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DEVELOPMENT OF AN ADVANCED EXPERIMENTAL ROTARY TEST RIG AND FIRST TEST RESULTS WITH A 60 kN-MAIN ROTOR

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Abstract

In addition to measurements of power to thrust ratio and rotor loads during rig testing of helicopter rotors, test technology for the investigation of aeroelastical and structural dynamic relationships is becoming more and more emphasized. This is principally because the test results obtained can be used for the verification of predicted dynamic behavior and configuration of some important rotor design parameters.

To achieve these objectives, a rotary test rig with advanced experimental attributes – as far as prime mover, swashplate control and thrust measuring device are concerned – for testing of rotors up to 70 kN thrust was developed and put into service at MBB Helicopter Division (in cooperation with HENSCHEL-FLUGZEUGWERKE).

The required power in a widely variable rotor RPM range is obtained by a vertically installed direct current drive unit. Swashplate control permits the performing of stationary or periodical monocyclic, multicyclic (whirling) and collective inputs.
For thrust measuring a strain-gaged sensor ring is integrated into the shaft bearing system.

The experimental apparatus and procedures and first test results with a 60 kN-bearingless rotor are discussed in this paper.

1. Introduction

The design and development of helicopter rotors require test facilities, especially rotor rigs, to get knowledge about dynamic system characteristics. In the preproduction stage rotary rigs are used also for balancing as long as simpler rigs are not available. In the past one relied on investigations within the rated range of rotor speed and on simpler methods exciting the rotating frequencies and attached great importance – also during ground tests – putting the rotor out of ground effect. With the demand to measure and verify, very early, the predicted dynamic properties, the desired lower power consumption and lower loads of new rotors, the requirements for better experimental and analytical methods also increased.

The MBB-RPS 60 rotary test rig serves the following requirements

- In order to improve the accessibility the hub height was kept low and the ground effect (here: $h/_D = 0{,}45$) was considered of secondary importance.
  The facility can therefore be covered by a (movable) sheetmetal hangar by means of which the maintainability is improved and the test preparation time is reduced.

- With an infinitely variable electrical prime mover acceleration and deceleration behavior can be programmed and rotor response can be examined within the entire speed range at any desired torque.

- Rotor thrust measuring is performed by a sensor ring which is integrated into the shaft bearing system.

- For the experimental investigation of lead/lag damping of the rotor with regard to the excitation and modal behavior (rotor modes) new techniques are introduced.

2. Description of the test rig

2.1 Basic technical data

• Max. power	P : 1230 kW
• Speed range	n : 0–420 min^{-1}
• Max. torque	M_d : 45000 Nm
• Rotor diameter	D : < 14 m
• Rotor thrust	T : –10 to 70 kN
• Height (rotor hub above ground)	H : 5,4 m
• Max. shaft moment (rotating)	M_M : 40 000 Nm
• Max. moment of rotor inertia	J : 5000 kgm^2
• Max. lateral force	F : 400 kN

2.2 Arrangement and principle of operation

The rotary test rig was designed as far as possible as a universal test facility for testing of main rotors up to 70 kN and can be operated with high stability within a speed range of 0 to 120 % of the relevant rated speed.
The rotor blade angle control system can be controlled steady-state or periodically in mono- or multicyclic (3×120°) configuration up to $5\,\Omega_{Rotor}$ (≈ 40 Hz) by microprocessor or potentiometer inputs.
The collective pitch control is totally separated from the cyclic input system.

The described rotary test rig (Fig. 1) consists of a direct driven vertically installed DC motor (AEG) which is fixed to a ferro-concrete foundation with a weight of about 400 tons. A small room below the motor permits maintenance and inspection of the slipring and the slow auxiliary drive unit.
An intermediate housing is connected to the upper motor flange. Within this housing the shaft and the torquemeter, with soft bending but torsionally stiff couplings is assembled, as well as the lubrication and cooling system for the shaft bearing and collective control system.

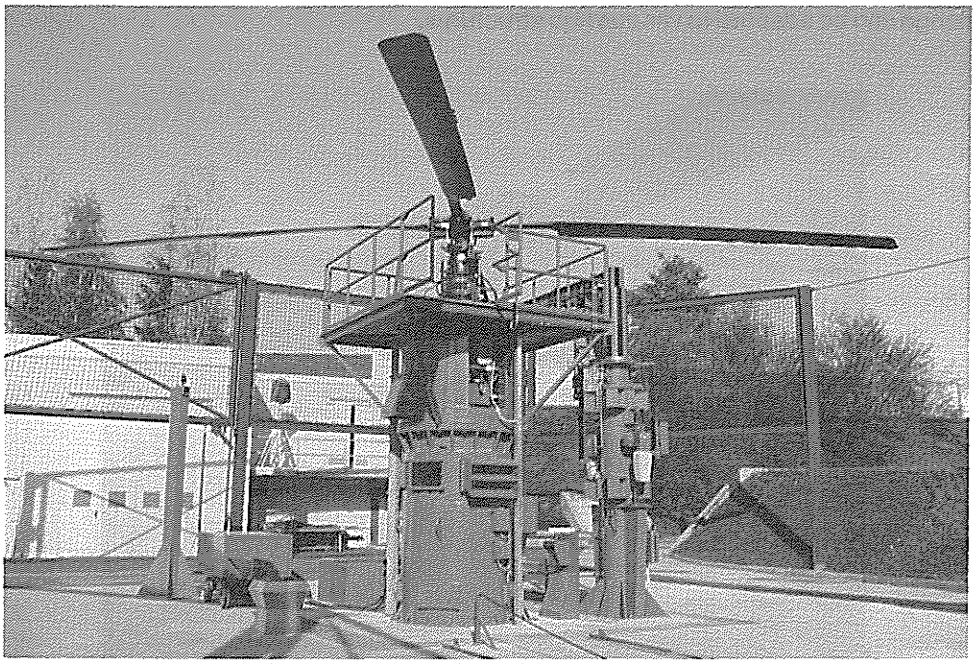


Fig. 1 MBB-RPS60, Rotary Test Rig

An assembly dolly with a lateral-mounted blade elevator is used for installing blades on the hub. Until the removable hangar and the dolly are moved aside the motor cannot be started (Fig. 2).

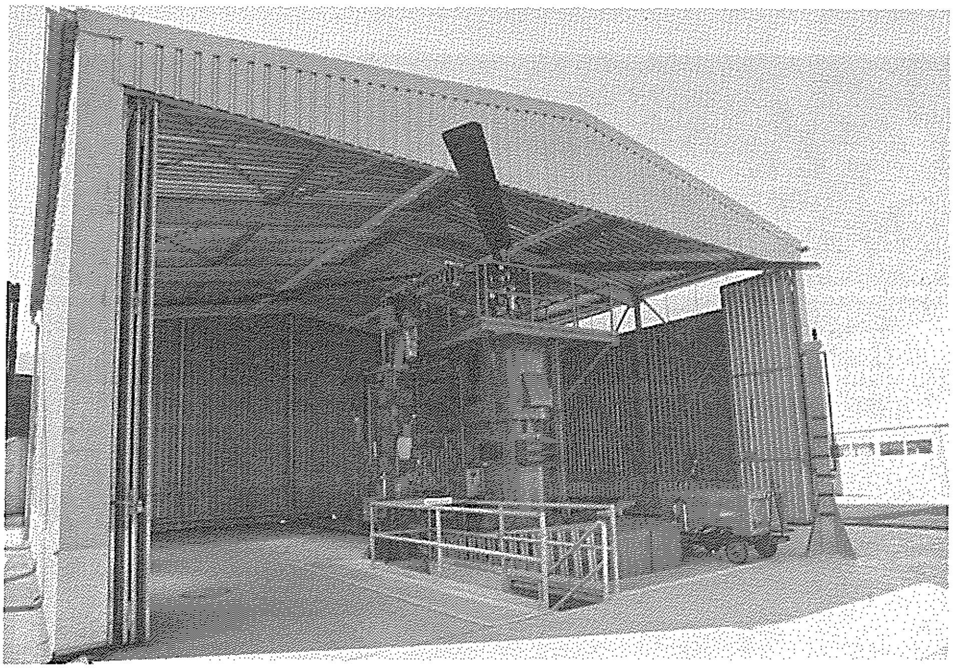


Fig. 2 MBB-RPS60, Rotary Test Rig with Dolly and Removable Hangar

The housing for the shaft bearing and the thrust measuring system carries the bearings for an external driven screw spindle (∅ 400 mm) on which the unit, carrying the non-rotating booster rods, can be moved up and down.
The swashplate is fixed by a spherical calotte bearing and slides up an down the shaft and so it was possible to avoid the requirement for a gimbal mixing unit (Fig. 3).
The rotating part of the swashplate is directed by two opposite cams and designed for the attachment of 4 pitch links.
The upper hub flange can be adapted to various hub structures.

