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SIMULTANEOUS VIBRATION AND BVI NOISE FEEDBACK FOR CLOSED LOOP HIGHER HARMONIC CONTROL: INFLUENCE OF ROTOR DYNAMICS ON CONTROLLER DESIGN

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Abstract

In order to investigate the effects of simultaneous vibration and Blade Vortex Interaction (BVI) noise feedback for closed loop Higher Harmonic Control (HHC), a wind tunnel entry was performed with the DLR rotor test rig in the German Dutch Wind Tunnel (DNW). The tests were based on former investigations which had shown that both disturbances can be reduced considerably by means of HHC. Although it turned out that, in single mode case, a noise reduction is accompanied by an increase of the vibration level and vice versa, a reduction of one disturbance while at least maintaining the other was one objective of the tunnel entry. As known from preceding open loop tests in the DNW, one prerequisite for the achievement of this goal is a proper adjustement of the higher harmonic control parameters which have to be optimized according to the actual flight condition. Therefore a suited closed loop controller is required being able to keep both disturbances small at steady as well as unsteady flight conditions. With this respect the rotor dynamics become very important which, in case of the BO105 main rotor, are dominated by the second flapping mode and therefore allow a vibration reduction in all degrees of freedom with only one HHC frequency, namely the 3/rev. Since on the other hand, a 5/rev HHC input showes a comparatively small vibration reducing potential but is quite satisfying with respect to BVI noise suppresion, a (3+5)/rev controller, as will be shown, is well suited for a simultaneous vibration and BVI noise feedback.

1. Introduction

Due to its hover and low speed flight capabilities the helicopter plays an important role in today's air traffic. It is not only used for public service purposes but also covers missions like search and rescue, ermergency medical and offshore support. However an extension of the helicopter employment to passenger transport objectives which would help to relieve the growing transportation problem on ground and in air is only exceptionally registered even in densly populated countries like Japan for example. One important aspect for this inacceptance is the comparatively high helicopter vibration and BVI noise level, the latter one being most intense during landing approach. It is not only inconvenient for passengers and crew but also represents an annoyance for the population on ground. Therefore intensive work has been done in the past to reduce both the vibration and the BVI noise level.

Although for the vibration problem a number of reduction methods were developed over the years [1], it was difficult to meet the more and more stringent vibration requirements. Therefore alternative methods had to be developed allowing to meet the human vibration tolerance limits. Theoretical and experimental studies have shown [2-18] that this goal can be achieved by means of higher harmonic control, a method which superposes a high frequency blade pitch angle with, in general, low amplitude to the conventional one. It allows a modification of the unsteady aerodynamic loads and therefore is well suited to affect the rotor blade's excitation in a way that leads to a minimization of the vibration level.

Furthermore it has the potential to influence the BVI noise which originates from the unsteady aerodanamic interaction between a lift generating blade and the vortex system shed by the preceding blades. It should hypothetically be reduced by decreasing the blade lift and vortex strength while increasing the blade-vortex separation distance at the blade vortex encounters [19], a request which does not necessarily lead to a minimum of the vibrations. Therefore the design of a controller which works with simultaneous BVI noise and vibration feedback was one main objective of wind tunnel experiments in the German Dutch Wind Tunnel. They were based on former investigations which focussed on a reduction of the vibration level and an explanation of the vibration reducing phenomena in case of a hingeless rotor system.

2. HHC Effects on Vibrations and BVI Noise

2.1 Vibration Reducing Potential of HHC

The tests aiming on a reduction of the vibration level were conducted in the DNW closed test section with the DLR rotor test rig ROTEST (Fig. 1). It is equiped with a high number of sensors allowing a comprehensive observation of the system state.

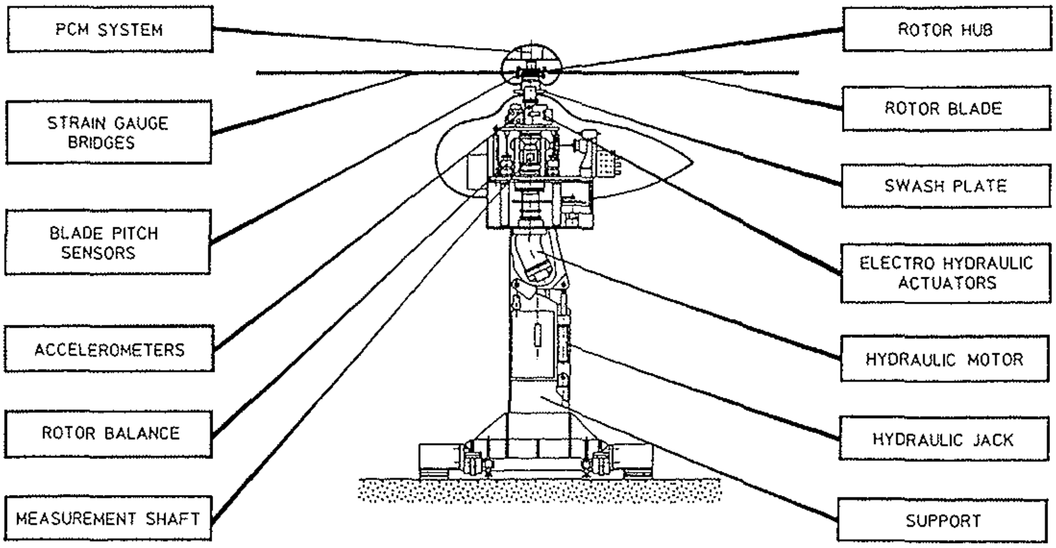

Fig. 1 Schematic of DLR Rotor Test Rig

Strain gauges, for example, are applied to the rotor making it possible to determine the rotor reaction to HHC inputs by surveying the flapping, lagging and torsional motion of the blades. The vibrations in the fixed system can be measured with the rotor balance which incorporates seven sensor systems consisting of a strain gauge part and a pieco electrical part. Whereas the strain gauge part allows a measurement of the static forces, the pieco electrical part makes it possible to determine the dynamic forces, both with a hight accuracy. The accelerations in the fixed system can be measured by three additional accelerometers which are implemented close to the rotor. These sensors can also be applied to a real helicopter allowing to generate wind tunnel results comparable with flight test data.

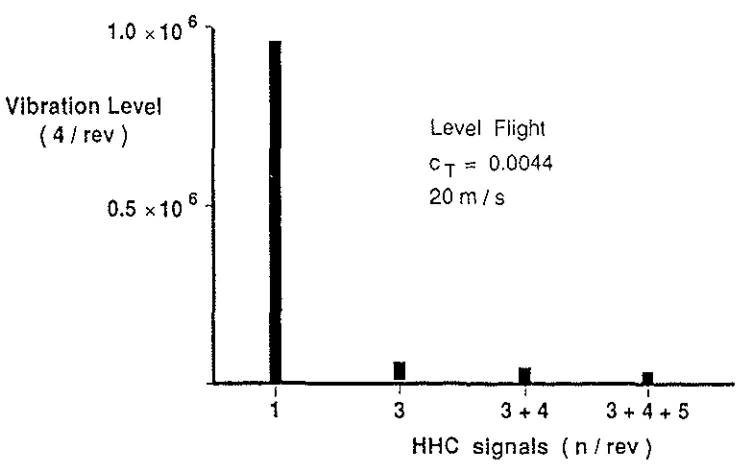

Fig. 2 Vibration Level for Different HHC Input Combinations

For the wind tunnel test the higher harmonic control parameters were adjusted manually by the test engineer in order to allow a systematical investigation of the rotor reaction to HHC inputs. One result of these tests is shown in fig. 2 which demonstrates that a 3/rev blade pitch angle yields nearly the same vibration reduction as can be achieved with a combination of two or three higher harmonic control signals. The reason for this behaviour is illustrated in fig. 3 which makes clear that the 3/rev blade flapping moment is dominant within the whole range of speed whereas the 4- and 5/rev part nearly vanish and therefore are neglectible. Obviously the rotor used for the wind tunnel tests mainly reacts to the blade forcing terms with the second flapping mode having an eigenfrequency ratio of 2.7.

