HELICOPTER BLADE-VORTEX INTERACTION NOISE REDUCTION BY ACTIVE ROTOR CONTROL TECHNOLOGY[1]

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Abstract

Helicopter blade-vortex interaction noise is one of the most severe noise phenomena and is very important both in community annoyance and military detection. Research over the decades has substantially improved basic physical understanding of the mechanisms generating rotor blade-vortex interaction noise and also of controlling techniques, particularly using active rotor control technology. This paper reviews active rotor control techniques currently available for rotor blade-vortex interaction noise reduction, including higher harmonic pitch control, individual blade control, and on-blade control technologies.

1. INTRODUCTION

Helicopter impulsive noise is known to originate from two distinct aerodynamic events: the compressible flow field due to high tip Mach number on the rotor's advancing side, called high-speed impulsive noise, and unsteady pressure fluctuations on the rotor blade due to interactions with vortices generated by preceding blades, called blade-vortex interaction (BVI) noise. These types of noise are loud and impulsive in nature, which is significant both for military detection and community annoyance (Refs.1 - 6).

When a rotor operates in descent or maneuvering flight, a rotor blade passes close to trailing tip vortices. These interactions are plotted in a top view for a typical descent flight condition as shown in Fig. 1, which shows multiple interactions in both the advancing and retreating sides.

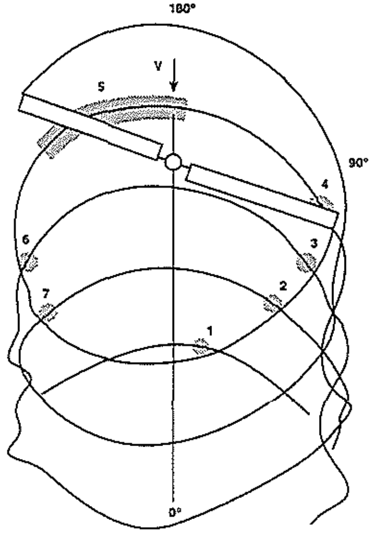

Fig. 1 BVIs during partial-power descent (from Ref. 7)

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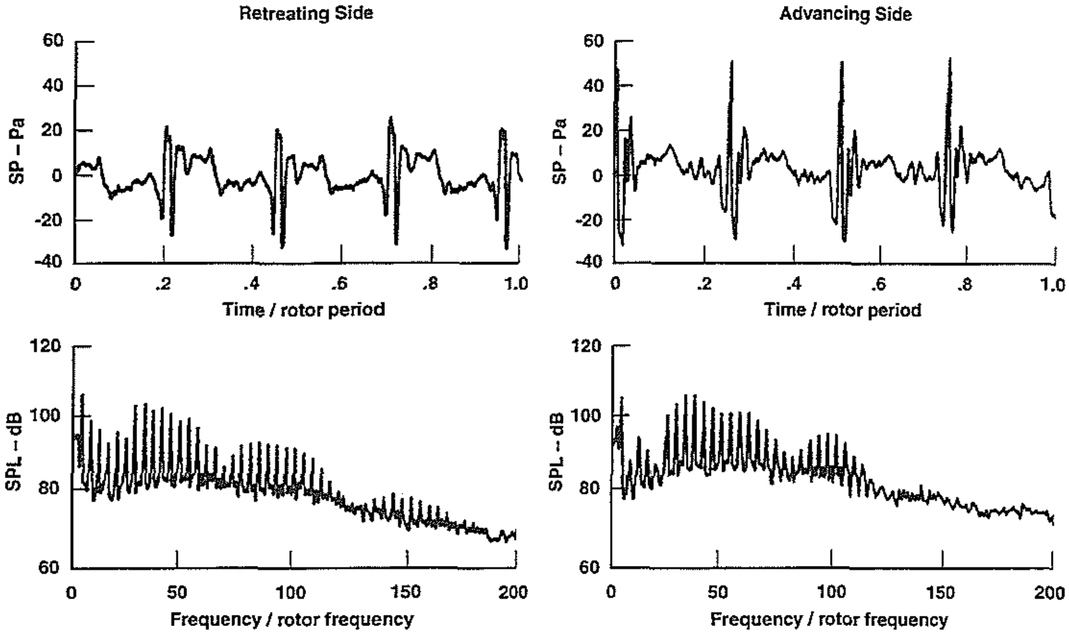


Fig. 2 Typical BVI impulsive noise characteristics (from Ref. 8)

During these interactions, the blade experiences unsteady pressure fluctuations and generates loud, impulsive noise, called blade-vortex interaction (BVI) noise. A typical noise signature of a 4-bladed model rotor in a normal descent flight is shown in Fig. 2, where BVI noise pulses are distinctive and are dominating in the mid-range frequency spectrum. Similar noise signatures are also observed in full-scale flight(Ref. 9).

An important feature for gaining a better insight into BVI phenomena and associated noise characteristics is the unsteady blade surface pressures, where the leading edge pressures clearly identify the aerodynamic BVI phenomena in both the first and fourth quadrants. One of the important findings from these experimental data is that the BVI phenomena are concentrated near the leading edge of the blade on both the upper and lower surfaces.

Another important feature is the blade section airloads, which determine the rotor wake characteristics, the tip vortex strength, and the BVI geometry.

The blade-vortex interaction miss distance is also an important parameter. Using the blade flapping and torsional characteristics, the blade tip deflection response and blade airload histories along the azimuthal angle can be modified to control the blade-vortex miss distance and eventually the BVI noise by utilizing active blade control concepts.

Recently, active blade control techniques, such as higher harmonic control (HHC) or individual blade control (IBC), were investigated with significant success in reducing BVI noise. The HHC concept excites the blade pitch angle at a fixed frequency through the basic swashplate collective and cyclic flight inputs. With this, all blades are excited simultaneously at a given frequency through proper phasing the control inputs, thus the frequency variation is very limited. To increase the control flexibility of input variables, the IBC concept has been developed to independently actuate individual blades in a rotating frame through the rotor hub. The test data indicated that very significant simultaneous reductions in both BVI noise and hub vibrations could be obtained using multiharmonic IBC inputs. To further increase of the control flexibility of input variables, various concepts using distributed smart actuators along the blade span are actively being investigated to control blade tip loading distribution, blade tip deflection, or aerodynamic response during interactions.

2. ACTIVE ROTOR CONTROL CONCEPTS

Helicopters are conventionally controlled via a swashplate sliding up and down the rotor shaft and tilting relative to it. This system is very successful in producing monocyclic (i.e., one cycle per rotor revolution) blade feathering angles, allowing the pilot to control the helicopter's position and attitude. However, this control system is not capable of preventing blades from entering adverse flow conditions during steady or maneuvering flight. A potential solution of this problem is to sense rotor behavior and act through additional or new controls to eliminate or reduce the detrimental characteristics. The answer is active rotor control(Ref. 11).

Several types of rotor active control concepts are studied ranged from full blade feathering through direct lift flap and controllable twist to different kinds of circulation control(Ref.12). Extensive theoretical and experimental studies have been conducted in order to investigate these concepts. The high potential benefits of these concepts are: (1) reduction of vibration, noise, control loads, blade stresses, and power input; (2) avoidance of stall, compressibility effects, gust and disturbance responses, and vortex interactions; and (3) elimination of rotor instabilities.

