# FULL-SCALE WIND TUNNEL INVESTIGATION OF A HELICOPTER INDIVIDUAL BLADE CONTROL SYSTEM

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## Abstract

This paper discusses the preparations and plans to test an individual rotor blade pitch control system in the 40- by 80- Foot Wind Tunnel at the NASA Ames Research Center. The test will be performed on a full-scale BO-105 rotor system using a control system made by Henschel Flugzeug-Werke, GmbH, Germany. The Individual Blade Control (IBC) actuators have been designed to replace the pitchlinks of the rotor system. The paper presents a brief historical perspective on the development of the individual blade control system and then describes the present IBC actuators and the wind tunnel test hardware. A discussion of the intended test matrix, expected potential benefits of IBC, and simulation results are included.

## Acronyms

| | |
|---|---|
| BVI | Blade vortex interaction. |
| HFW | Henschel Flugzeug-Werke, GmbH. |
| HHC | Higher harmonic control. Blade pitch control produced by oscillating the swashplate at multiples of the rotor rotational frequency. |
| IBC | Individual blade control. Blade pitch control produced from actuators on each blade in the rotating system. |
| RTA | NASA Ames rotor test apparatus. |

## Introduction

To provide greater understanding of the potential benefits of individual rotor blade control, an international joint United States/German comprehensive wind tunnel test program will be conducted in the NASA Ames 40- x 80- Foot Wind Tunnel. The use of actuators in the rotating system, one for each blade, represents a breakthrough in rotor control technology. Such individual rotor blade control provides for new control methodologies in vibratory hub load reduction, fuselage vibration suppression, rotor blade airload modification, Blade Vortex Interaction (BVI) noise abatement, and rotor performance improvements through blade stall suppression and lift redistribution.

The approach for the wind tunnel testing is to test the HFW IBC hardware on the NASA/U.S. Army Rotor Test Apparatus (RTA). The testing will be done in the 40- by 80- Foot Wind Tunnel at the NASA Ames Research Center using a full-scale MBB BO-105 rotor system. HFW will fabricate the IBC actuators, control electronics, and adaptation hardware required to interface the IBC system to the RTA and rotor. The adaptation hardware includes a new hub adaptor and a hydraulic slipring to transmit hydraulic power to the rotating system. The Individual Blade Control (IBC) actuators have been designed to replace the pitchlinks of the rotor control system. The first wind tunnel entry will evaluate the open-loop effects of IBC on rotor performance, acoustics, vibration, and loads. A second closed-loop control entry will use an advanced controller developed by the DLR (German Aerospace Research Establishment) in cooperation with NASA, HFW, Eurocopter Germany, and the U.S. Army Research Labs.

The objectives of the present paper are to present the IBC control system together with a discussion of the potential benefits to be demonstrated by the wind tunnel testing. The paper will first present a brief historical perspective on the development of the individual blade control system and then describe the IBC system and the wind tunnel installation. This

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will be followed by an overview of the test matrix for the first wind tunnel investigation. Lastly, a few pretest prediction results showing how IBC might reduce rotor hub loads and BVI noise are presented.

## History

The concept of individual blade control is not new. The ability to control the angle of attack of each rotor blade has been desired ever since the pioneering work of Kretz[1], Lemnios[2], McCloud[3], and Ham[4,5]. These investigators realized that helicopter control through the conventional swashplate, whether for trim or other objectives, was fundamentally limited for rotor systems with four or more blades.

To see this limitation, consider the introduction of 2/rev collective control on two-bladed and 4-bladed rotor systems. Suppose, for example, it is desired to introduce a 2/rev pitch schedule to avoid blade stall by decreasing the blade pitch in the stalled region on the retreating side. For a two-bladed rotor, the blades are 180 deg. apart (or one 2/rev period apart) and both blades can follow the same pitch schedule when excited at 2/rev through the swashplate, as shown in fig. 1. Figure 2 shows that when the same 2/rev collective swashplate motion is introduced to four-bladed rotor system, two blades follow the desired pitch schedule of fig. 1, while the other two are out of phase.

Therefore, using swashplate control, a four-bladed rotor must be excited at 4/rev collective, and a 5-bladed rotor at 5/rev collective, and so on, if the blades are to follow the same pitch schedule around the azimuth. This shortcoming of the conventional swashplate limits the degrees of freedom available for reducing rotorcraft vibrations, loads, and acoustics. Nevertheless, owing to the expense and added complexity of IBC control systems, development of IBC hardware was held until the simpler higher harmonic control (HHC) concept using conventional swashplate actuators could be better explored. Today, it is recognized that HHC has been rather extensively investigated through analytical methods[6-17], wind tunnel testing[18-23] and flight tests[24-27]. Although HHC has been shown to be effective for vibration reduction and BVI noise suppression, the weight of the hydraulic system and constraints of the swashplate geometry limit its overall effectiveness to the point where the benefit obtained using HHC approaches the cost of implementation. For this reason, HHC systems have not seen application in commercial helicopters.