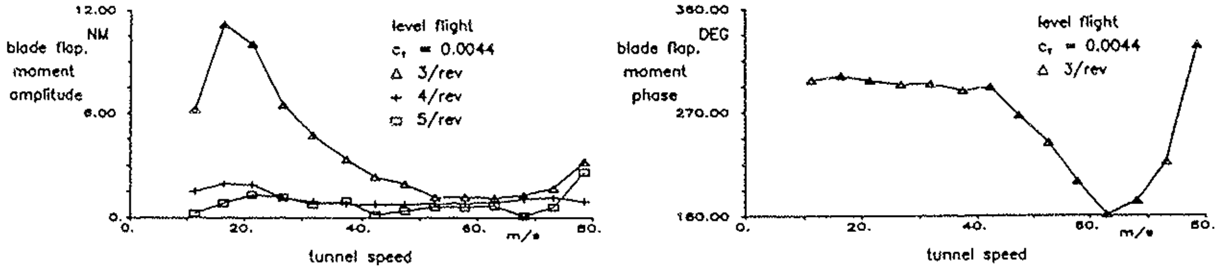

Fig. 3 Blade Flapping Moment at r/R = 0.15

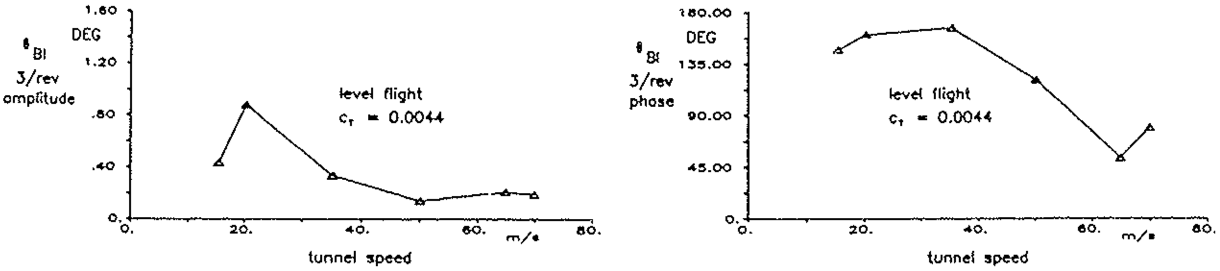

Fig. 4 Optimum 3/rev Amplitude and Phase Shift

However a 3/rev blade pitch angle obviously succeeds in suppressing the excitation of the second flapping mode, provided its amplitude and phase shift is varied with speed as shown in fig. 4. In combination with fig. 3 it demonstrates the good correlation of the HHC parameters with the 3/rev blade flapping moment thus supporting the assumption that the corresponding part of the blade motion forms the major reason for the vibrations in the fixed system and therefore has to be avoided. Being achievable with a 3/rev blade pitch angle (fig. 5) a simultaneous reduction of all dynamic rotor forces and moments is possible even in single mode case as is shown in fig. 6 exemplarily for a velocity of 50 m/s.

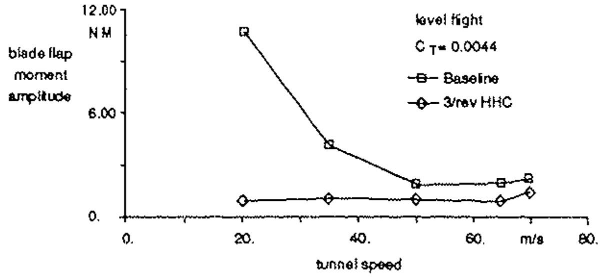

Fig. 5 3/Rev Blade Flapping Moment at r/R = 0.15

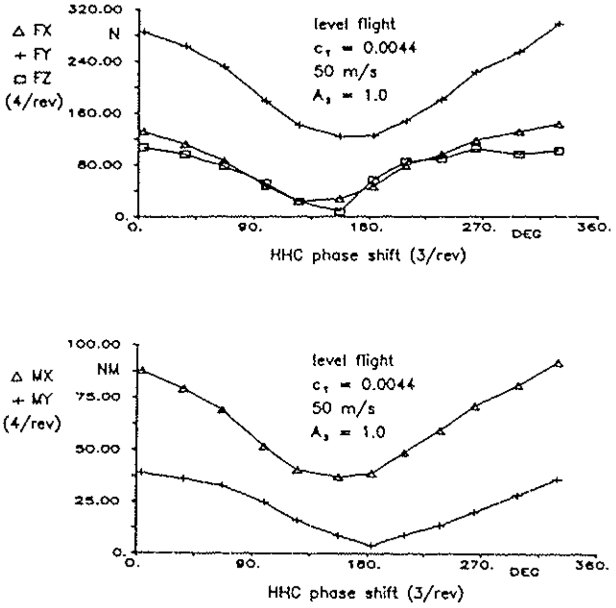

Fig. 6 Dependance of 4/Rev Rotor Forces and Moments on 3/Rev Phase Shift Shift

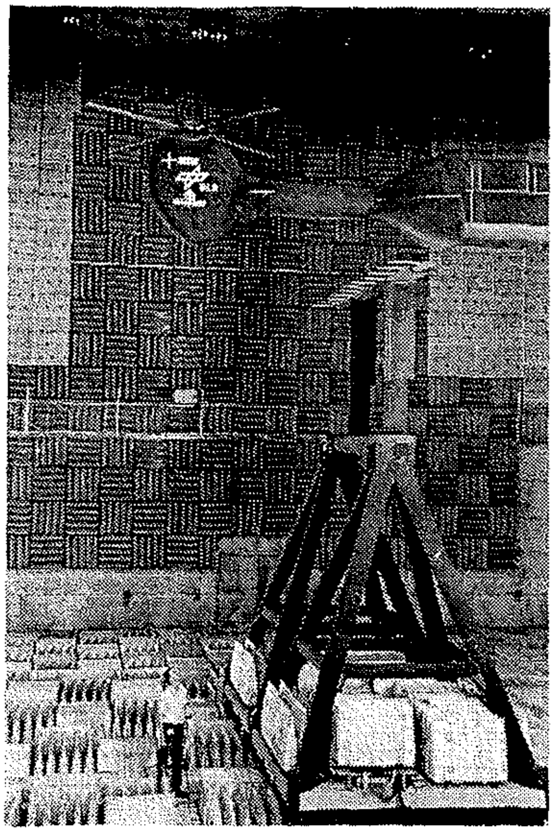

Fig. 7 DLR Rotor Test Rig in DNW

2.2 Noise Reducing Potential of HHC

For the tests aiming on a suppression of both the vibration and the BVI impulsive noise level the DLR rotor test rig was installed in the DNW open jet configuration which is known to be associated with a low background noise level as well as excellent anechoic properties and flow characteristics. Fig. 7 shows the DNW open jet configuration with the HHC test set-up including the movable in-flow microphone array. It was mounted on a traversing system which made it possible to measure the radiated noise of the rotor within a large plane below the hub, thus allowing to determine both, the achieved noise reduction and the changes in directivity pattern. Besides these movable microphones three stationary ones were implemented at the fuselage, two of them on the starboard side and one on the port side (fig. 8). They were considered to serve as feedback sensors for the closed loop controller to be designed and during the open loop tests conducted before were used for correlation purposes between the noise measured at the fuselage and on "ground" (more precise in the microphone plane).

