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FULL SCALE WIND TUNNEL INVESTIGATION OF AN INDIVIDUAL BLADE CONTROL SYSTEM FOR THE BO 105 HINGELESS ROTOR

by

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Abstract

This paper describes a full-scale investigation of the HFW-IBC-System in the 40- by 80- Foot Wind Tunnel at the NASA-Ames Research Center. The concept of the HFW-IBC-System is covered briefly with special respect to safety precautions. The test facility and the measured parameters are described, as well as the test conditions and the IBC signals tested. The paper concludes with some preliminary results obtained during the test and an outlook on a follow-on test campaign and future activities.

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 by actuators at each blade in the rotating frame
RTA	NASA-Ames Rotor Test Apparatus

1. Introduction

Henschel Flugzeug-Werke GmbH, located at Kassel, Germany, has developed an Individual Blade Control (IBC) System for the Boelkow-type hingeless rotor. The HFW-IBC-System was successfully flight tested in cooperation with Eurocopter Germany on a BO 105 helicopter in 1990 and 1991 [1,2]. The flight test results were very encouraging in terms of vibration and noise reduction, but didn't answer the question of rotor performance improvement by IBC, especially by 2/rev control. The reason was that safety considerations limited the control capability of the IBC-System as well as rotor thrust and airspeed of the helicopter. This research program was supported by the German Ministry of Research and Technology.

To further explore the benefits of IBC, a joint U.S./German research project was installed to conduct a full-scale wind tunnel investigation of the HFW-IBC-System, adapted to a BO 105 hingeless rotor. It is part of the U.S./German MoU on Helicopter Aeromechanics. The participants of this MoU are the Department of the Army and NASA on the U.S. side and the Ministry of Defense and the DLR on the German side. The German Ministry of Defense also funded the efforts of HFW and Eurocopter Germany for this test.

The National Full-Scale Aerodynamic Complex at the NASA Ames Research Center provides outstanding capabilities for full-scale testing of fixed-wing aircraft as well as rotorcraft. The test was conducted in the smaller one of the two test sections, which is 12 m (40 ft) high and 24 m (80 ft) wide. A NASA-owned instrumented BO 105-rotor and the HFW-IBC-System were installed on the Rotor Test Apparatus (RTA).

For the wind tunnel test, HFW manufactured a set of actuators which replace the conventional RTA pitch links, and added some improvements to the HFW-IBC-System. It is able to produce IBC pitch angles of max. 3.0° at up to 6/rev (42 Hz). This is a substantial improvement over the flight tests, where IBC was limited to 0.42° and 5/rev. The test was conducted in an open-loop manner.

The primary objective of the BO 105 IBC test was to evaluate the feasibility of the HFW-IBC-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 such a system would preclude it's incorporation on any production flight control system. The IBC benefits anticipated include improvement of rotor performance, noise suppression, and reduction of rotor oscillatory loads and vibration. Of special interest is the question, if these advantages can be gained simultaneuosly.

The test was successful and provided a lot of valuable data. Substantial reductions of noise and vibration level were found during the test campaign, as well as a distinct effect of 2/rev control on rotor power required. However, a comprehensive evaluation of the data has to determine how much of the lastnamed effect contributes to changes in the rotor trim state.

The test results are a valuable database for further development of the IBC concept, in particular the design of a closed-loop controller. Unfortunately, the capability of the HFW-IBC-System could not be completely explored, because stress limits of the RTA control system were hit earlier than expected. A second wind tunnel test campaign in spring 1994 is going to use strengthened test hardware and will hopefully provide additional data at high speed and high thrust conditions with IBC inputs of max. 3.0°.

2. The HFW-IBC-System

The most important components of the HFW-IBC-System are the actuators and the controller, which are desribed in the next paragraphs. Additional components are the hydraulic block with valves, pulsation dampers etc. in the RTA, the electric and hydraulic slipring assembly, a mast fairlead with hydraulic lines and wire harness, and a hub adaptor. These parts are described in [3].

2.1 Actuators

The HFW-IBC-System features servo-hydraulic actuators in the rotating frame which replace the conventional pitchlinks between the swashplate and the blade pitch horn (Fig. 1). This overcomes the constraints of Higher Harmonic Control (HHC) Systems with actuators in the fixed frame. Due to the swashplate, these HHC-Systems can generate only certain rotor harmonics in the rotating frame.

The most important technical data of the actuators are:

actuator stroke	± 9 mm
IBC blade pitch	± 3 degrees
max. frequency	42 Hz (6/rev)
actuator force	5 kN
hydr. pressure	207 bar
length	682 mm
mass	5 kg

The frequency response of the actuator is shown in fig. 2. The upper line represents the frequency response without load while the lower line with 3 kN max. load is roughly in accordance with the circumstances during the wind tunnel test.

Fig. 3 shows a cut of an IBC actuator. The working piston is located in the upper part of the actuator. (Note that the non-hatched area in the plane of the lock pistons represents a channel cut in the working piston, which does not consist of two parts!) The working piston is controlled by a servovalve.

The HFW-IBC-System has an emergency shutdown feature, which centers and locks the actuators in case of hydraulic pressure loss within one half rotor revolution. Then they operate like a standard pitch link, which allows the rotor operator to control the rotor as usual by the primary controls.

To provide redundancy, there are two lock pistons per actuator, each of which is able to center the working piston. They are loaded by pressurized gas volumes. Once locked, the force required to move the working piston against the locking device is more than 10 kN, which is far higher than any anticipated pitch link load. The lock pistons release when sufficient hydraulic pressure is fed to the actuator.

The lower part of the actuator is merely a housing to provide the correct actuator length. It covers two LVDTs as stroke sensors and carries a full-bridge strain gage for measurement of actuator force. Attached to the lower actuator housing is a box which contains signal conditioning electronics and connectors.

The actuators operate under a centrifugal acceleration of 40 g, so their weight had to be kept low. They underwent a fatigue test to prove sufficient service life for the BO 105-IBC test. The centrifugal force of 2 kN was simulated by weights.

2.2 Controller

The IBC wind tunnel test was an open-loop approach. The desired IBC inputs were stored in files on a PC harddisk, containing amplitude and phase angle for each frequency from 0/rev to 6/rev. The IBC-System is operated by the PC and a potentiometer which controls overall gain. The IBC-operator selects an input command and transmits it to the control rack of the HFW-IBC-System. It contains two independent systems (main and monitoring system), each of which owns a VME-bus computer and additional electronics. The controller block diagram is shown in fig. 4.

