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THE EFFECT OF HHC TO A FOUR BLADED HINGELESS MODEL ROTOR

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Abstract

A four bladed hingeless rotor system was used for application of higher harmonic control (HHC) inputs. With the objective to get a better knowledge of the dynamic behaviour of rotor forces and moments theoretical and experimental investigations were conducted. Wind tunnel measurements in the DNW with the DFVLR rotor test rig included different advance ratios and trimmed flight conditions scaled down from the BO-105 helicopter.

After a brief description of the test equipment, the sensor arrangement, the data acquisition, and data reduction the evaluation of the reference data will be described.

In the second part of this contribution the effect of the 3/rev, 4/rev, and 5/rev control inputs to the vibratory hub and blade loads are demonstrated. The major aspect to be discussed is the extraction of nonlinearities and couplings in the control inputs, which are the amplitudes and phases of the three higher harmonic blade pitch angles.

Additionally comparisons of the cost function, evaluated at simulations runs and the wind tunnel tests, are described. The cost function gives a value for the vibration level in the dedicated rotor system which is an input for most of the common HHC algorithm.

1. INTRODUCTION

One of the research programs at the DFVLR deals with the reduction of vibratory rotor loads utilizing Active Control Techniques especially Higher Harmonic Control (HHC). Various detailed studies and analytical simulations (e.g. Ref. 1,2,4) have been done to quantify the requirements of HHC for the four bladed model rotor operated at the DFVLR Institute for Flightmechanics, followed by wind tunnel tests in the DNW in April this year (Fig. 1). It was the first comprehensive proving of the specially designed HHC hard- and software under realistic conditions. The development of this system needs more than three years and results in an advanced feedback regulator (Constant System Response Regulator) for the commercial hydraulic actuators, a full digital HHC controller, a Realtime Quick Look Processor, and a fast data acquisition system with various on line data reduction capabilities. So the wind tunnel test program included several different objectives.

The major aspect was to check the proper operating of the different new hardware components. The next step was the evaluation of the basic data set for the tests with HHC. Wind tunnel speed variations were performed with a step width of 5 m/s in the range of interest between 10 m/s and 50 m/s. For all configurations the first task was to adjust the collective control angle to the same value than that of the BO-105, then correcting the shaft tilt angle until the scaled thrust of the BO-105 was achieved, and at last to turn the cyclic pitch angles to values which yield zero hub moments.

The basic configuration for HHC investigations was determined at 20 m/s as the model rotor produces at the largest dynamic forces and moments at this velocity. Next for a given amplitude of a single higher harmonic the control phase was shifted between -180 degrees and +180 degrees by steps of 30 degrees. Reaching a steady state condition the data acquisition was taken over nearly 1.6 seconds. During this time of operation the Realtime Quick Look Processor calculates the quality criterion and shows this value on a graphic display. That makes it possible to check the effect of the manual adjusted control angles at the moment of operation. Additionally the linear spectrum of the balance sensors was displayed. Finally tests were conducted to investigate the effect of a simultaneous application of the 3,4, and 5/rev control.

2. THE HHC HARDWARE COMPONENTS

As described in an earlier paper (Ref.2) the Rotor Test Stand (RTS) is equipped with a large amount of specially designed components to get the capability for a precise HHC. The primary parts are the Constant System Response Regulators controlling the electrohydraulic servo actuators, and the digital HHC Signal Processor (Fig. 2). The HHC Signal Processor computes the actual necessary displacements of the three hydraulic actuator pistons from given higher harmonic control amplitudes and phase angles. The moment of computation and output is initiated by a digital rotor azimuth angle encoder. This task is initiated 128 times at every rotor revolution. So the 4/rev signal for the swashplate adjustment is generated by 32 steps. The update of the -for the first tests manually given- control inputs is performed every 200 ms and enables a continuous variation of these values.

After computing the HHC signals and the digital to analog conversion is performed these signals are used as reference inputs for the Constant System Response Regulators. The regulators, each for one actuator, compares the reference signal and the actuator output. In the case of differences between the two signals, the regulator adjusts the amplitude and/or phase until the actuator output coincides with the reference signal. A correction is only necessary when the characteristic of the servo system varies, e.g. caused by a change in the rotating frequency or when the oil temperature varies.

Fortunately these correction values are an indication for the differences of the actual system characteristic and the normality too. As most of the malfunctions in hydraulic servo systems are indicated by altering the system characteristics, these correction values can be utilized by a fast fail-safe servo disabling.

Additionally to the higher harmonic control angles displayed by the HHC Signal Processor, a rotor blade was instrumented to measure the blade root pitch. The Realtime Quick Look Processor calculates the FFT of this signal and displays graphically and numerically the amplitudes and phase of the blade root pitch. It was the task of the operator to observe or check the system characteristics of the swashplate and pitch links. The pitch links were also equipped with strain gauges to measure the dynamic loads. They were observed in the frequency domain for safe operation with HHC.

The forces and moments generated by the rotor system were measured by the Rotor Balance. The installed piezo force transducers guarantees high accuracy over a wide range of dynamic load amplitudes. To get a quick look of the effectiveness of higher harmonic control inputs, the RQP processes the seven piezo signals in two different ways. The first task was to calculate the linear spectrum of each sensor signal. For the next step the seven spectra were superposed and graphically displayed. At last the 4/rev component was used to calculate the value of the quality criterion which was displayed graphically and numerically. This facility gives the possibility to assess online the effect of the HHC. Displaying the linear spectrum up to 140 Hz an important information is available, too, about the general reaction of the rotor system.

