Design and First Tests of Individual Blade Control Actuators

Peter Richter and Hans-Dieter Eisbrecher
Henschel Flugzeug-Werke, Kassel, Germany
Valentin Klöppel
MBB, Munich, Germany

Abstract

In order to increase the helicopter's share in future air traffic, its efficiency, reliability and its public acceptance have to be improved. Using modern technologies it is possible to reduce weight, power requirement, noise, pilot's workload and maintenance efforts and to increase comfort and flight envelope. One tool to realize a relevant part of these goals is the Higher Harmonic Control HHC, but it is only possible to superimpose some selected harmonic functions to the 1/rev input. By means of a new control system using actuators between swashplate and rotor blade the total range of superimposition from single-harmonic-control up to individual-blade control can be opened.
HFW designed such a new control system. Tests were carried out on test benches and on a whirl tower before flight tests on a BO 105 started. The results of these tests are shown and an outlook to the planned program continuation is given.

1. Introduction

In order to keep or even increase the helicopter's share in today's and future air traffic, its efficiency, reliability and its public acceptance have to be improved.

There are several modern technologies at hand to reduce weight, power requirement, noise, pilot's workload and maintenance efforts and to increase comfort, safety and flight envelope. One promising tool to realize a relevant part of these goals is the "Higher Harmonic Control" (HHC).

The results obtained with this technique up to now, in particular vibration and noise reduction, show that the conventional control has to be extended in order to exploit the full potential of future helicopters (Ref. 1, 2. 3).

The different Higher-Harmonic-Control-Systems designed and tested during the last years, were installed below the swashplate. With the exception of three bladed rotors, all these arrangements, Fig. 1.1, had the handicap, that by reason of the transferfunction of the rotating swashplate only some selected harmonic functions could be superimposed on the 1/rev input (Ref. 4).

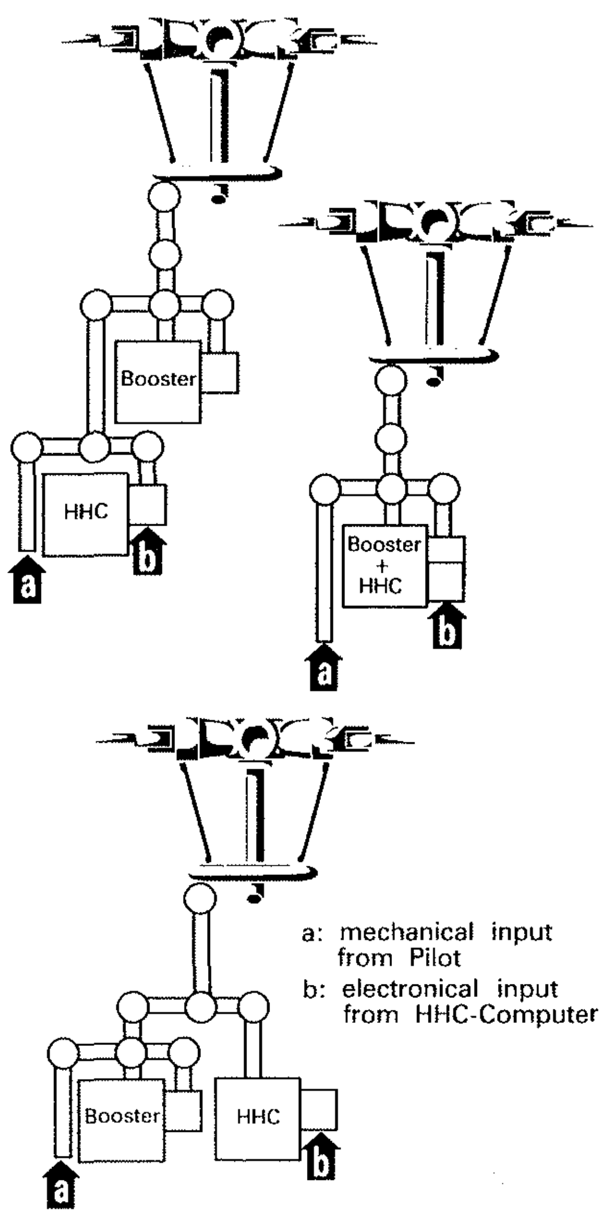
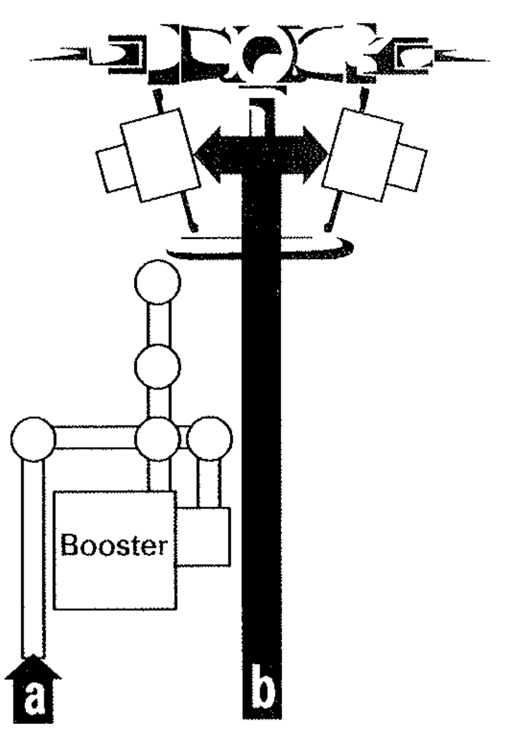


Fig. 1.1 HHC Arrangements

On this background HFW designed a control system featuring actuators installed between swashplate and rotor blade, Fig. 1.2. This installation opens the total range of superimposition, from single-harmonic via multi-harmonic to individual-blade-control (Ref. 5).



a: mechanical Input from Pilot
b: electronical Input from IBC-Computer

Fig. 1.2 IBC Arrangement

The development of this new control system started in 1985, first flight tests were carried out in March 1990 on a MBB BO 105, Fig. 1.3.