Recently, Henschel Flugzeug Werke (HFW), a subsidiary of Eurocopter-Germany, has developed high bandwidth actuators for the rotating system which replace the pitchlinks of the rotor system. The development of this system began ten years ago with low-speed actuators for individual blade tracking control. This use of actuators, one to control the pitch of each blade, represented a breakthrough in rotor control technology. However, a new system, capable of introducing significant IBC input up to 5/rev, opened a path to explore new control methodologies in rotor loads alleviation, vibratory hub load suppression, BVI noise abatement, and blade stall suppression. This system was successfully flight tested in 1990 and 1991 at Eurocopter's Ottobrun facility at the imposed low control authorities of ± 0.19 deg. and ± 0.42 deg., respectively[28]. Changes in blade loads, fuselage vibration, and noise were noted.

To better define the benefits of the new IBC technology, HFW has designed a set of actuators capable of introducing IBC inputs up to 12/rev. The increased number of harmonics permits the Fourier synthesis of controls much more complex than simple harmonic motion. The new system will also be able to operate at much higher control authorities than the flight test system (up to ±3.0 deg. at 2/rev and ±0.5 deg. at 12/rev). The wind tunnel data obtained will include hub forces and moments, control loads, blade loads, blade pressures, and blade accelerations. In addition, a microphone traverse will be used to acquire acoustic data at several locations under the rotor.

## HFW IBC System and NASA Wind Tunnel Installation

The HFW IBC system will be tested on the NASA/U.S. Army rotor test apparatus (RTA) in the Ames 40- By 80-Foot Wind Tunnel. A picture of the BO-105 rotor installation on the RTA is shown in Fig. 3. The IBC system is comprised of the IBC actuators, a hydraulic distribution network, and the controller for the actuators. A description of the test stand and IBC system are presented below.

Rotor Test Stand

The RTA test stand uses two, 1500 HP electric motors. As shown in Fig. 4, the transmission and motors are supported by a framework of structural steel beams and are covered by non-structural aluminum fairings. The RTA rotor shaft has 3 inches of center clearance through which a wire harness can be passed to carry data from the rotor hub to a slipring mounted underneath the transmission. The RTA has a rotor balance to measure the dynamic hub forces and moments generated by the rotor.

The RTA has actuators for both primary trim control and dynamic excitation. The primary actuator pushrods are connected to the swashplate by means of a walking beam, as shown in Fig. 5. The fulcrum of each walking beam is supported by a bearing connected to a rotary actuator which introduces the dynamic content through rotation about an eccentric cam.

For the IBC test, 3000 psi hydraulic fluid for the IBC actuators is routed up the wind tunnel struts to a hydraulic control block located inside the RTA, Fig. 6. This control block contains the emergency shutoff valves and the pulsation dampers needed to regulate the hydraulic pressure supply. From this control block, hydraulic lines are routed to a hydraulic slipring which functions to transmit the hydraulic supply and return pressure to the rotating frame. The hydraulic slipring is commercially available and made by Glyco, Inc. Two supply and two return hydraulic lines pass from the hydraulic slipring to the hub adaptor through the rotor shaft as shown in Fig. 7. The hydraulic slipring has a center hole to allow passage of instrumentation and control lines up the rotor shaft from the electrical slipring and phototach. The rotor hub adaptor, which connects the rotor hub to the RTA rotor shaft adaptor, was made new by HFW to allow distribution of instrumentation and hydraulic lines to each of the IBC actuators. The hub adaptor supports the entire weight of the the hydraulic pipes, hydraulic slipring, electrical slipring, and phototach assemblies in order to provide a single load path through the rotor balance. Journal bearing near the hydraulic slipring are used to provide centering alignment and anti-torque for the electrical and hydraulic sliprings, but take no axial load.

BO-105 Rotor System and Instrumentation

The BO-105 rotor is a 4-bladed, hingeless rotor system. The fiberglass blades are made by Eurocopter and are attached to a hub of forged titanium. The BO-105 rotor used for the wind tunnel test is owned by NASA and instrumented to monitor blade loads, blade accelerations, and blade pressures. Table 1 shows the location of the blade instrumentation. The strain gages are provided to both monitor safety of flight and to provide information on how the IBC affects the overall blade loading. Four torsional strain gages along the blade span and four accelerometers at the blade tip will provide information on the blade angle of attack during IBC excitation. In particular, it is desired to know if the blade pitch motion at the blade tip follows the IBC pitch control introduced at the blade root. The blade torsional dynamics could make this motion quite different. In addition, surface-mounted pressure transducers installed at the leading edge of the blade will be used to detect the presence of BVI. The data from these transducers will be used to suggest possible IBC pitch schedules to reduce BVI noise generation.

IBC Actuators

Individual blade control is achieved by replacing the pitchlinks of the rotor system by the servo-actuators shown in Fig. 8. The working cylinder is controlled by a Moog 32 Series servo valve located on the actuator. Actuator displacement is measured by two LVDTs and axial stress is measured by a full-bridge strain gage on each of the actuators. The characteristics of these actuators have been listed in Table 2. Figure 9 presents a plot of the maximum pitch deflection possible as a function of the input frequency. The actuators were designed to operate under a centrifugal load of 40 g.

In the event of hydraulic power loss or emergency manual shutdown, the actuators can be locked to center position within one-half rotor revolution. The working cylinder, the shaft going top to bottom on Fig. 8, has been machined with a channel cut into its mid-section. This channel is tapered to allow engagement of centering side wedges. When the IBC hydraulic pressure is off, the wedges are forced into the channel by gas pressure from two cylinders (the two side canisters on the actuator housing). The wedges are retracted by application of the 3000 psi hydraulic pressure. On loss of hydraulic pressure, the actuator pistons are automatically engaged to center the actuator in mid position. In the extended or locked position, each wedge alone can support an axial force of 10,000 N.