2.1 Blade Root Control Concepts : HHC and IBC

During the last two decades a large number of investigations were concerned with active blade control systems utilizing full blade feathering or active blade root control: the higher harmonic control (HHC) system, which is characterized by the implementation of the actuators below the swashplate, and the individual blade control (IBC) system, in which each blade is controlled individually by pitch link actuators in the rotating system (Fig.3).

The original intention in developing and applying HHC for rotors was to improve helicopter ride quality (i.e., to reduce the considerable vibration level). Numerous analytical and experimental studies demonstrated that HHC is capable of reducing the vibration level up to 90% and to provide 'jet smooth' ride qualities for the helicopter.

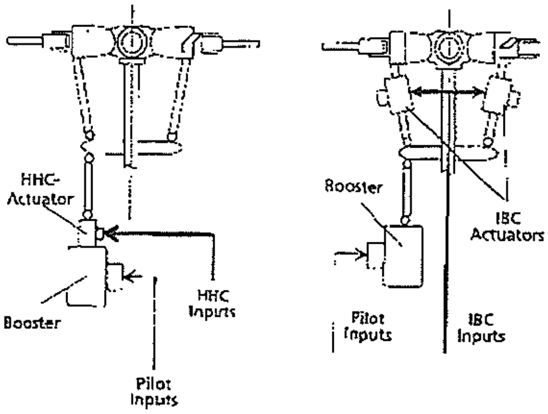


Fig.3 Active blade root control concepts (HHC/IBC) (from Ref. 13)

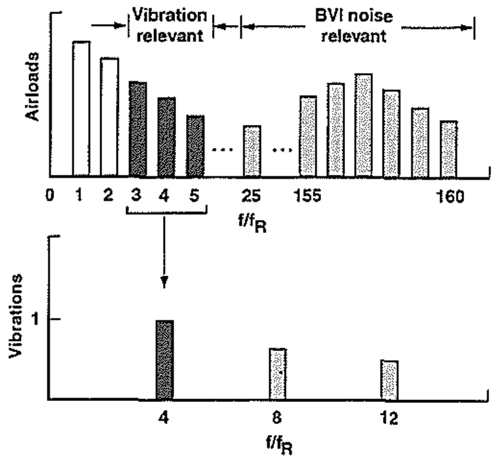


Fig.4 Airload and vibration characteristics (from Ref. 13)

The rotor induced vibration of a helicopter originates from the unsteady aerodynamic forces acting on the rotor blades, which are caused by reverse and radial flow as well as shock and stall effects and are clearly associated with discrete rotor azimuth positions. Consequently, the aerodynamic blade loads are periodic with the corresponding frequency spectra mainly consisting of rotor harmonics. These spectra reveal strong amplitudes in the low-frequency range (Fig.4) which, due to the limited blade stiffness, excite the rotor blades to oscillate in flapwise and lead-lag direction. These deflections generate inertia and elastic forces, in combination with the aerodynamic excitations forming the resulting blade loads.

Summing up these blade loads to yield the forces acting in the fixed system, the individual harmonics substantially cancel each other.

$P_n = (b+n)\,P$

where

n an integer number,

b the number of blades, and

P the rotor rotational frequency or period.

The remaining loads are integral multiples of the blade passage frequency as shown in Fig.4 for a four-bladed rotor.

From these harmonics, the lowest one not only is associated with the strongest amplitude (Fig. 4), but also represents the most annoying part. It is caused by blade loads in the frequencies of (b-1)P, bP, and (b+1)P harmonics, which can very well be affected by a blade pitch angle exactly at these frequencies. If the corresponding amplitude and phase shift values are properly adjusted, the blade oscillations can be controlled in a way that leads to a reduction of the corresponding hub loads and therefore to a minimization of the vibrations in the fuselage.

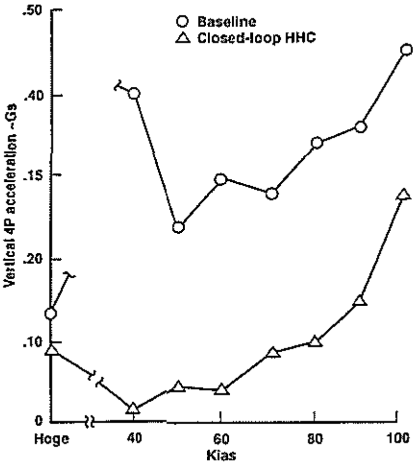


Fig.5 Vertical pilot seat accelerations (4P) versus airspeed (from Ref. 15)

The first flight test program using a higher harmonic blade feathering control technique was conducted to control vibration of a four-bladed helicopter rotor by the McDonnell Douglas Helicopter Systems (MDHS). With the HHC system engaged, the 4P pilot seat vibration levels were significantly lower than the baseline helicopter (Fig.5), and furthermore the system did not adversely affect blade loads or helicopter performance.

Aerospatiale Helicopter Division (now ECF) launched a research flight program in 1980 to test an active vibration control system based on HHC (Ref. 16). The main elements of the higher harmonic control system on the SA 349 helicopter include the swashplate control system (3P in the nonrotating system) generating control angles at the frequencies 2P, 3P, and 4P in the rotating system with a maximum HHC amplitude of 1°.

In cruise flight at 250 km/h the mean reduction in vibration level of 80% was obtained in the cabin with local reductions of 95 % at certain locations. Fig.6 presents flight test results obtained in 1985 from the HHC-equipped helicopter in comparison with the basic helicopter and a helicopter equiped with a passive-type vibration reduction system.

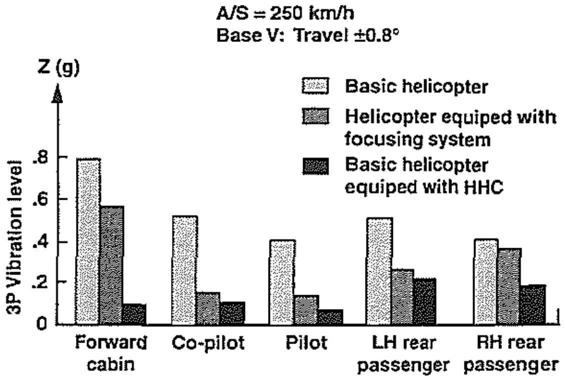


Fig.6 HHC flight test results (from Ref. 16)

Flight tests of an open-loop higher harmonic vibration control system were conducted by Sikorsky Aircraft on an S-76A helicopter during 1985 (Ref.17). The HHC system installation was designed to minimize modifications to the standard aircraft configuration. HHC inputs were generated by three hydraulic actuators installed in the nonrotating control system, providing blade feathering at frequencies of 3P, 4P, and 5P in the rotating system. Significant vibration reductions throughout the aircraft were demonstrated at forward speeds up to 150 knots. The capability of HHC to reduce vibrations was also demonstrated at varying rotor speeds and during maneuvers. Structural data obtained during testing showed a general increase in control system loads during HHC operation. No observable degradation of aircraft performance was noted during limited performance testing with the HHC system operational.

The HHC systems described above were investigated with the main objective of reducing the vibration level at certain locations of the helicopter. Subsequently, additional potential that HHC may also be effective for BVI noise reduction was investigated. For the first time, this benefit was demonstrated on different rotors in 1988 by wind tunnel tests of DLR in the DNW (Ref.18) and of NASA in Langley Research Center's TDT (Ref.19). In Fig.7 the HHC effect on BVI noise generation of a BO-105 model rotor is shown for different control modes with control frequencies of 3P, 4P, and 5P.