Of course, the RTS is equipped with additional sensors in the rotating and non-rotating system. For the normal operation in the wind tunnel e.g. the conventional control angles, the static rotor forces and moments, and the shaft tilt angle are indicated. Altogether 62 sensor signals were acquired, thirty-two from the rotating and thirty from the fixed system. A PCM unit digitizes the analog signals and a data acquisition computer stores the data on a magnetic tape. The time of recording depends on the test goal. In the case of HHC the data acquisition takes nearly 1.6 seconds or 1230 samples per channel.

3. THE WIND TUNNEL TEST PROGRAM

The primary goal of the wind tunnel tests was a comprehensive proving of the complete system inclusive the software modules for the different tasks, especially for the HHC Signal Processor, the Data Acquisition Processor and the Realtime Quick Look Processor (RQP). After an operation without failure was guaranteed the provision of a basis data set was necessary. At different wind tunnel speeds the dynamic response of the rotor system was measured in the range between 10 m/s and 50 m/s. To get comparable results to the BO-105 the adjustment of the rotor needs the following steps. At first the collective pitch was chosen from the BO-105 flight tests, at second the shaft tilt angle was varied until the rotor has the scaled thrust of $\approx$ 3700 N (Fig. 3). At third the rotor moments were trimmed to zero using the cyclic pitch control (Fig. 4).

The evaluation of the data from the test conditions are shown in Figure 5. Based on the forces and moments at the rotor balance the following quality criterion is plotted versus the tunnel speed in this figure:

$$GF = \sqrt{z^T W z}$$

with

$$z^T = (F_x, F_y, F_z, M_x, M_y)_{4/rev}$$

and

$$W = \text{diag } (1/N, 1/N, 1/N, 1/Nm, 1/Nm).$$

In this Figure the second curve is plotted comparing the dynamic response of the model rotor with the BO-105 dynamic behaviour. The two curves describe, strictly spoken, not the same effect, but show very well the dependency of the 4/rev forces and moments due to speed variation. The point of the highest vibration coincides with the maximum of the quality criterion. For the following first tests under HHC the speed of 20 m/s was chosen.

4. THE EFFECT OF THE 3/REV CONTROL

The tests with HHC were performed at 20 m/s wind tunnel speed, a thrust of 3670 N ($\vartheta_{coll.} = 6.6°$) and zero hub moments. After a steady state condition was achieved the operator enables the HHC Signal Processor. This was done by enabling the interrupt from the digital azimuth angle encoder which is attached to the rotor shaft. The processor generates no 4/rev signals in the case of zero control inputs, but it generates a periodic function which is a sum of harmonics of the rotating frequency. The operator can check this signal before he turns on the HHC amplitudes.

The test began with an 3/rev amplitude of 0.25 degrees (A3 = 0.25°). Then the control phase was shifted between -180 and 180 degrees ($-180° \leq P3 \leq 180°$). After each 30 degrees shift the manual control operation stopped followed by the data acquisition for 1.6 seconds. During the whole time the HHC was enabled, the operator observes the value of the quality criterion and the spectrum of the balance sensors. After the first run with A3 = 0.25° the amplitude was increased to A3 = 0.5° and the same procedure follows. The Figure 6 shows the results. Clearly visible is the region around -160° with the minimum of the quality criterion. In the region around zero control phase the dynamic rotor loads increases over the base line evaluated without HHC. Because it was the first test with HHC enabled we proceeded very cautiously and did not control this phase. Also obvious is the steady variation of the quality criterion in the whole range of control phase.

A closer look to the minimum region shows that the optimal control phase depends on the amplitude. The amplitude of 1.0 degree needs a phase which differs about 30 degrees from the case with small amplitudes. But the value of the quality criterion is not only influenced by the control phase. The Figure 7 shows the dependence on the 3/rev amplitude in the region of optimal control phase. The slope becomes zero if the amplitude increases over ≃ 1.1 degrees. Unfortunately there is no measuring point with larger amplitudes than 1.1 degrees because the manual control was suspended at the minimum value but the tendency of the quality criterion was observed.

The Figure second shows the plot of the quality criterion calculated without the inertial forces which are caused by the accelerated masses of the control hardware such as actuator pistons, swashplate, and blade root hardware. The influence is not significant but increases slightly the 4/rev forces and moments at the rotor balance. The effect grows with increasing control amplitudes. For realtime calculations of the quality criterion this influence is disadvantageous and must be considered at future tests.

The third curve in this Figure is only the squared quality criterion, as this type of cost function is often used by other authors especially if closed loop systems are considered. So this function was plotted for comparisons.

In the quality criterion all the different 4/rev are comprised to a scalar value. For a more detailed information about the effect of the HHC one must analyse the components itself. The 4/rev forces and moments at the rotor balance in the cases without and with optimal 3/rev HHC are illustrated by Figure 8. It shows the significant reduction of all five controlled components to less than a half. The dynamic part of the shaft torque was not available because the commercial torque indicator has had a build in low pass filter.