The main system generates signals for each servovalve by Fourier Synthesis. The resulting actuator stroke signal is measured by LVDTs and undergoes a Fourier Analysis. From this, the computer calculates corrections in gain and phase angle for each frequency, in order to generate a servovalve signal that yields the desired stroke. This is done for each actuator separately. Additionally, the main systems compares commanded and measured actuator stroke and generates a failure signal if the difference exceeds the allowable amount.

The monitoring system does not generate a servovalve signal, but compares commanded and measured actuator stroke and generates a failure signal if necessary. It is completely separated from the main system, with different power supply and a second set of LVDTs. This redundant stroke monitoring is an improvement over the flight tested IBC-system.

The frequency-domain controller of the HFW-IBC-System has proved very reliable and accurate in the wind tunnel as well as during flight tests. Despite the limitation on 6 frequencies and mean, non-harmonic signals can be generated in good approximation by means of a Fourier Synthesis, as shows fig. 5.

2.3 Safety Precautions

The most dangerous conditions for a rotor equipped with an IBC-system are a jammed actuator and uncontrolled actuator travel, because this would create a blade track split with possibly high blade and mast loads. To avoid jamming, the actuators are designed in a way that makes any kind of blocking unlikely. Additionally, the locking device would most probably drive the actuator in its center position when activated.

Uncontrolled actuator travel is made virtually impossible by the redundant stroke monitoring concept. If the main or monitoring system detects a failure, in particular insufficient control accuracy, an emergency shutdown is initiated. Three independent valves in the hydraulic block open automatically and shunt the hydraulic supply. The hydraulic pressure drops, and the lock pistons center and lock all actuators within one half rotor revolution. The rotor operator is able to establish a safe condition with the conventional controls.

Other failure conditions that lead to an automatic emergency shutdown are high actuator force, low hydraulic pressure, low or high rotor rpm and power failure, as well as a wind tunnel or rotor drive failure via an interlock. The IBC operator has a push button to initiate a shutdown manually. The system is operational again within a minute, without stopping the rotor. The emergency shutdown feature proved very reliable and effective during the entire test.

A new IBC commanded is accepted by the main and monitoring system only if the overall gain potentiometer is in its zero position in order to avoid sudden changes of the commanded signal. This makes operation of the HFW-IBC-System safe and time-effective.

To avoid exceeding structural limits, some thirty critical loads were displayed on a real-time bar-chart monitor in the control room within the IBC-operators field of view. This allowed for careful operation of the IBC-system when in the range of structural limits.

3. Test Conditions and Measurements

3.1 Test Facility

The National Full-Scale Aerodynamic Complex (NFAC) at NASA Ames comprehenses two wind tunnels. A scheme of the facility is given in fig. 6. The 40- by 80- Foot Wind Tunnel has a closed test section with semicircular sides of 20 foot radius and a closed-circuit air return passage. Fig. 7 shows a cross section of the test section. The air in the tunnel is driven by six 40-foot-diameter, 15 bladed, variable pitch fans powered by electric motors each rated at 12 MW (18,000 hp) with a 2-hr 25% overload capability. The speed ranges from 0 to 555 km/h (300 kts). The model is supported with three struts on a turntable, which is attached to a six-component floating frame balance system.

The Rotor Test Apparatus (RTA) is used for testing large-scale main rotor systems. Its design flexibility allows for the accomodation of a variety of rotor diameters and tip speeds. It is powered by two tandem-mounted, variable speed electric motors, which can provide up to 1100 kW (1500 hp) each. A rotor balance allows the direct measurement of rotor forces and moments independently from the RTA structural frame and fairing. The control system of the RTA allows for the input of HHC by dynamic actuators below the swashplate.

3.2 Static and Dynamic Data Acquisition

About 250 parameters were recorded in the static database, part of them as average, maximum and half peak-to-peak value. For about 75 parameters the time history over three rotor revolutions was recorded in the dynamic database.

The instrumentation of the IBC system comprised force and stroke of each actuator as well as the servovalve signals and the commanded signal for actuator No. 1. Fig. 8 gives an idea of the blade instrumentation, which is also listed in tab. 2. All IBC and rotor instrumentation was recorded in the dynamic database.

3.3 Acoustic Data Recording

The test section is lined with sound-absorptive material to permit acoustic research. The lining is 15 cm (six inches) deep over the entire test section. They are covered by aluminium hole-plates. These linings permit near-anechoic testing above 500 Hz.

Acoustic data were recorded from a fixed microphone on the retreating side and a movable traverse with two microphones on the advancing side. Fig. 9 and 10 show the microphone positions used during the test. The microphone struts and the model were not covered with acoustic material. The resulting reflections were determined by a bang test.

Because a full sweep with the traverse is rather time-consuming, only the park position of the traverse was used for most datapoints. Only the baseline case and IBC signals which caused a substantial reduction of the BVI noise level were covered with a full microphone sweep.

3.4 Test Conditions

The purpose of the test was the examination of IBC. IBC allows for a huge amount of different inputs to the rotor. To keep the number of data points in a reasonable magnitude, the number of test conditions had to be strictly limited. Therefore, nominal rotor rpm (425/min) and 1 g thrust ($C_T/\sigma = 0.07$) was selected for most of the test conditions. Besides hover, which served merely as a check-out case, three test conditions (determined by airspeed, thrust and shaft angle) were examined extensively and two test conditions briefly.

In wind tunnel tests, frequently a zero flapping case is choosen as the baseline case. The predecessor of the BO 105-IBC-Test in the wind tunnel, the Rotor Data Correlation Study performed by NASA and DLR with the same rotor, gave a strong indication that zero flapping conditions differ significantly from real flight conditions. It was decided to choose the baseline cases for the IBC-Test similar to real flight conditions in terms of thrust, pitching and rolling moment wherever feasible. Unfortunately, high control system loads were encountered in some of these test conditions. Zero flapping was used then as a fallback position.

IBC, especially the 2/rev, affects the trim condition of the rotor. In order to avoid overlapping effects from IBC input and trim changes, it was attempted to reestablish the thrust, pitching and rolling moments of the baseline case with the conventional controls after applying IBC. This could not be achieved satisfactorily in every case.

To study the effect of IBC on vibration, a transition condition with a high vibration level was choosen. The speed was 42.5 kts at a shaft angle of -2.0 degrees with zero flapping. A complete T-Matrix of 120 datapoints was recorded at this test condition. Another 30 datapoints were taken at the same speed, but with -2.5 degrees shaft angle and cyclic control inputs of -2.70 deg. lateral and 0.75 deg. longitudinal to match a comparable flight condition.