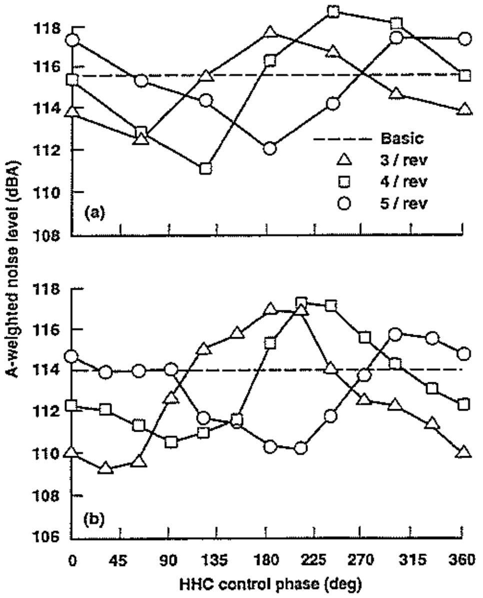


Fig.7 HHC effect on BVI noise generation for different control modes and for two rotor test conditions at constant M_H=0.64 and C_T=0.0044. (a) μ=0.138, α_{TPP}=4.6°; (b) μ=0.161, α_{TPP}=1.8° (from Ref. 18)

By comparing these results to corresponding baseline conditions (without HHC), significant noise reductions of 4 or 5 dB were found for low-speed descent conditions, where helicopter BVI noise is most intense. During the tests, it was observed that the vibration levels were unexpectedly increased for low noise HHC control settings, and no control setting was found to yield reductions of both vibration and noise at the same time.

With the objective of simultaneously reducing the vibration level, the BVI noise, and the power required, and in addition, to avoid rotor instabilities, an IBC system was developed at ZF Luftfahrttechnik (ZFL) in Germany (Ref. 20). The system was implemented by replacing the rotating control rods of a BO-105 helicopter with hydraulic pitch-link actuators.

The first flight tests of a four-bladed rotor controlled by an IBC system took place in 1990 and 1991 in cooperation between ZFL and ECD. The IBC system was first tested in a harmonic mode with open-loop control inputs with 2P to 5P frequencies. The maximum blade pitch angle amplitude was 0.4° and the flight velocity was selected between 61 and 113 knots. The results of these flight tests were promising, but due to the amplitude limitations of the flightworthy control system it was not possible to demonstrate the full capability of the IBC technology.

Subsequently, two full-scale wind tunnel tests were conducted to evaluate the full potential of IBC to improve rotor performance, to reduce BVI noise, and to alleviate helicopter vibrations, under a cooperative effort between NASA, the U.S. Army, ZFL, ECD and DLR. The IBC servo-actuators and control system were designed and manufactured by ZFL and installed on the Rotor Test Apparatus (RTA) equipped with a full-scale BO-105 rotor system in the 40- by 80-foot wind tunnel at Ames Research Center(Ref.21). The data generated in the two test programs in 1993 and 1994 indicated that significant simultaneous reductions of both BVI noise and hub vibrations could be achieved using multiharmonic IBC inputs. The data also showed that performance improvements of up to 7 % could be obtained using 2P inputs at high-speed forward flight conditions.

Fig.8 shows simultaneous noise and vibration reduction using different control amplitudes at 2P frequency and at a phase angle of 60°. BVI noise reductions of up to 10 dB locally were obtained in front of the rotor on the advancing side, with the average reduction being in the range of about 4 to 8 dB. The best reduction achieved in 4P hub loads was on the order of 90 % with simultaneous noise reductions as noted above.

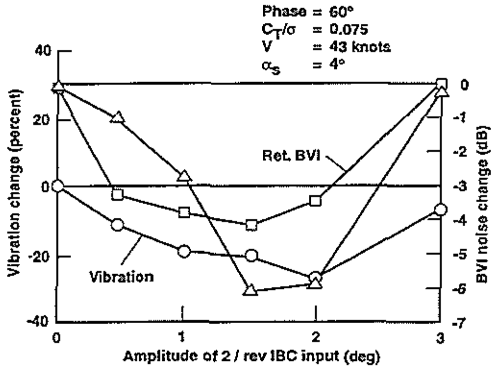


Fig.8 Correlation of BVI noise and vibrations for *control inputs with 2P frequency:* ○ *for vibration,* △ for adv. BVI, and □ for ret. BVI (from Ref. 21)

2.2 Controller Design

For the performance of the whole active control system, in addition to the hardware for rotor control, the closed-loop controller design is of utmost importance. Numerous approaches have *been proposed and some have been implemented* and tested. Most of the investigated controllers are adaptive ones in the frequency domain and can provide vibration reduction of about 80 to 90 %.

The controller in the frequency domain assumes a steady state operating condition and a quasi-steady dynamic rotor behavior. This means that the rotor response and the control inputs are periodic, and the control law can be expressed in terms of the Fourier coefficients of the rotor *response and the resulting* control inputs. Consequently, a harmonic analysis and a harmonic synthesis are required for implementing the frequency domain controller.

In the case of a time domain control, the operating condition of the rotor is not necessarily assumed to be steady and therefore the realistic representation of the dynamic response behavior of the rotor is essential for the controller. In addition to the other benefits, with a time domain *controller the stability of the system* can be improved by an appropriate feedback gain. This system stabilization is not only beneficial for improving the damping characteristics of the rotor, but also it can be used for high frequency disturbance rejection control tasks (Ref.22).

Up to now, frequency domain control was preferred for active rotor control applications due to the complex dynamic behavior of the rotor. For time domain controllers, sophisticated methods for rotor modeling and controller design are required.

3. HHC AND IBC FOR BVI NOISE REDUCTION

3.1 HHC Investigations

In 1985, Aerospatiale (ECF now) demonstrated the ability of reducing BVI noise in flight on a Gazelle SA 349 experimental helicopter (Ref.23). Two types of measurements were made by using first a closed-loop HHC system for vibration reduction and second an open-loop HHC system for noise reduction. In this latter case, the purpose of the test was to determine the controls necessary to minimize noise through a systematic investigation of amplitude and phase variations of the HHC system.

During the flight tests, noise levels were measured by microphones installed on the helicopter skids and on the ground. The most convincing results were obtained during approach at 6° slope and 28 m/s flight velocity by using a 1° amplitude 3P control (the Gazelle has a three-bladed rotor). As shown in Fig.9, HHC removes the acoustic pressure peaks induced by BVIs. A large reduction of almost 6 TPNdB of the maximum noise level has been measured by a microphone under the flight track (-3.5 EPNdB). Note that the microphone on the aircraft left-hand side provides a clear view of the noise reduction obtained when HHC is working. Such a signal could probably be used in an HHC closed-loop system. This very promising 1985 result has led Aerospatiale to carry out a model rotor test at the DNW jointly with MBB, DLR, and NASA.

In early 1988, initial acoustic results were obtained from a HHC experiment conducted in the DNW closed test section with the objective of demonstrating the effectiveness of higher harmonic blade pitch control to reduce rotor BVI impulsive noise (Ref.18). This test was performed as part of a HHC demonstration experiment of

DLR (Ref.24) with the 4 m diameter, 40 % geometrically, Mach, and dynamically scaled model of a four-bladed, hingeless BO-105 main rotor.