IBC Controller

The IBC actuators are controlled by a controller made of two computer systems referred to as the main and monitoring systems. Both computers are made by Dy4 and use the 68000 Motorola microprocessor. The controller block diagram is shown in Fig. 10.

The signals for the IBC actuators are generated only by the main system. However, both systems monitor the position of the IBC actuators and check for operational errors. This redundancy has been added to greatly reduce the possibility of uncontrolled actuator travel and running with blades out-of-track.

For open-loop testing, the amplitude and phase of each harmonic (1 to 12 per revolution) is converted to a time domain control through Fourier synthesis. These controls are sent to the actuator servo valves. A Fourier transform of the first LVDT measurement signal is then performed by the main system to determine the harmonic content of the response motion. By comparing the harmonic response amplitudes and phases to those commanded, a proportional error signal is generated to further correct the actuator motion if required in order to achieve zero position error.

Operating in parallel with the main system, the monitoring system functions to double check the positions of the actuators. It receives LVDT input information from the second LVDT (two per actuator). Both the main and monitoring systems have failure identification hardware and software to identify conditions requiring shutdown of the IBC system. For example, if the LVDT position measurement of one system does not agree with the commanded position, then an emergency shutdown is generated. Other error conditions include loss of the wind tunnel power, loss of rotor RPM, loss of hydraulic pressure, and excessive actuator axial force load. Both the main and the monitoring systems check for all system errors and both have equal priority to initiate a call to lock-out the IBC motion.

In addition to the main and monitoring systems, a personal computer (PC) is attached to the main and monitoring systems to allow easy and safe introduction of the IBC control signals. In the previous flight tests, the sine and cosine amplitudes of 2/rev, 3/rev, 4/rev, and 5/rev were introduced through a hand-held box of potentiometers. Since the new system can accept inputs of up to 12/rev, that approach is too cumbersome. The PC allows the harmonics of sine and cosine to be introduced from a pre-programmed spread sheet of commands. By using the PC and a pre-programmed control list, the possibility of erroneous user input is greatly reduced. The PC is also needed to introduce exacting ratios of harmonics, like those needed to produce a pulse in blade pitch over a narrow azimuth range.

To maintain safety during the wind tunnel test, the commands from the PC input file will be stepped through one at a time. Further, each command cannot be implemented until an overall gain in common to all actuators is set to zero first. However, after the open-loop testing proves IBC and rotor system safety of operation, future wind tunnel entries will have the PC spreadsheet approach replaced by a self-adaptive, closed-loop controller. This controller will then automatically choose the correct harmonic amplitudes and phases needed to suppress vibration, noise, loads, and/or to improve rotor performance.

Test Objectives and Data Points

The primary objective of the BO-105 IBC test program is to evaluate the feasibility of the individual blade control concept as a viable means of active rotor control. If the benefits to be gained through use of an IBC system are not significant, the added complexity of the IBC system would likely preclude it's incorporation on any production flight control system. The IBC benefits anticipated include improvement of rotor performance, suppression of BVI noise, and reduction of rotor oscillatory loads and vibration. Previous analytical and wind tunnel tests have shown reduction of rotor oscillatory loads, vibration, and BVI noise using single-frequency HHC input through the conventional swashplate. It is expected that these gains can be surpassed using an IBC system and that improvement of rotor performance at high-speed can also be obtained.

The IBC test data will be acquired at three primary conditions: 1) a low-speed flight condition having the maximum transition vibration, 2) a low-speed condition having high BVI noise, and 3) a high-speed/high-thrust condition capable of producing some rotor blade stall effects and having high vibration. The reason for the choice of few flight conditions is to provide enough test time to introduce the widest possible variety of IBC controls within the allowed wind tunnel test time. The rotor thrust will be selected to simulate a 1g level flight condition ($C_T/\sigma \approx 0.07$) in most cases. The rotor speed will be adjusted about the nominal 425 RPM to maintain a constant hover tip Mach number ($M_H \approx 0.64$). In most cases, the rotor will be trimmed to maintain thrust and zero flapping in order to evaluate the effect of IBC on rotor performance.

The first data sets to be acquired will be for single-frequency IBC input. These data will indicate how the blade loads, hub vibrations, rotor performance, and BVI acoustic noise are affected by introduction of harmonics 1/rev to 12/rev. It has been shown in previous small-scale model testing that single-frequency HHC input of 3/rev, 4/rev, and 5/rev could reduce hub vibrations and BVI acoustic noise on a model BO-105 rotor, though not always at the same time [48-50]. However, as mentioned above, HHC and IBC are the same only at excitation frequencies of 4/rev, 8/rev and 12/rev when applied to a four-bladed rotor. Other harmonics produce an out-of-track rotor using HHC through the swashplate, but not for IBC. Highest priority will be assigned to harmonics 2/rev - 6/rev, with special attention on using 2/rev input to avoid blade stall at high-speed/high-thrust conditions.

Multi-frequency inputs will then be evaluated to determine if combinations of the single-frequency inputs can be used to obtain additive benefits. Perhaps the vibration reduction seen using one harmonic may add to the vibration reduction achieved using a different harmonic to create a further reduction in vibration. Or, perhaps by using a combination of harmonics, both vibration and noise may be alleviated at the same time.