To examine the effect of IBC on noise, a 6-degree approach at 64 kts was selected. A rotor angle of attack of 3.9 degrees was calculated for this flight condition, which resulted in a 3.0 degree shaft angle when the wind tunnel corrections were taken into account. This test condition produced a high level of BVI noise in a range of shaft angles from 2.5 to 4.0 degrees. Acoustic data were also recorded at several other test conditions.

Performance improvements by IBC were expected only at high speed or high thrust conditions. Approximately 1 g thrust ($C_T/\sigma = 0.07$) at advance ratio 0.3 (127 kts) and 0.4 (170 kts) were choosen as test conditions. The 127 kts-condition was tested thoroughly, also in terms of vibration and noise. High blade and control system loads were encountered at the 170 kts condition. This caused failures of instrumentation which was indispensable for safety reasons. Therefore only few datapoints were taken at 170 kts, and stall-delay effects at very high speed could not be examined. Additional stall- delay testing was done at an 80 kts high thrust ($C_T/\sigma = 0.12$) condition. Table 1 lists all baseline conditions used during the test.

3.5 IBC Inputs

As mentioned in section 2.2, the IBC signals are generated by Fourier Synthesis of multiples of the rotor rotational frequency, i. e. 2/rev to 6/rev. The introduction of collective and 1/rev signals by the HFW-IBC-System is possible. However, a collective input would limit the usable actuator stroke, and a 1/rev input would affect the rotor trim condition, which is not desirable. Therefore collective and 1/rev inputs by IBC were not used.

Six frequencies, each independently adjustable in amplitude and phase, yield a huge number of combinations. To gain a better understanding of the rotor reaction on IBC, more than 90 percent of the IBC inputs used in the test were single frequency inputs. Especially most of the vibration reduction tests consisted of single frequency inputs to determine a T-matrix. Only few multiple harmonic signals were derived from the test data to check if the transfer behaviour of the rotor can be considered linear.

For noise reduction purposes, also 2/rev, 3/rev and 6/rev single frequency inputs were used. During the preparation of the test, other signals had been designed especially for BVI noise reduction purposes. These were pulses and doublets, shown in fig. 11 and 12. As stated earlier, these signals do not have a 1/rev component because of the effect on the rotor trim condition.

When the pulse signal is commanded to the IBC actuators, the desired pitch angle time history results at the root of the blade. On the other hand, the mechanisms producing BVI- noise are located near the tip of the blade. Therefore, a wavelet signal was created, which took into account the torsional transfer behaviour of the blade for the different harmonics. Therefore, the IBC-signal does not look like a pulse, but this signal introduced at the blade root should result in a peak at the blade tip (fig. 13).

To study the effect of IBC on rotor performance, 2/rev signals were used primarily. Other frequencies could be added for optimization, but only little contribution of frequencies higher than 2/rev were expected. Fig. 14 gives an idea of the combination of conventional blade pitch and IBC control at high speed.

4. Preliminary Results

The debugging and comprehensive evaluation of the database is still ongoing. Therefore, the results presented here refer to effects which could be identified during the wind tunnel test by hand-recording some parameters. Under this respect they have to be considered as preliminary. The focal points are vibration, noise, and performance.

The possibility of vibration reduction by higher harmonic blade feathering has been shown several times in the past [4,5,6]. For a BO 105 model rotor, 3/rev, 4/rev and 5/rev inputs generated by a HHC system substantial reductions were achieved during wind tunnel tests performed by DLR [7]. 2/rev and 6/rev inputs to a four-bladed rotor require actuators in the rotating frame. The HFW-IBC-System offers this capability, so that the effect of these harmonics on vibration could be tested in the wind tunnel for the first time ever.

Most vibration-related datapoints were taken at 42.5 kts, which is a flight condition with a high vibration level. Vibrations are determined by the 4/rev part of five rotor balance components (thrust, aft force, side force, pitching and rolling moment).

The tests showed that 2/rev and 6/rev inputs have also substantial capability for vibration reduction. This had not been expected, because 2/rev and 6/rev forces and moments in the rotating frame do not transfer into the fixed frame. It is likely that 2/rev and 6/rev blade pitch inputs contribute to the vibration reduction by interharmonic couplings.

This offers a new perspective for vibration reduction, because there are five input frequencies (2/rev to 6/rev) available for the reduction of five rotor components. If the transfer behaviour between IBC inputs and rotor components is roughly linear, the complete cancellation of 4/rev rotor components by multiharmonic inputs might be possible. Some multiharmonic input cases were tested in the wind tunnel, the results will be available soon.

Most of the vibration testing covered single frequency inputs. The results will allow to determine the transfer behaviour (T-Matrix) between IBC inputs and rotor components. This is an important information for the future design and test of an IBC controller that calculates the optimum IBC input automatically.

At the beginning of the test, the effect of IBC on rotor forces and moments without blades and wind was measured. From this, an Inertia Compensation Matrix was determined. This allows to distinguish between the effects of aerodynamics and inertia on vibration. It showed that aerodynamic and inertia effects are in the same order of magnitude for the IBC wind tunnel test arrangement. This means that for future IBC designs, inertia effects deserve special attention.

The suppresion of Blade Vortex Interaction (BVI) Noise has become a focal point of active control research in the last few years. The positive effect of active control on noise was shown by DLR during HHC-tests in the DNW as well as during the IBC flight tests [8]. IBC allows for the introduction of blade pitch signals designed especially for BVI-noise suppression, such as single or double peaks etc. This kind of signals was used intensively during the IBC wind tunnel test.

To determine the most effective IBC signal in real-time during the test, the acoustic data were high-pass filtered with a cut-off frequency of 150 Hz. This is different from the methods which are currently being used for an extensive analysis. However, this should give an idea of what is to expect as final results.

Surprisingly, a 2/rev input proved far more effective in BVI-noise suppression as peaks and signals like that. Reductions of up to 6 dB at one microphone position were noted. Furthermore, not only the BVI-noise, but also the low-frequency noise was diminished. This was achieved by a 2/rev input of ±1.0° amplitude and pitch angle minima at 30 and 210 degrees azimuth angle (fig. 15).

This hand-recorded data give no idea how far changes in the rotor trim state or in the rotor noise pattern contribute to the noise reduction. A complete evaluation of the acoustic database is actually performed by NASA. Nevertheless, the big potential of IBC, and especially 2/rev control, for helicopter noise reduction is obvious.

One important questions is if less noise and less vibration can be achieved simultaneously. At the BVI test condition, the normal force vibration at the optimum 2/rev phase angle for BVI-noise suppression was less than in the baseline case, although not optimal. This indicates that improvements in noise are not necessarily accompanied by a higher vibration level, instead, the simultaneous achievement of noise and vibration reduction might be possible. Of course, the other vibration components also have to be considered for a dedicated statement on this item.