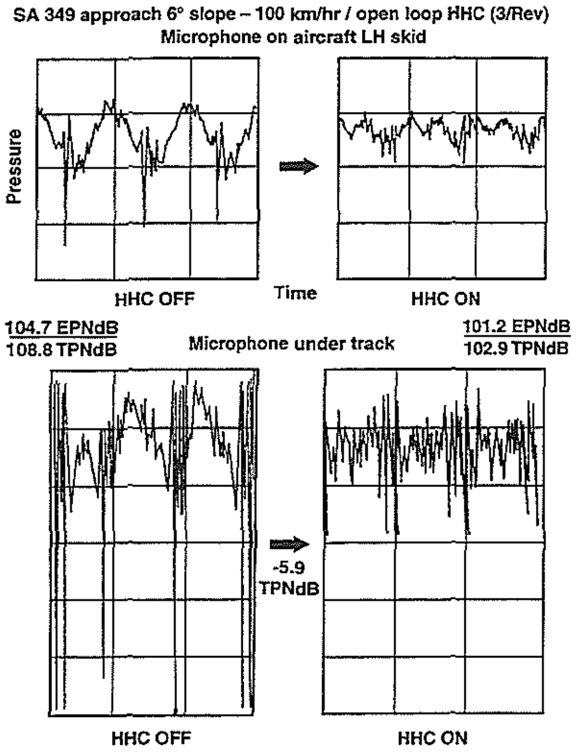


Fig.9 BVI noise reduction with HHC: flight tests on SA349 (from Ref. 23)

The 3P, 4P, and 5P HHC modes were measured with systematic variation of the HHC phase angle. Significant noise reduction of the order of 5 dBA was measured for particular HHC settings, but at the cost of increased vibration levels (Fig.7). At optimum pitch control settings for BVI noise reduction, analytical results demonstrated that vortex strength and blade-vortex miss distance are increased at the interaction location, resulting overall in reduced BVI noise generation. At optimum pitch control settings for vibration reduction, there are adverse effects on blade loading, vortex strength and blade-vortex miss distance, which explains the measured increased noise levels (on the order of 3 dBA).

In 1988 and 1989, a rotor test was conducted in the NASA Langley TDT to examine the use of HHC to reduce BVI noise (Refs.19,25). A dynamically scaled, four-bladed, articulated rotor model was tested in a heavy gas (R-12, nominal pressure of 0.45 atmosphere). Acoustic and vibration measurements were made for a large range of matched flight conditions where prescribed (open-loop) HHC pitch schedules were superimposed on the normal (baseline) collective and cyclic trim pitch. A new sound power measurement technique was developed for the reverberant field in the hard-walled tunnel. By comparing the results using 4P HHC to corresponding baseline (without HHC) conditions, significant mid-frequency noise reductions of 5 to 6 dB were found for low-speed descent conditions where BVI is most intense. For other flight conditions, noise was found to increase with the use of HHC. Low-frequency loading noise, as well as fixed and rotating frame vibration levels, showed increased levels with HHC.

The change in character of the rotor noise sources with the use of HHC can be observed through the instantaneous acoustic pressure time histories (Fig.10). The use of HHC diminished the BVI levels and, perhaps, the number of BVI occurrences. Mid-frequency noise reductions are higher (a maximum of 5.6 dB measured) at the lower speed descent conditions where BVI noise is most intense. The use of 4P HHC produces increased low frequency loading noise, but its effect, as based on subjective A-weighted (dBA) measure, is not important when significant mid-frequency BVI noise reduction is attained. However, the overall significance of the increased low frequency noise should not be minimized due to other annoyance criteria and military detection concerns. The use of HHC was found here to increase vibratory loading.

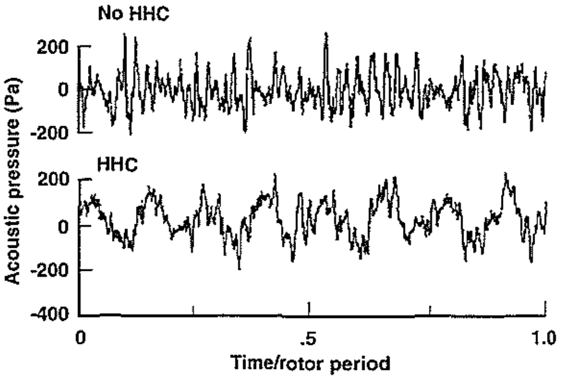
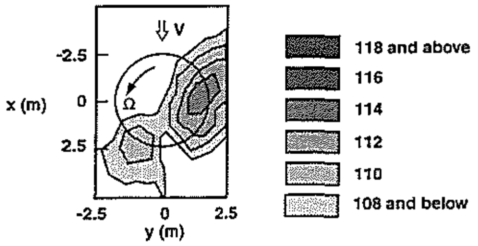
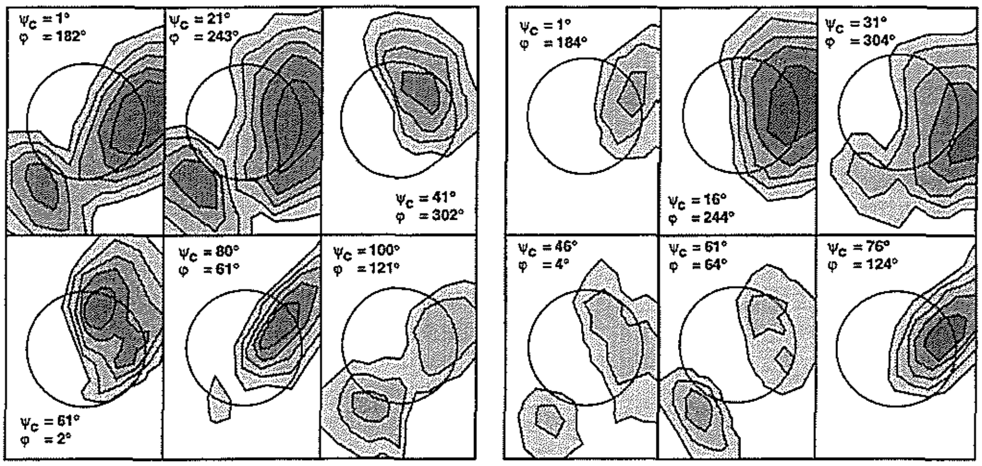


Fig.10 Microphone signal time histories with and without HHC inputs for μ=0.11 (α =8.0°). HHC amplitude is $\theta_c = -1.2°$ at ψ_c=60°. (from Ref. 25)

In 1990, a three-nation cooperative HHC acoustic test was conducted in the DNW, which built upon the experience gained in France (full-scale), and in the United States and Germany (model-scale) during the early HHC acoustic testing. This scaled model rotor test was designed to further establish the noise reduction potential of HHC by measuring the noise directivity characteristics. The experimental approach involved the measurement of noise and vibration with and without prescribed, open-loop HHC blade pitch inputs, which comprised 3P, 4P, and 5P pitch schedules and some mixed modes.