A convenient way to study tradeoffs between optimizing rotor thrust (q), suppressing oscillatory hub forces (F) and moments (M), fuselage vibration (Z), and BVI noise (B) is to form a weighted quadratic performance index (J) of the form

$$J = q^T W_q q + F^T W_F F + M^T W_M M + Z^T W_Z Z + B^T W_B B$$

where the elements of q, F, M, Z, and B are the sine and cosine coefficients for a selected number of harmonics. A single-step control to minimize J can then be found using a deterministic, minimum variance approach as discussed in Ref. 8, assuming the harmonics of IBC control ($\Delta\Theta$) can be linearly related to the harmonics of the response coefficients in the performance index by simple transfer matrices. Determination of the transfer matrices can be done either by direct examination of the single-frequency response data or by a least squares regression analysis as discussed in Ref. 13. Using these transfer matrices, simultaneous optimization of thrust and reduction of vibration and noise may be studied by adjusting the values of the $W_q$, $W_F$, $W_M$, $W_Z$, and $W_B$ weighting matrices in the performance index.

On the other hand, using a Fourier synthesis approach, multi-frequency IBC excitation up to 12/rev can also be used to shape the blade pitch schedule in the form of a wavelet pulse or doublet as shown in Fig. 11. Such waveforms may be useful in eliminating BVI noise or increasing rotor performance, and may also have a marked effect on control loads, blade loads, and vibration. Although spanning the entire control space of these types of waveforms is not possible in one wind tunnel test, a limited survey can be accomplished for one- or two-pulse inputs.

## Simulation Results

Many harmonics and a variety of pitch schedules can be introduced with the IBC control system. Simulations have been conducted to assess which inputs will be most likely to produce beneficial results. These results help both to shape the test matrix and to understand the mechanisms producing the IBC benefits.

The rotor hub forces and moments were calculated at NASA Ames Research Center using CAMRAD/JA (for Comprehensive Analytical Model of Rotorcraft Aerodynamic and Dynamics / Johnson Aeronautics) for the isolated BO-105 rotor case. Figure 12 shows the effect of ±2 deg. 2/rev IBC input at an advance ratio of 0.40. The performance index, J, was created as the sum of the oscillatory drag force, side force, vertical force, rolling moment, pitching moment, and torque. (Since the half-peak-to-peak values are positive, a quadratic performance index is not needed.) As seen in the figure, the 2/rev input was seen to significantly lower or raise the overall forces and moments, depending on the relative phase of the IBC input.

On the other hand, Fig. 13 shows that ±2 deg. IBC input at an advance ratio of 0.30 produces slightly beneficial effects for 2/rev, but that ±2 deg. 3/rev, 4/rev and 5/rev IBC input are detrimental. The reason is that the ±2 deg. IBC input amplitude is too high since the baseline hub loads are already fairly low at this advance ratio. This illustrates that study of hub loads reduction in areas where the loads are already low is perhaps not the best use of the wind tunnel test time. Figures 14 and 15 show that when ±1 deg. 3/rev, 4/rev, and 5/rev IBC input is applied at an advance ratio of 0.10, that the hub forces (Fig. 14) and hub moments (Fig. 15) can be reduced, though not necessarily at the same time.

Simulations done at the NASA Langley Research Center show that IBC input can also be used to reduce BVI noise. These simulations were done using the Langley developed HIRES (High Resolution) CAMRAD code for the isolated BO-105 rotor case. Both simple harmonic and complex motion were considered. Figure 16 shows a number of simple harmonics can produce significant reductions in BVI noise levels.

## Acknowledgements

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**Table 1 Rotor Blade Instrumentation**

| Blade Transducer | % Radial Station |
|---|---|
| Flapwise Strain | 14, 57 |
| Chordwise Strain | 14, 57 |
| Torsional Strain | 35, 40, 57, 80 |
| Pressure | 60, 70, 80, 90 |
| Acceleration | 30, 50, 70, 95 |

Table 2. IBC Actuator Technical Detail.

| | |
|---|---|
| Cylinder Stroke | ± 10 mm = ± 3.0 deg. blade angle |
| Piston Area | 4.24 $cm^2$ |
| Length | 682 ± 10 mm |
| Weight | 4.2 Kg (approximate) |
| Maximum Allow. Axial Force | 8600 N (Static)<br>3500 N (Oscillatory) |
| Servo-Valve Type | Moog 3254.3000 I 1000 4PCP BVN<br>54 liter/min at p = 207 bars |
| Position Measure | 2 LVDT's |
| Force Measure | Strain gage, full measuring bridge |

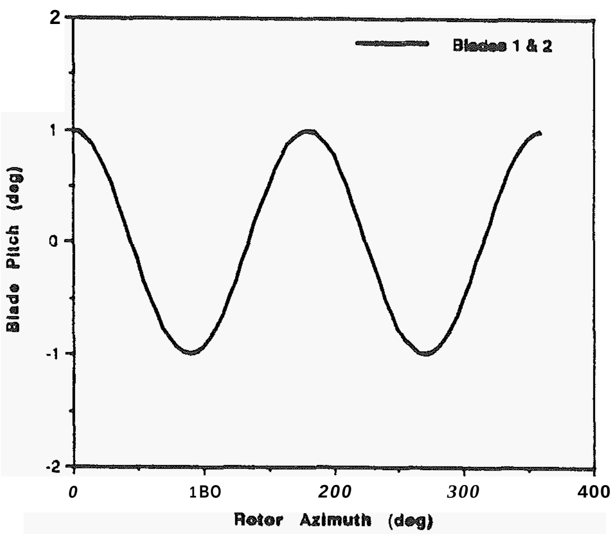


Figure 1. Effect of 2/rev collective HHC input on 2-bladed rotor.

