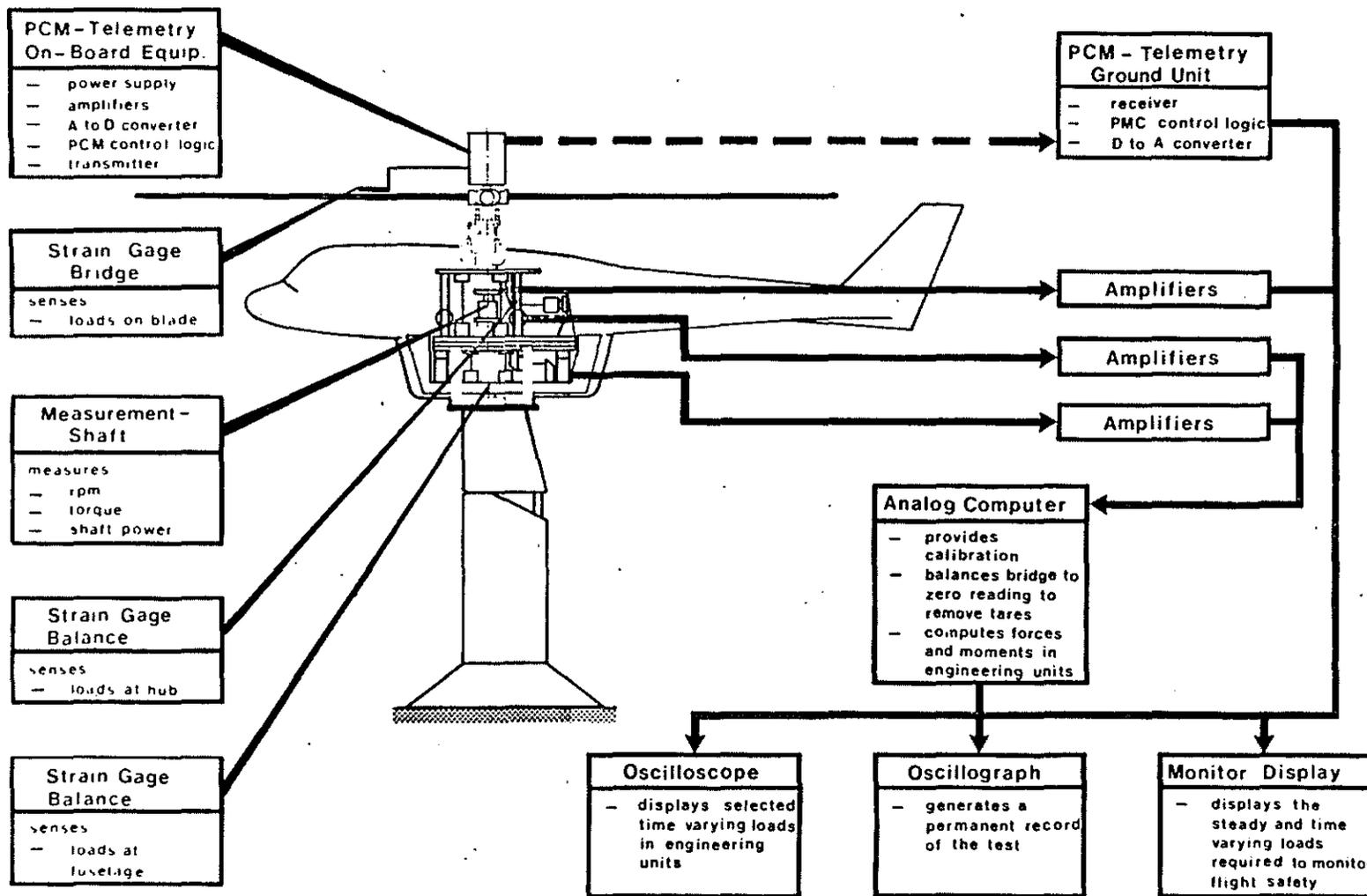


Fig.4: Quick-Look Data System

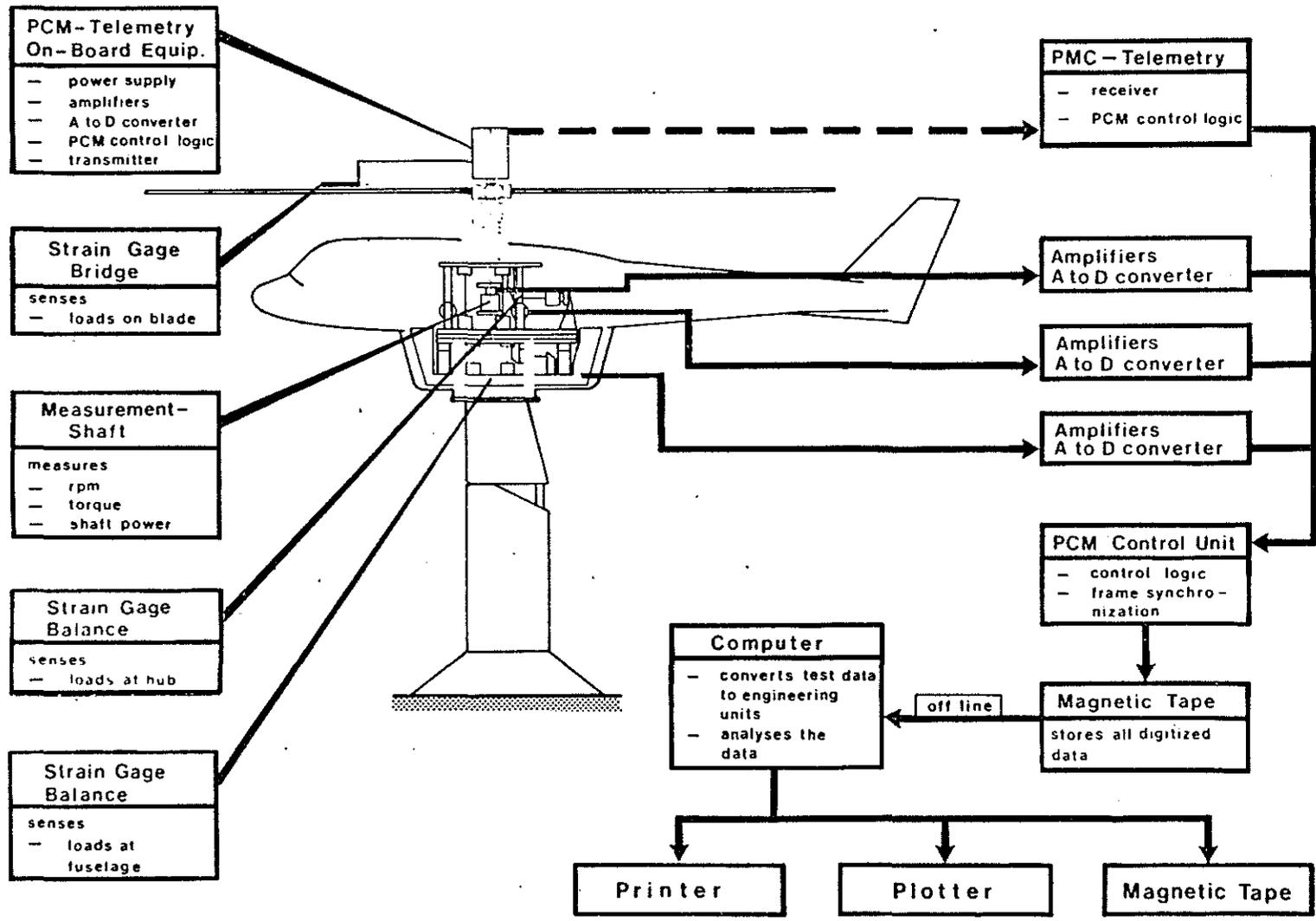


Fig.5: Dynamic Data System

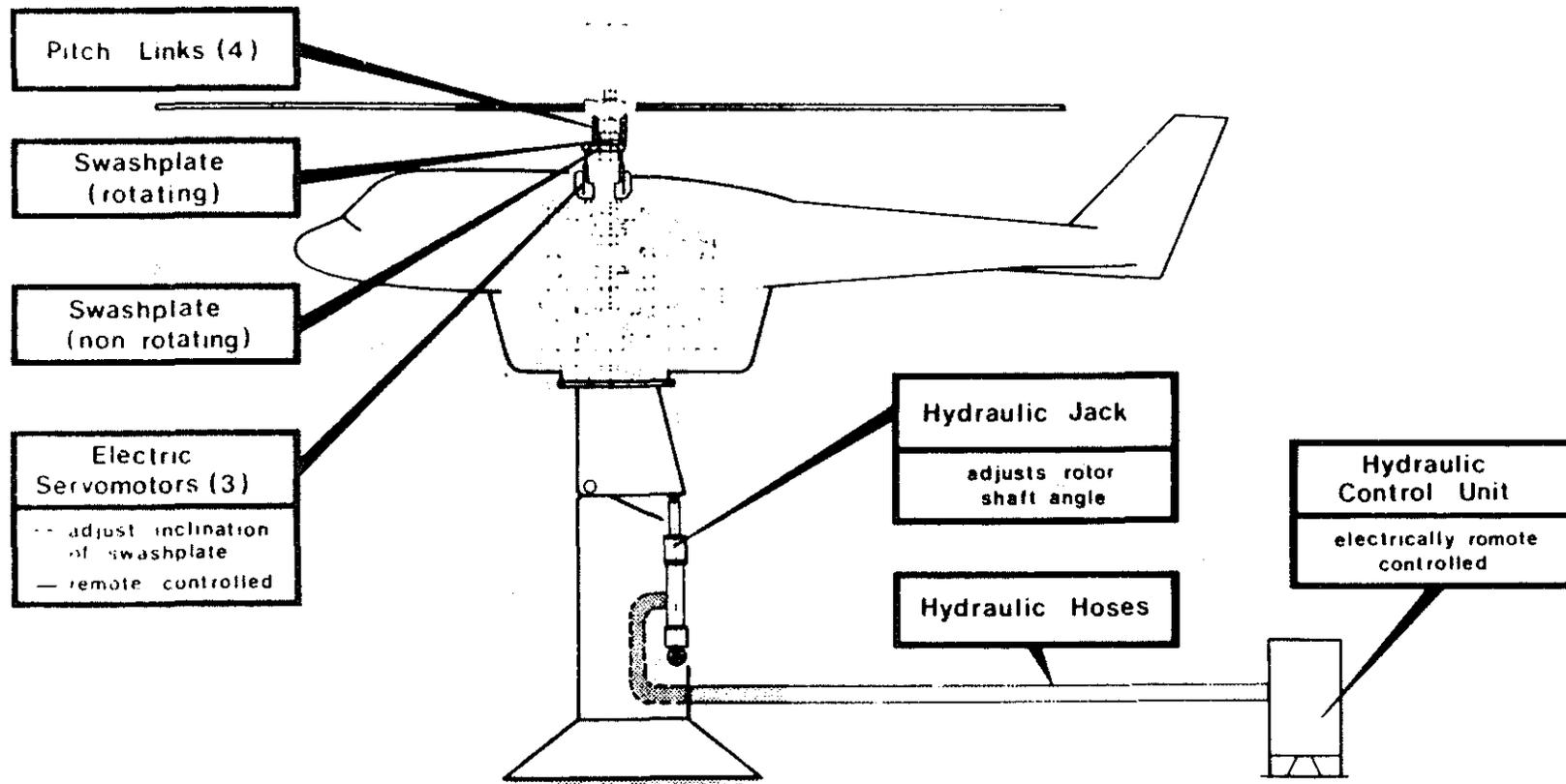


Fig.6: Control System