Besides the resulting forces and moments at the rotor balance in the fixed system the blade root moments also indicate a variation in the dynamic rotor loads. The blades were instrumented with strain gauges at different radial positions to measure the flapwise and chordwise bending moments. For demonstrating the effects, the flap bending moment at 15 % radius is illustrated by Figure 9. Here the signal is analyzed in the frequency domain up to the 5-th harmonics. The conditions compared here are the trimmed flight without and with optimal 3/rev HHC. Unexpected is that the most distinct percentage variation at the amplitudes occurs not at the 3/rev frequency but at 2/rev. In the case of conventional flight the 2/rev flap bending moment is negligible. It increases to a value which is the same as at 1/rev. The amplitude at the third harmonics decreases as expected. A significant reduction also occurs at the fifth harmonics while the influence on the 4/rev is only small.

The increasing level of the 1/rev amplitude must also be considered. It was observed that the static rotor moments which were controlled to zero at the beginning of the test, changes to non-zero values when the active control was engaged. Small variations (<1%) were also observed during the tests. Summarized one can say that the 3/rev blade control

reduces all balance forces and moments for more than 50%,

changes the spectral components of the flap bending moment significantly,

affects the trim state,

has a nonlinear effect which depends on the amplitude and phase.

5. THE EFFECT OF THE 4/REV CONTROL

Comparable to the test procedure with the 3/rev HHC, about forty different combinations were investigated of the 4/rev amplitude and the control phase. But after the first adjustments it was clearly determinable, that the quick look quality criterion did not show the expected results. Of course the value of the quality criterion depends on the control phase but the level grows when the 4/rev amplitudes increase, see Fig. 10. However the measurement procedure was completed and the balance forces and moments were corrected off line with the inertial forces caused by the accelerated mass of the control hardware.

The results are illustrated in Fig. 10. It is visible that the online calculated quality criterion has the minima at about the same control phase as the quality criterion calculated with the cleaned values. As expected the function has one distinct minimum at about 110 degrees control phase. The dependence of the quality criterion on the 4/rev HHC amplitude is illustrated in Fig. 11. The plotted function shows the value of the quality criterion versus the 4/rev blade pitch at optimal control phase. The minimum is achieved at 0.7 degrees blade pitching. At higher amplitudes the quality criterion increases rapidly. Another result is the fact that the 4/rev control achieves nearly the same reduction in dynamic loads as the 3/rev blade feathering but with a 30 % less blade pitching amplitude.

To show the reason for this effect the spectrum of the blade flap bending moments at 15 % radius are plotted in Fig. 12. The most reduction occurs at the third harmonics. The level was reduced to 25 % of the initial value. In contrast to the 3/rev HHC, the second harmonic component of the bending moment was less affected by the 4/rev control. The 4 and 5/rev bending moment indicates also a small variation. Without the second harmonic, the spectrum nearly looks like the spectrum with 3/rev control.

Therefore it is not astonishing that the balance forces and moments have the same tendency as illustrated in Fig. 13. All forces and moments are clearly reduced, the lateral force even by 94 %. Summarizing, the 4/rev control achieves the same level of the quality criterion and nearly the same reactions at the blade root as the 3/rev control, but with lower pitching angles. Unfortunately the rotor reaction cannot be measured online because the accelerative forces in the mechanical control hardware disturbs the measurement.

6. THE EFFECT OF THE 5/REV CONTROL

The last application of a single higher harmonic control considers the 5/rev blade feathering at various amplitudes and control phases. In Figure 14 the results are plotted. Again there exists only one region with optimal control phase ($-30^\circ \div 10^\circ$). The blade root pitch is considerable high for minimizing the quality criterion. This can be seen better in Figure 15. The value of the quality criterion decreases slowly with increasing 5/rev pitching amplitudes and it could be, that the true minimum was not reached at 1.0 degree amplitude. However the 5/rev control does not reduce the value of the quality criterion with the same efficiency as the 3 and 4/rev control.

This is also indicated by the spectrum of the blade bending moment shown in Figure 16. Only the third harmonics is dropped to 44 % of the initial value but the fourth harmonics increases for three times. Although the first and second harmonics are influenced by the 5/rev HHC.

The resulting forces and moments in the fixed system are shown in Figure 17. It can be seen that only the moments and the lateral force at the balance are particular smaller than the initial values. The vertical and longitudinal forces are only slightly reduced. Summarizing the results of the 5/rev HHC one can say that this single higher harmonic works not so effectively as the single 3/rev and 4/rev HHC. This result is illustrated again in Figure 18. The left two beams are the values of two different quality criterions, calculated with the initial conditions (without HHC):

$$GF_F = \sqrt{F^T F} \quad ; \qquad F^T = (F_x, F_y, F_z)$$

and

$$GF_M = \sqrt{M^T M} \quad ; \qquad M^T = (M_x, M_y)$$

The next three pairs of beams are the values of these quality criterions at optimal single higher harmonic control. Now it can be seen that the 3/rev HHC achieves the best reduction followed by 4/rev and 5/rev HHC. It is also visible that the reduction of the moments dominates at 3 and 5/rev HHC. The resulting force vector is mostly influenced by the 4/rev HHC. One important result is the fact that all single higher harmonics drop the levels of the 4/rev forces and moments to values lower than 50 % of the initial amplitudes (except the force at 5/rev HHC).