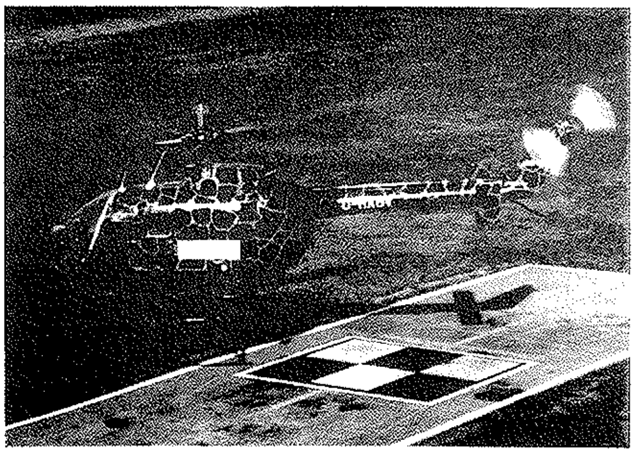


Fig. 1.3 BO 105S1 during first Flight Tests

2. Individual Blade Control

The useful maximum speed of helicopters is limited by rotorinduced vibrations and by the efficiency of the forward flying main rotor. Vibrations and efficiency depend on non-optimized pitch angles relative to the momentary air-flow direction and speed and on the blades' dynamic behaviour. To counteract these effects it is advantageous to control the pitch angle in a more favourable way. The advantages of such an improved pitch angle control system are expected to be increased performance and flight mechanic stability and a lower level of vibration, noise and pilot's workload.

Different system configurations have been developed and tested within the last decade. Generally two types of systems must be distinguished, the HHC systems that work below the swashplate and the IBC systems that work above the swashplate in the rotating system.

IBC-Sytems allow the correction of pitch angle not only at selected harmonic frequencies but depending on the actuators' frequency range also arbitrary control functions can be realized. Such a system allows to increase the flight enve lope of modern helicopters in differnt ways. Stall flutter max be controlled by a disturbance rejection controller (see Fig. 5.1) by use of notches for the blades' first natural torsion modes.

The required power is reduced by a redistribution of the thrust with respect to the rotor disk. Fore and aft areas of the disk, featuring favourable flow velocities, are loaded more intensely, showing characteristics of a 2/rev control.

Vibrations and noise are usually compensated in the case of a four-bladed rotor by 3-, 4- and 5/rev inputs.

The appearance of stall or its negative effects, which increase vibrations, noise and pilot's workload and decreases the flight mechanic stability, can be forced back by specific blade reactions such as described in Ref. 3.

3. Technical Description of the IBC-System

HFW started the development of this new control system in 1985. The control system, Fig. 3.1, consists of

- the hydraulic actuators
- the actuator control
- the hydraulic power transmission
- the data transmission
- the safety control.

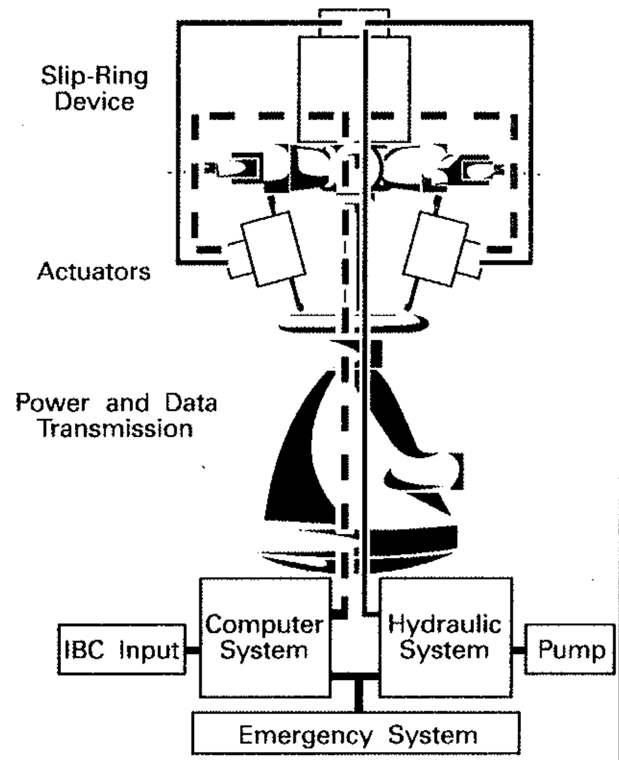


Fig. 3.1 IBC System Configuration

The actuators are installed between swashplate and rotor blade, hydraulic power and data are transmitted via slip-ring devices through the rotor mast from the non-rotating system to the rotating system, actuator control and safety control are installed in the cabin.

The program was started by constructing independently controllable, trimmable control rods in order to improve recognition of dynamic and aerodynamic blade irregularities (Ref. 6). The external force impacts as exerted on these trimmable control rods during flight tests were a first data base for the development of the IBC actuators, Fig. 3.2.