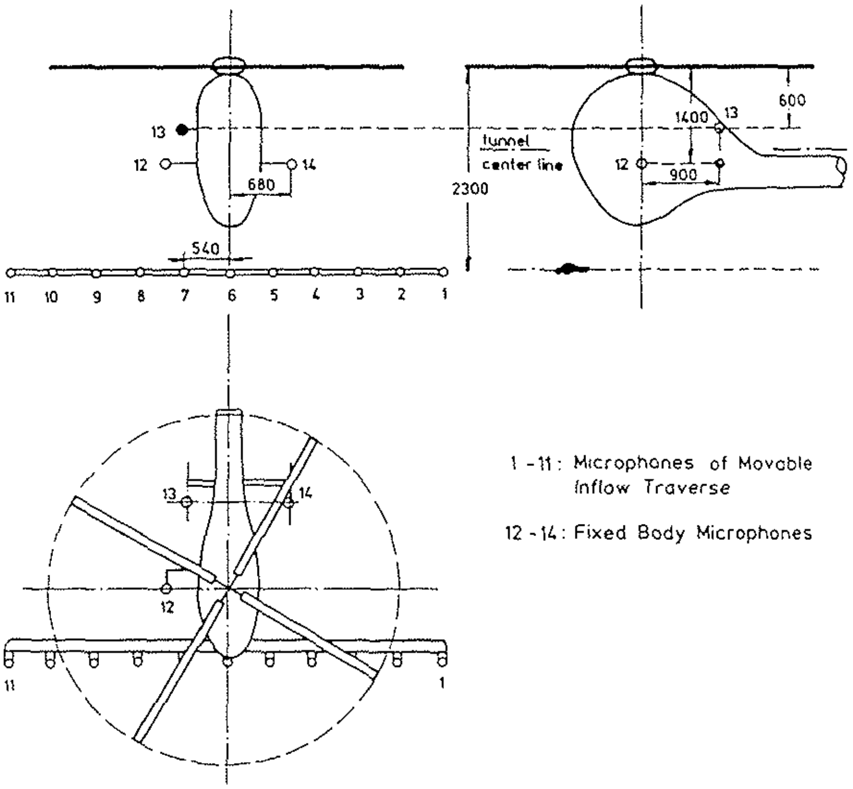

Fig. 8 Microphone Arrangement

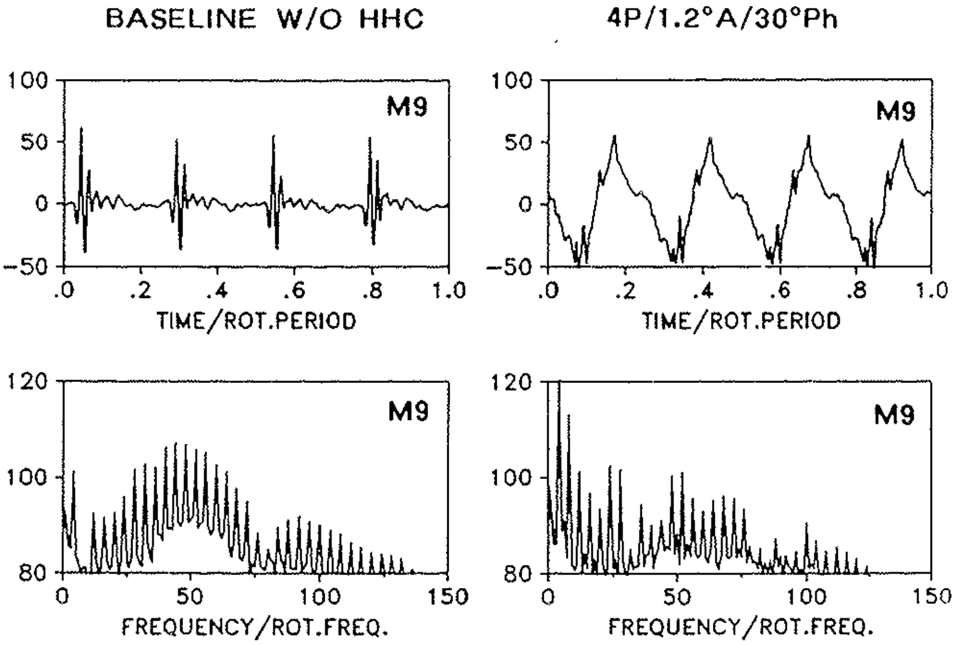

Fig. 9 HHC Effects on BVI Noise Level

One result of these open loop tests is shown in fig. 9 which demonstrates the effects of higher harmonic control on the BVI impulsive noise by means of sound pressure time histories and the corresponding frequency spectra. They result from an observer location at maximum advancing side BVI and make clear that, in case without HHC, strong pulses occur, each one being related to a blade-vortex interaction. The corresponding frequency spectra reveal a large number of blade passage frequency harmonics, which in the mid-frequency range are distinctly reduced when higher harmonic control is enabled. Low-frequency noise is seen increased, however the levels are not important on a subjective (for example A-weighted) noise scale compared with the mid-frequency (BVI) levels. Therefore a so called mid-frequency noise level has been introduced, taking into account only the 6th to 40th blade passage frequency harmonic, i.e. the 24th to 160th rotor harmonic.