7. THE PITCH LINK LOADS

One reaction of interest in the case of HHC are the pitch link loads. Therefore the results of the data analysis are demonstrated in Fig. 19. The solid lines are the pitch link forces at different frequencies (3, 4, 5/rev) obtained with disassembled blades. As expected the force is proportional to the frequency and to the pitching amplitudes. In contrast the broken lines show the pitch link forces in the case of optimal HHC with attached blades. It becomes obvious that now the dependence on the frequency is only small. At 4 and 5/rev blade feathering the pitch link loads have nearly the same level while the 3/rev HHC generates slightly lower loads. At 5/rev the forces obtained with rotor blades attached are nearly the same as with disassembled blades.

This effect can only be explained with the low first torsion eigenfrequency which should be at $\omega_\varphi/\Omega = 3.7$. The blade root pitching excites the first torsion eigenmode which has probably a low impedance in the environment of airflow. An effect caused only by aerodynamic pitching moments is unlikely because the 5/rev pitch link loads without HHC are very small. A similar result was found in an analytical study (Ref. 1).

8. THE EFFECT OF SIMULTANEOUS 3, 4 AND 5/REV HHC

After the tests with single HHC were completed the effect of simultaneous application of all three higher harmonics was considered. For that, the 3/rev HHC was adjusted to the optimal control angles and after the 4 and 5/rev HHC enabled. During the variation of the amplitudes and phases, the realtime calculated value of the quality criterion was observed to achieve a minimization of the vibratory rotor forces and moments. But the result was not so good as expected because the inertial forces of the control system influences the realtime quality criterion unfavorable when the 4/rev blade pitching was increased. Thus results in a very small 4/rev control value (0.18 deg.). The 5/rev blade feathering needs 0.4 deg. amplitude and -14 deg. phase shift. At larger amplitudes the quality criterion grows up.

Figure 20 illustrates the measured forces and moments at the balance. All components are clearly reduced (Fx=44%, Fy=81%, Fz=33%, Mx=69%, My=50%). The relative small reduction of the vertical force can be explained with the nonoptimal 4/rev control. The phase of the 5/rev pitch is the same as when single 5/rev HHC was applied. It can suggest that the optimal phase at single HHC is an optimal phase at superimposed control too.

The corresponding blade bending moments are shown in Fig. 21. Clearly visible are the changes at the first harmonics. The 1/rev component increases about 30 %, the amplitude of the 2/rev blade bending moment grows up to 63 % of the basic harmonic (without HHC=2%) and the 3/rev drops by 63 %. The 4/rev is changed by +38 % and the 5/rev by -21 %. One can see that the amplitudes now are nearly inverse proportional to the rotating frequency.

9. COMMENTS ON THE WIND TUNNEL TEST RESULTS

The analysed tests were performed at 20 m/s tunnel speed (μ = 0.09) and trimmed flight conditions. It was the primary goal to get an insight into the dynamic response of the model rotor when HHC was applied. Therefore the model was extensively instrumented. For variation the six HHC inputs were chosen.

The data analysis validates the effect pointed out in Ref. 5 that a hingeless rotor with a low first torsion eigenfrequency needs large control angles at the low speed region. Rotors with stiff blades in torsion achieve the minimization of the vibratory loads by significant smaller pitching angles as shown in Ref. 6. It leads to the deduction, that the first torsion mode dominates the effectiveness of Higher Harmonic Control. This assumption is confirmed by the distinct reduction of the 3/rev blade bending moments with each higher harmonic blade feathering frequency. The effects achieved during the tests differ in some cases from the simulation runs (Ref. 1, 4), e.g. there are the moments only less influenced by the 4/rev blade control. Nevertheless, the effectiveness of the different single HHC, indicated by the quality criterion, shows the same tendency.

Another effect caused by the HHC is the changing of the trim state. This was primary indicated by the 1/rev component of the blade bending moment but was confirmed by the rotor balance measurements. The deviations are only small and can be corrected by conventional control angles without affecting the dynamic loads.

At the RTS the hydraulic actuators are arranged on the upper plate of the rotor balance. This leads to the circumstance that the dynamic rotor loads are superimposed by the accelerative forces from the mechanical control system hardware. For a realtime calculation this is an undesirable influence. One possible way to correct the realtime analysis is to take into account the following relations:

$$z^* = z - M_z \theta$$

with

$$z^T = (F_x, F_y, F_z, M_x, M_y)$$

$$M_z = \text{Matrix of derivatives } \frac{\partial z_i}{\partial \theta_i}$$

(when blades are disassembled)

$$\theta^T = (\theta_3, \theta_4, \theta_5)$$

For a full scale rotor the ratio of control forces and dynamic rotor loads will be smaller because the mechanical control hardware (actuators, swashplate, etc.) at the model rotor are not scaled.

The control system electronics proved reliable and functioned without failure throughout the tests. The mechanical hardware was also reliable and it was no maintenance necessary, but during the application of higher harmonics, especially the 5/rev blade pitching, an increasing temperature at the swashplate was observed. Therefore only short periods (e.g. 10 min.) with active control were conducted.

10. CONCLUSIONS

- The first wind tunnel tests have validated the concept of the HHC Signal Processor. Therewith an active controller system component is available to generate higher harmonic blade feathering with excellent accuracy (amplitude: ± 0.012 degrees, phase: ±1.5 degrees)

- The advanced Constant System Response Regulators make it possible to utilize commercial servo hydraulic actuators. Differences in the system characteristics of the three servo systems are compensated, in the amplitude with 0.5 % and in the phase with 0.3 % tolerance.