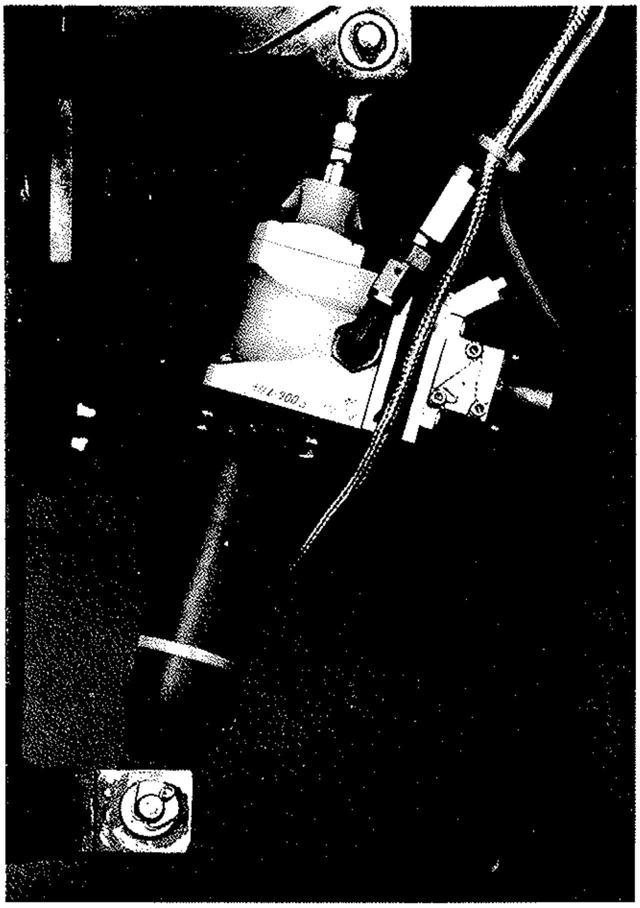


Fig. 3.2 IBC Actuator

An actuator stroke of 30 mm respectively 10 degrees of pitch angle on a BO 105 was initially assumed for IBC puposes. For construction of a trial installation for rig tests, the authority was limited to 25 mm. The stroke of the actuator is controlled by a Moog servo valve. The actuator was designed to cope with the centrifugal force involved. An innovative control means was constructed to meet the special operating conditions, Fig. 3.3 and 3.4.

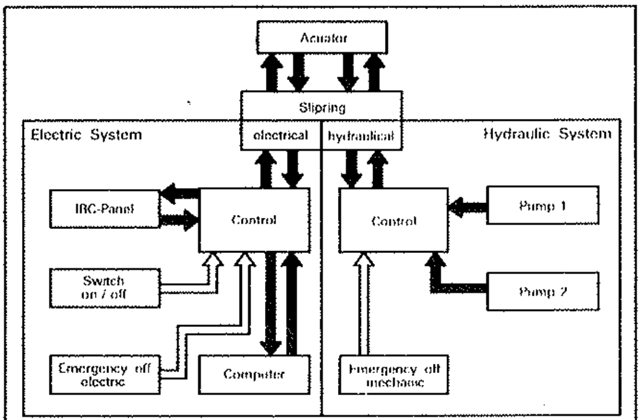


Fig. 3.3 IBC-Control-System

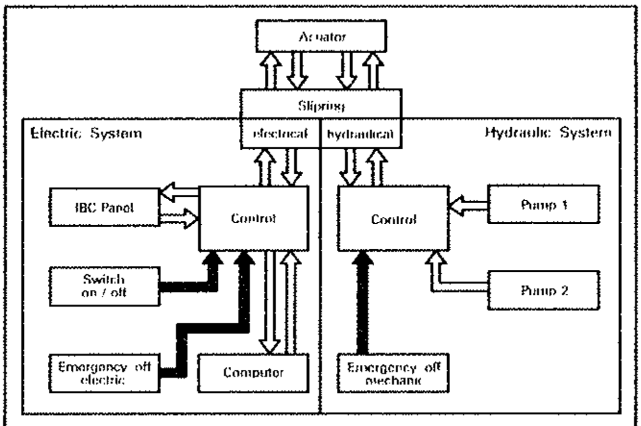


Fig. 3.4 Shut-Off-System

Based on the overall satisfactory results achieved on a test stand, the actuator and the control unit were refined and extended in several stages. Final trials showed a quasi-stationary control operation to be possible with an adequate degree of accuracy, even when the actuator was exposed to high control forces. The final version of the actuator was equipped with an experimental fail-safe-provision which neutralizes the actuator in case of malfunction.

4. Tests and Results

4.1 Rig tests

The actuators and the complete system were tested at HFW's test stand under realistic conditions. Fig. 4.1.1 shows a test - installation on the new BO 108 main gear box FS 108. These tests were part of the development and basis of the acceptance procedure to get this new system to first flight tests. By this all possible operating conditions were simulated.

Single-harmonic control at 2-, 3-, 4- and 5/rev. was tested to get detailed informations about