The shaft angle of the baseline case was 3.5 degrees. For slightly different shaft angles (2.0 deg. to 4.0 deg.) the optimum 2/rev input phase for BVI-noise reduction remained nearly constant. On the other hand, when the shaft angle was increased over 4.0 degrees, the baseline case produced much less BVI noise. When the same 2/rev signal was applied to this flight condition, the rotor noise increased. The consequence is that IBC-signals optimized for BVI noise suppression should only be introduced if the existance of BVI noise at the baseline condition is known.

One major objective of the test was to determine the effect of 2/rev control on rotor performance at high speed and high thrust conditions. Improvements are anticipated due to stall suppresion on the retreating side and compressibility effects on the advancing side.

Changes in rotor power in the magnitude of 40 to 50 hp were seen on the real-time display during the test. Unfortunately, the effect of 2/rev control was superimposed by changes in the rotor trim state (thrust, rolling and pitching moment) which could not be eliminated during the test. At this time, it is not clear how much of the effect on rotor power was caused by IBC or other effects, so that the power reduction potential of IBC is not definite. A thorough evaluation of the database in combination with theoretical calculations validated by the test data, and the intended second wind tunnel test will provide an answer to this interesting question in near future.

5. Future Plans

The datailed evaluation of the database will take some more time, at NASA as well as in Germany. The data will also be compared to scaled wind tunnel tests performed by the DLR and the IBC flight tests performed by HFW and Eurocopter Germany. The data will also serve to validate theoretical calculations, especially with CAMRAD/JA.

A second wind tunnel entry is planned by NASA and HFW in March 1994. The main objectives of this test are to make use of the full capability of the HFW-IBC-System (3.0° of blade pitch angle) and to take more data points at high speed and high thrust conditions to evaluate the possible performance improvements by IBC.

For this test, it is necessary to have higher load limits on some NASA test hardware. Therefore the stress analyses have been reviewed, a new swashplate for the RTA will be manufactured, and some other parts will be improved. Some minor changes will be made to the HFW- IBC-System. The feasibility of retrimming the rotor in terms of thrust and moments will also be improved.

It is still a long way to the wide application of IBC to helicopters. This wind tunnel test has provided a good database for future development of the IBC-technology, and important complements will hopefully result from the second wind tunnel entry. The next step after this test has to be the development of a closed-loop controller, to allow completely automatic operation of the IBC-system.

6. Conclusion

In March and April of 1993, a full-scale wind tunnel investigation of the HFW-IBC-System was conducted in the 40- by 80-Foot Wind Tunnel at NASA-Ames Research Center in cooperation with DLR and Eurocopter Germany. The test conditions were characterized by high vibration (transition), high BVI noise (approach), high speed (advance ratio 0.3 and 0.4) and high thrust ($C_T/\sigma = 0.12$). A comprehensive data evaluation is currently being performed. During the test indications for substantial reductions in noise as well as in vibrations were found.

Vibration reduction was achieved by all frequencies from 2/rev to 6/rev. A complete cancellation of the five vibratory components (thrust, aft force, side force, pitching and rolling moment) might be possible, because five frequencies are available for this task.

A 2/rev input proved very effective for BVI noise suppression. The noise data have to be thoroughly reviewed to determine if, besides IBC, changes of the rotor trim state and the noise pattern contributed to the noise reduction. The results will be compared with DLR data for a scaled BO 105 rotor in the DNW.

Performance improvements by IBC were not clearly visible, because stress limits of some test hardware precluded the use of the full IBC capability, and retrimming problems overlapped the effect of IBC on performance. Nevertheless the data will allow for a comparison with theoretical models to determine this effect.

A second wind tunnel entry is planned for March 1994. Improved test hardware will allow the use of IBC pitch angles up to 3.0° also in high speed and high thrust conditions. A new procedure to retrim the rotor will be used for easy comparison of baseline and IBC test conditions.

The successful wind tunnel test of the HFW-IBC-System and its continuation in 1994 will provide important information for further development of the IBC-technology, especially for the design of a closed-loop controller.

7. Acknowledgements

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Advance Ratio	Thrust Level (CT/Sigma)	Shaft Angle (degrees)	Trim Condition	Characteristics	Data Points
0	n/a	0	n/a	Inertia Compensation	32
0	0,071	-10,0	Zero Flapping	Hover	13
0,1	0,071	-2,0	Zero Flapping	High Vibration	64
0,1	0,071	-2,5	Lat. Cycl. -2,7 deg., Long. Cycl. 0,75 deg.	High Vibration	33
0,15	0,071	3,5	Zero Flapping	High BVI-Noise	119
0,3	0,071	-7,3	Zero Flapping	High Speed	22
0,3	0,071	-9,0	Lat. Cycl. -0,7 deg., Long. Cycl. 4,0 deg.	High Speed	24
0,4	0,071	-2,5	Zero Flapping	Very High Speed	5
0,2	0,120	-3,0	Zero Flapping	High Thrust	19

Tab. 1: IBC test conditions

IBC Blade Instrumentation

Blade No.	Parameter	Location (r)
All	Blade Pitch	n/a
1	Flap bending	0,10
1	Chord Bending	0,57
1	Torsion Moment	0,34
3	Torsion Moment	0,40
3	Torsion Moment	0,57
3	Torsion Moment	0,80
3	Pressure	0,60
3	Pressure	0,70
3	Pressure	0,80
3	Pressure	0,90
4	Flap Acceleration	0,30
4	Flap Acceleration	0,50
4	Flap Acceleration	0,70
4	Leading Edge Acc.	1,00
4	Trailing Edge Acc.	1,00