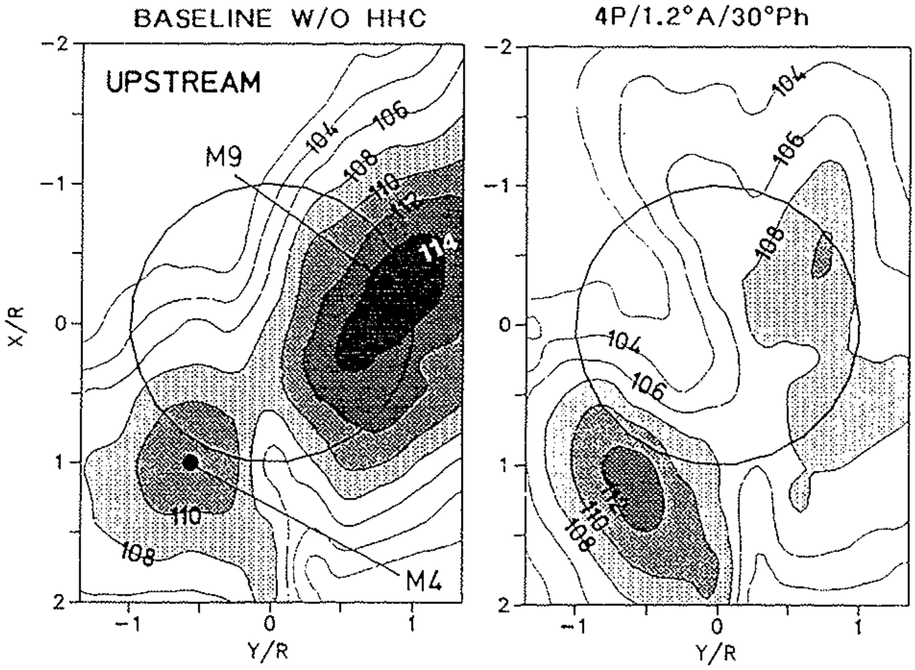

Fig. 10 HHC Effects on BVI Noise Level and Directivity Pattern

The distribution of this measure on "ground" for the case with and without HHC is shown in fig. 10 which makes clear, that a considerable noise reduction can be achieved if a suited higher harmonic blade pitch angle is superposed to the conventional one. Not only the maximum level occuring on the advancing side at roughly 120^{0} rotor azimuth but even the averaged level of the whole measurement plane is diminished by 5 dB and 3.5 dB respectively.

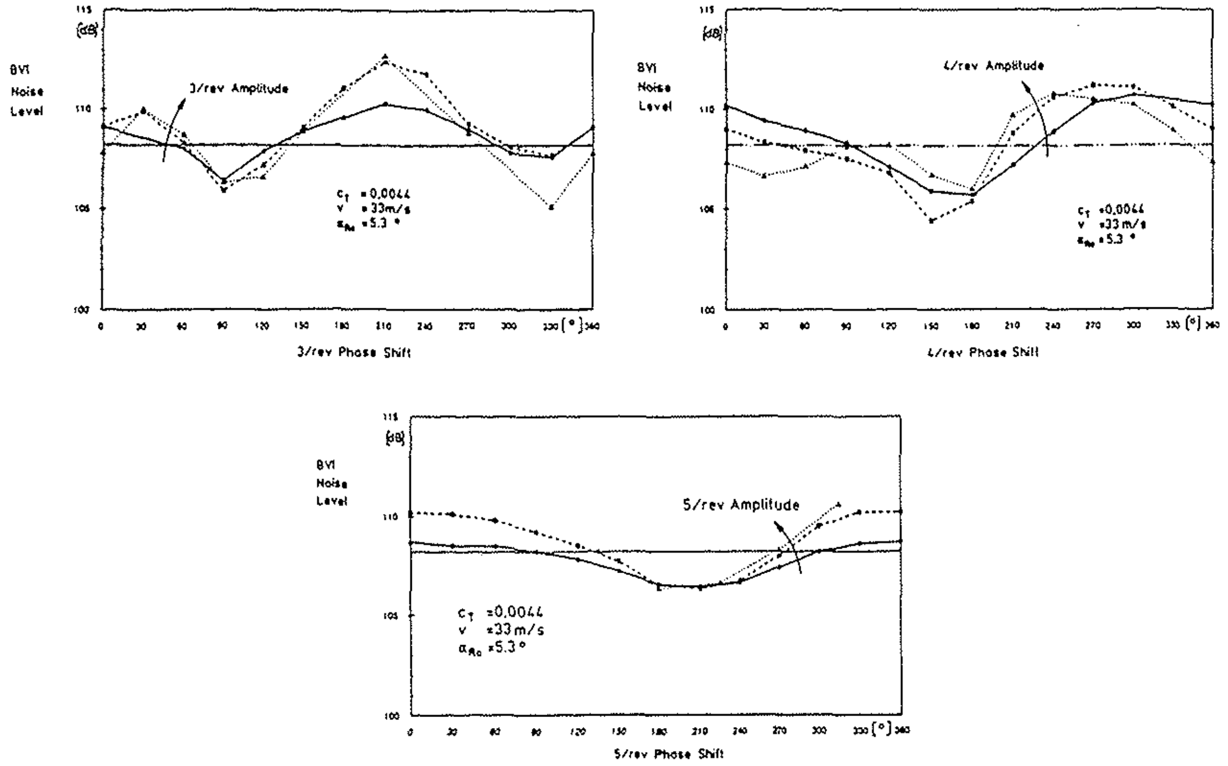

Fig. 11 Dependence of BVI Noise Level on HHC Phase Shift

Fig. 11 shows the averaged mid-frequency noise level plotted versus HHC phase shift and demonstrates that a number of local minima occur except in case of 5/rev HHC. This mode therefore, although being not the most effective one, as can be seen from fig. 12, is of special interest for a simultaneous vibration and BVI noise feedback provided it yields a good compromise between both disturbances if combined with a 3- or 4/rev blade pitch angle.