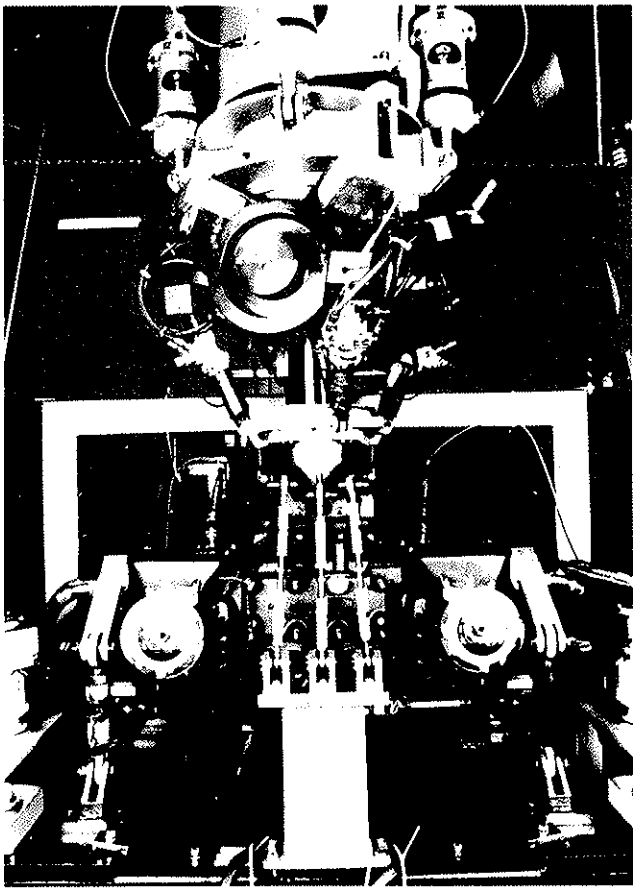


Fig. 4.1.1 IBC System on a Test Rig

the transfer-function of the actuators. Multi - harmonic control was tested intensively to simulate normal flight conditions and to check the system's behaviour in long time tests. Last but not least emergency procedures were simulated. The behaviour of this new system was totally satisfying, Fig. 4.1.2, so that the next step of tests could be started at MBB's in Ottobrunn. For these tests the system was installed on the main gear box of the BO 105 S1 chosen for later flight tests.

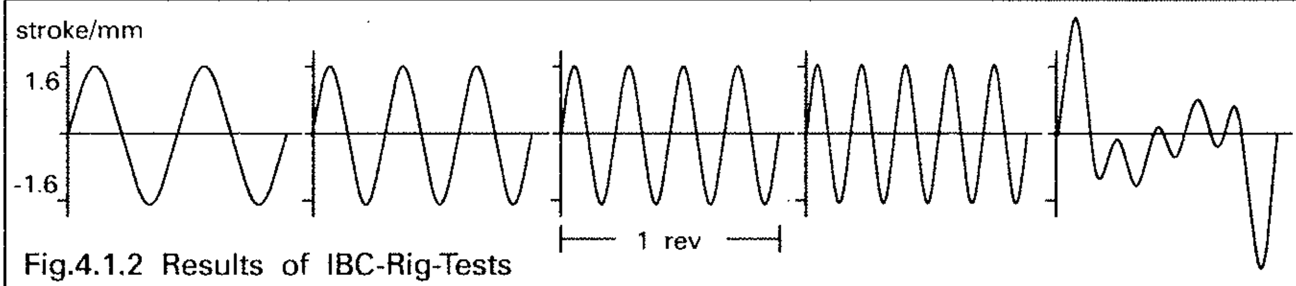


Fig.4.1.2 Results of IBC-Rig-Tests

4.2 Whirl Tower Tests

By whirl tower tests with a BO 105 rotor, Fig. 4.2.1 and 4.2.2, the complete new technology including technical reliability, functional characteristics, vibration reduction potential, emergency procedures and run-aways were validated successfully with a HHC authority of $\theta_{HHC} = 1.4°$.

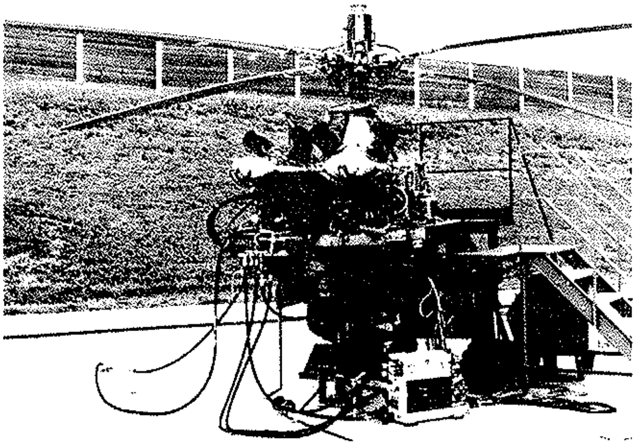


Fig. 4.2.1 IBC System on the Whirl Tower

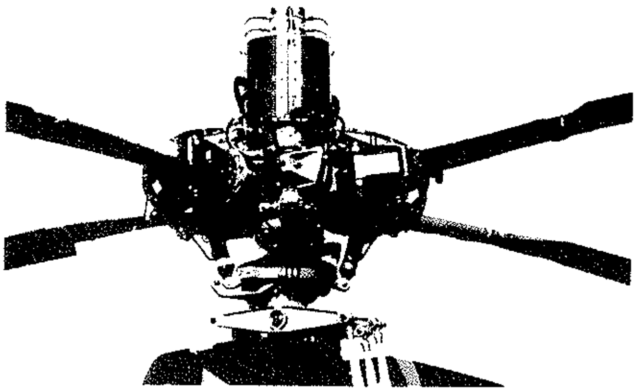


Fig. 4.2.2 Main Rotor with IBC Actuators

The potential of the HHC-System to influence the vibratory characteristics of a BO 105 rotor is demonstrated in Fig. 4.2.3. The Fig. 4.2.4 illustrates the 5/rev response of the blade root moments in flap, lead-lag, and torsion on a HHC input of $\theta_{5\Omega} = 1.4°$.