Pressure Sensors at 5 % Blade Chord
Flap Accelerometers at 25 % Blade Chord

Tab. 2: Blade instrumentation for the IBC test

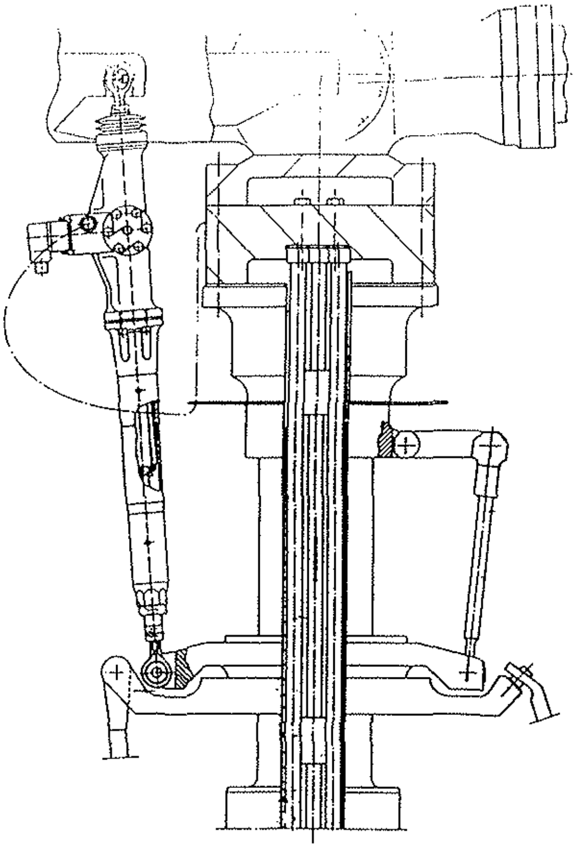

Fig. 1: IBC actuator arrangement

IBC Actuator Characteristics

Frequency Response

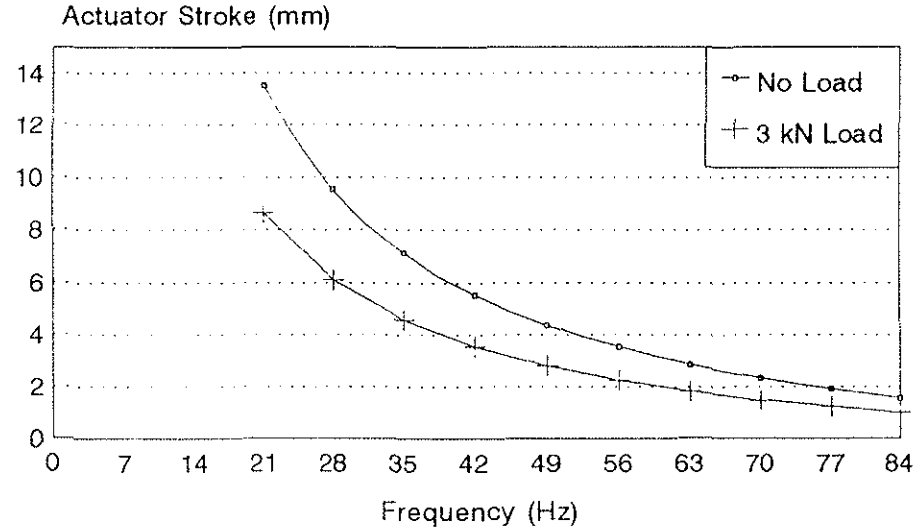

Fig. 2: Frequency response of IBC actuators