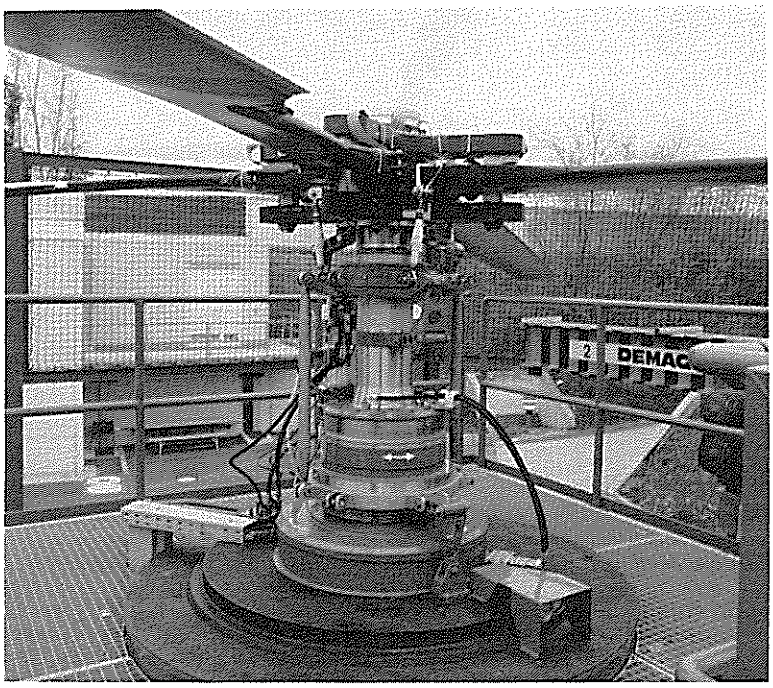


Fig. 3 MBB-RPS60, Blade Control System

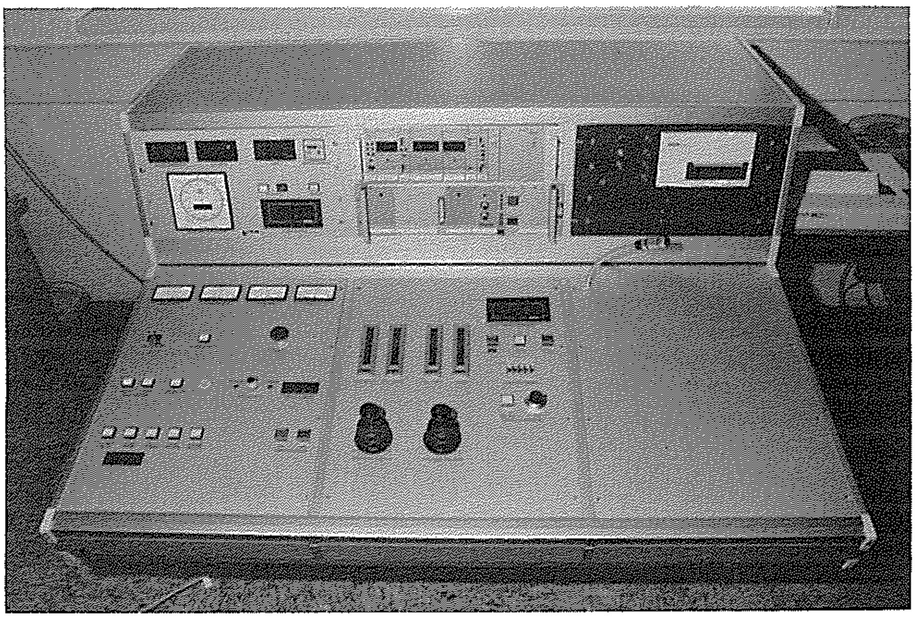


Fig. 4 MBB-RPS60, Control Panel

2.3 Drive system

2.3.1 Operating principle and limitations

The requirement for a stable speed behavior at fast changing torque and for adjustable acceleration and deceleration rates was satisfied by selecting an externally ventilated direct current shunt-wounded motor with separate supply of armature and field.
The rectifier for armature supply is constructed as a fully-controlled three-phase bridge. Separate thyristor bridges are installed for driving and deceleration.

Moreover torque controlling with limiting of the shaft torsional moment is performed and, if required, electrical damping of torsional oscillations is provided.

The following chart shows the main characteristics of the electric drive and supply system.

Converter-Transformer

Electrical power:	2200 KVA
High-tension voltage:	20 KV three – phase
Low-tension voltage:	770 V
Rated current:	2 × 1000 Amp

Prime mover

Power:	1230 kW
Voltage:	770 VDC
Current:	1600 Amp

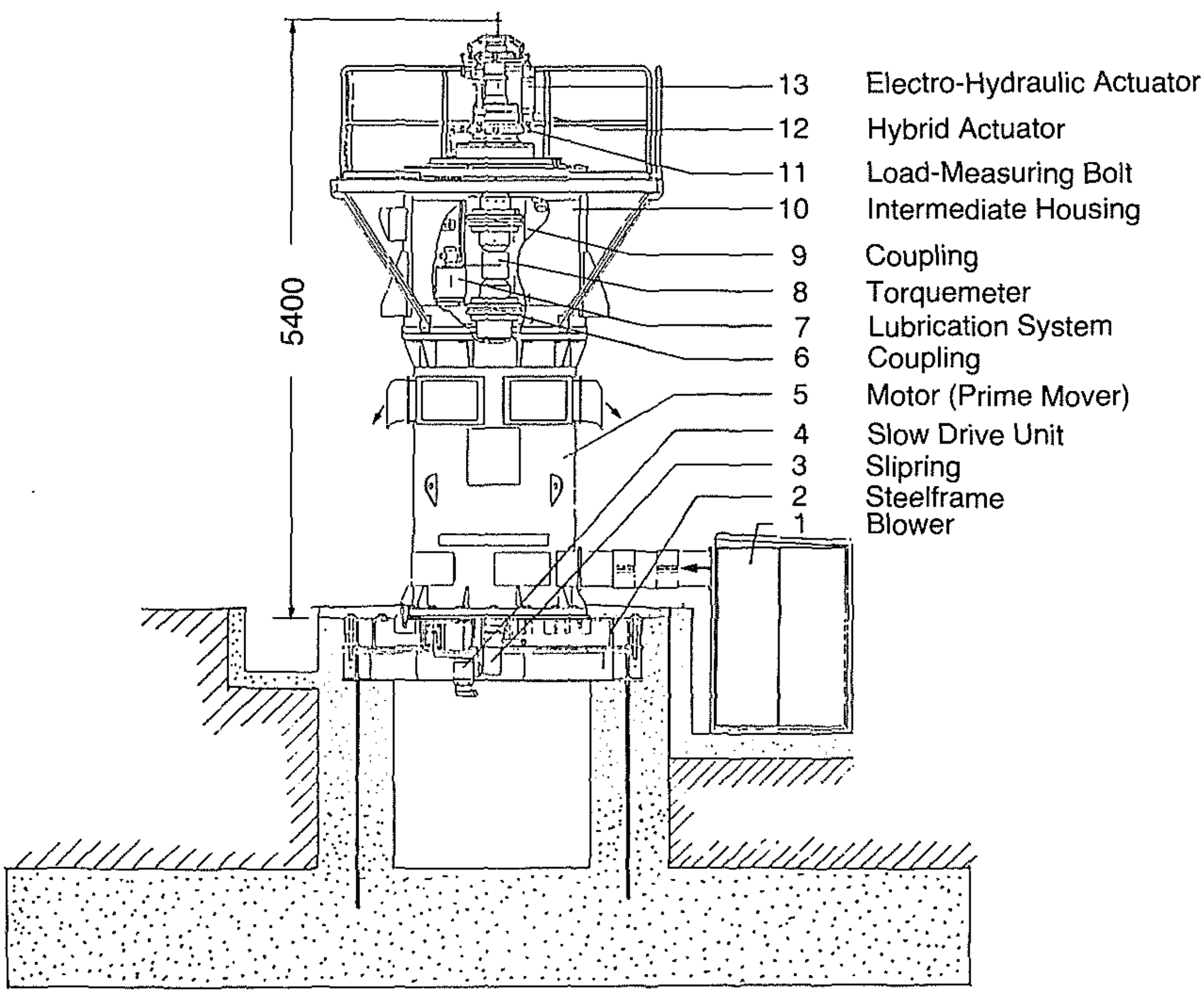


Fig. 5 60 KN-Rotary Test Rig

For safety reasons within the power/rotor speed range of the electric drive various operational limitations are established.
The sensors concerned are supplied by an **uninterruptable power supply** which provides protection against power failures.