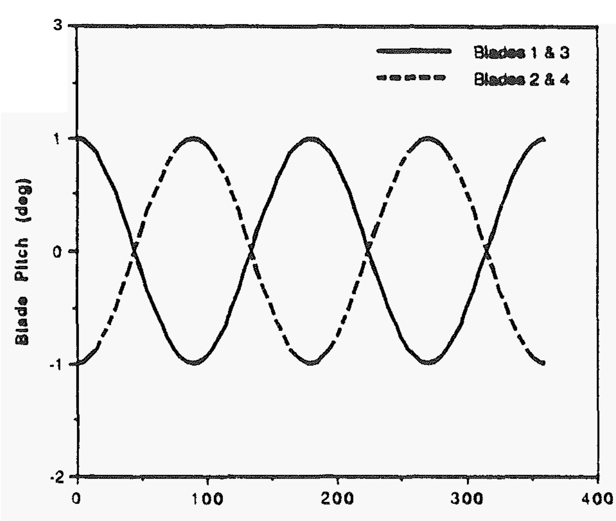


Figure 2. Effect of 2/rev collective HHC input on 4-bladed rotor.

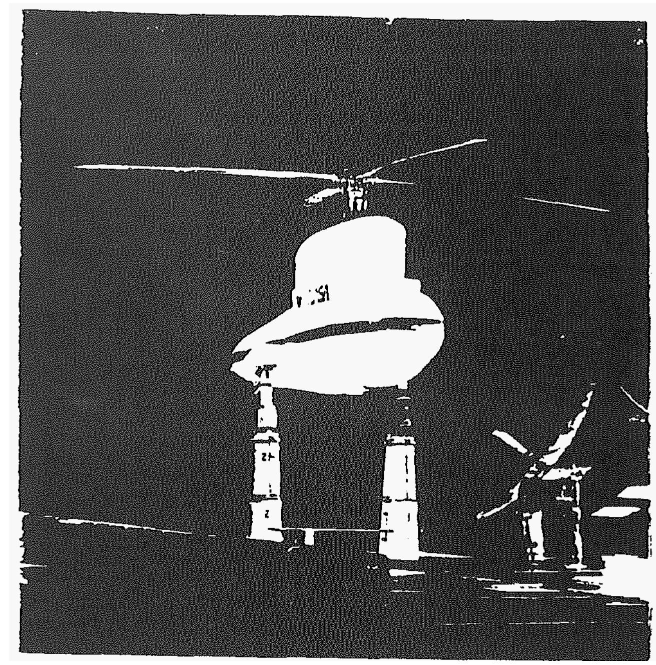

Figure 3. BO-105 rotor on RTA in NASA Ames 40- By 80-Foot Wind Tunnel.

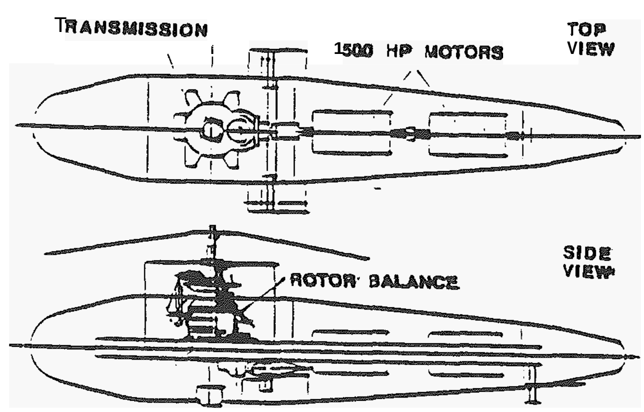


Figure 4 Rotor Test Apparatus (RTA).