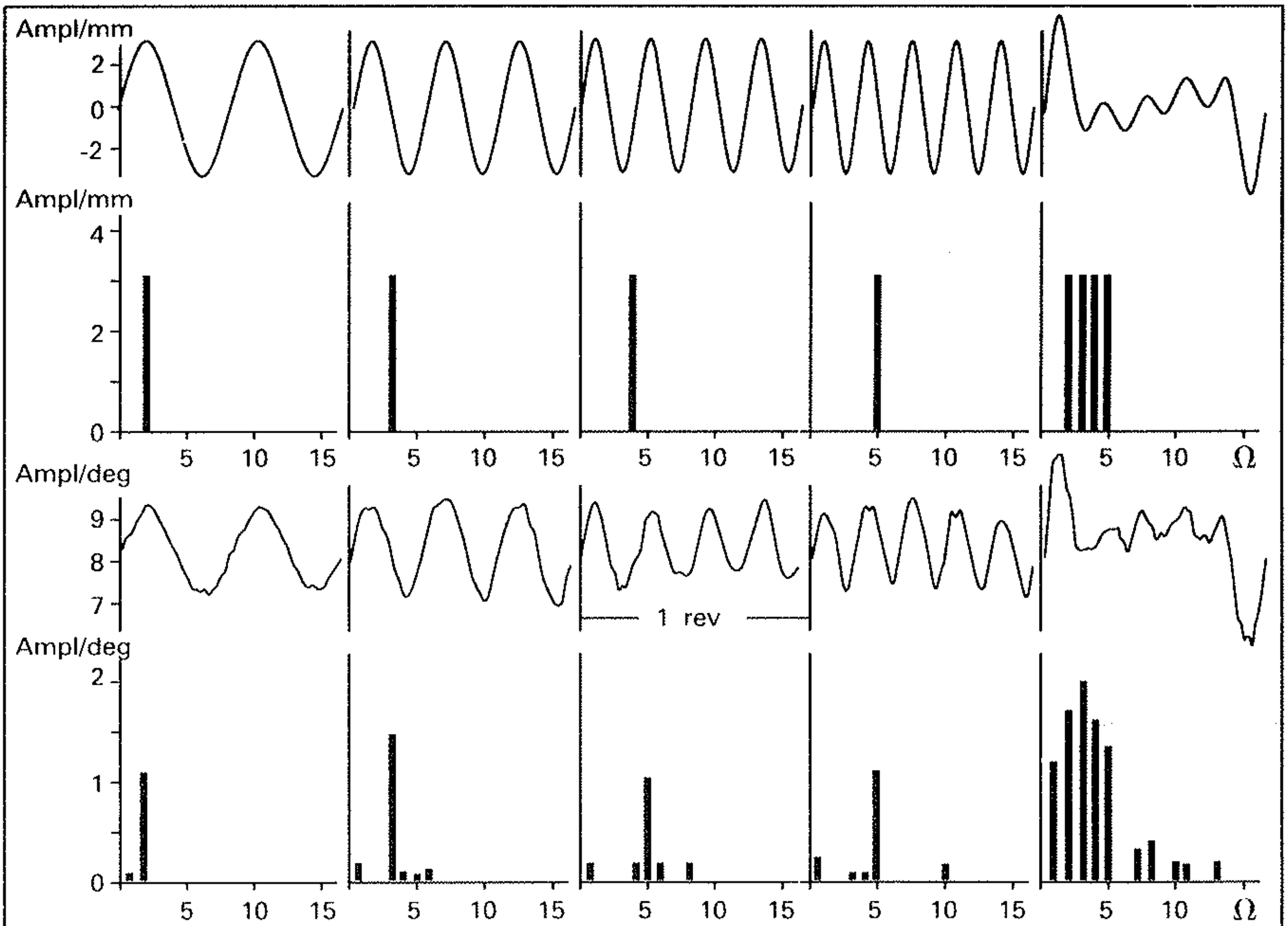


Fig. 4.2.3 Actuator Stroke (top) and Pitch Angle during Whirl Tower Tests

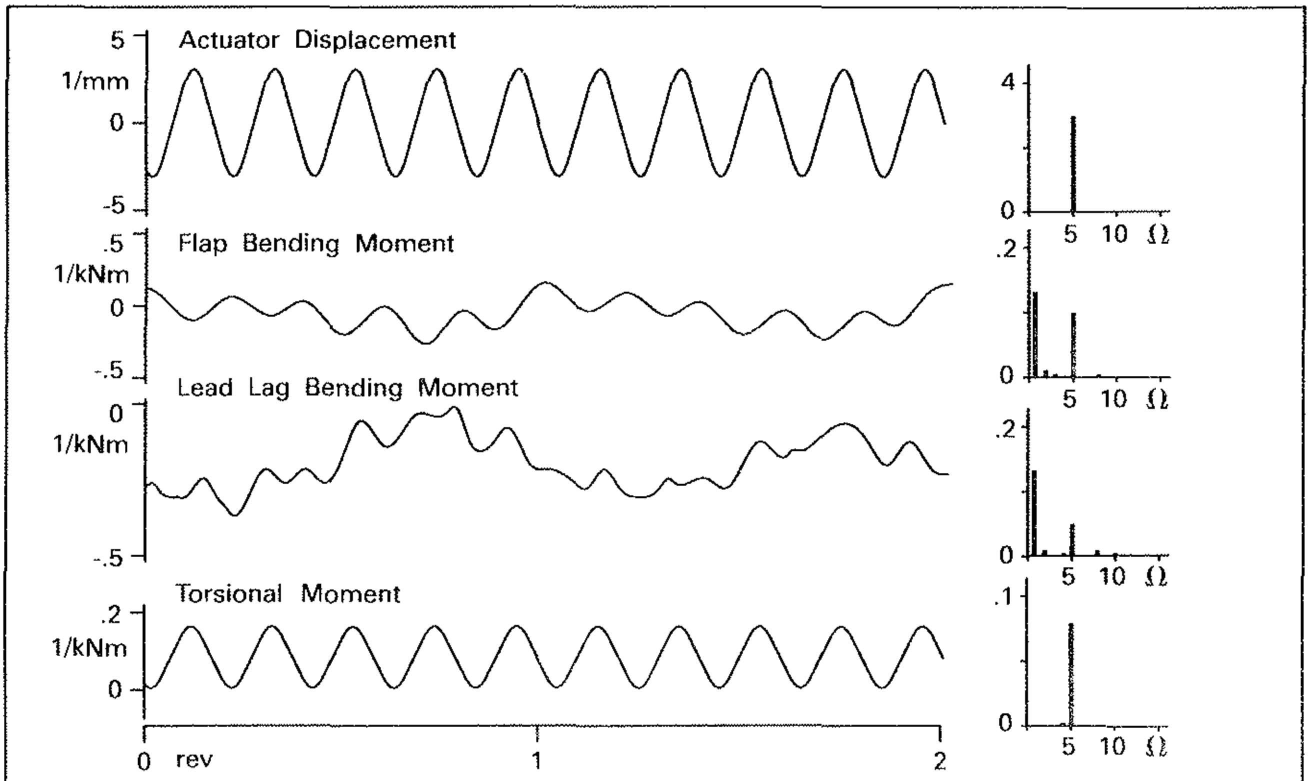


Fig. 4.2.4 System Responses at 5/rev Inputs

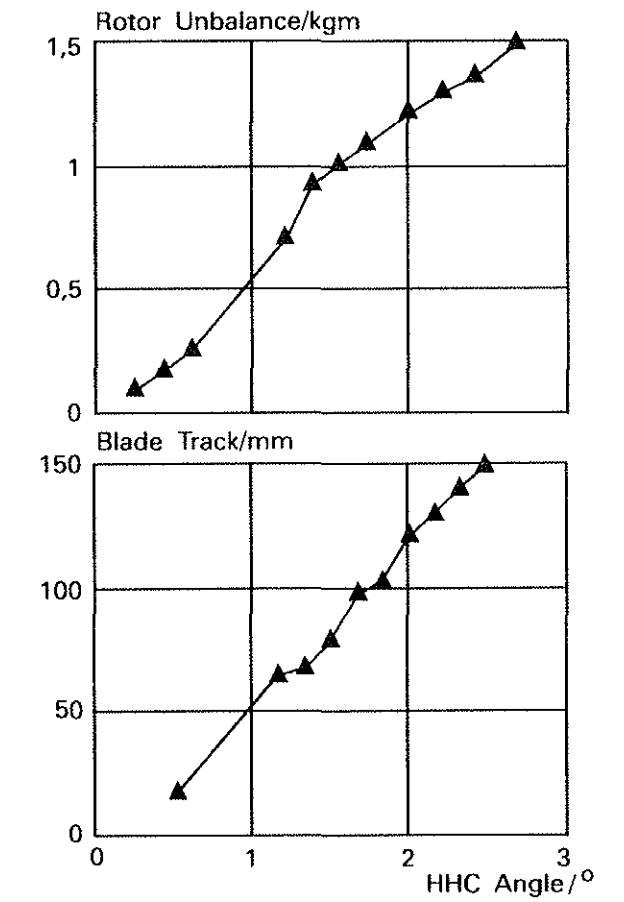


Fig. 4.2.5 Results of Run-Away-Tests

The control system's unique capacity to individually run every actuator bears the danger of arbitrary motions of all blades in case of a malfunction of the feedback and supervisory control system. Therefore run-away tests near 1g thrust with an authority of $\theta \approx 2.5°$ were conducted, leading to a tracksplit of $\Delta Z \approx 150$ mm and an unbalance of $M_u \approx 1.5$ kgm, Fig 4.2.5, corresponding to a balancing weight of $m_{bal} = 4$ kg in the blade attachment bolt ($r_{bolt} = 