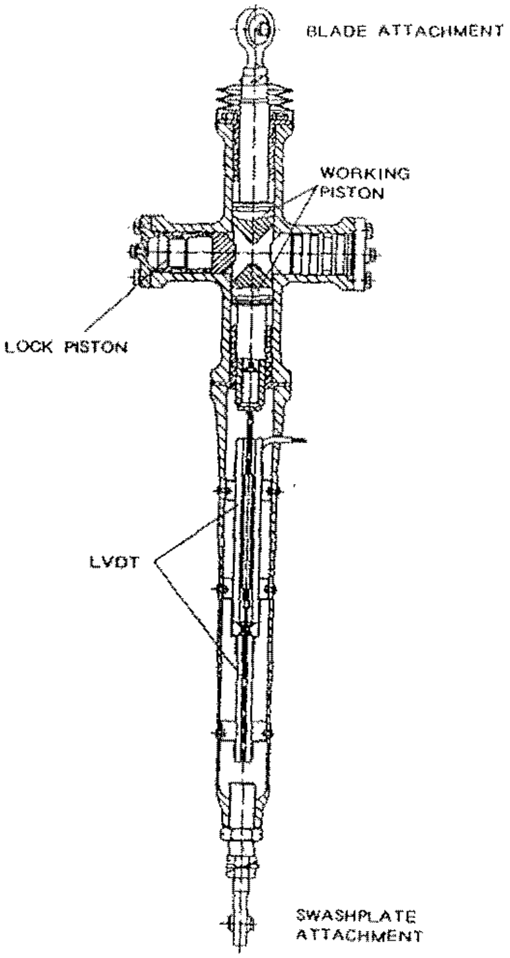

Fig. 3: Cut of IBC actuator

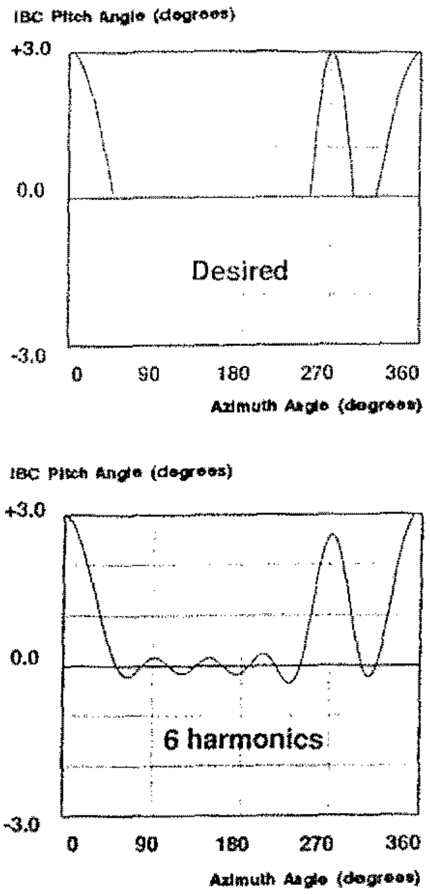

Fig. 5: IBC signal approximation by Fourier Analysis

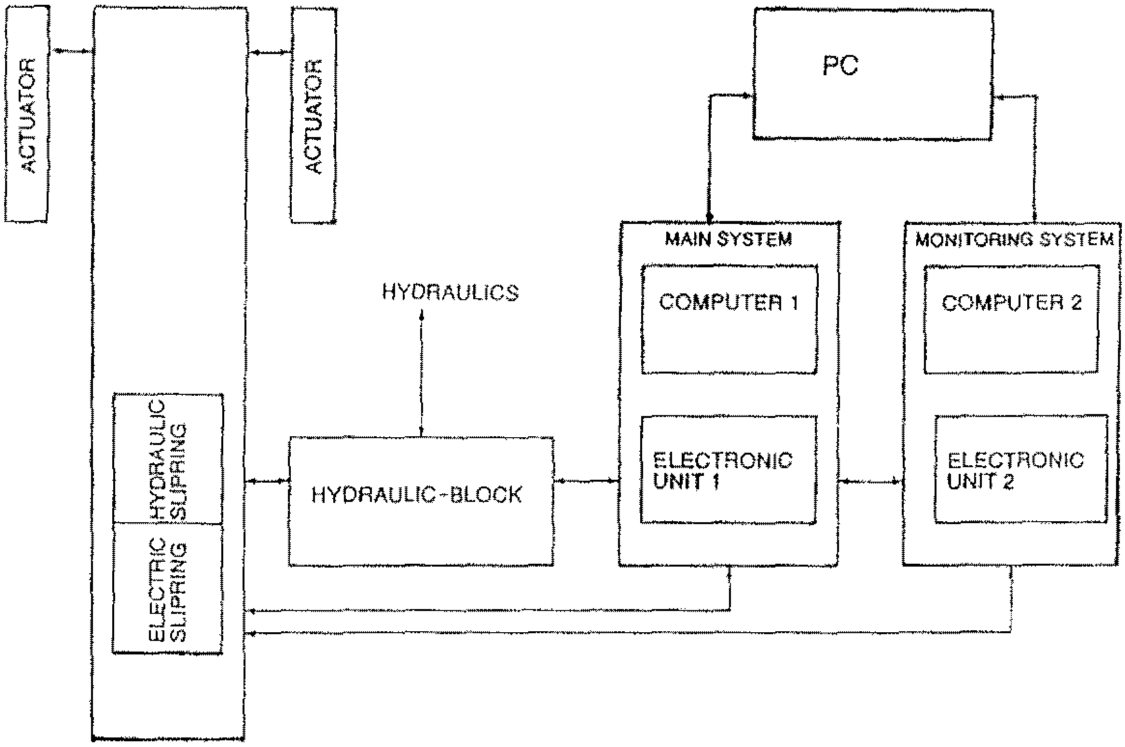

Fig. 4: IBC controller block diagram

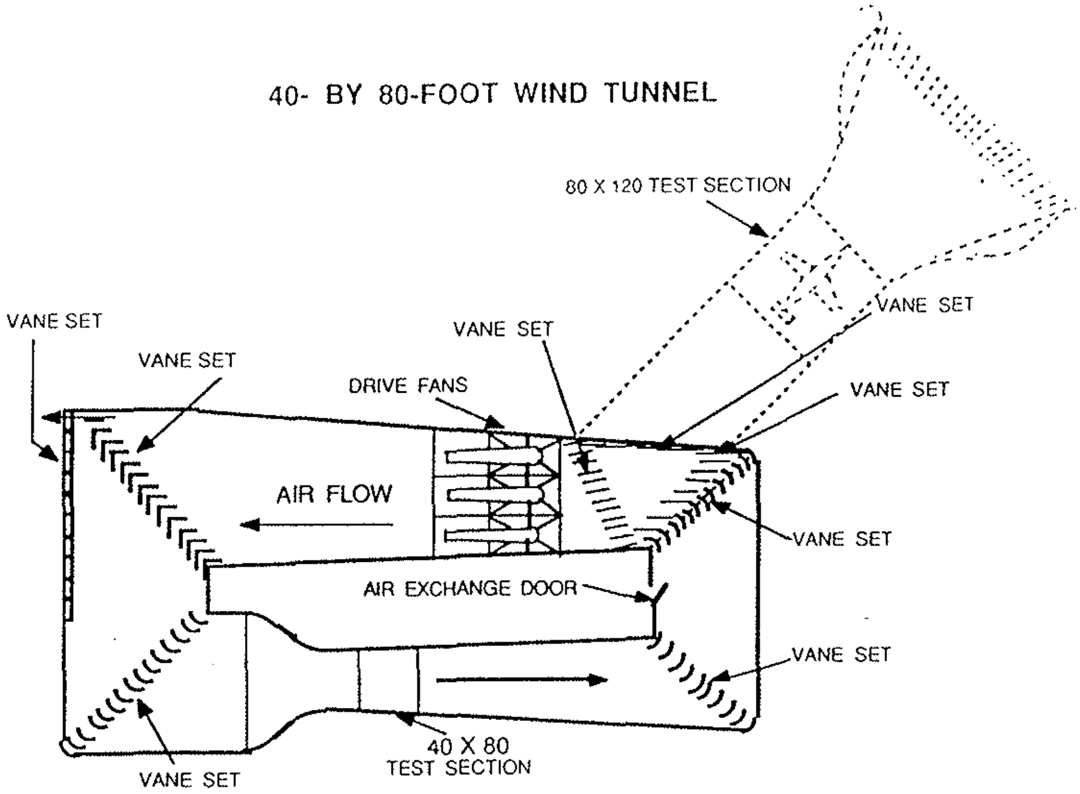

Fig. 6: **Scheme of the 48x80 / 80x120 Wind Tunnel**

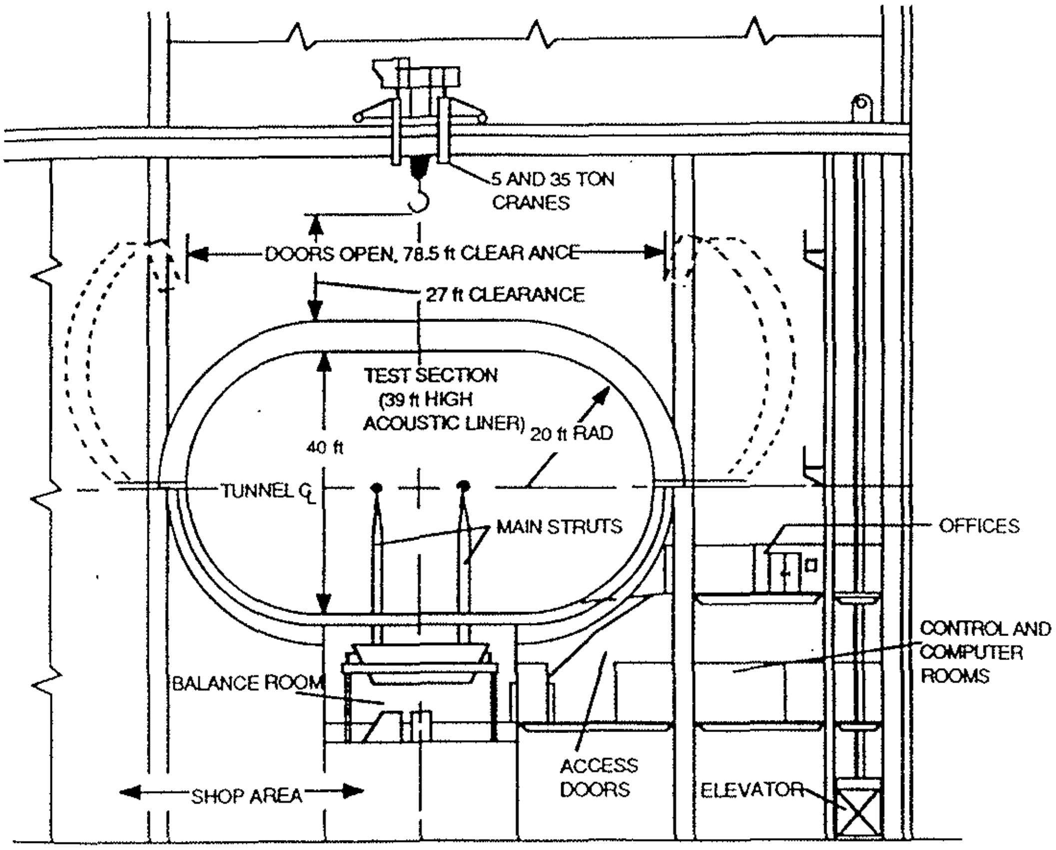