	Type of limitation	Consequence at exceeding/failure
1	Starting torque, torquemeter-guided, adjustable with blackbox setting	No start
2	Acceleration torque, torquemeter-guided, slope and max. value black-box setting	Free wheel run-down
3	Torque limit, torquemeter-guided, adjustable with control potentiometer	Speed slows down
4	Armature current limit, rotortype-dependent, blackbox setting	Free wheel run-down (if limit (3) fails)
5	Second armature current safety limit, blackbox setting	No further speed increase
6	Max. armature current blackbox setting	No further increase of torque and speed
7	Deceleration torque limit, blackbox setting (activated by STOP)	Free wheel run-down (deceleration by current feed-back)
8	Speed limit, adjustable with control potentiometer	No further increase of speed
9	Speed limit, tachosignal monitoring, rotortype-dependent, blackbox setting	No further increase of speed (if limit (8) fails)
10	Speed limit (redundancy), pulse signal monitoring, blackbox setting	No further increase of speed (if limits (8) and (9) fail)
11	Vibration limit, oscillating signal by choice, rot.-type dep., adjustable	Free wheel run-down
12	Regulator voltage monitoring	Free wheel run-down
13	*Failure monitoring of up to 30 functions of motor & auxiliary systems*	*Warning only or free wheel run-down* with previous warning
R	Rotor run-up trend	–

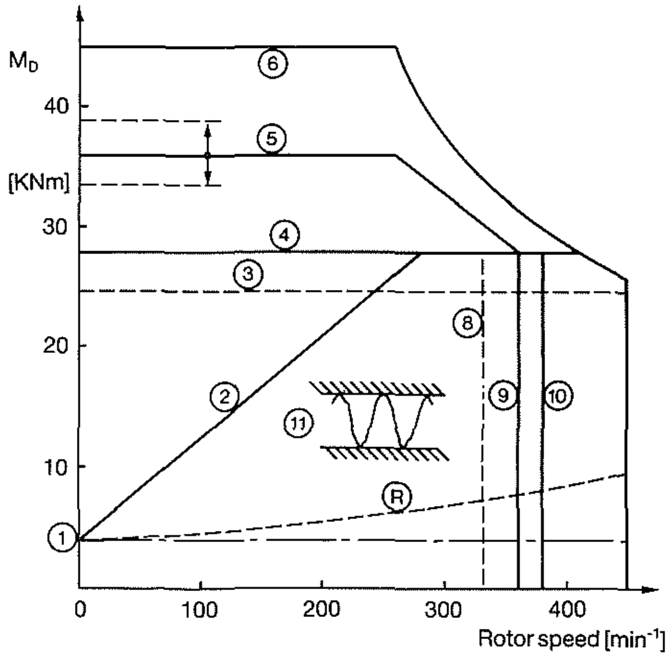


Fig. 6 Operational Limitations of the Prime Mover

Some of the limits can be adjusted from the operator's place by dial switch, but those which should not be changed during test sequence can be adjusted by black box setting at powerless condition only (Fig. 6). Figure 4 shows the control panel.

Oscillations of torque and rotor speed are very small, so that blade-dynamic measurements can be done without disturbances.

Deviation of rotor speed after a strong power increase or decrease is less than 1 % of the rated value.

Clockwise and counterclockwise rotational direction is possible.

Measuring lines coming out of the rotor run through the hollow shaft to the slipring, mounted below the electric motor.

2.4 Blade control and excitation

2.4.1 Collective pitch control

The collective pitch control (Fig. 7) is performed by moving the swashplate vertically with 3 booster rods, which are equipped with linear actuators (see 2.4.2.1).

The booster rods are connected to a nut; the vertical movement of this nut is produced by a frictionless and wear-resistant screw spindle, driven by a tooth gear (i = 0.176).
Because of the requirement for high repeatability and control-accuracy of the collective pitch (0.1 °) a backlash-free transmission was achieved by prestressing the nut.
The bevel gear for the drive of the screw spindle is driven by a variable three-phase asynchronous motor, which is equipped with a gear unit and a spring-loaded disk brake.

The rate of change can be controlled continuously between 0 and 1.2 °/sec.
The range of the collective pitch control depends on the rotor type and lies between -2 and + 18 °.

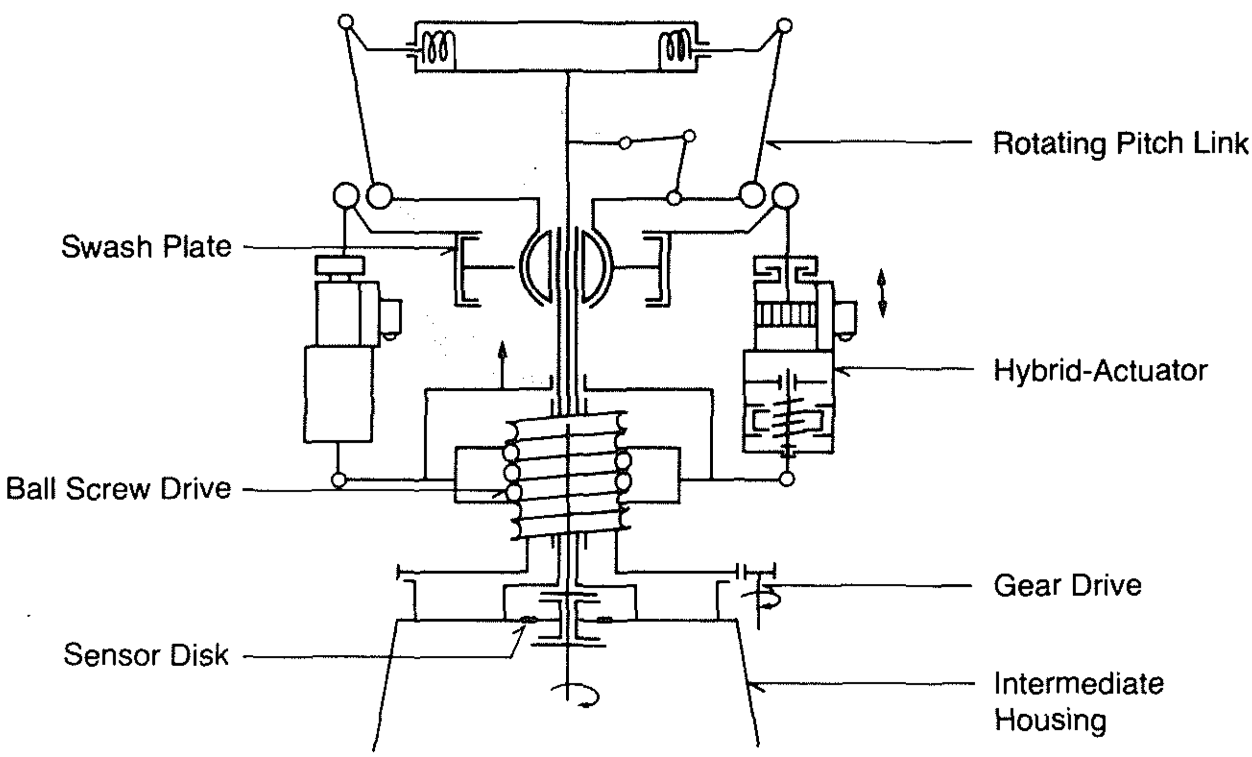


Fig. 7 Collective Pitch Control, Schematic

2.4.2 Cyclic control and excitation

Swashplate and threaded sleeve render two operation methods possible:

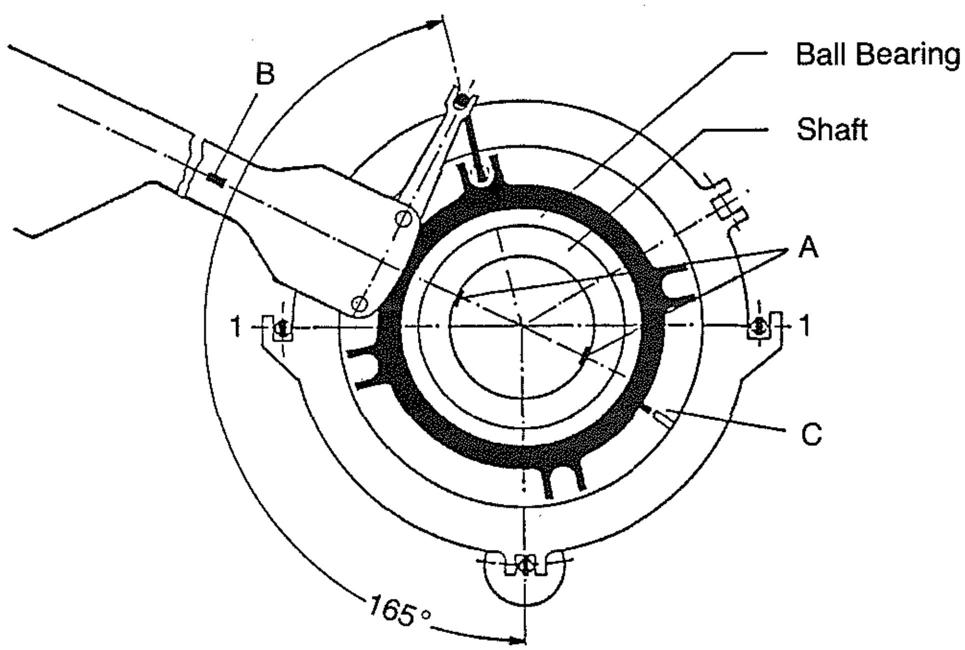
- 0/90°-support (monocyclic)
- 3 × 120°-support (multicyclic)

2.4.2.1 Monocyclic control inputs

- Principle of operation and experimental benefits

The non-rotating part of the swashplate is supported in a 0/90°-position by two rigid rods.