372$ mm). The BO 105 balancing allows for a range of $m_{bal} = 100$ gr (tolerance) to 300 gr. Nevertheless no load limit was exceeded.

4.3 Flight Tests

Fig. 4.3.1 BO105S1 during Pre Flight Check

The flight tests, Fig 4.3.1, started with an IBC authority of 0.16° due to safety reasons.
Fig 4.3.2 illustrates the measurement and control equipment.

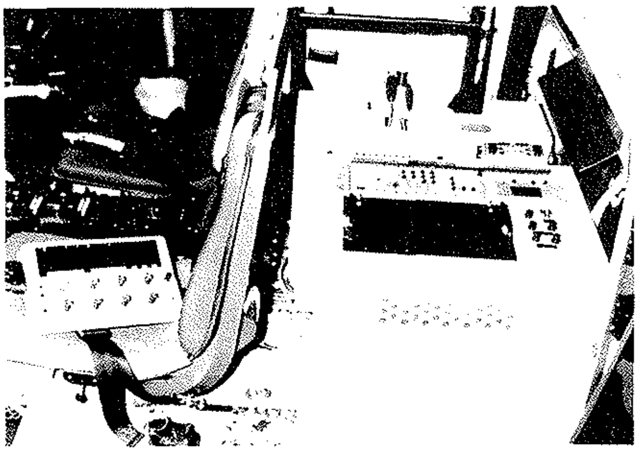


Fig. 4.3.2 Measurement and Control Equipment

Due to the limited flight time available, the flight tests implied vibration reduction by HHC inputs. This task doesn't require individual blade control as it can be accomplished by HHC inputs in the fixed system. However this way of testing allows for a well viable function test of the entire system subsisting in hingeless rotor and IBC.