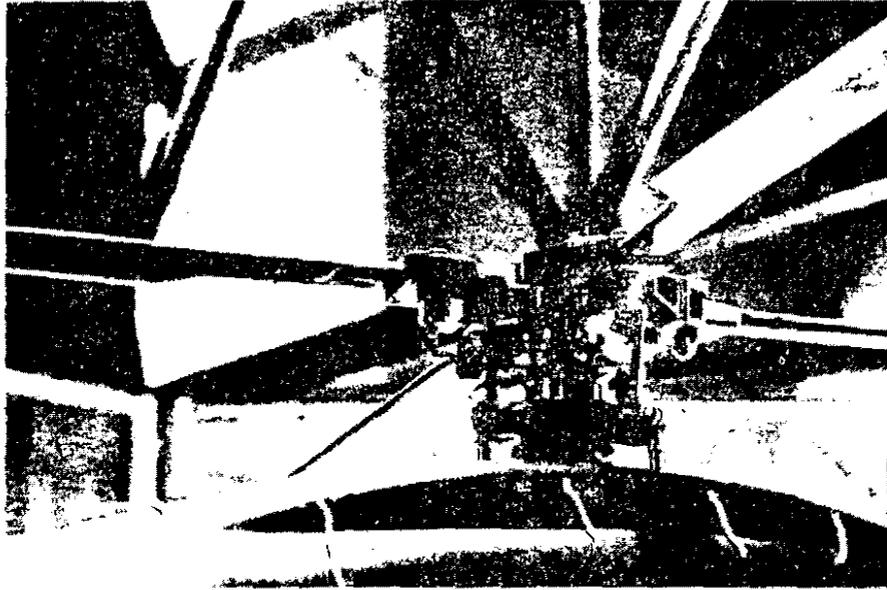


Fig.7: Rotor Model

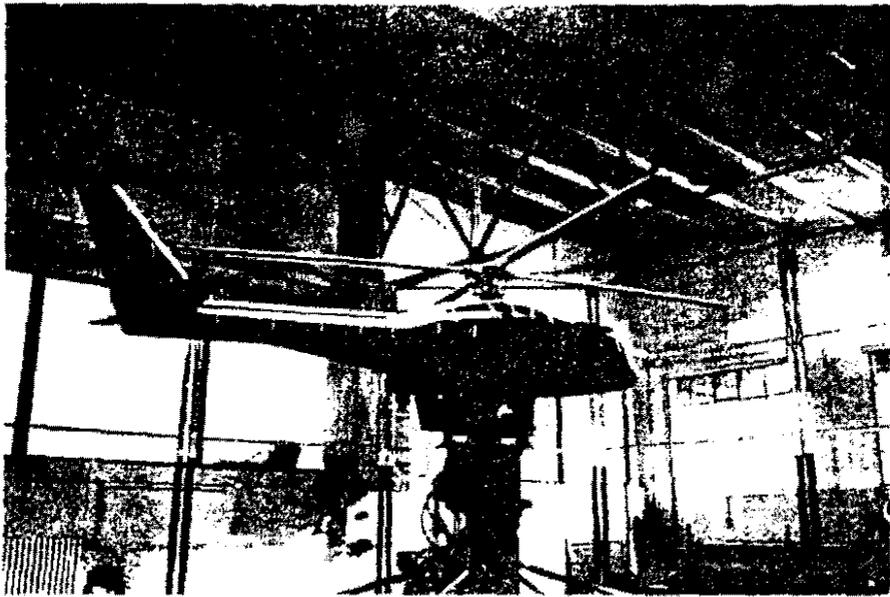


Fig.8: Fuselage Model

- Ratio of linear dimensions $\frac{l_1}{l_2}$
- Mach number $Ma = \left(\frac{\text{inertia forces}}{\text{compressibility forces}} \right)^{1/2}$
- Reynold's number $Re = \frac{\text{inertia forces}}{\text{viscous forces}}$
- Froude number $Fr = \frac{\text{inertia forces}}{\text{gravity forces}}$
- Density ratio $\frac{\rho_s}{\rho} = \frac{\text{structural density}}{\text{fluid density}}$
- Elasticity ratio $\frac{E}{\rho \cdot V^2} = \frac{\text{structural elasticity}}{\text{fluid compressibility}}$