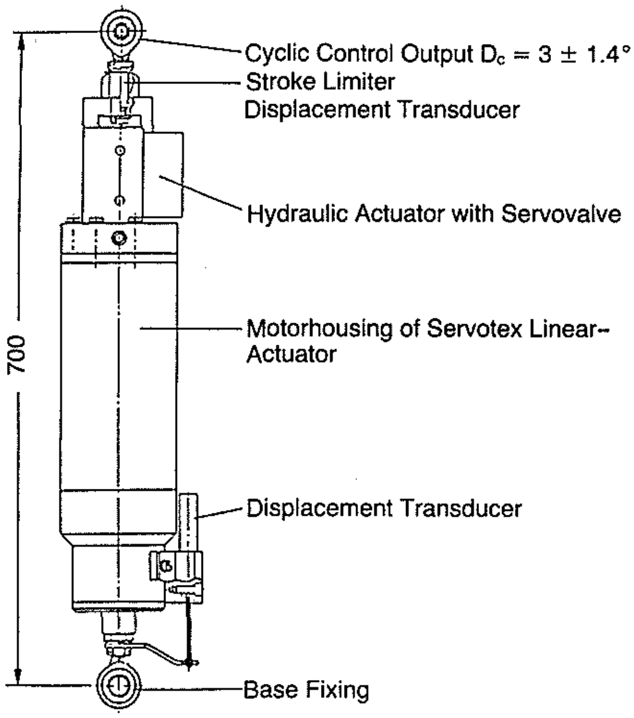
Swashplate tilting is accomplished by a hybrid actuator acting around axis 1-1.



A Measuring point of shaft bending moment
B Measuring point of flap bending moment
C Once-Per-Rev Pulse (striker)

Fig. 8 0/90°-Swashplate Support

This hybrid actuator (Fig. 9) consists out of a slow **electrical linear motor** with a self-locking ball screw drive flanged together with a dynamic electro-hydraulic actuator for small cyclic inputs.



Electro-hydraulic Actuator	
Piston area:	3.9 cm^2
Stroke:	8 mm
Response:	18 Hz/45° (at 3 dB)
Supply pressure:	160 bar

Linear Ball Screw Actuator	
Motor type:	DC-Motor
Supply voltage:	150 VDC
Current:	8 Amp
Velocity:	1°/sec/5000 N
Force:	10,000 N
Stroke:	35 mm
Accuracy:	0.05 mm
Control circuit:	High power pulse code modulation

Fig. 9 Design Data of the Hybrid Actuator

With the **electrical linear actuator** steady-state cyclic inputs up to 3° are applicated at different collective angles.
Blades are then in a forced flap excitation and are oscillating in resonance with the airloads in the first rotor harmonic (Fig. 10, 11, 12).

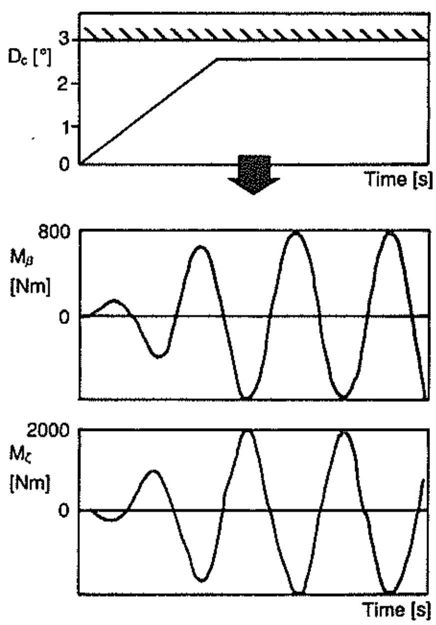


Fig. 10 Stationary Cyclic Input (Schematic)

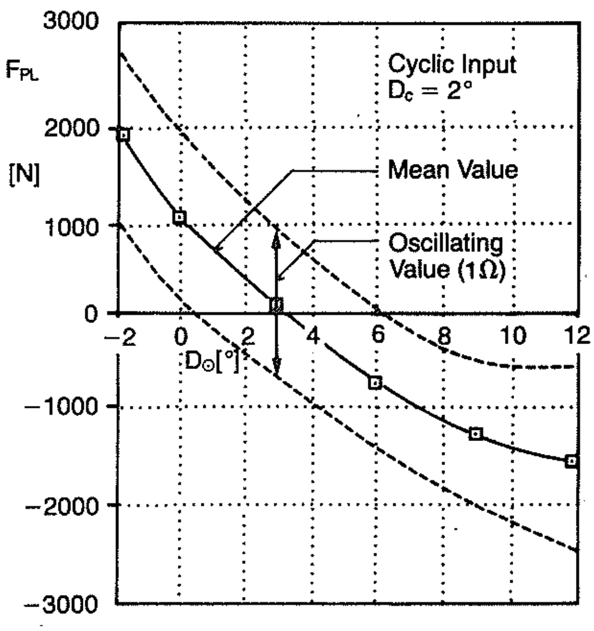


Fig. 11 Effect of Steady-State Cyclic Input on Pitch Link Load

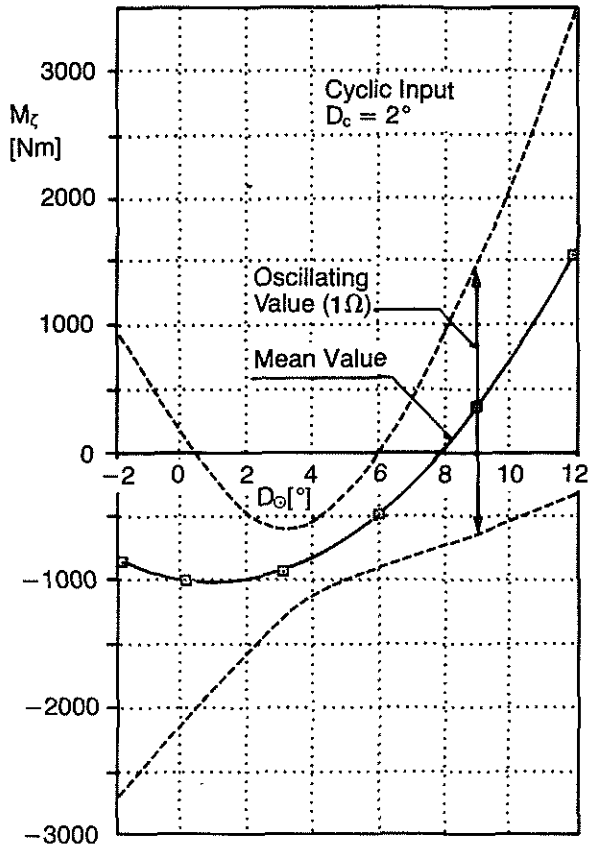


Fig. 12 Response of Inplane Bending Moment after a Steady State Cyclic Input of $D_c = 2°$

Analysis of these one-per-revolution-loads at the blade root and the shaft (Fig. 13) gives information about the handling and control qualities of the rotor system, especially the phasing between cyclic control input and flapping moment or the available control shaft moment and about stress loading of the blade structure, pitch links and booster rods.

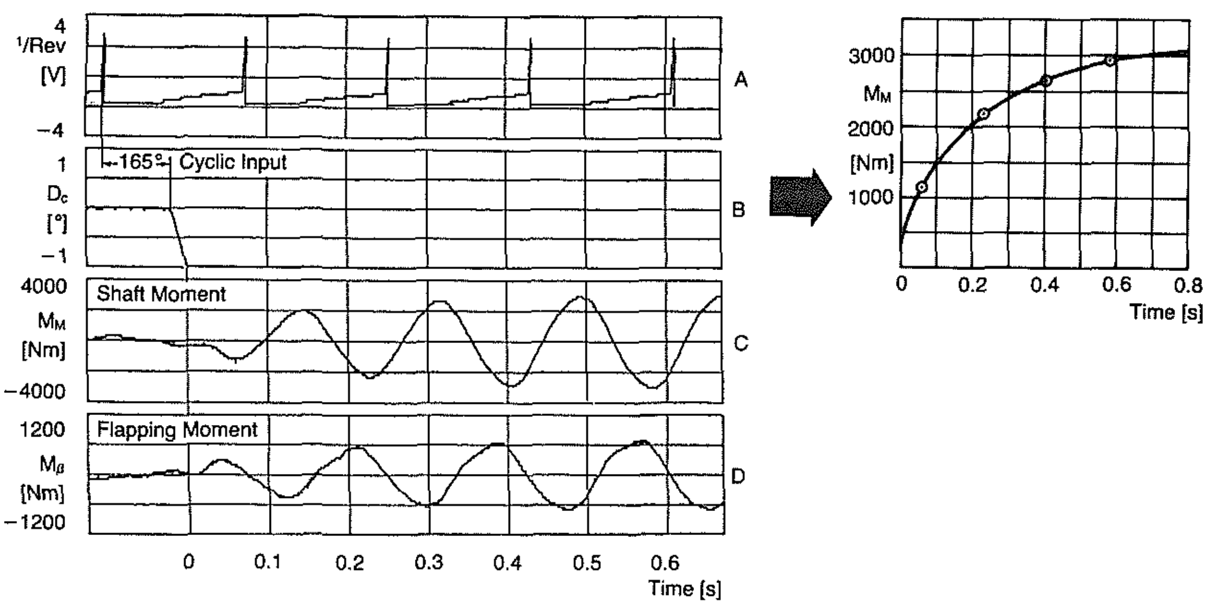


Fig. 13 Increase of Control Moment Owing to Cyclic Control Input of $D_c = 1°$

With the **fast electro-hydraulic actuator** periodical ($\Omega-\omega_\zeta$)-excitation of the first coupled regressing inplane mode of a blade is performed while rotor collective pitch is used to achieve desired thrust level.

Inplane damping is derived from the decay curve of the inplane bending moment after stopping the excitation and calculating the damping ratio by applying the logarithmic decrement technique to that trace (Fig. 14).