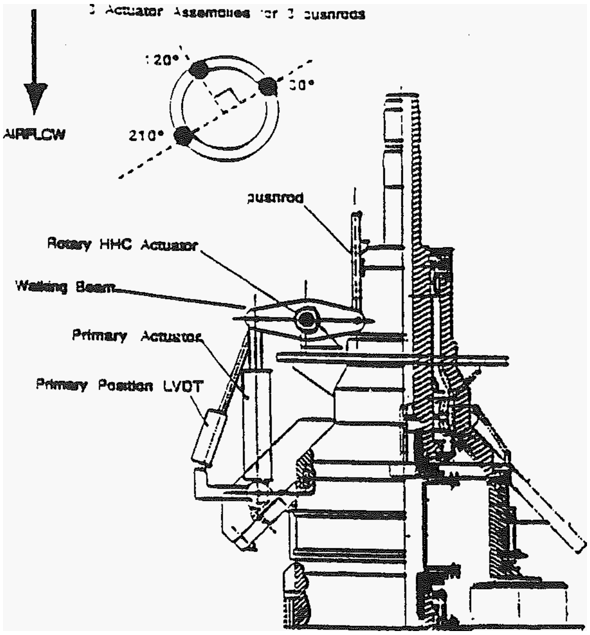


**Figure 5. RTA control system geometry**

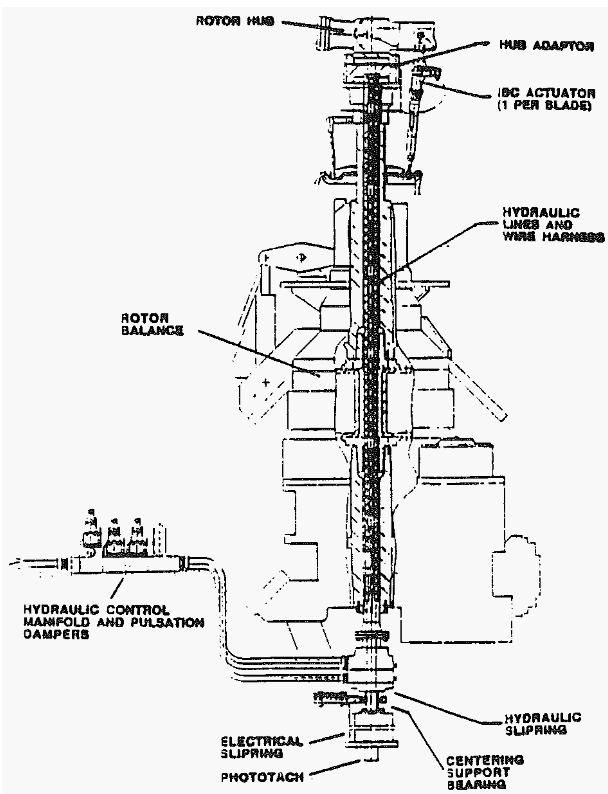


**Figure 6. Installation of IBC system**

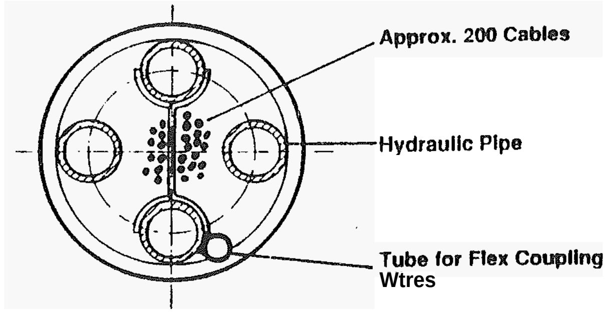


**Figure 7 Cross-section of rotor shaft**

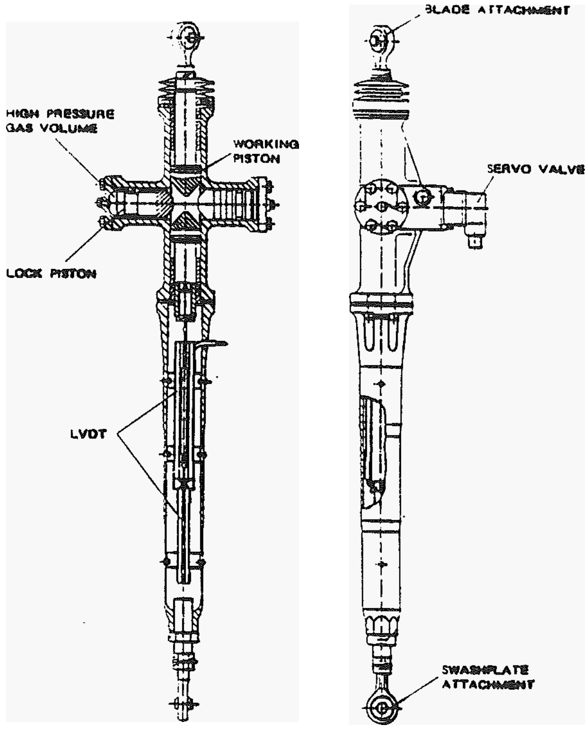


**Figure 8. IBC servo actuators replacing the standard BO-105 pitchlinks.**

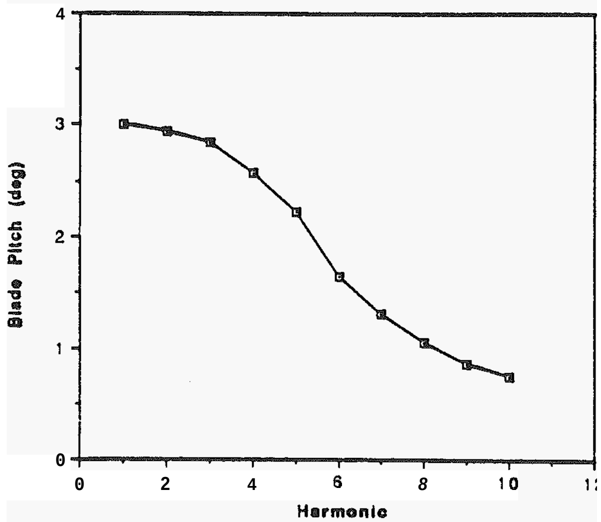


**Figure 9. Actuator frequency response.**

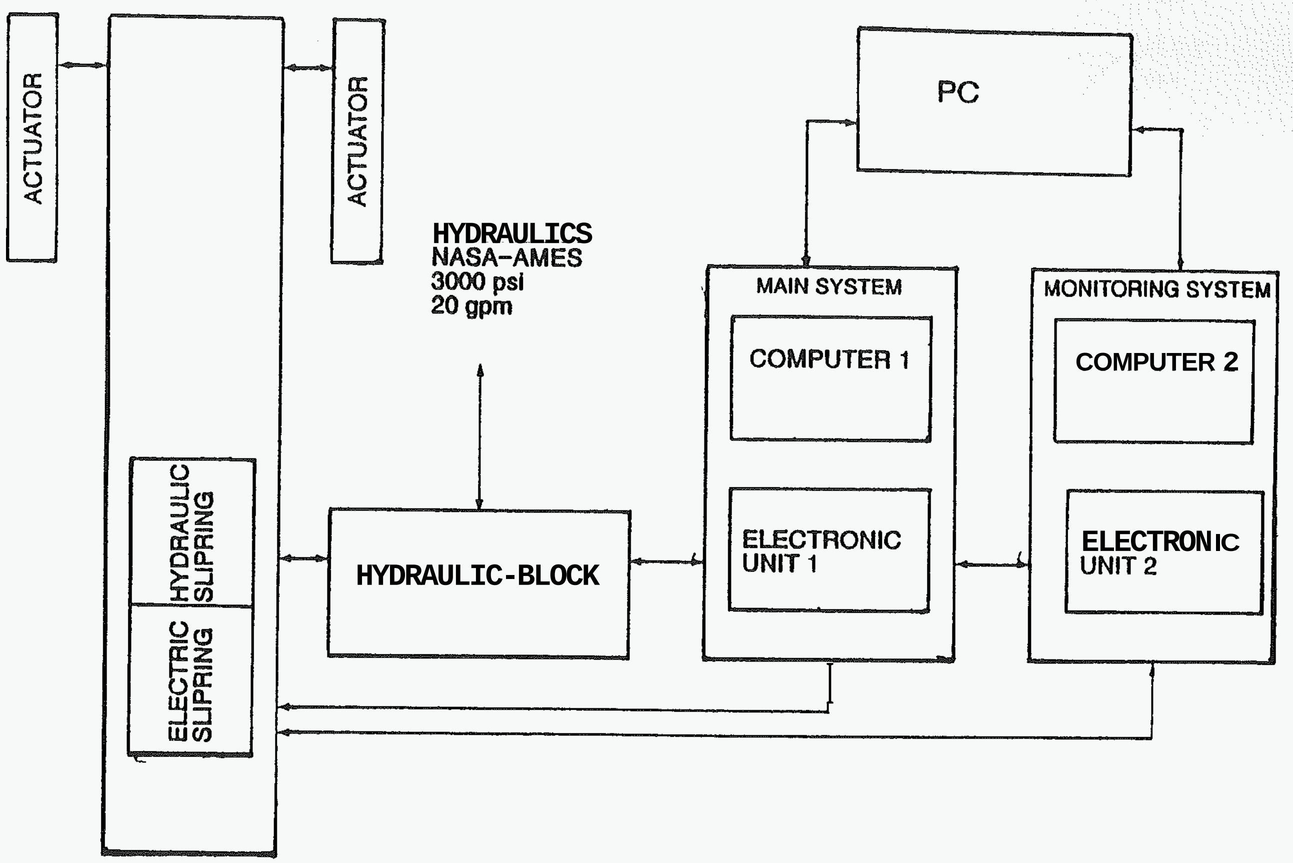