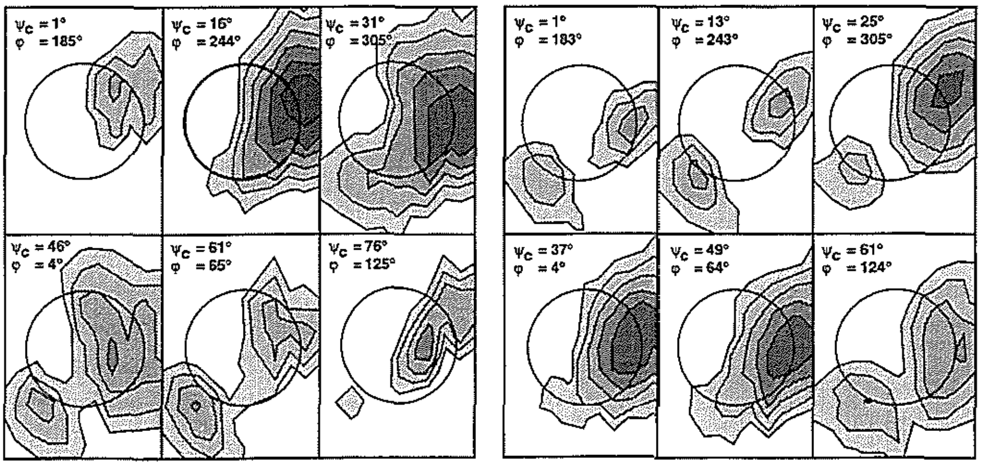


(a) Baseline, No HHC



(b) 3P HHC, $\theta_c \approx -0.8°$

(d) 3P HHC, $\theta_c = -1.2°$



(c) 4P HHC, $\theta_c \approx -0.8°$

(e) 5P HHC, $\theta_c = -0.8°$

Fig.11 Mid frequency (BVI) noise directivities for different HHC and phases for a 6° descent flight at μ=0.15 (from Ref. 27)

For the first time, an HHC rotor acoustic test was performed in an anechoic environment, which allowed uncontaminated measurements of BVI noise and the resulting influence of multicyclic pitch control on the directivity pattern (Refs.26, 27). The DLR model rotor test rig together with a traversing inflow microphone array was installed in the DNW open test section. The rotor was a 40 %, geometrically and dynamically scaled, four-bladed, hingeless BO-105 main rotor.

Examples of the effect of HHC variations (HHC mode, amplitude, and phase) on mid-frequency (BVI) noise level directivity are shown in Fig.11 for a 6° descent flight at $\mu = 0.15$. Significant changes of the noise level and directivity were measured; the maximum BVI noise level was reduced by about 6 dB for a 4P HHC schedule with 1.2° amplitude and azimuth control angle of 54°.

The maximum noise reduction was accompanied by increased low frequency noise and vibration levels, although a few HHC schedules were found in which BVI noise was reduced without an increase in vibration.

In 1991 a bilateral German-French model rotor experiment in the DNW was conducted with the objective of testing a number of different closed-loop control approaches for BVI noise reduction by higher harmonic control(Ref.28). A simple quadratic optimum control algorithm was insufficient for stable operation, but a more sophisticated adaptive frequency domain controller with additional vibration feedback was capable of reducing the maximum BVI level by a similar amount as for open-loop operation without increasing vibrations. Also, for level flight conditions, this adaptive frequency domain controller was stable and could be used for vibration reduction.

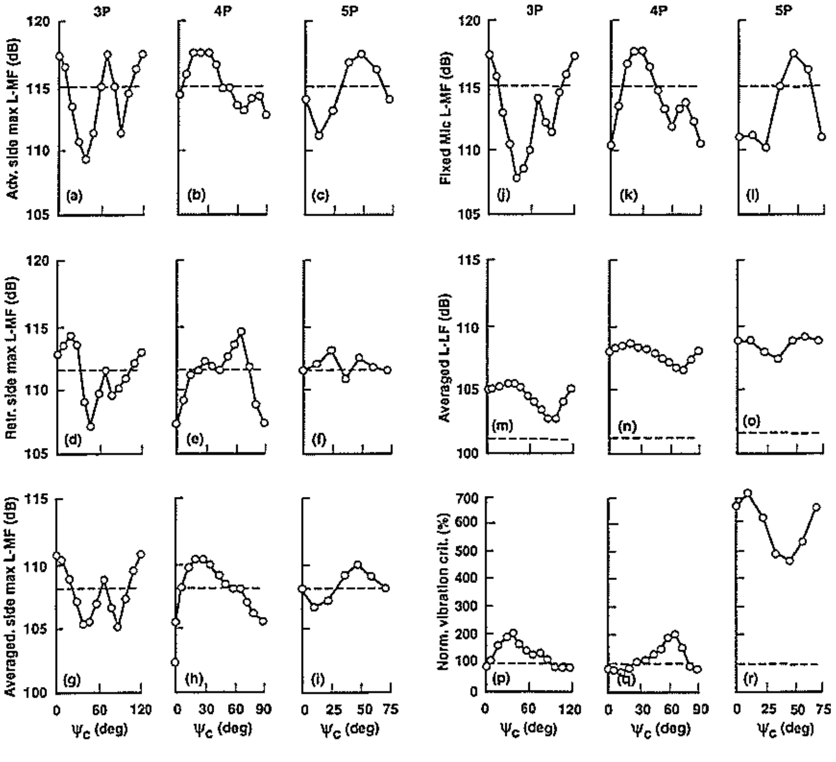


Fig.12 Noise and vibration levels versus azimuth control angle for different HHC modes for a typical BVI condition of a 6° descent flight at μ=0.15. - - - baseline case without HHC (from Ref. 10)

In order to improve the physical understanding and the mathematical modeling of the effects of the higher harmonic blade pitch control technique on impulsive BVI noise and vibration, a major cooperative research program(Refs.10, 29,30), the HART(Higher-harmonic Aeroacoustic Rotor Test) program, was conducted employing a 40% geometrically and dynamically scaled BO-105 main rotor in the open-jet anechoic test section of DNW. Extensive efforts concerning pretest noise predictions including the effect of multicyclic pitch control were made, employing various aeroacoustic prediction codes (Ref.31).

Within the experimental effort, a comprehensive set of acoustic, aerodynamic, dynamic response, performance, and rotor wake data was acquired with a pressure and strain gauge instrumented blade and by application of nonintrusive optical measurement techniques. In agreement with previous tests, a BVI noise reduction of approximately 6 dB (about 50% of the maximum acoustic pressure amplitude) was obtained for 3P HHC, 0.85° pitch amplitude, and 38° azimuth control angle (Fig.12). Vibration reduction of about 30% was accomplished for 3P, 0.85° amplitude, and 119° azimuth control angle. In general, at maximum noise reduction increased levels for low frequency noise and vibrations were observed, but for a small number of HHC settings both noise and vibrations were noticeably reduced.

3.2 IBC Investigations

A common feature of all HHC systems is that the actuators are located underneath the swashplate in the nonrotating frame. As a consequence all blades simultaneously undergo the identical pitch motion through proper phasing the control inputs and the number of HHC modes is restricted (e.g., due to the 4P excitation of the swashplate in the case of a four-bladed rotor, only 3P, 4P, and 5P HHC modes are possible). This limitation is overcome by introduction of the actuators in the rotating frame, which allows IBC and a larger number of HHC modes comprising 2P up to 10P or more.