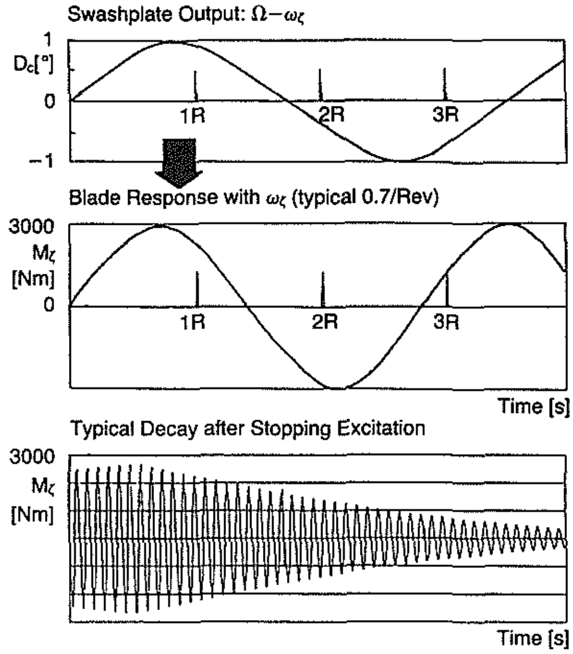


Fig. 14 Periodical Monocyclic Input and Decay of Inplane Bending Moment after Excitation.

Furthermore higher "rotating frequencies" from the blades can be examined up to the 3rd flap and the 2nd lag mode with this simple excitation technique.

2.4.2.2 Multicyclic control inputs

- Principle of operation and experimental benefits

The non-rotating part of the swashplate is supported in a 3 × 120°-position by 2 electro-hydraulic actuators and one hybrid actuator.

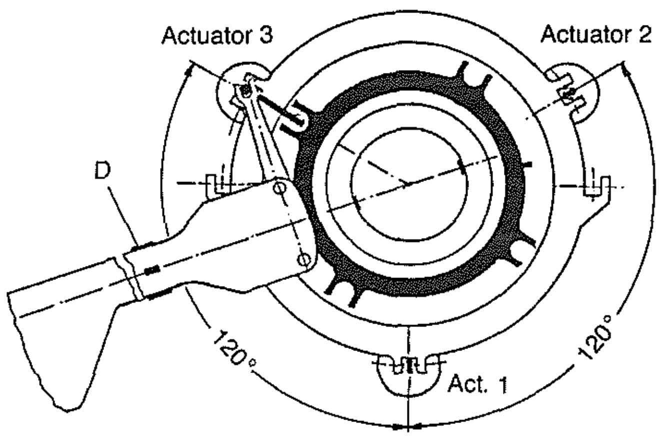


Fig. 15 3 × 120°-Swashplate Support

D Measuring point of lead-lag-bending moment

With this arrangement it is possible to excite not only the rotating natural frequencies and mode shapes of the single blades but especially the modes of the complete rotor.

By application of collective inputs with all 3 actuator outputs in phase 2nd and 3rd flapping modes can be measured at different collective pitch levels, if desired.

By application of swashplate inputs following phase-shifted actuator outputs ($\psi = 120°$) excitation and measuring of the 2 cyclic rotor modes (of 4 modes of a four-bladed rotor) can be performed.

a) Forward whirl mode (referring to the direction of rotor rotation), equivalent to the regressing mode in the rotating system.

   This motion is characterized by in-phase oscillation of opposite blades and the center of gravity rotates with a frequency of $\Omega - \omega_\zeta$.

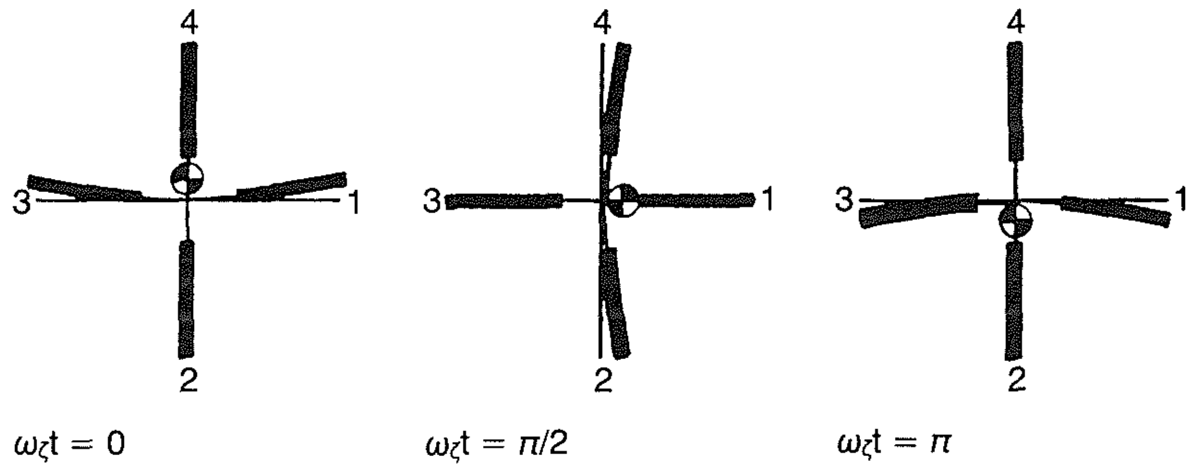


Fig. 16 Direction of Hub Center Whirling
(= Rotating Center of Gravity of the 4 Blades)

b) Backward whirl mode, equivalent to the advancing mode in the rotating system.
   This motion is characterized by the rotating of the center of gravity with a frequency of $\Omega + \omega_\zeta$.

   Examination of the zero mode (the collective rotor mode) is not interesting with reference to the occurrence of instability at air resonance, because all blades are oscillating with the same lead/lag-amplitude and same phase.

   The reactionless mode will also not be examined.

2.4.2.3 Actuator controlling

The 3 actuators are controlled by an actuator control processing system (ACPS) which provides the sine waves for the hydraulic actuator control.
It is based on a 16 bit microprocessor in conjunction with three digital memory-guided wave function generators. Their outputs are transmitted to the servo system of the electro-hydraulic actuators.

Single-actuator-operation (described in para 2.4.2.1) is possible as well as multicyclic operation with and without 120°-phase shift between the actuator.

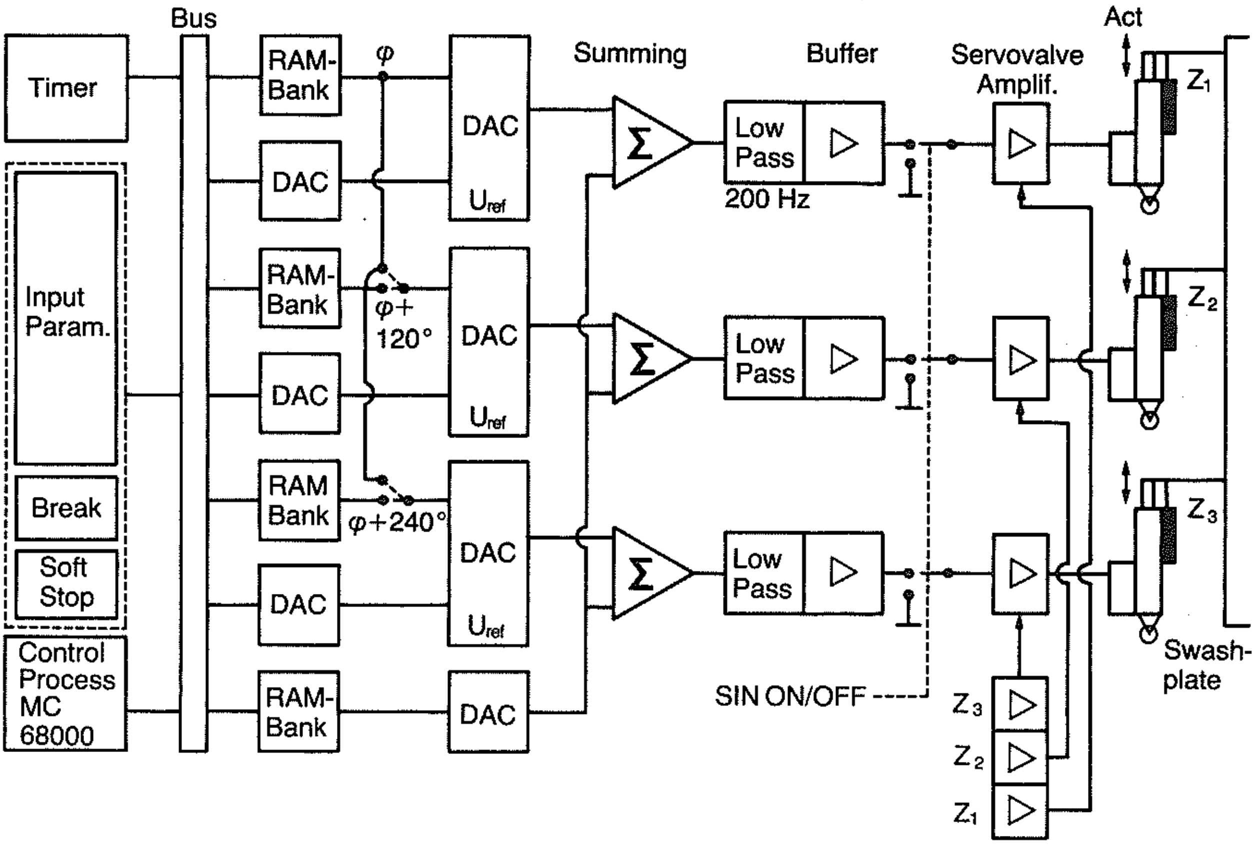


Fig. 17 Actuator Control Processing System

The sensors used to independently determine blade motions are usually strain gauge bridges attached at the blade root of all blades.
At the moment a practical, nearly on-line, solution of a multiblade coordinate transformation for investigation of the cyclic modes is under study.
This procedure is shown schematically in Fig. 18.