Figure 10. IBC controller block diagram

Harmonics (in degrees)

| np | SINE | COSINE |
|---|---|---|
| 1 | -0.470 | 0.900 |
| 2 | 0.000 | 0.300 |
| 3 | 0.417 | 0.540 |
| 4 | 0.000 | 0.694 |
| 5 | -0.325 | 0.129 |
| 6 | 0.000 | -0.270 |
| 7 | 0.214 | -0.060 |
| 8 | 0.000 | 0.096 |
| 9 | -0.109 | -0.035 |
| 10 | 0.000 | -0.065 |
| 11 | 0.028 | 0.023 |
| 12 | 0.000 | 0.027 |

WAVE MEAN = 0.716

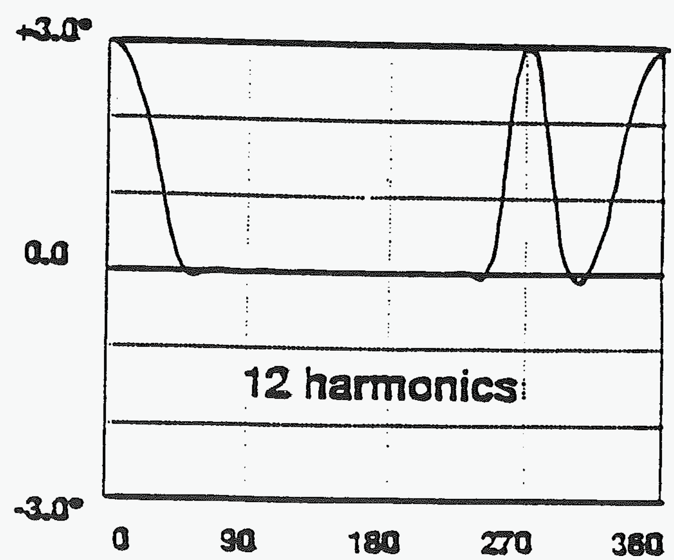


Figure 11. Wavelet produced using Fourier synthesis.