Fig. 7: 40- by 80-Foot Test Section

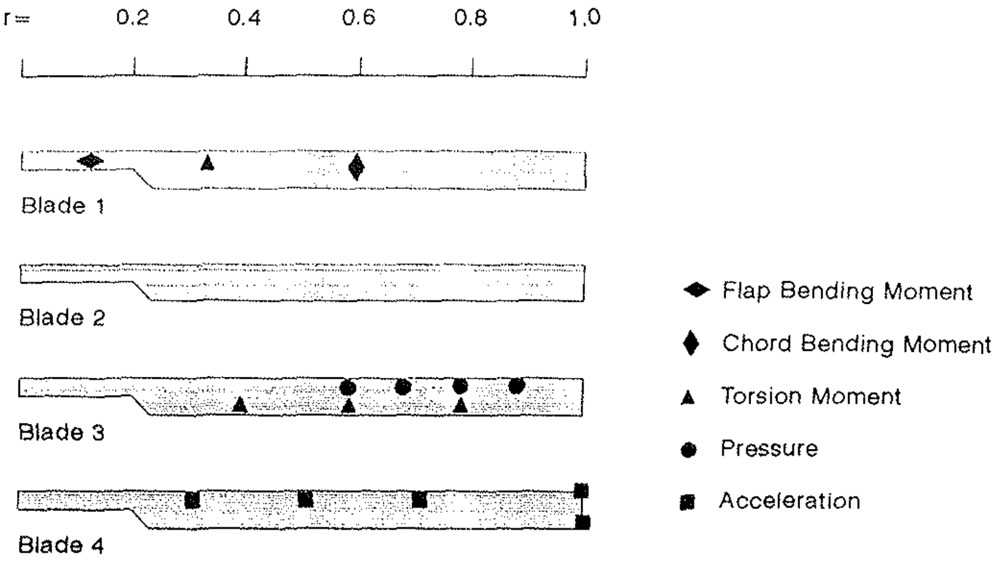

Fig. 8: Blade instrumentation for the IBC test

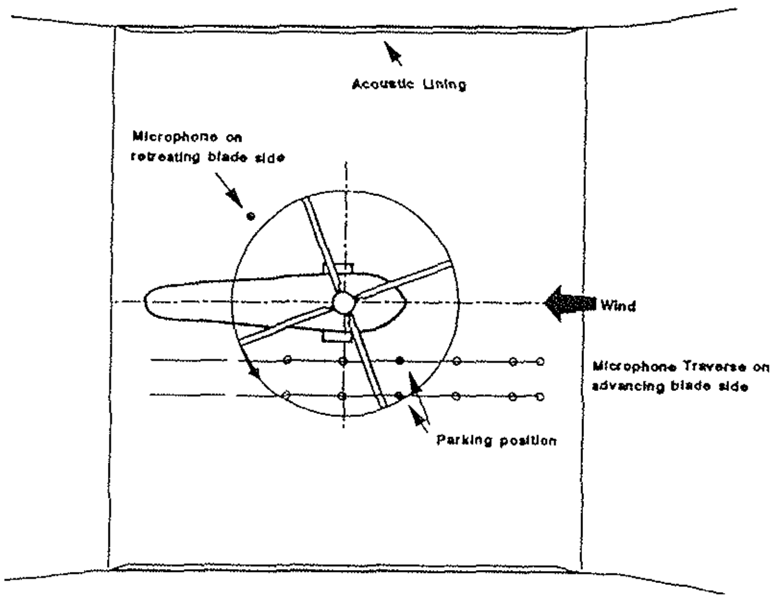

Fig. 9: Microphone positions

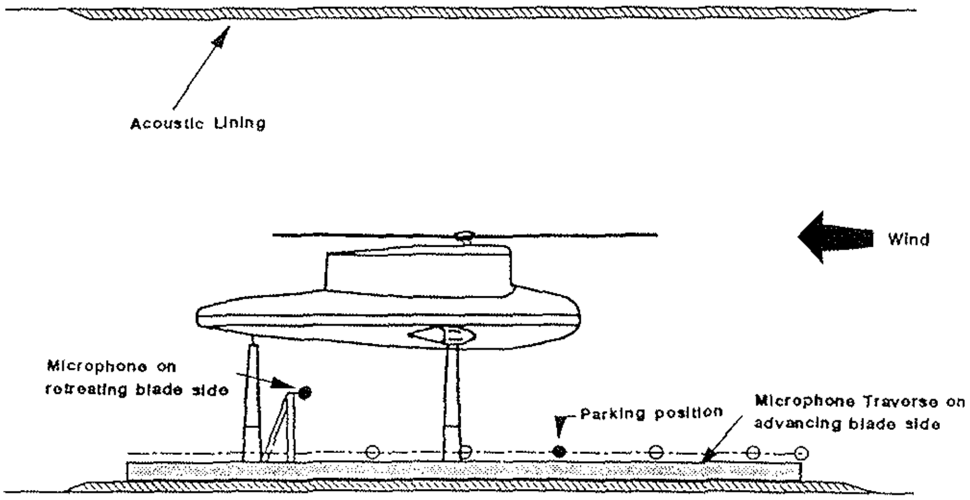

Fig. 10: Microphone positions

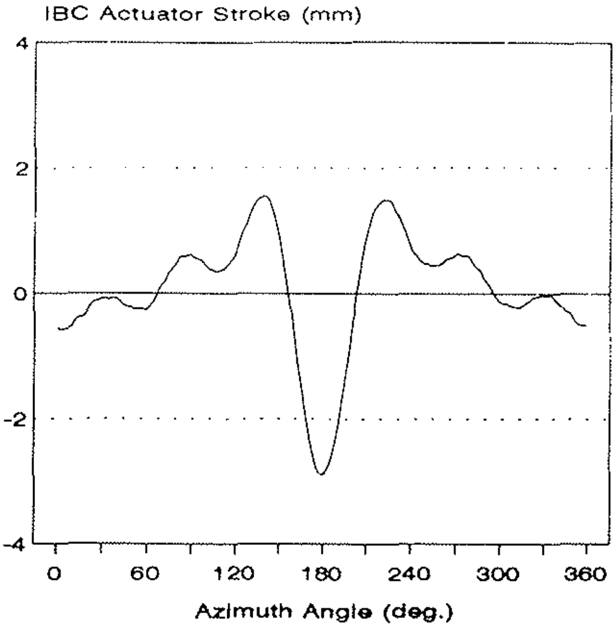

Fig. 11: IBC-signal "Negative Pulse"