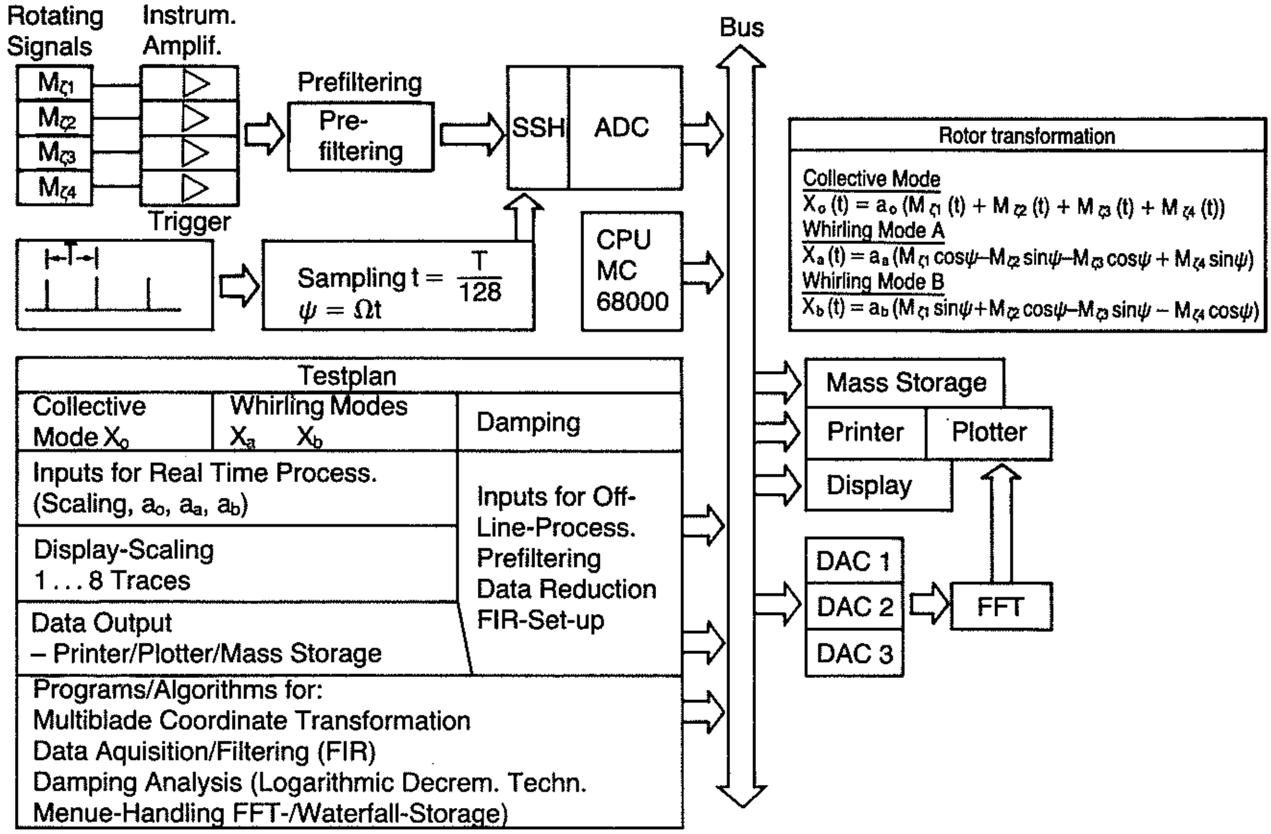


Fig. 18 Test Procedure for Investigation of Rotor Modes

2.5 Measuring equipment

2.5.1 Sensors

All sensing of blade loads as well as pitch link loads and shaft moment is done by strain gauges or strain gauge bridges.
Others like temperature, pressure, vibration etc. are measured with state-of-the-art transducers. The following sensor signals are of particular interest.

- Booster loads
- Rotor thrust
- Rotor torque

2.5.1.1 Booster loads

The booster loads are measured by strain-gauged load measuring bolts (VIBROMETER) (Fig. 19). They connect the vertically moving threaded nut (a) with the booster rods (b) and/or the hybrid actuator (c).

Measurement is achieved twice to get single rod signals (cyclic loads) and the combined signal (collective load).

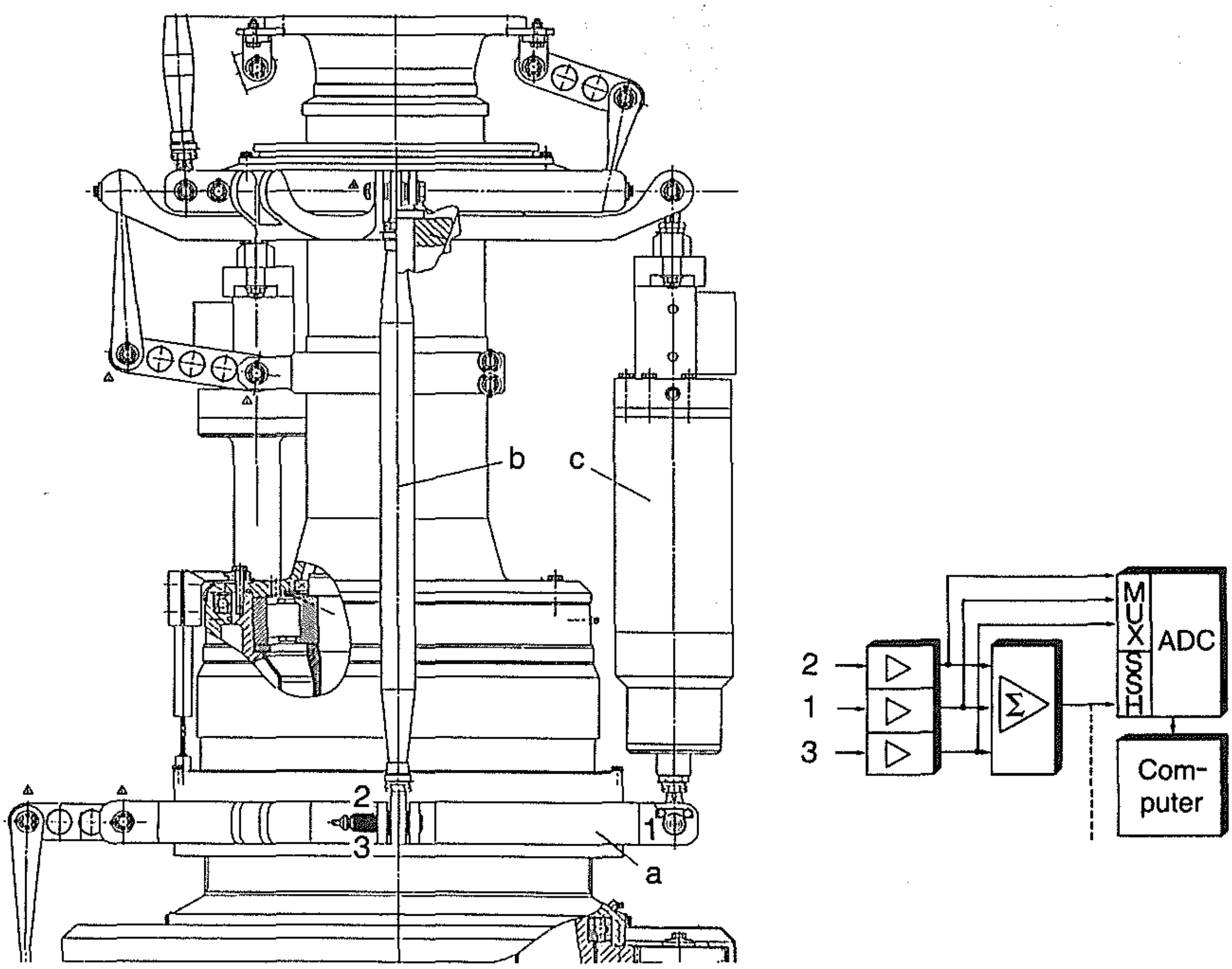


Fig. 19 Booster Load Measuring

2.5.1.2 Rotor thrust

Rotor thrust is measured by a complex sensor ring system (technical support by INA and Hottinger-Baldwin) which is integrated into the shaft bearing system.
Technical effort was relatively high because of the required linearity, small hysteresis and repeatability as well as low sensitivity to displacement due to change of temperature and due to deficient clamping stiffness.

Because of booster rod arrangement booster loads caused by aerodynamic forces and torsional spring forces will decrease or increase the vertical shaft load according to their direction so that they have to be added to the sensor disk signal with the correct sign. Summing of ($F_{B1} + F_{B2} + F_{B3}$) and adding to thrust T is performed in two ways: analog and by digital computation (Fig. 20).