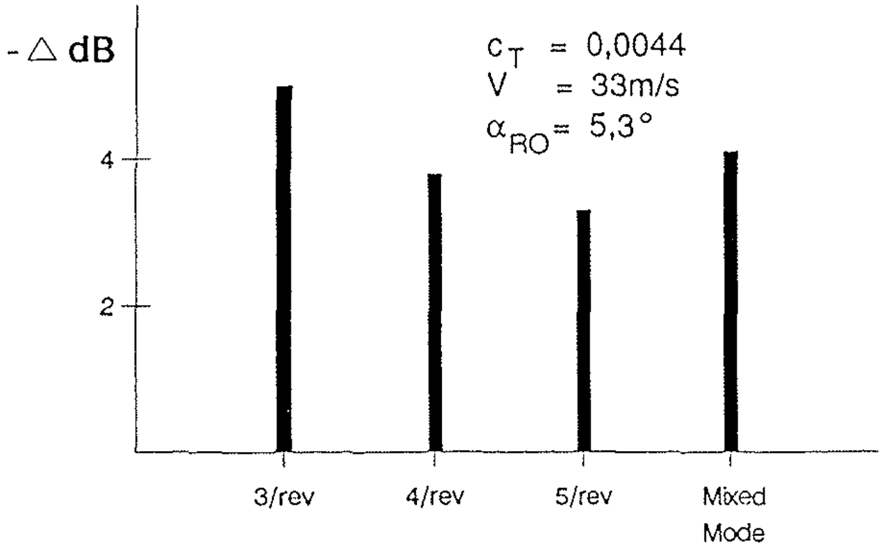

Fig. 12 BVI Noise Reduction by Higher Harmonic Control

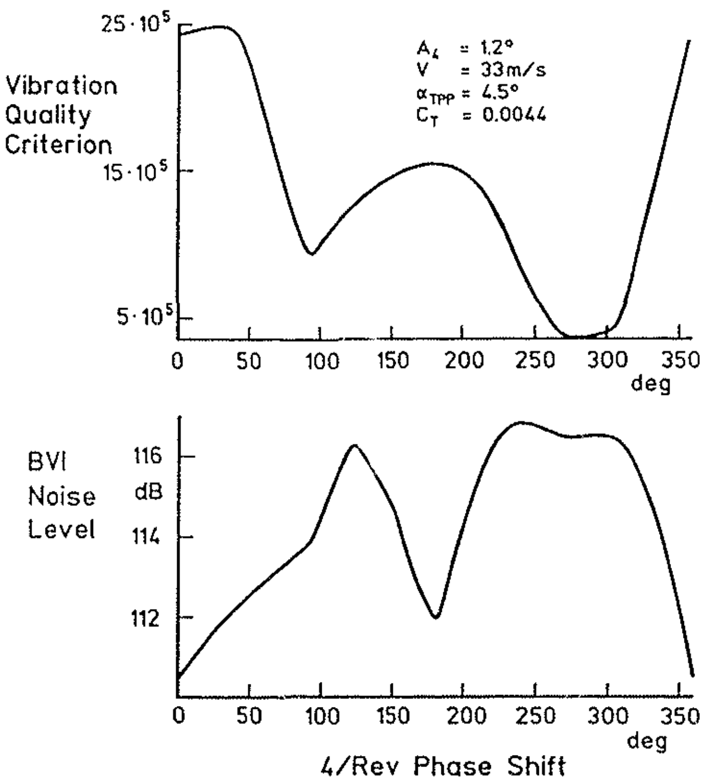

Fig. 13 Correlation of BVI Noise and Vibration Level for 4/Rev HHC

2.3 Correlation of BVI Noise and Vibration Level

Besides the noise reducing potential of HHC another topic of the open loop wind tunnel tests was the BVI noise/vibration correlation. It is shown exemplarily for a 4/rev blade pitch angle in fig. 13 which makes clear that, in single mode case, the BVI noise reaches its minimum when the vibrations reach their maximum and vice versa. Since this correlation is not only inconvenient for passengers and crew but also imposes strong dynamic loads on the material, systematic investigations were also performed with mixed mode cases, hoping that at least a good compromise between the BVI noise and the vibration level can be achieved. Fig. 14 shows the results of these investigations and makes clear that a better vibration/BVI noise correlation can be achieved if a (3 + 5)/rev or a (4 + 5)/rev blade pitch angle is superposed to the conventional one. In both cases a local minimum occurs at 270^{O} and 320^{O} respectively which is clearly associated with the absolute vibration minimum. Whereas in case of a (4 + 5)/rev HHC input a very sharp BVI noise minimum occurs, a (3 + 5)/rev blade pitch angle yields a broader one being very advantageous for a controller which works with BVI noise and vibration feedback.

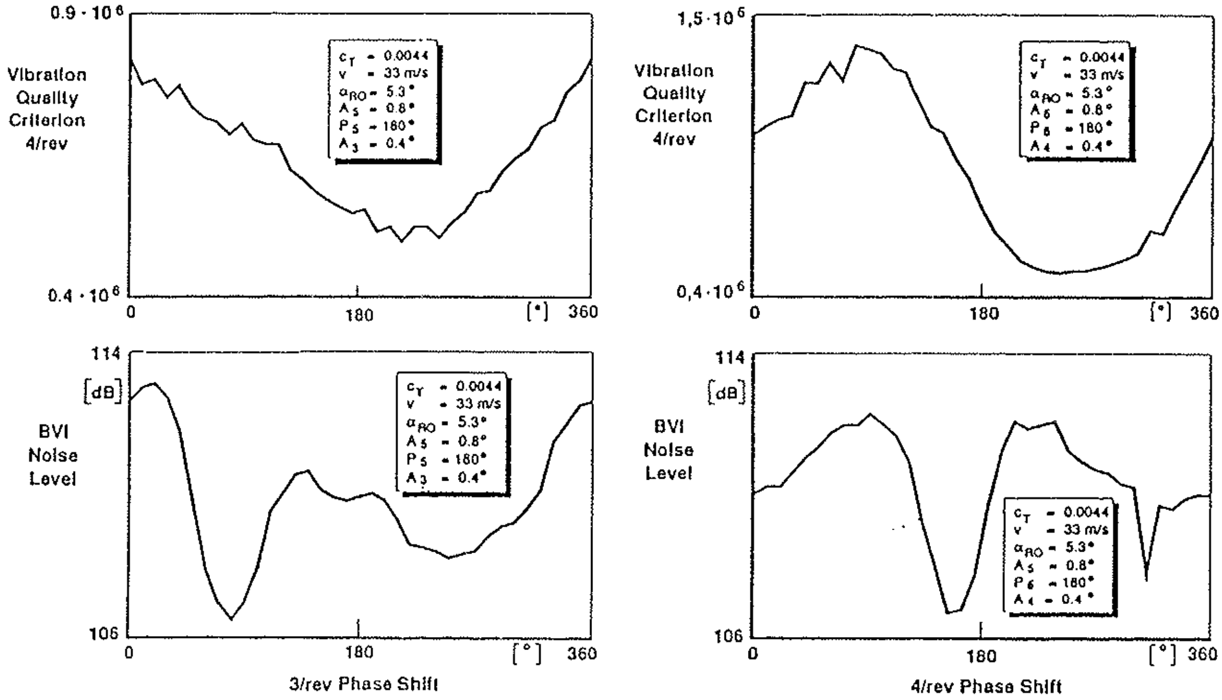

Fig. 14 Correlation of BVI Noise and Vibration Level for Mixed Mode HHC

3. Closed Loop Control Algorithm

3.1 Controller Architecture

The control algorithm envisaged for a simultaneous feedback of vibrations and BVI noise was decided to be an adaptive one working in the frequency domain. It consists of a Kalman filter and a minimum variance controller and gains informations about the actual efficiency of a higher harmonic blade pitch angle on the BVI noise and the vibrations by identifying the corresponding transfer function in every cycle [20]. Based on these informations, the minimum variance controller determines the higher harmonic control parameters leading to a minimum of the quality criterion

$$I = \begin{bmatrix} \underline{z}_N \\ \underline{z}_V \end{bmatrix}^T \cdot \underline{W}_z \cdot \begin{bmatrix} \underline{z}_N \\ \underline{z}_V \end{bmatrix}$$

with

$\underline{z}_N$ the noise vector,
$\underline{z}_V$ the vibration vector,

and

$\underline{W}_z$ a weighting matrix.

Whereas the noise vector $\underline{z}_N$ consists of up to 60 harmonics of the above mentioned BVI noise representing frequency range, the vibration vector $\underline{z}_V$ is formed by the 4/rev vibrations of the fixed system. Both are taken into account by the controller according to the elements of the weighting matrix $\underline{W}_z$, thus allowing to achieve at least a good compromise of the reduced noise and vibration level.

3.2 Controller Investigation by Simulation

3.2.1 Model Formation

Before the test campaign the control algorithm was subjected to offline simulations in order to investigate its transient and stationary behaviour. Due to the high amount of CPU time occuring in case of an accurate theoretical model, these simulations were based on open loop wind tunnel data arranged within a threedimensional array. Besides the data measured in wind tunnel, this array contained the linearly interpolated BVI noise levels for an amplitude stepwidth of 0.01° and a phase shift stepwidth of 0.1°. Fig. 15 shows the resulting surface and demonstrates that a number of local minima occur. They were feared to prevent the controller from finding the optimum HHC parameters thus allowing only a small reduction of the BVI noise by closed loop HHC.