- For minimizing the quality criterion in the low speed region relatively large control angles are necessary.

- The single HHC achieves a good reduction of all 4/rev components. A common used quality criterion for closed loop control can be dropped by 90 %.

- The chosen quality criterions show a steady behaviour and are utilizable in a feed back controlled system.

- Variations in the trim state were observed but they did not reduce the effectiveness of HHC.

- Pitch link loads are nearly independent on the pitching frequency but proportional to the pitching amplitudes.

- Accelerative forces at the mechanical control hardware can affect the measurements of the dynamic rotor loads.

- Further wind tunnel tests are required to expand the envelope in which HHC (including single HHC) has been demonstrated at this rotor.

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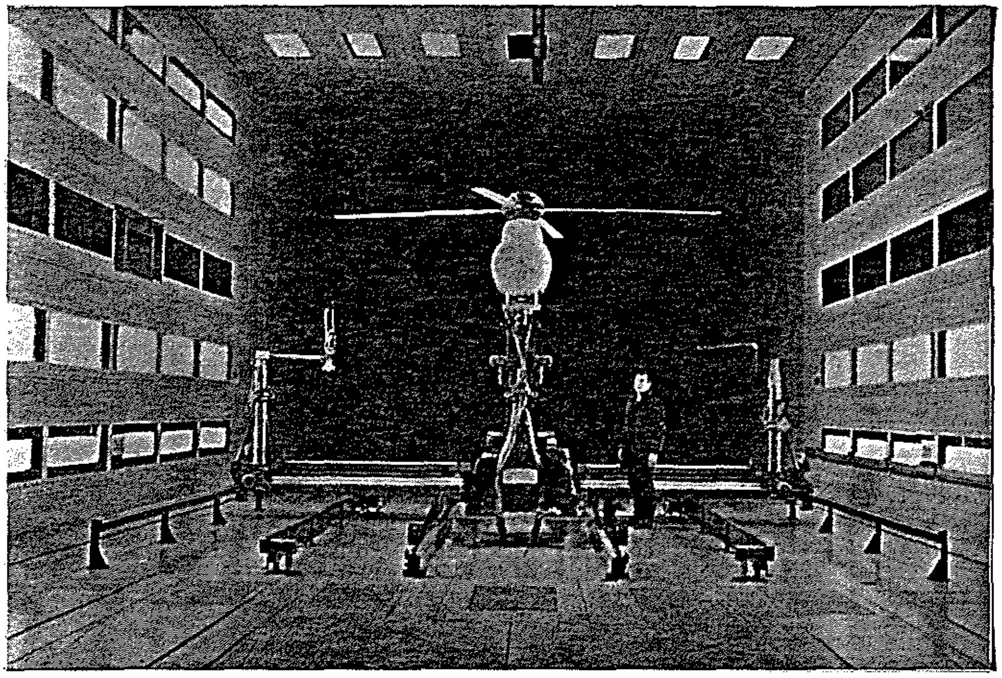