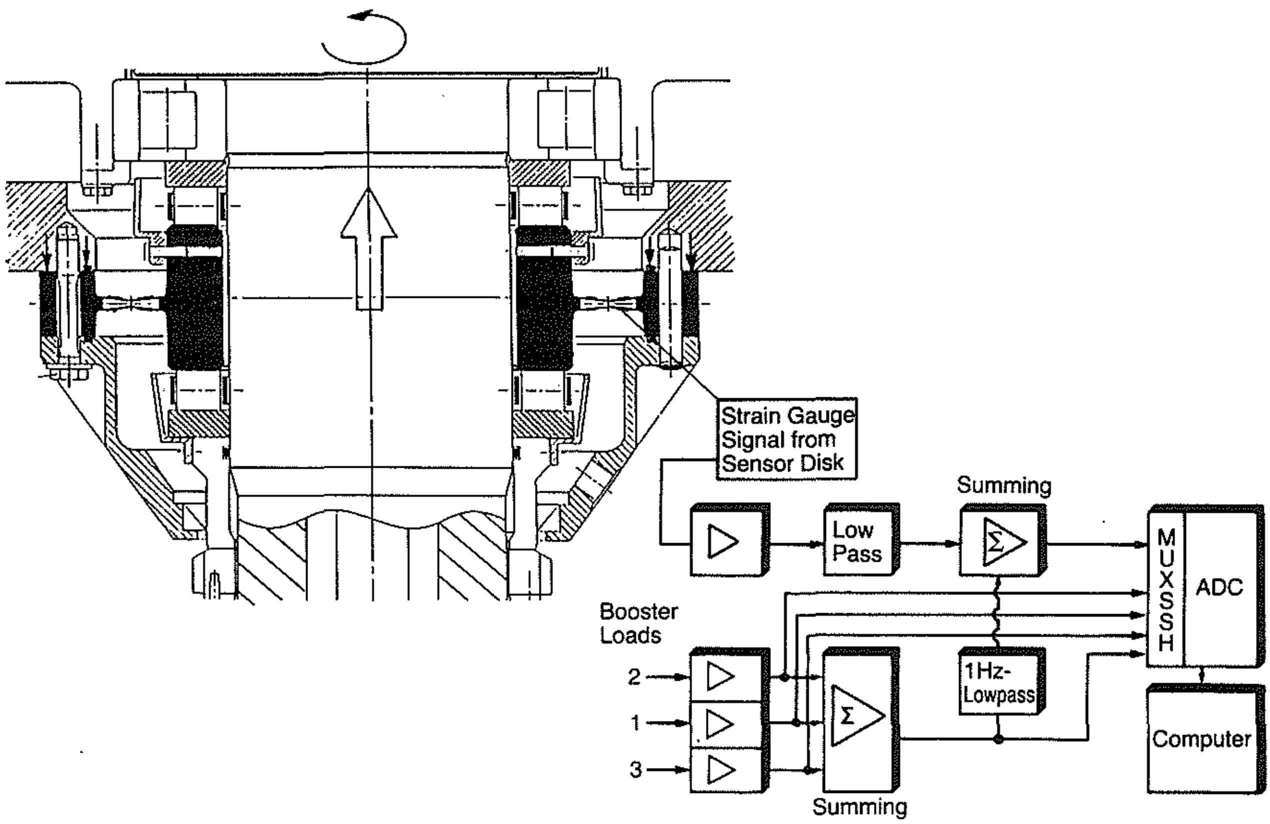


Fig. 20 Rotor Thrust Measuring, Data Aquisition

2.5.1.3 Rotor torque measuring

The applied torque measurement system (VIBROMETER) is a non-contact type which measures the rotational deflection of the power output shaft.
Nominal torsional moment is 50000 Nm.
The inductive bridge of the stator coil is supplied by a carrier frequency amplifier.
After demodulating and low-pass filtering and conditioning the signal output is proportional to the applied torque. The speed pick-up is integrated into the housing of the shaft torquemeter and consists out of a light source and a cam wheel. Pulses are produced by reflecting light and a phototransistor. After amplification and frequency/voltage converting the output can be used for analog multiplication with the torquemeter signal in order to get the shaft power.
Digital information of torque, rotational speed and power is provided.

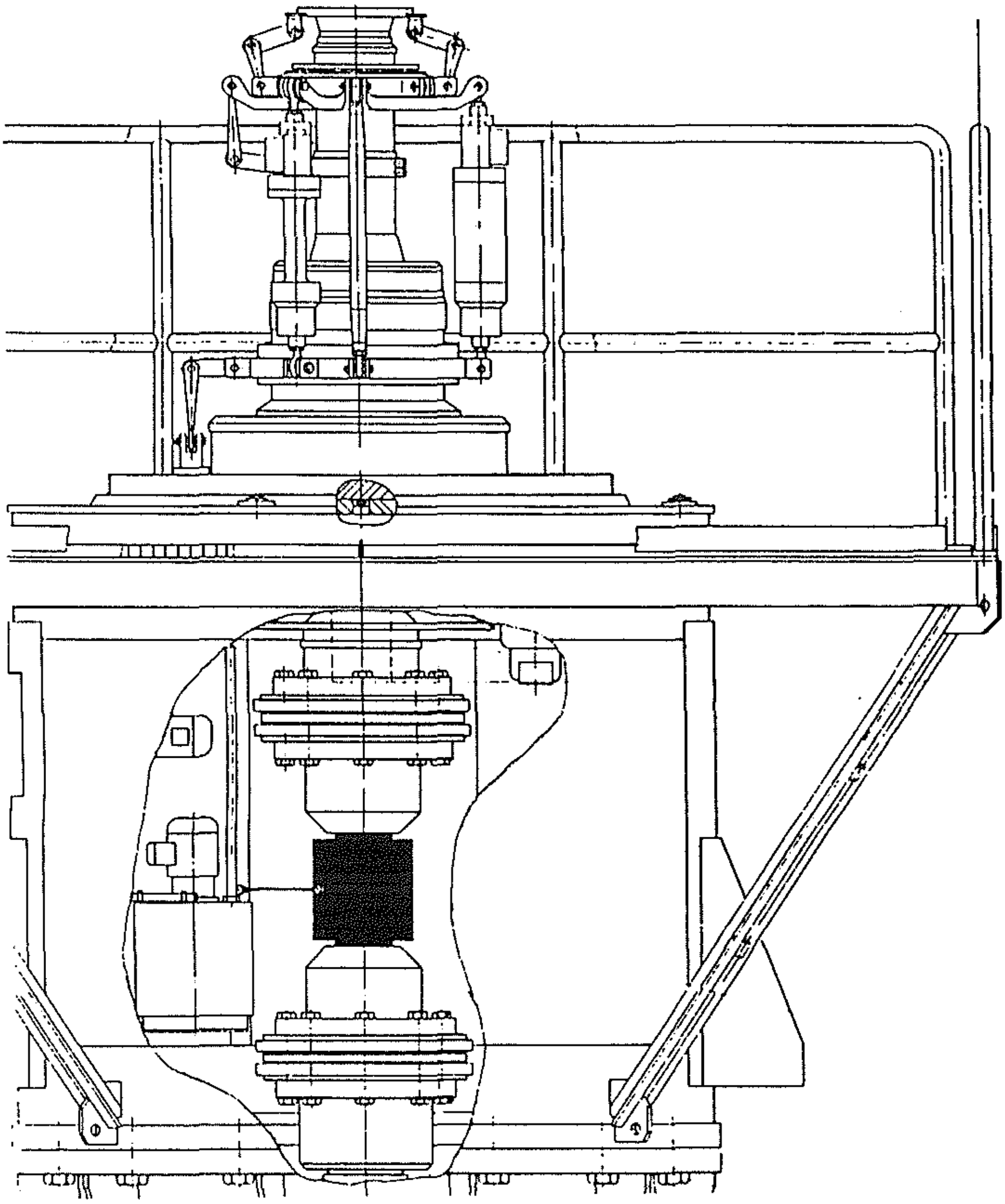


Fig. 21 Torque Measuring System

2.5.2 Measuring data aquisition and processing

Main parts of this system (Fig. 22) are:

- 64 sensor channels
- Signal conditioning system
- Differential amplifier system
- Analog data distribution, recording and indicating
- Programmable gain amplifier
- Data sampling and conversion
- Aquisition bus for input data control and monitoring
- Processing bus for data processing recording and data analysis and data output

Signals from the rotating system are transferred by a slipring with 120 channels mounted below the motor.