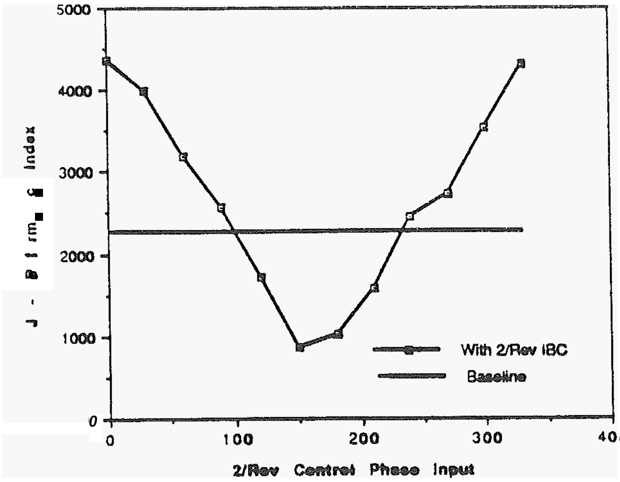


**Figure 12. Effect of ±2 deg. 2/rev IBC input on the oscillatory hub forces and moments at 0.4 advance ratio.**

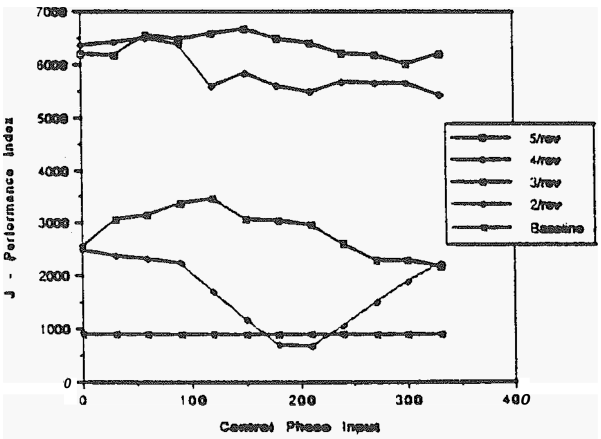


**Figure 13. Effect of ±2 deg. 2/rev, 3/rev, 4/rev and 5/rev IBC input on the oscillatory hub forces and moments at 0.3 advance ratio.**

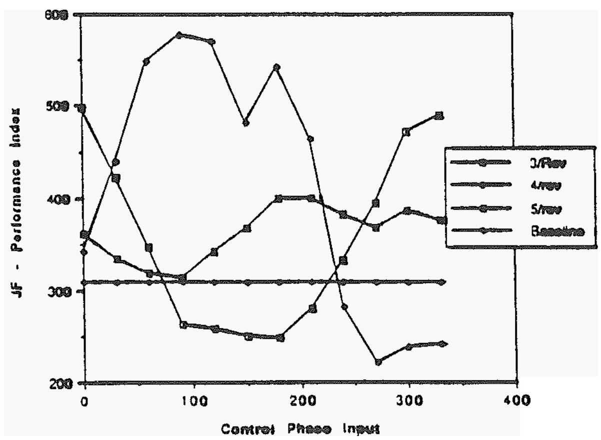


**Figure 14. Effect of ±1 deg. 3/rev, 4/rev and 5/rev IBC input on the oscillatory hub forces at 0.1 advance ratio.**

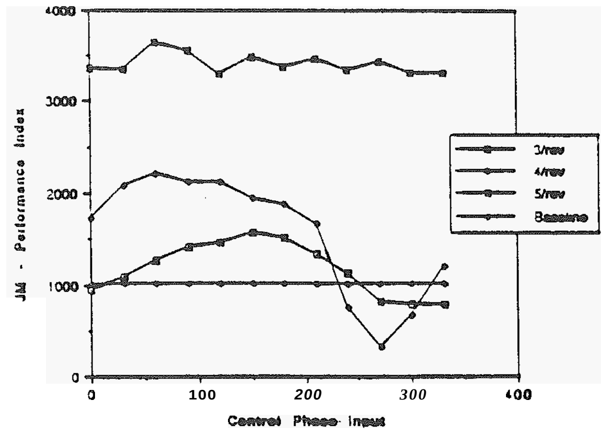


**Figure 15. Effect of ±1 deg. 3/rev, 4/rev and 5/rev IBC input on the oscillatory hub moments at 0.1 advance ratio.**

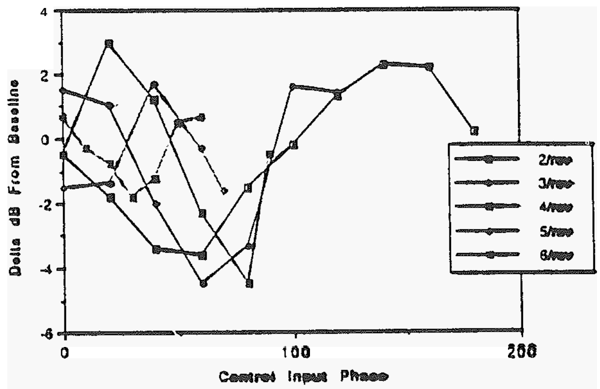


**Figure 16. Effect of ±0.8 deg. 2/rev, 3/rev, 4/rev, 5/rev, and 6/rev IBC input on BVI noise at 0.1 advance ratio.**