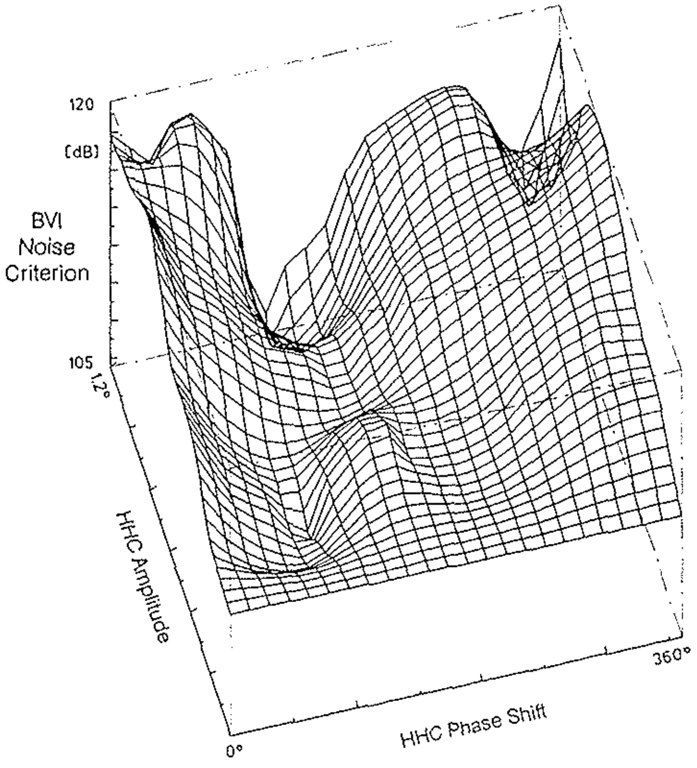

Fig. 15 Representation of Wind Tunnel Data by Means of Three Dimensional Array

3.2.2 Steady and Unsteady Controller Behaviour

Due to the local minima occuring in fig. 15 the control algorithm envisaged for the wind tunnel tests was feared to wander in the parameter range without converging to a noise minimum or, if working stable, to find a local minimum only. Therefore the main objective of the offline simulations was an investigation of the steady controller behaviour before attention was also payed to the controller response time. Fig. 16 shows one result of these simulations which had to be conducted with one HHC frequency only instead of three since the open loop data base didn't allow a model formation for mixed mode cases. The figure makes clear that the control algorithm approached directly the amplitude and phase shift values which during the open loop tests were found out to be associated with the absolute noise minimum. The response time was with 6 steps very small thus making the controller to a promising solution for an automatic reduction of the BVI noise at least.

3.3 Controller Realization

Due to the counteracting BVI noise/vibration correlation found out during the open loop tests, the objective of the closed loop wind tunnel entry was to develop a controller which is able to achieve not only a remarkable BVI noise reduction but furthermore a good compromise between the noise and vibration level. The controller therefore had to work with BVI noise and vibration feedback signals simultaneously as is indicated in fig. 17. It shows the block diagram of the closed loop system and clarifies that the noise and the vibrations had to be transformed to the frequency domain by a Fast Fourier Transform (FFT) and a Recursive Harmonic Analysis (RHA) respectively before both of them were fed to the controller. Depending on the system inputs of the test engineer, the vibrations had either to be ignored or to be taken into account for the determination of the optimum HHC parameter values which then had to be retransformed to the time domain by means of a Harmonic Synthesis (HS).

Fig. 18 shows the corresponding hardware architecture which was especially developed and realized for the HHC noise wind tunnel entry. Due to the high sampling rate required for the noise signals and the CPU time consuming algorithms like FFT, RHA and HS for example, it was decided to design a transputer based system which is not only variable with respect to computational power but also allows an implementation of the control and transformation algorithms with a high level programming language. From fig. 18 it can be seen that the system is built by 6 groups of transputers, each one being connected by so-called 'links' with its neighbours. The system can be operated via the Man Machine Interface (MMI) realized by a PC-AT with transputer board. It allows a menue driven adjustement of the system parameters and with that a time efficient selection of the number of noise and vibration feedback signals, the controller cycle time etc.

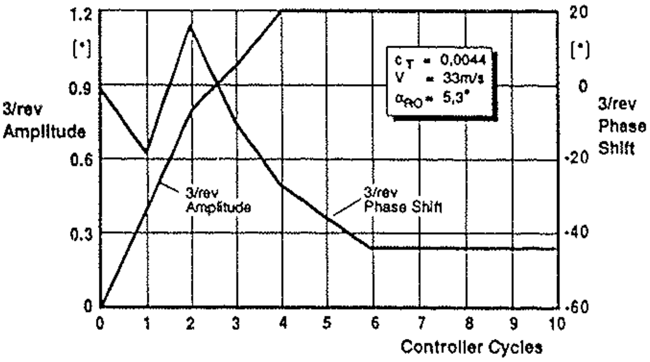

Fig. 16 Simulation of BVI Noise Controller

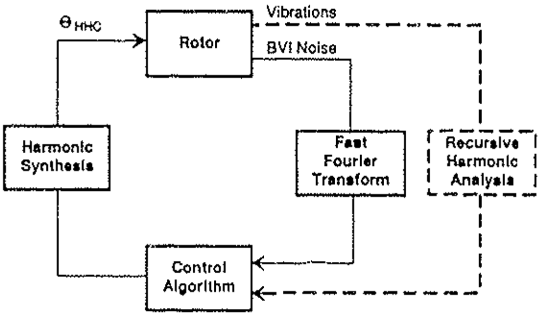

Fig. 17 Block Diagram of Closed Loop System

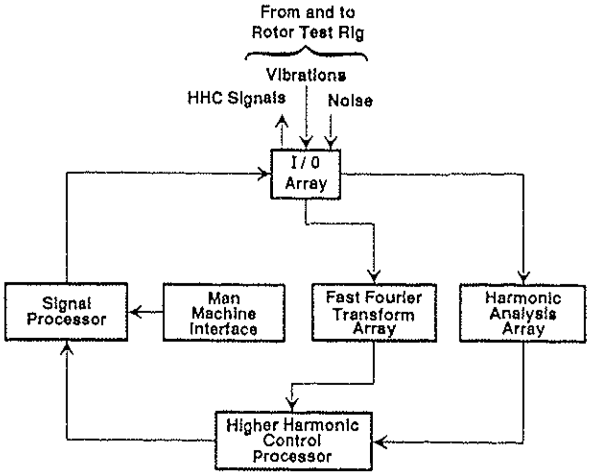

Fig. 18 HHC Transputer System

Once initialized via the MMI, the transputer elements start to work independently from each other, exchanging data only when it is required. Whereas the IO-Array cares for a synchronous sampling of the noise and vibration feedback signals, the FFT- and the RHA-Array perform an online FFT of up to two microphone signals and an RHA of up to three vibration signals respectively. The results are passed to the Higher Harmonic Control Processor (HHCP) which determines the optimum HHC amplitude and phase shift values by means of the closed loop control algorithm. The retransformation to the time domain is performed by the Signal Processor (SP) which closes the loop by transmitting the input signals for the HHC actuators via the IO-Array to the rotor test rig.