Fig. 1: The RTS in the DNW

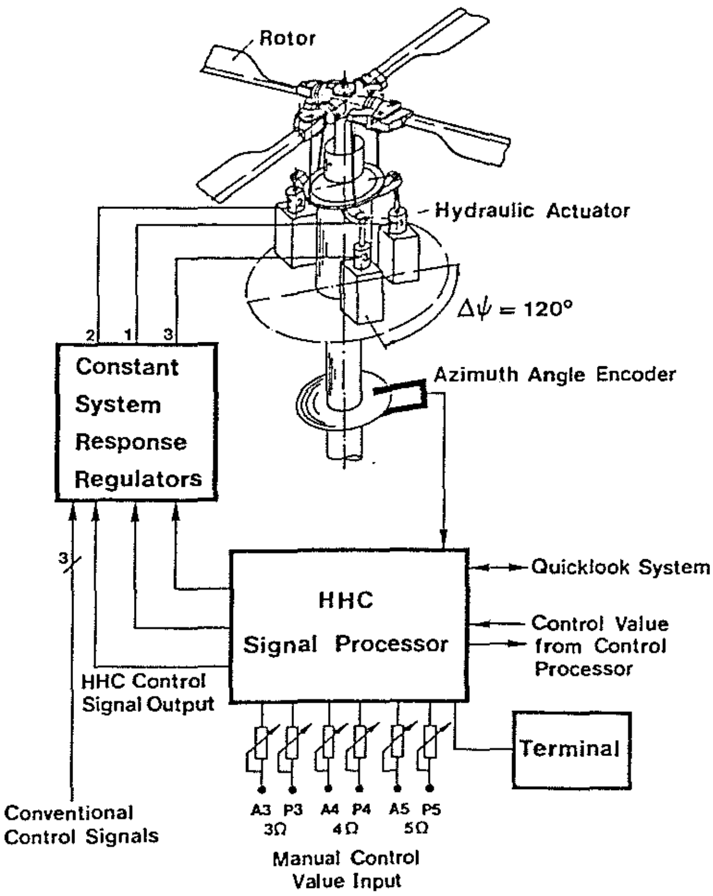


Fig. 2: HHC Hardware Parts at the RTS

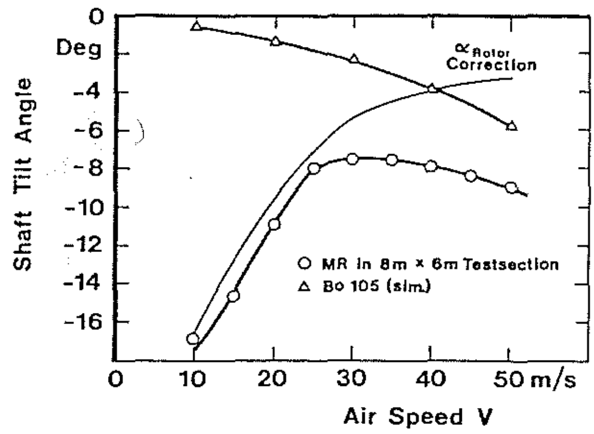


Fig. 3: Shaft Tilt Angle vs. Tunnel Speed

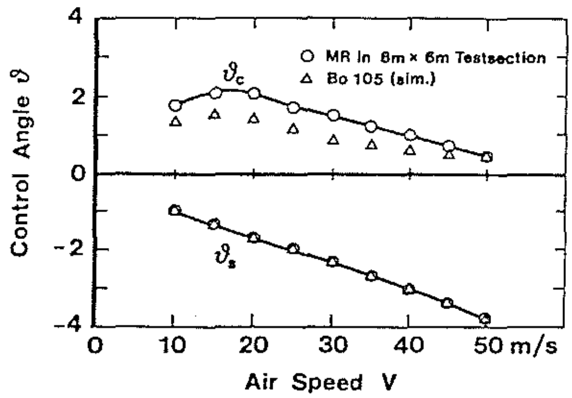


Fig. 4: Cyclic Blade Control Angles vs. Tunnel Speed

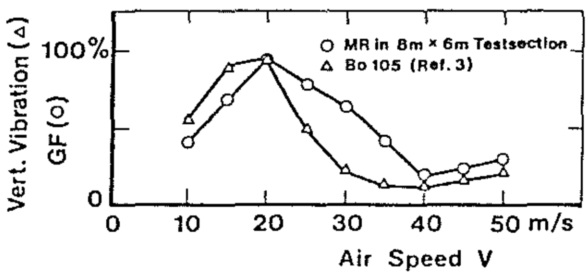
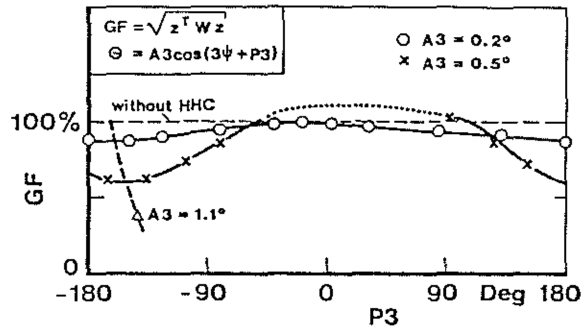


Fig. 5: Value of Quality Criterion vs. Tunnel Speed



).6: 3/rev Control – Value of Quality Criterion Depending on the Control Phase

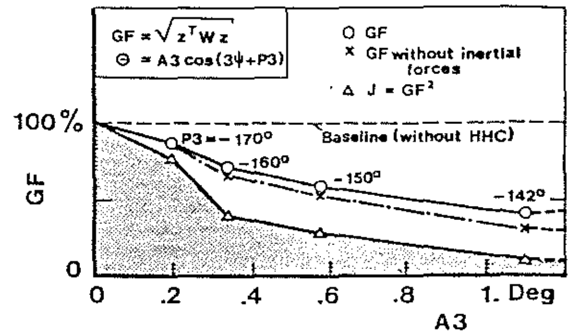


Fig. 7: 3/rev Control – Value of Quality Criterion Depending on the Control Amplitude