An IBC system, designed and manufactured by ZFL (Ref.20), was flight-tested jointly with Eurocopter Germany (formerly MBB) on a BO105 helicopter in 1990 and 1991(Ref.32). It represented the first flying four-bladed helicopter with blades individually controlled. For safety reasons, the harmonic modes were restricted to values between 2P to 5P in order to reduce the number of free control parameters. Initial flight tests focusing on BVI noise reduction were conducted for 5P IBC input at 0.5° amplitude and azimuth control angle of 120°. For a low speed, 6° descent flight (a typical BVI condition) a flyover noise reduction benefit of about 4 dBA was measured (Fig.13). The limited thrust and speed of the flight tests in conjunction with the low authority of the actuators prevented an exploration of the full potential of the IBC system.

Consequently, a new IBC system with higher control authority and with increased frequency response was developed and a full-scale BO-105 rotor system with an improved IBC system was tested in the 40- by 80-foot wind tunnel at NASA Ames Research Center in 1993(Refs.32,33,34). Primary objectives of the IBC test were to evaluate the capabilities of such a system to reduce BVI noise, oscillatory loads, and rotor vibrations and to increase rotor performance. The IBC system was installed by replacing the four conventional rotating pitch links between the swashplate and the rotor blade with servohydraulic actuators. A conventional swashplate was employed for collective and cyclic inputs.

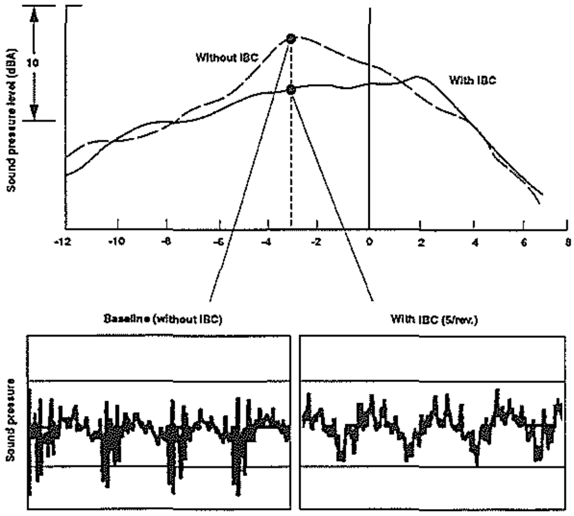
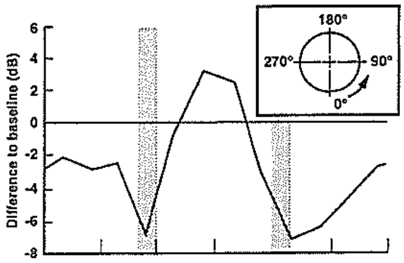


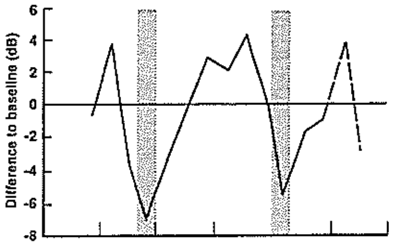
Fig.13 Flyover noise time histories of a BO-105 with and without IBC control (input mode 5/rev, 0.5° amplitude, negative blade pitch at 120° azimuth, centerline microphone.) (from Ref. 32)

For a typical BVI test condition (low speed, 6° descent) noise reductions of up to 7 dB were measured by different single mode IBC inputs. As shown in Fig.14, 2P and 3P modes were most effective and the 6P input was less beneficial. Variation of the flight condition indicated (as in HHC applications) that a fixed pitch schedule is unsuitable for optimum noise reduction at different descent conditions, suggesting the need for a fast closed-loop controller that may be based upon feedback of an appropriate pressure sensor signal.

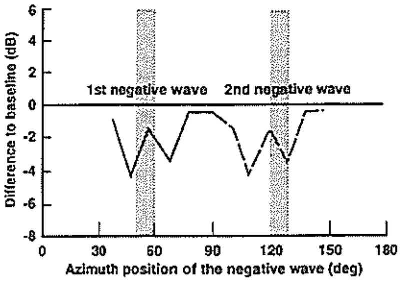
In 1994 an IBC follow-on test was conducted in the 40- by 80-foot wind tunnel with the objective of investigating the influence of both single-harmonic and multiharmonic IBC inputs on noise, vibration, and performance (Refs.21,35).



(a) 2/rev IBC input



(b) 3/rev IBC input



(c) 6/rev IBC input

Fig.14 Differences of sound pressure levels to the baseline for 2-, 3- and 6/rev IBC input function versus the position of the maximum negative amplitude on the advancing blade side corrected to the tip (microphone 1, nominal rotor condition, 1° amplitude) (from Ref. 32)

For all single-harmonic inputs (3P through 6P), BVI noise reductions measured at a fixed position on the order of 5 dB were obtained. For a 2P input, a maximum reduction of about 7 dB was measured at 1° amplitude and about 10 dB at 1.5° amplitude for the strong BVI noise flight condition.

Simultaneous reductions in acoustics (7 dB) and vibrations (20%) were achieved with a 2P input. Multiharmonic IBC inputs (combined 2P and 5P input) achieved the best BVI noise reduction benefit, 12 dB, at a fixed microphone location. For this combination also a maximum 90% reduction of 4P vibrations was measured in comparison to the baseline (without IBC) condition.

4. ANALYSIS OF BVI PHENOMENA AND NOISE WITH HHC

The three parameters associated with BVI noise will be discussed, including the experimental data: blade-vortex miss distance, airloads, and blade deflections. The main parameter of BVI noise is the blade-vortex miss distance as confirmed by the examination of HART experimental results (Refs.10,29,30,31).

In the HART test, very valuable information on BVI geometry, vortex strength, and core size was obtained from the flow visualization and nonintrusive flow field measurement techniques such as laser light sheet (LLS) and laser Doppler velocimetry (LDV) and on elastic blade deflections from applications of a projected grid method (PGM) and a target attitude in real time (TART) method(Ref.10). From the LLS technique, qualitative images of the tip vortex structure (e.g., double vortices for the MVcase) were attained and along with quantitative information on tip-vortex geometry segments and on blade-vortex miss distance near the azimuth of interaction. By LDV applications, the velocity vector fields of the tip vortices generating most intense BVI were determined. More insight into the vortex structure was gained and the double vortex system for the MV HHC case was verified.

Vortex strength (circulation) of the interacting vortex was found consistent with previous results, confirming a structured distribution within the vortex, but showed only limited effect on BVI noise in this test. The retreating side values were significantly higher than on the advancing side, but they did not change much with the HHC application. Vortex core radius was determined and was observed to be 50% larger on the advancing side compared to the retreating side for the baseline descent case investigated. For MN control settings the core size was increased on the retreating side by about 70% (while core size on the advancing side could not be determined). Elastic blade deflections attained along the blade span by PGM and strain gauge measurements and at the tip by the TART method clearly showed that the blade-vortex miss distance was increased for minimum noise blade pitch control and decreased for minimum vibration.