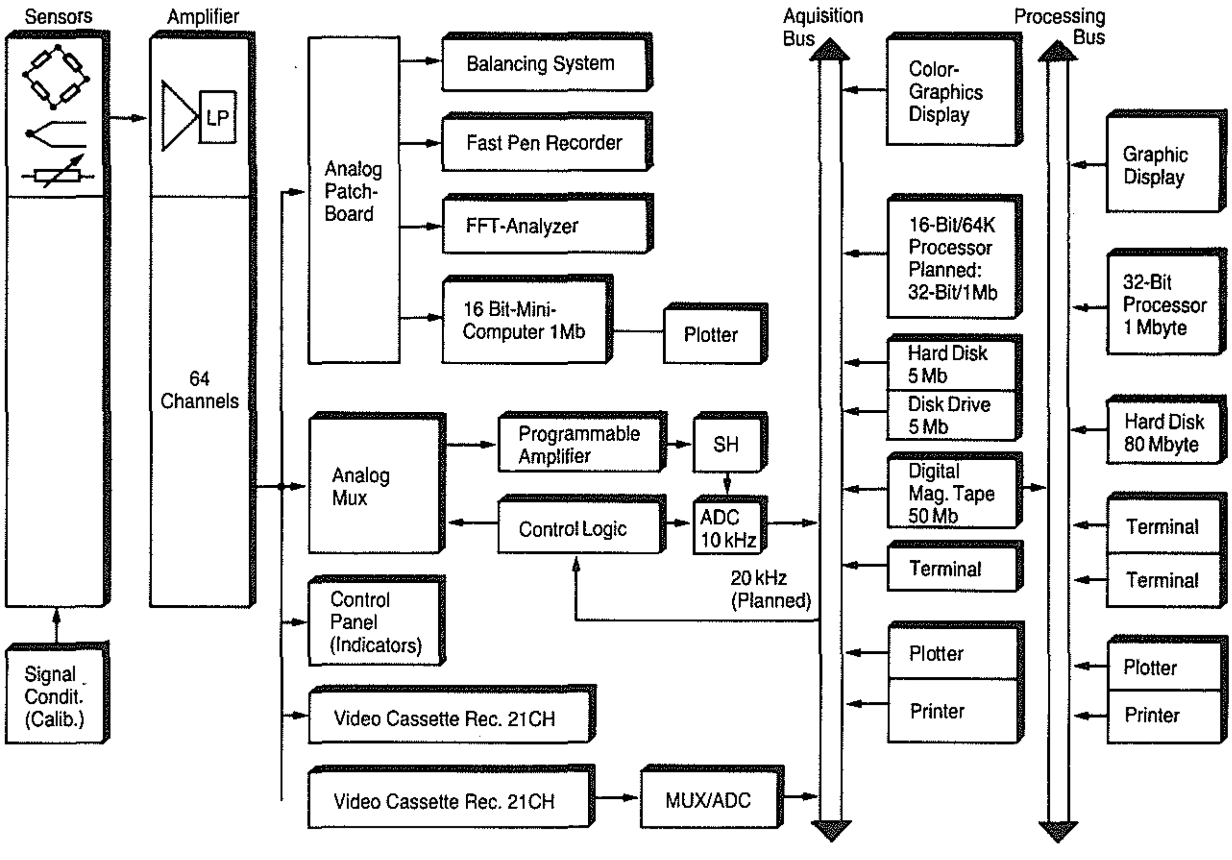


Fig. 22 Block Diagram of Data Aquisition and Processing System

2.5.3 Tracking and balancing system

For the measuring of track, lead/lag and vibration (for balancing) the Rotor Analysis Development System (RADS/Stewart Hughes) is used (Fig. 23).
This system is based on a passive optical sensor which operates in the visible part of the electromagnetic spectrum. It consists of a focused lens, two narrow-beam directional photodiodes, an analog processing module and a pulse generator.
The image of a passing blade overhead is focused onto the photodiodes and prevents light from reaching them. Whenever the ABT detects a significant change in the level of light it generates a timing pulse to the DAU.

Output displays (for a specified number of revolutions) are

- Absolute track (above ABT)
- Relative track (blade displacement relative to mean track)
- Track relative to blade 1
- Absolute lag angle [degree]
- Relative lag [mm]
- Vibration, amplitude and phase [ips, deg]

Steady-state measurements and run-up (transient) measurements can be done and results are recorded and/or displayed in a graph, polar plot or table.

Technical data of RADS

• Input	up to 2 accelerometers up to 2 velocity pick-ups one magnetic pick-up
• Tracking accuracy	± 2 mm
• Lead/lag accuracy	± 0.2 mm
• ABT measuring point	1.5 to 5.0 m

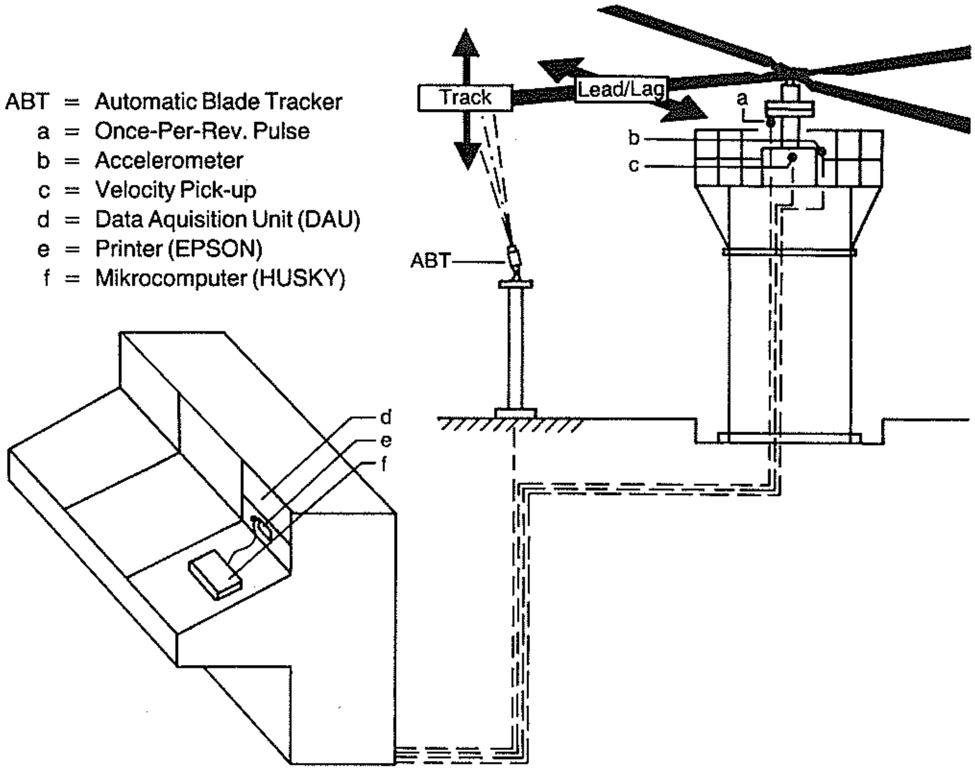
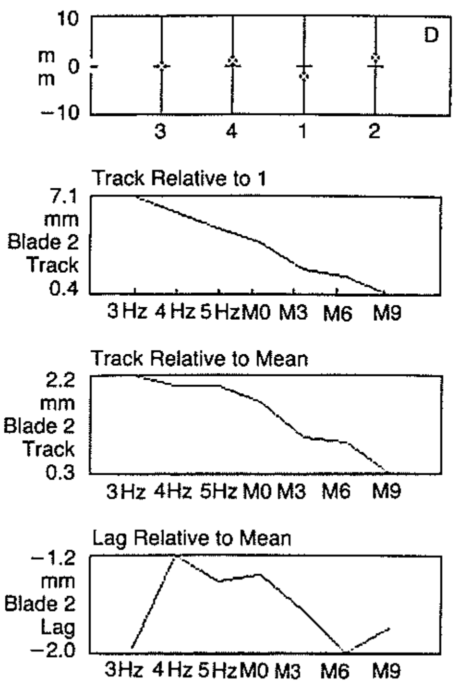
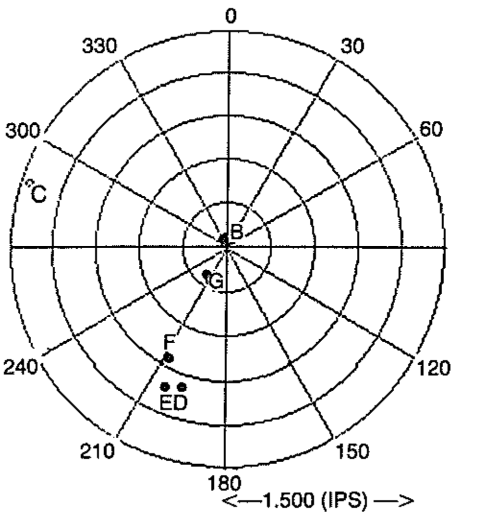


Fig. 23 Rotor Analysis Development System
(RADS, Stewart Hughes)
Installation Principle for Track and Lead/Lag Measuring and Balancing





MBB2 WT2 02-12-1988 Sortie 9

Main Rotor 1R RMS Vibration
Channel: 4

Test	ID	Amp	Phase (IPS/DEG)
3 Hz	A	0.051	270
4 Hz	B	0.058	0
5 Hz	C	1.439	288
M0	D	0.909	197
M3	E	0.946	203
M6	F	0.778	207
M9	G	0.207	217

Vibration Diagnostics

CH4:	Balance (GMS)			
	3	4	1	2
3 Hz	*	*	*	*
4 Hz	*	*	*	*
5 Hz	0	0	13	0
M0	0	0	0	8
M3	0	0	0	8
M6	0	0	0	7
M9	0	0	0	2

Fig. 24 Track/Lag- and Balancing Polar Plot during Run-up and Steady-State at Different Collective Pitch

3. Outlook

After confirmation that the performance requirements of the rotary test rig had been fulfilled, measurements with the experimental prototype rotor of PAH 2 are still in progress.
Within the ALH and PAH 2 programs the next generation of rotor systems are to be examined very soon. More detailed results will be published in a subsequent paper, covering more aspects of the multicyclic excitation technique.

4. References

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