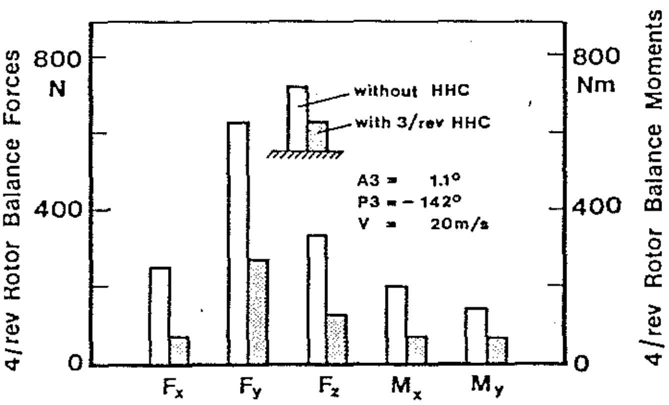


Fig. 8: Rotor Balance Forces and Moments with Optimal 3/rev Control

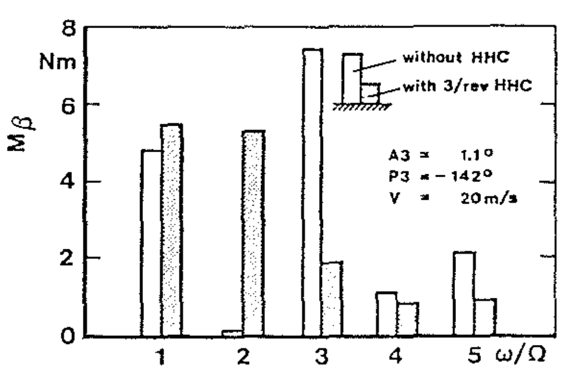
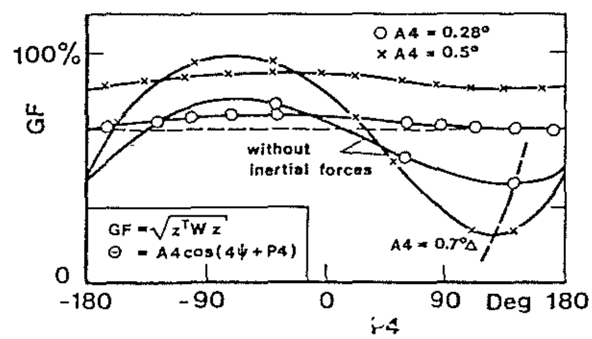


Fig. 9: 3/rev Control – Flapwise Blade Bending at r/R = 15 %



|. 10: 4/rev Control – Value of Quality Criterion Depending on the Control Phase

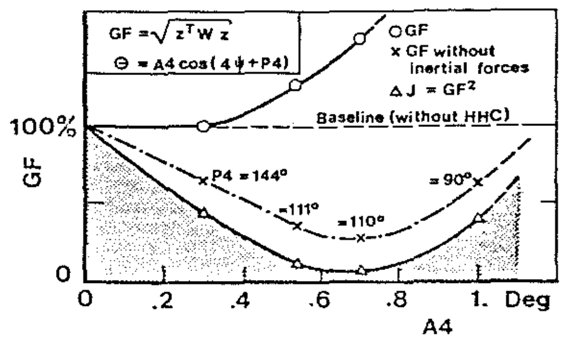


Fig. 11: 4/rev Control – Value of Quality Criterion Depending on the Control Amplitude

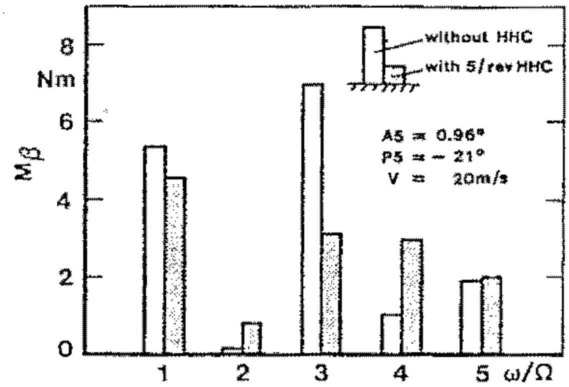


Fig. 12: 4/rev Control — Flapwise Blade Bending at r/R = 15 %

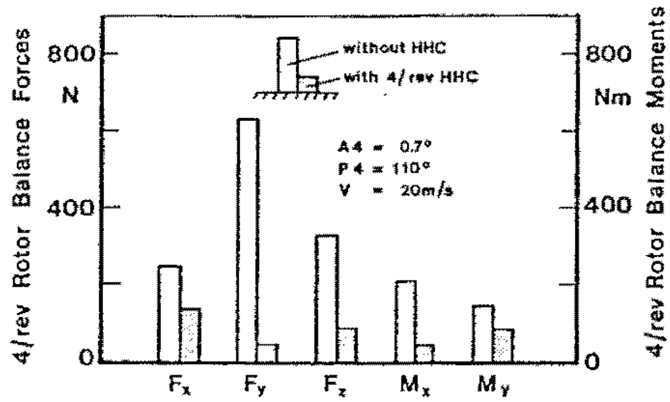


Fig. 13: Rotor Balance Forces and Moments with Optimal 4/rev Control

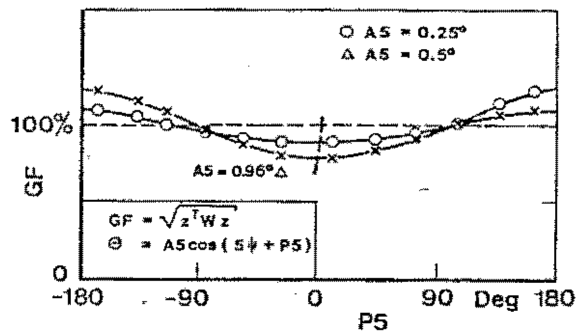


Fig. 14: 5/rev Control — Value of Quality Criterion Depending on the Control Phase

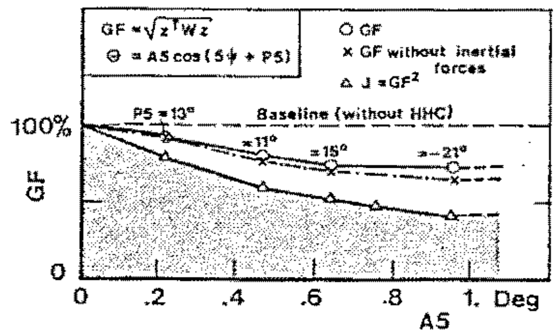


Fig. 15: 5/rev Control — Value of Quality Criterion Depending on the Control Amplitude