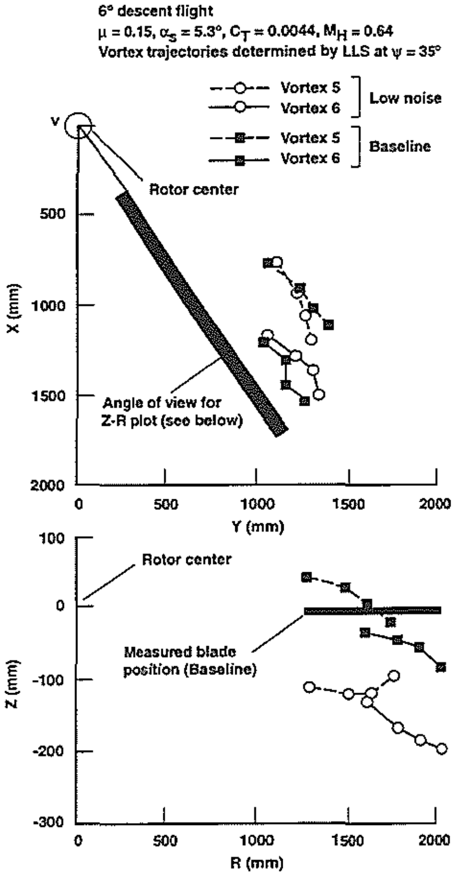


Fig.15 Vortex trajectories determined by LLS at ψ=35° (6° descent flight, μ=0.15, α_s=5.3°, C_T= 0.0044, M_H=0.64) (from Ref. 8)

Fig.15 compares the baseline case (without HHC) to the minimum noise configuration achieved from adjustment of the HHC phase setting. As shown in the figure, in the vicinity of the azimuth where blade-vortex parallel interactions occur on the advancing side (at about ψ=50°), the vertical blade-vortex miss distance is increased by about 120 mm (one blade chord length). Two mechanisms are expected to increase the blade-vortex miss distance: (1) generation of high induced velocities between the azimuth at which the interacting vortex is created and the azimuth of interaction with a following blade; and (2) downward deflection of the blade tip by the time the vortex is created, upward deflection at the occurrence of interaction. To assess possible contributions from these mechanisms, two kinds of experimental results from the HART tests are examined: the blade airloads derived from integration of the measured blade pressures and the blade flapping deflection.

Fig.16 compares the azimuthal distribution of blade airloads at different spanwise sections for the baseline and the minimum noise cases. As shown in the figure, when HHC is set for minimum noise, high airloads are achieved in a large azimuthal area between the generation of the interacting vortices (about ψ=130° for advancing side interactions) and the interaction azimuth (about ψ=50°). Consequently, high induced velocities are created, which push down the interacting vortex. As an example during the HART tests, with monocyclic control the airloads $C_N M^2$ at 0.87 R varied between 0.10 and 0.11 in the range of ψ= 90° through 130°; with optimum HHC, $C_N M^2$ varied between 0.10 and 0.18. Similar trends were also found at 0.75 R and 0.97 R.

Fig.17 shows, for the same test cases, the blade flapping deflection (resulting from both kinematics and aeroelastic deformations). This figure shows the spanwise distribution of the flapping deflection in the vicinity of the interaction azimuth and the blade tip deflection as a function of azimuth. As shown in the figures, compared to the baseline case, HHC at minimum noise provides: (1) a downward blade tip deflection (between 10 and 20 mm) by the time the interacting vortex is generated which causes a lower location of the vortex with respect to the blade; and (2) an upward deflection (+10 mm) by the time the interaction occurs. Both effects tend to increase the blade-vortex miss distance at the interaction azimuth by 20 to 30 mm.

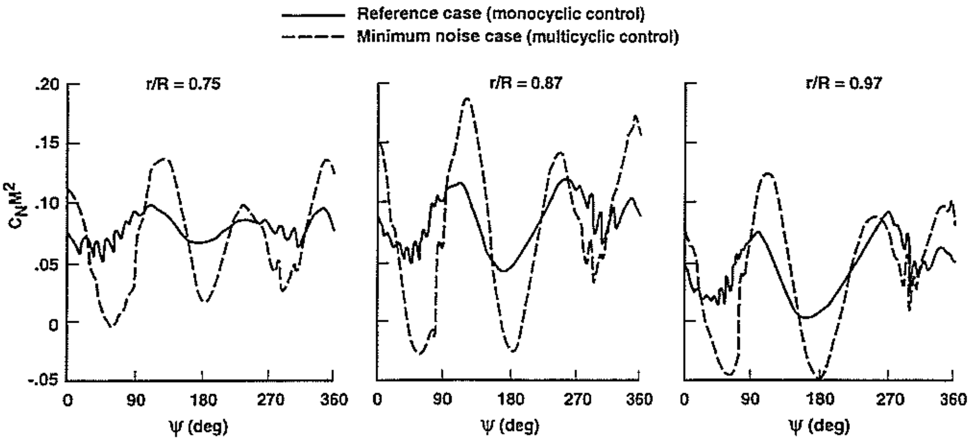


Fig.16 Airloads on rotor blades for BVI configurations

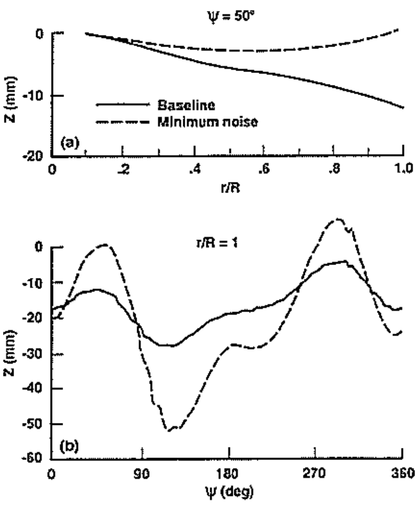


Fig.17 Flapping deflection (without precone) (6° descent flight, μ=0.15, α_s=5.3°, C_T=0.0044, M_H= 0.64) (a) blade deflection along the span, (b) blade tip deflections versus azimuthal angle

The blade deflection effect is, however, far too small to account for the 120 mm increase in blade-vortex miss distance shown by the LLS measurements. This miss distance increase is in fact, to the first order, a consequence of the azimuthal distribution of the blade airloads achieved through adjustment of the HHC phase.

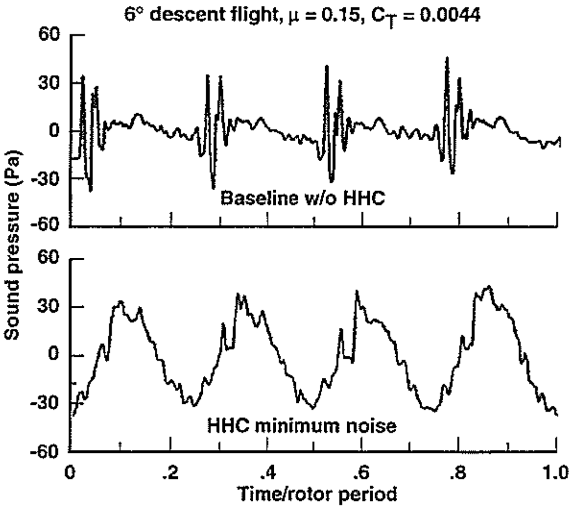


Fig.18 Sound pressure time histories (from Ref. 8)

The consequences of the previous airload history and blade-vortex miss distance are: (1) a large reduction of the noise pressure peaks associated with the BVI event as shown in Fig.18; and (2) a large reduction of the BVI noise levels as shown in Fig.19, which presents the BVI noise radiation pattern below the rotor. This figure also shows that the maximum mid-frequency BVI noise level (related to the helicopter acoustic nuisance) can be reduced by more than 6 dB compared to the baseline case. It must be noted, however, that HHC increases the low-frequency noise, which can be penalizing as far as the helicopter noise detectability is concerned.