3.4 Wind Tunnel Test Results

3.4.1 Controller Convergence and Stability

Although the offline simulations had shown that the control algorithm seems to be well suited for a BVI impulsive noise reduction by higher harmonic control, the question was, how it would act under real conditions. Therefore the first closed loop wind tunnel tests were performed in single step mode allowing an exact observation of the controller behaviour and, in case of problems, an opportune and proper intervention into the test run.

Within these investigations it turned out that, due to the fluctuation of the BVI noise occuring even at a steady state rotor condition, the feedback signals represented by the FFT output had to be averaged 15 times in order to guarantee a stable operation of the HHC system. This averaging feature provided, the control algorithm converged directly to stationarity, independent if working with a 5/rev or 4/rev blade pitch angle (fig. 19). At least with respect to stability, this control approach therefore seemed to be quite

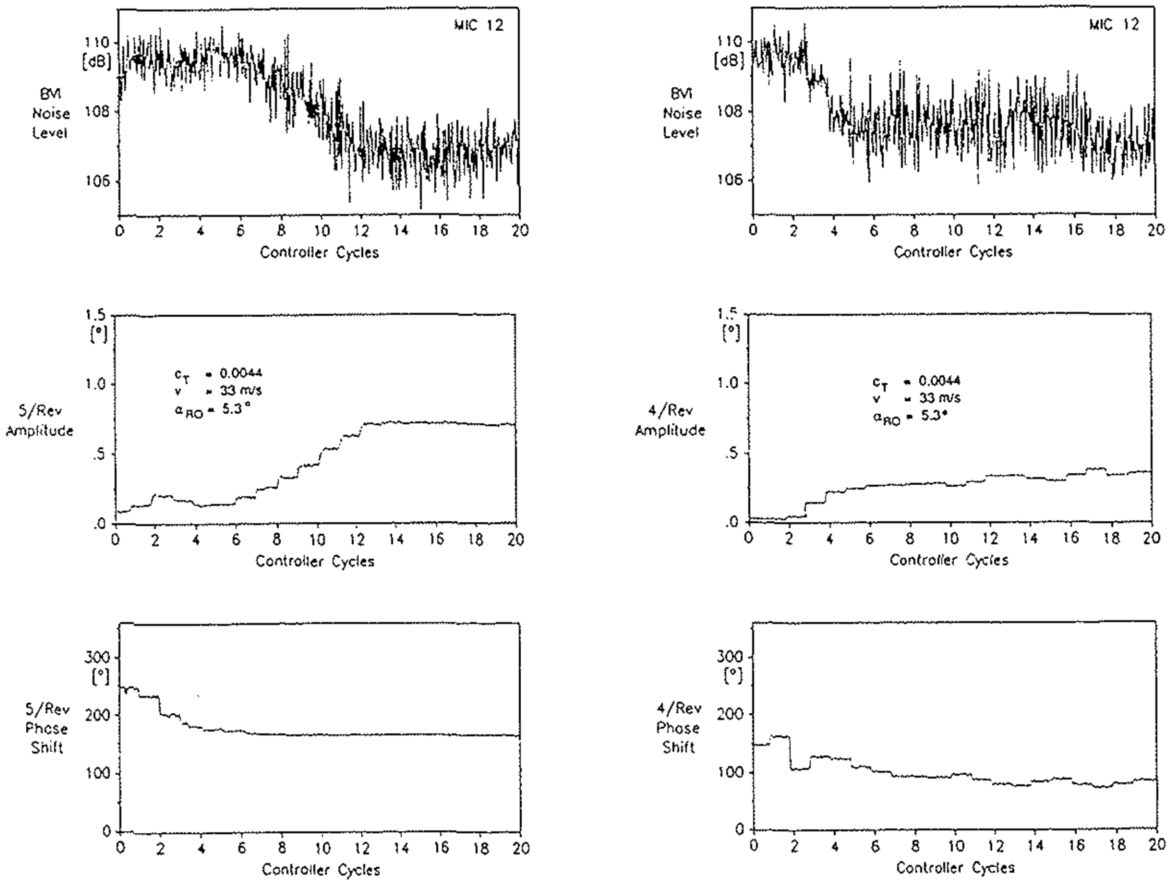

Fig. 19 Wind Tunnel Result of BVI Noise Controller

suited for BVI impulsive noise reduction by higher harmonic control, for what reason the achieved noise reduction on "ground" was determined in the next step.

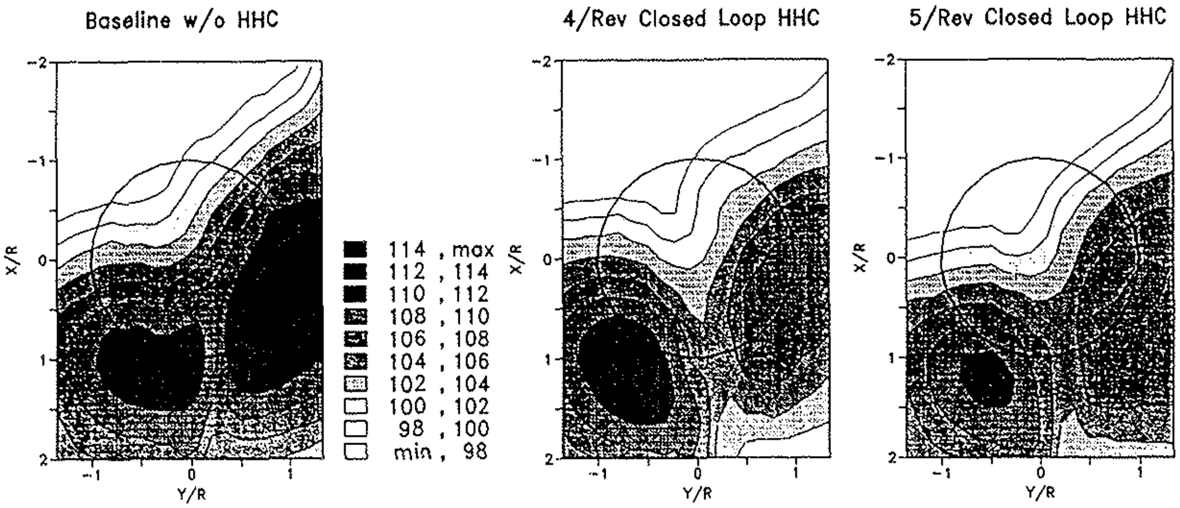

Fig. 20 BVI Noise Pattern Variation by HHC Controller

3.4.2 Achieved Noise Reduction

After having demonstrated stationarity at least for the nominal test condition, the next question was which noise reduction has been achieved on "ground". Therefore the HHC parameters ascertained by the control algorithm in steady state were adjusted manually by the test engineer before the BVI noise pattern underneath the rotor was determined by means of the movable inflow microphone array. Fig. 20 shows the resulting contour plots and makes clear that, although working with one body microphone for feedback purposes only, the control algorithm determined HHC amplitude and phase shift values which led not only to a lower BVI noise level close to the fuselage (fig. 19) but furthermore to a remarkable noise reduction on "ground" (fig. 20).