Fig.9: Constant Parameters for Complete Rotor Simulation

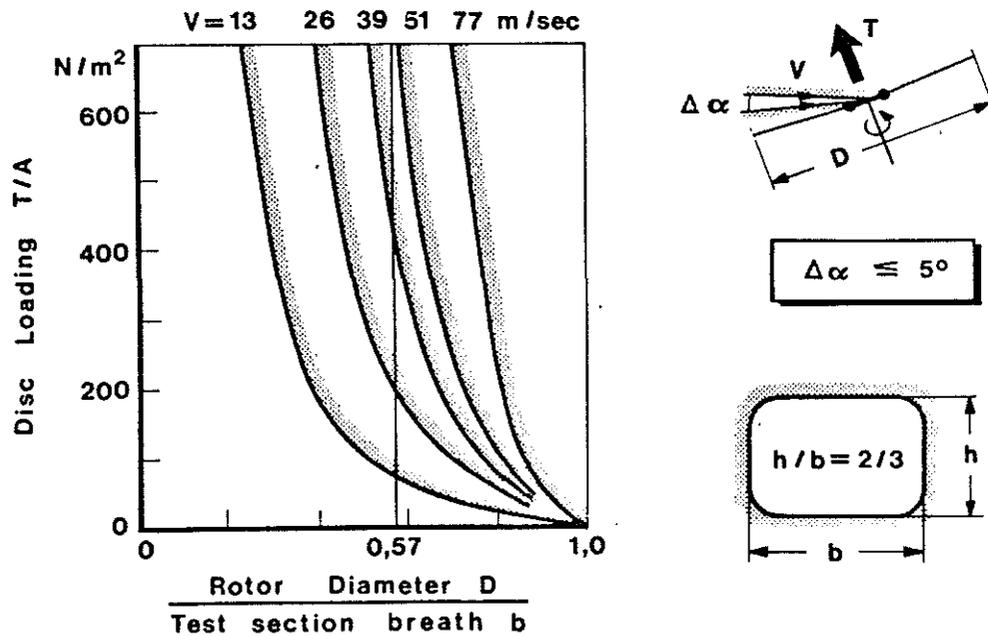


Fig.10: Wind-Tunnel Interference Limits

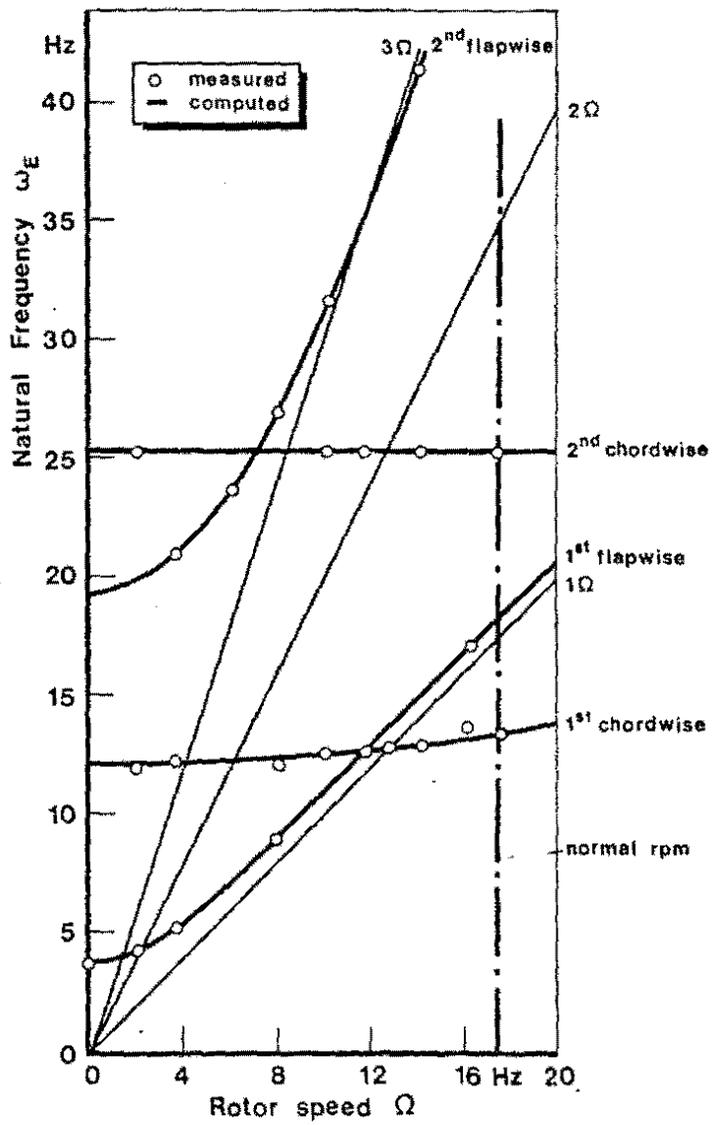


Fig.11: Resonance Diagram