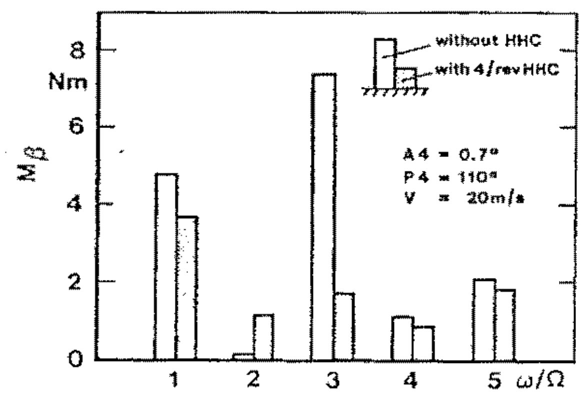


Fig. 16: 5/rev Control — Flapwise Blade Bending at r/R =15 %

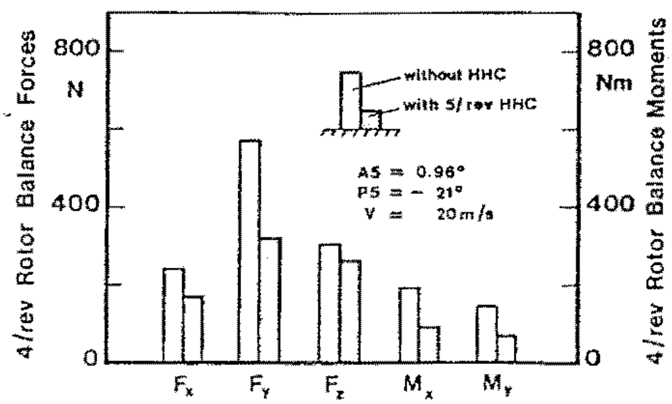


Fig. 17: Rotor Balance Forces and Moments with optimal 5/rev Control

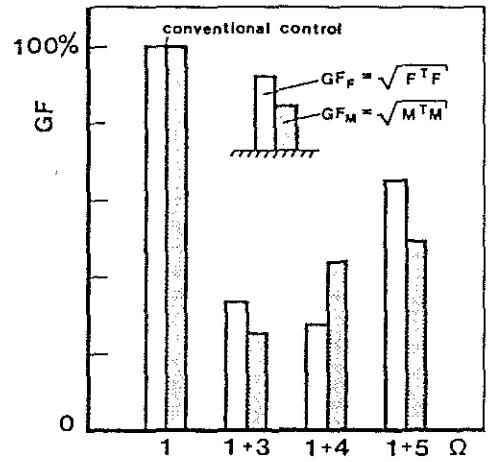


Fig. 18: Comparison of Different Single HHC Effectiveness

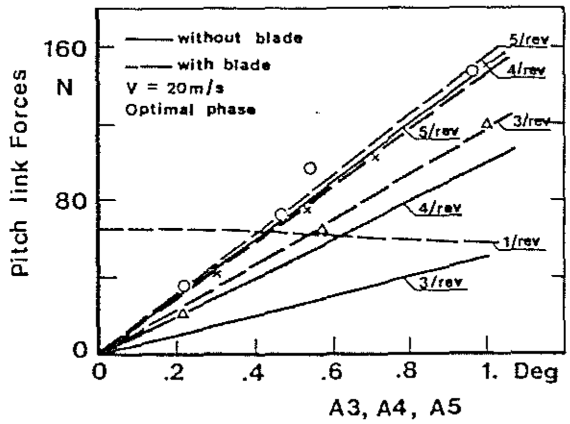


Fig. 19: Pitch Link Loads vs. HHC Blade Pitch Amplitudes

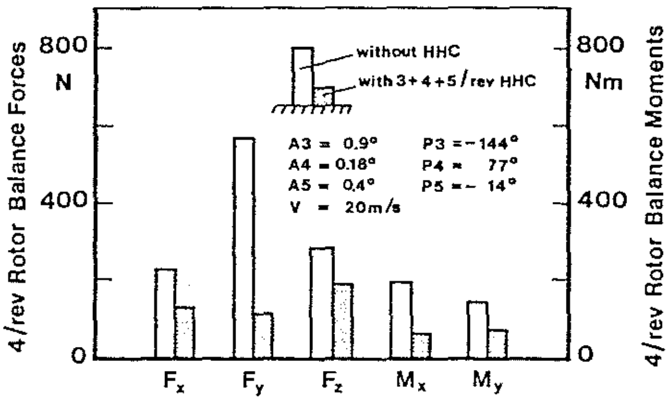


Fig. 20: Rotor Balance Forces and Moments with Simultaneous 3+4+5/rev Control

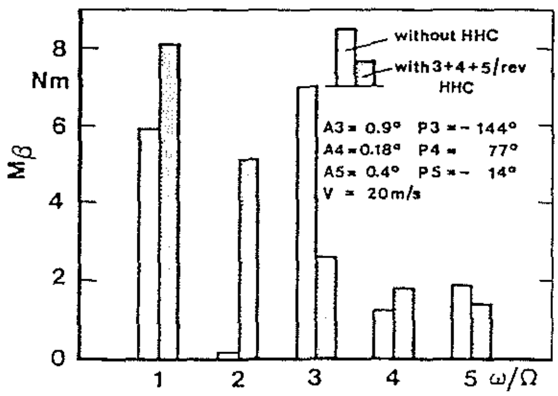


Fig. 21: Simultaneous 3+4+5/rev Control – Flapwise Blade Bending at r/R = 15 %