Due to the low higher harmonic control authority no significant influence on cabin vibrations could be expected. Nevertheless trends of such an influence could be made visible by a variation of the higher harmonic control phase ϕ, the relationship between higherharmonic pitch θ_{HHC} and ϕ being:

$$\theta^{*} = \theta_{HHC} \cos(n\,\omega t - \phi)$$

with

θ_{HHC} = HHC amplitude
n = order of control harmonic

Fig. 4.3.3 illustrates the characteristics of the vertical 4/rev cabin vibrations for the following conditions:

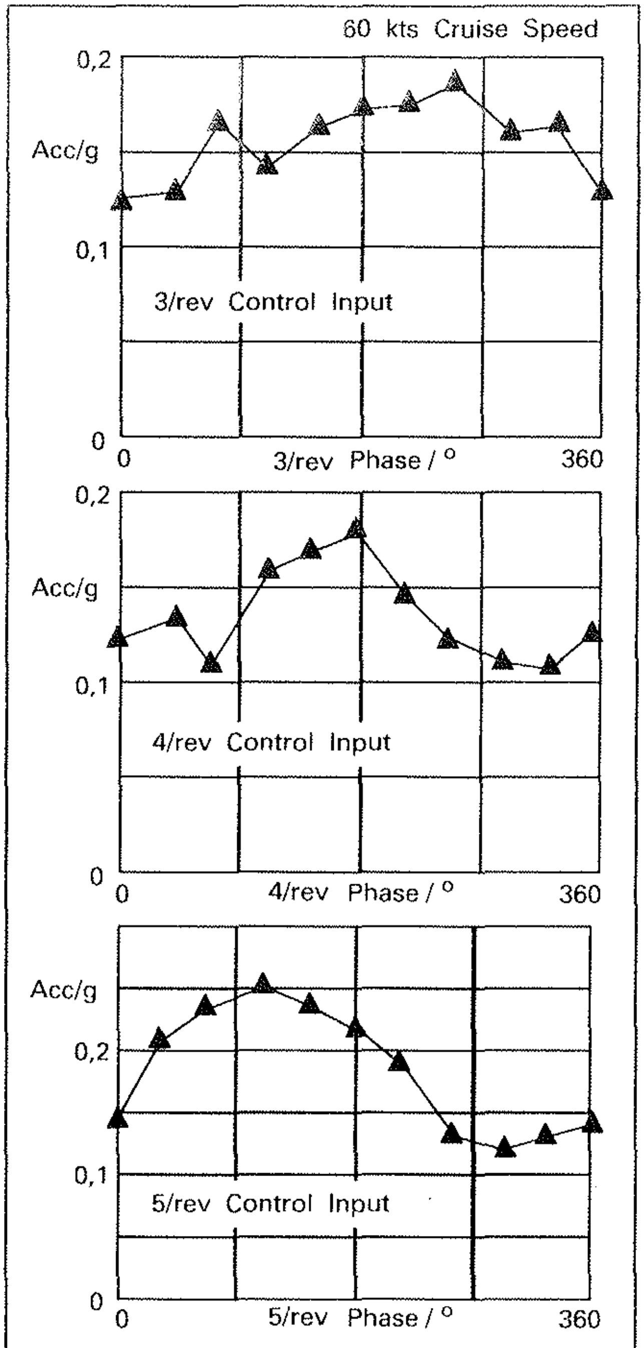


Fig. 4.3.3 Vertical 4/rev Cabin Vibration

- control amplitude θ_{HHC} = 0,16°
- control harmonics 3/rev, 4/rev and 5/rev
- control phase $0° \leq \phi \leq 360°$
- flight condition: cruise with v = 60 kt
- measurement position: cabin floor behind the pilot's seat

- helicopter: BO 105 test carrier, blades without pendulum absorbers.

Fig. 4.3.4 describes in an analogue way the results of 3/rev and 4/rev control inputs for a velocity of 115 kt. The different accelaration curves feature a clear reaction on the HHC inputs in a bandwidth of about 0,05 to 0,1 g.

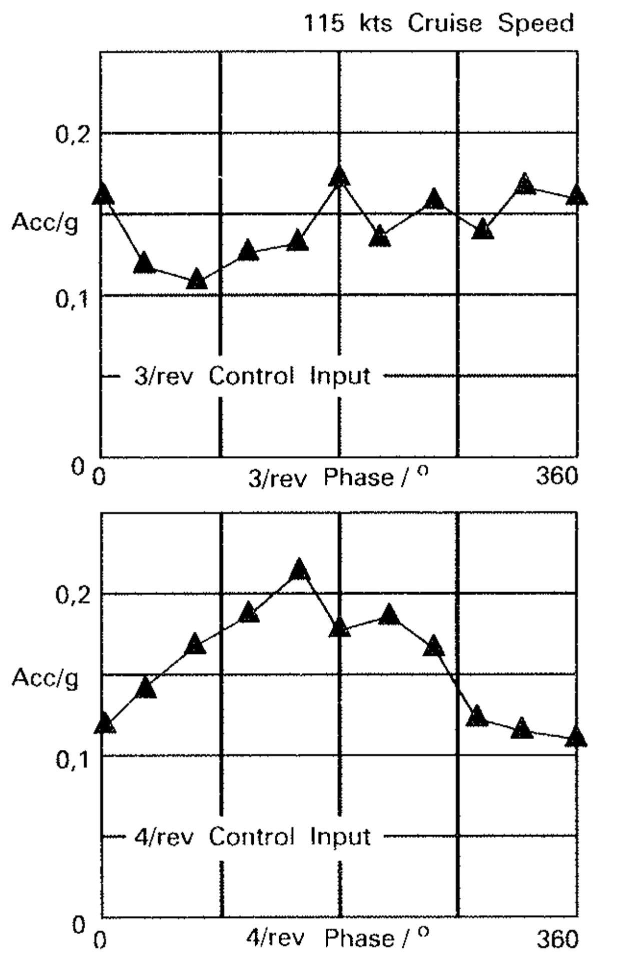


Fig. 4.3.4 Vertical 4/rev Cabin Vibration

The corresponding 3/rev flap bending moments at the blade root as important vibration sources are depicted in Fig. 4.3.5 for a 3/rev excitation. Here the bandwidth of the HHC influence is about 25 to 30 Nm.