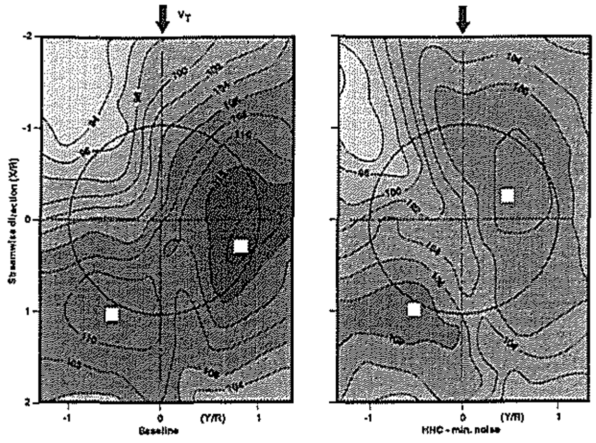


Fig.19 BVI noise pattern below the rotor (from Ref. 8)

In summary, HHC has proved to be an efficient technique for BVI noise reduction in descent flight. This effect is achieved primarily through global changes in the aerodynamics, and thus wake and tip vortex trajectory changes over the rotor disk which modify the geometry of the BVI. Even if stronger vortex intensities are created, the dominating effect for the noise reduction is the increase of blade-vortex miss distance, mainly due to the larger induced velocities through the rotor disk which accelerate the downward convection of the vortices.

5. SMART ACTIVE ROTOR CONTROL CONCEPTS FOR BVI NOISE REDUCTION

Both HHC and IBC have been investigated based on the concept of controlling the blade pitch at its root. These HHC and IBC techniques have been shown to be able to substantially reduce noise and vibration levels, but increased in some cases edgewise bending moments, torsional moments, and control loads. Furthermore, the implementation of these techniques may require additional power, weight, and complexity. Smart structures technology may be able to address some of these shortcomings if it is capable of exerting the large forces and moments at sufficiently high frequencies. The current research to develop a smart rotor system is mainly directed at two approaches: first, embedding distributed actuators along the blade span to induce rotor twist distribution, and, second, utilizing active trailing edge flap, elevon concept, or active vortex generators.

Recently, nonharmonic deflections of the trailing edge were tested in the NASA Langley 14x22 foot wind tunnel to control blade tip loading distribution, which both alters the rotor wake structure and weakens the tip vortex strength (Refs.36,37). A flap was mechanically deflected upward by 12.5° up to 20° in limited rotor azimuth ranges. Fig.20 shows an acoustic time history for a baseline (non-active flap) case, which exhibits a typical BVI pressure pulse, and also shows the time history for the 12.5° flap motion, which exhibits no clear BVI impulse and a more broadband nature. In the BVI-dominated frequency range, the harmonic content of the signal with the flap active reduced the peaks by 10 dB or more. However, there is an increase in low harmonic noise levels and power required for the 12.5° flap case. Since helicopters have excess power available during descent, this power penalty may not in itself be a major problem to ultimate use of the concept. In summary, a 4 dB decrease in the overall sound level was obtained with the active trailing flap.

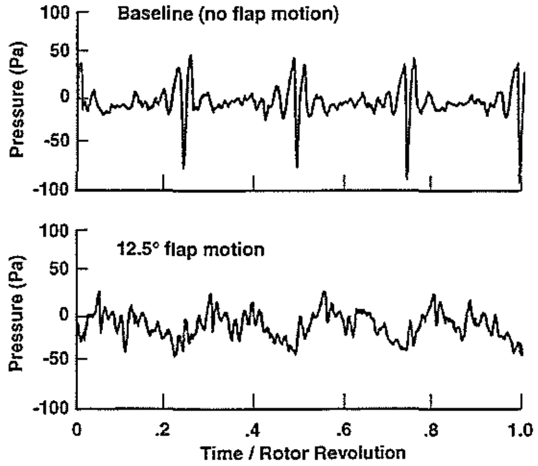


Fig.20 Time histories at maximum BVI location in active flap rotor test (from Ref.37)

Smart structures involve distributed smart actuators and sensors to apply localized strains to modify the blade shape in a controlled manner. A comprehensive review on helicopter applications was given in Refs.38-42. Many types of actuators and sensors are being considered, such as piezoelectric materials, shape memory alloys, electrostrictive materials, magnetostrictive materials, electro-rheological fluids, and fiber optics. These smart materials can be integrated with rotor blades by surface bonding or embedding without causing any significant changes in the mass or structural stiffness of the blade, inducing alteration of twist/camber of airfoil that in turn will cause variation of lift distribution or modify the blade aeroelastic deformation.

Two six-foot rotor models were built and tested (Ref.38): active blade twist control incorporating embedded piezoceramic elements, and active trailing edge flap models with smart actuators. A six-foot diameter four-bladed bearingless rotor model was embedded with banks of specially shaped piezoelectric actuators at ± 45° on the top and bottom surfaces. This rotor was tested in hover, and tip twisting of the order of 0.2° was achieved at 900 RPM with a 4P excitation. With the distributed actuators, local torsional changes, and consequently the blade tip deflection, are induced along with flapping deformation. For the second concept, a six-foot diameter two-bladed bearingless rotor model was mounted with a trailing edge flap actuated with a piezo-bimorph. Oscillatory flap deflections up to 2° at 900 RPM have been obtained, but a major drawback was its complex hinges and leverage system where considerable performance losses took place, especially at higher rotational speeds. A better concept was investigated where a bending-torsion coupled composite beam with surface-bonded piezoceramic was used to actuate the flap. A six-foot diameter rotor model was tested in hover, and a flap deflection of 4° was obtained at 900 RPM. However, more research has to be done before practical applications on helicopters.

6. CONCLUSION

Research conducted in the last decade has produced remarkable advances in understanding of the generating mechanisms of and also in controlling rotor blade-vortex interaction (BVI) noise. Several important physical parameters were identified: wake structures and trajectory, blade-vortex miss distance, rotor induced velocity distribution, and blade aeroelastic deformation.

Active rotor control techniques such as higher harmonic pitch control (HHC), individual blade control (IBC), and smart rotor control concepts have been reviewed for BVI noise reduction. The HHC technique has achieved substantial benefits in vibration reduction as well as noise reduction, but generated penalties such as power, weight, complexity, and limited control flexibility. However, this technology provided fundamental understanding of the active rotor control concepts to reduce BVI noise and served as an ideal basis for further developments. A comprehensive test database with this HHC technique is available for fundamental understanding of the noise generation and controls. The IBC technique has been developed with adequate control authority and with high frequency response. A full-scale rotor with an improved IBC system with blade root control was tested for BVI noise and vibration reduction and achieved substantial advances in reducing simultaneously both the vibration and noise levels. Particularly, multiharmonic IBC inputs achieved the best BVI noise and vibration reduction.

Currently, smart structures are being actively investigated to further advance the current active rotor control technology for noise and vibration reduction, such as active trailing edge flap and active blade twist control concepts with piezoelectric materials or shape memory alloys. The physical benefits generated by HHC and IBC control techniques can be produced by blade pitch or twist variations along the blade span by localized smart structure actuations in a rotating frame, potentially with much less power required. However, the capabilities of the currently available smart structures/materials are still limited for practical helicopter applications.

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