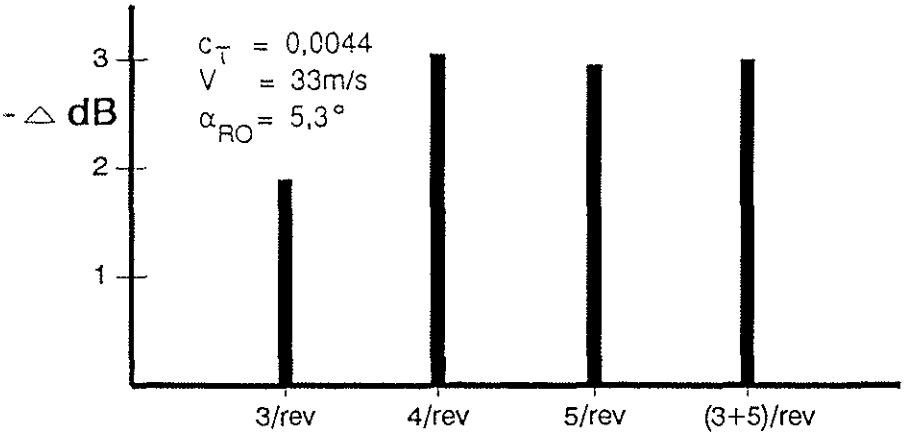

Fig. 21 BVI Noise Reduction Achieved by HHC Controller

Based on these results the control algorithm was operated with a 3/rev blade pitch angle at the same flight condition, too. The achieved noise reduction which is compared with the 5/rev and 4/rev results in fig. 21 was with 1.8 dB rather disappointing and demonstrated that the most effective HHC mode (fig. 12) is not necessarily the best suited for a closed loop BVI noise controller. However, due to its high vibration reducing potential mentioned above, a 3/rev blade pitch angle was very interesting for a simultaneous feedback of BVI noise and vibrations, for what reason the behaviour of the control algorithm if working with a (3 + 5)/rev HHC mode but BVI noise feedback only was investigated in the next step. The achieved noise reduction, again compared with the single mode ones in fig. 21 was similar to the 5/rev and 4/rev result and therefore was very promising for a simultaneous vibration and BVI noise feedback.

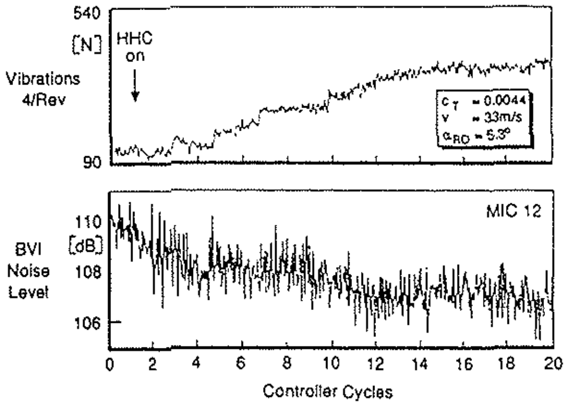

Fig. 22 Performance of HHC Controller with BVI Noise Feedback

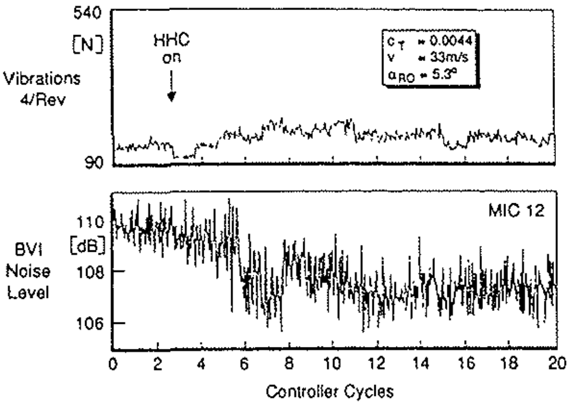

Fig. 23 Performance of HHC Controller with BVI Noise and Vibration Feedback

3.4.3 Influence of Additional Vibration Feedback

Due to the counteracting correlation of vibrations and BVI noise shown in fig. 16, the question was, whether a simultaneous feedback of both disturbances leads to an improvement of the control result. Therefore tests were also conducted with the control algorithm using a (3+5)/rev HHC mode and one body microphone as well as one vibration sensor for feedback purposes. The result is shown in fig. 26 and fig. 27 which make clear that an additional vibration feedback had quite a positive influence on the achieved BVI noise and vibration level. Whereas in case of BVI noise feedback only a noise reduction was accompanied by an increase of the vibrations (fig. 26), an additional feedback of vibratory loads allowed a similar noise reduction as achieved before, however, this time with a nearly unaffected vibration level (fig. 27). Therefore investigations were also performed at other flight conditions which, as can be seen from fig. 28, were very successful too since they yielded a noise reduction of 2-4 dB.

Very interesting and important was an investigation of the controller behaviour at a "non-BVI" flight condition in order to find out, whether in this case the noise or the vibrations are increased. Therefore a test run was also conducted at a tunnel velocity of v = 33m/s and a pitch attitude of α_{Ro} = -0.7° (fig. 28). It showed that the control algorithm was able to deal with these conditions too and remained nearly inactive thus avoiding to generate neither noise nor vibrations. This control approach therefore is well suited for a continous operation within the whole flight envelope, reducing the noise without increasing the vibrations in BVI flight conditions and reducing the vibrations without increasing the noise in the remaining part of the flight envelope, thereby requiring no adaption to the actual flight condition by the crew for example.

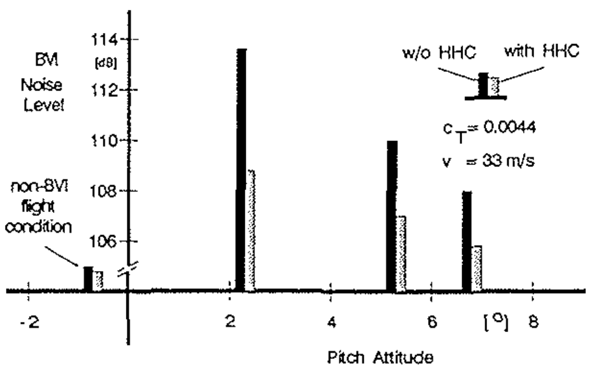

Fig. 24 Noise Reduction of (3+5)/Rev Controller

4. Conclusions

Based on the data of an open loop wind tunnel entry conducted with the DLR rotor test rig in the DNW, a closed loop control algorithm for simultaneous vibration and BVI noise feedback was developed and investigated. In a first step it was subjected to simulations which showed that, even in case of relative strong disturbances, the control algorithm converged directly to stationarity, reducing the noise not only close to the fuselage but furthermore within a large plane below the rotor. The achieved reduction of the BVI level was with 5 dB similar to the one of the open loop tests and therefore very satisfying. Since the controller succeeded, in addition, to avoid an increase of the vibrations when reducing the noise on the one hand and, on the other hand, was able to notice the absence of BVI impulsive noise in forward flight, the control algorithm can be operated continously while reducing the vibrations and BVI noise depending on where they are most intense.

5. References

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