5. Planned Program Continuation

The tests conducted up to now have been a first step to evaluate the potential of IBC. Due to safety restrictions the IBC authority had to be kept low. On the other hand the BO 105 as test carrier cannot represent sufficiently the flight

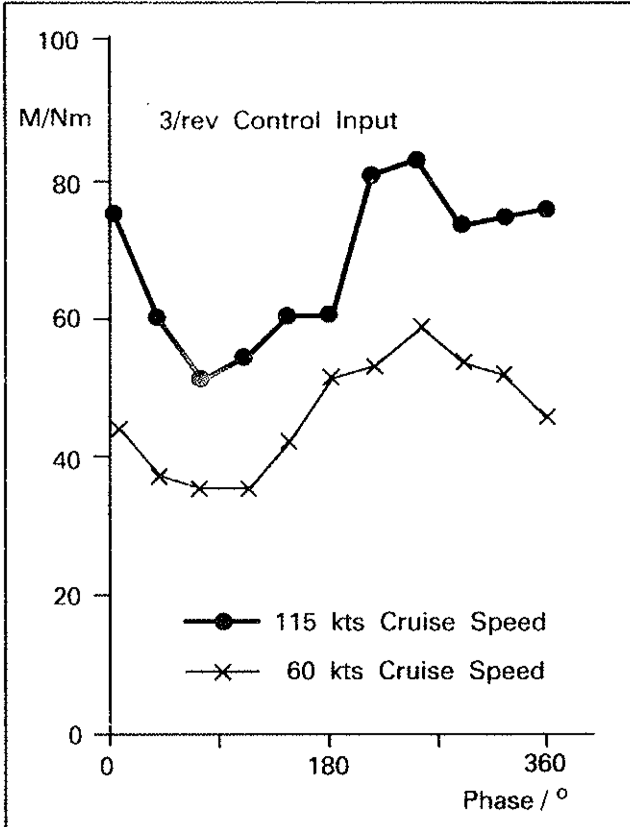


Fig 4.3.5 3/rev Blade Root Moment

envelope aimed at by future designs. Therefore wind tunnel tests with a BO 105 rotor, equipped with advanced blades and an IBC authority of 5° will take place in the NASA Ames 40 by 80 ft wind tunnel. The goals of these tests will be mainly

- to increase the rotor's flight envelope by power reduction and stall delay
- to reduce the noise of blade vortex interaction, compressibility and stall
- to test feed-back measures and
- to further test and improve the reliability of the control system.

Power reduction and stall delay are the goals, which can be achieved only by individual blade control.

A feedback system for this application is proposed for example in Ref. 3. Fig 5.1 shows a system consisting in 4 different branches:

- one simple 2/rev controller for the identification of amplitude and phase for minimum power requirement,

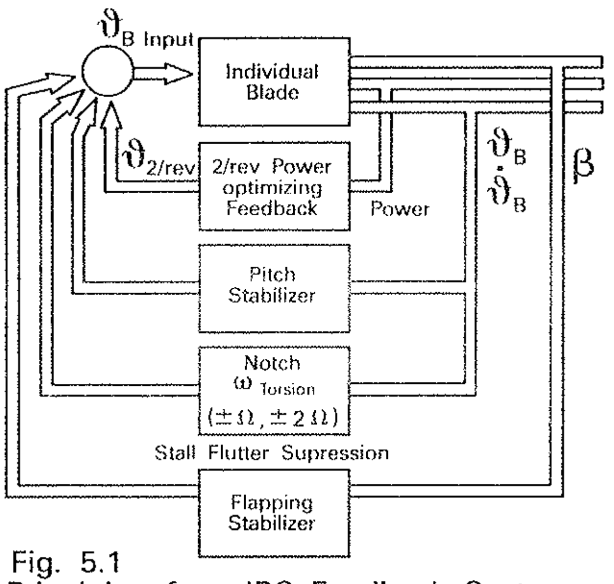


Fig. 5.1
Principle of an IBC Feedback System

- a stabilizer of blade torsion based on blade pitch and pitch velocity,
- a disturbance rejection controller based on a notch, tuned to the first natural torsion frequency and possibly in addition to this frequency $\pm\ \omega\ \pm\ 2\ \omega$, and
- a stabilizer of rotor flapping.

For flight tests with higher IBC authority a redundancy of actuators and control system will be developed and tested. This will be the main challenge for the control system described as the effort necessary to cope with this task compared to the realized advantages of IBC will define the chances of a potential application in future helicopters.

6. Conclusion

An IBC system was developed and tested. The results of the different tests show, that it is possible to superimpose individual-blade control functions to the 1/rev. swashplate control and that responses to these control functions can be measured as rotor blade reactions. The potential of this new rotor control technology will be validated during windtunnel tests in the near future. Then there will be the basis for the development of IBC helicopters that meet the goals

- higher cruise speed
- lower vibration level
- reduced noise
- lower power requirement
- stall delay.

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