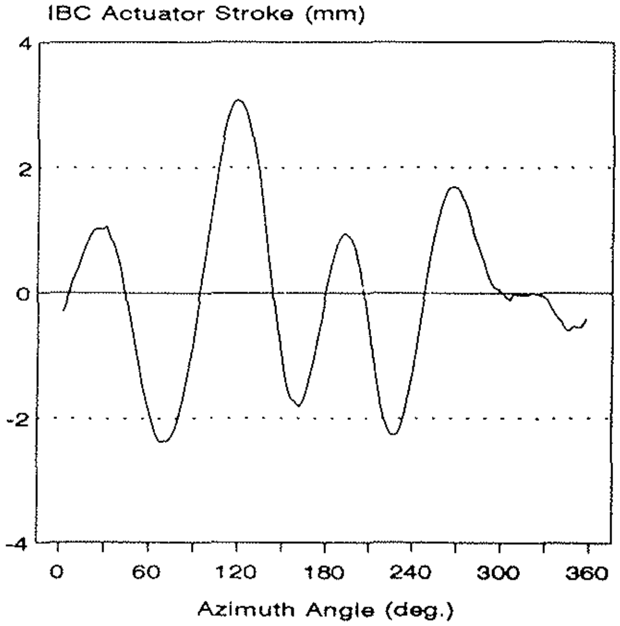

Fig. 12: IBC-signal "Doublet"

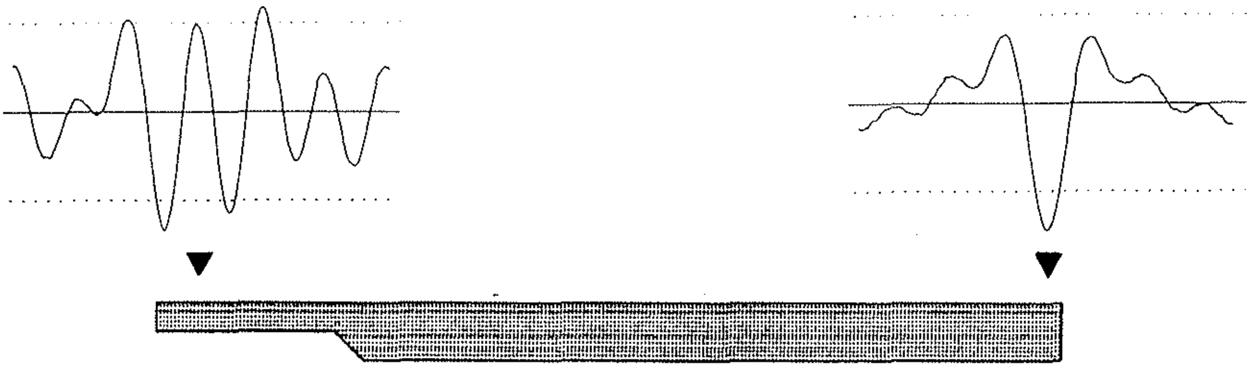

Fig. 13: "Wavelet" at the blade root yields "Pulse" near the blade tip

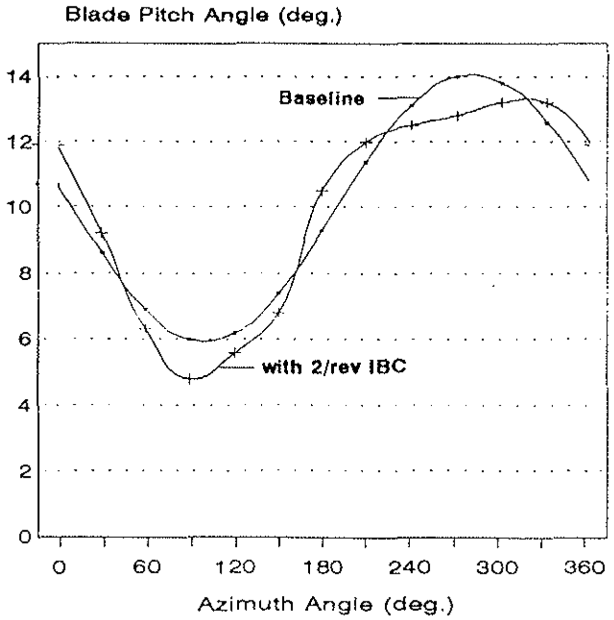

Fig. 14: Combination of cyclic control and 2/rev IBC at high speed

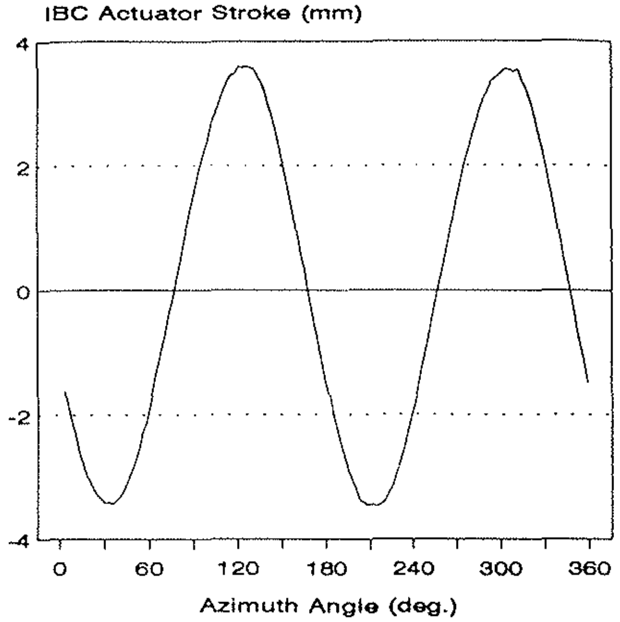

Fig. 15: 2/rev signal with high BVI-noise suppression effect