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BVI IMPULSIVE NOISE REDUCTION BY HIGHER HARMONIC PITCH CONTROL: RESULTS OF A SCALED MODEL ROTOR EXPERIMENT IN THE DNW

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ABSTRACT

A model rotor acoustics test was performed to examine the benefit of higher harmonic control (HHC) of blade pitch to reduce blade-vortex interaction (BVI) impulsive noise. A dynamically scaled, four-bladed, rigid rotor model, a 40% replica of the BO-105 main rotor, was tested in the German Dutch Wind Tunnel (Deutsch-Niederländischer Windkanal, DNW). Acoustic measurements were made in a large plane underneath the rotor employing a traversing in-flow microphone array in the anechoic environment of the open test section. Noise characteristics and noise directivity patterns as well as vibratory loads were measured and used to demonstrate the changes when different HHC schedules (different modes, amplitudes, phases) were applied. Dramatic changes of the acoustic signatures and the noise radiation directivity with HHC phase variations are found. Compared to the baseline conditions (without HHC), significant mid-frequency noise reductions of locally 6 dB are obtained for low speed descent conditions where BVI is most intense. For other rotor operating conditions with less intense BVI there is less or no benefit from the use of HHC. Low frequency loading noise and vibratory loads, especially at optimum noise reduction control settings, are found to increase.

SYMBOLS

- $a_0$: speed of sound, m/s
- $C_T$: Rotor thrust coefficient, thrust/$\rho\pi R^2 (\Omega R)^2$
- $f$: frequency, 1/sec
- $f_{bp}$: blade passage frequency, number of blades multiplied by $\Omega/2\pi$
- $GF$: vibration quality criterion, rms value of 4/rev components of balance forces and moments, normalized to baseline GF without HHC, %
- $M_H$: hover tip Mach number, $\Omega R/a_0$
- $n^P$: $n$th harmonic of rotor rotational period
- $R$: rotor radius, m
- $r$: radial distance from hub, m
- $\alpha$: effective $a$ corrected for free jet wind tunnel effects, deg
- $\Theta$: calculated full-scale helicopter flight path angle, positive in descent, deg
- $\theta_c$: amplitude of higher harmonic pitch at $\psi_c$, deg
- $\phi$: phase angle of higher harmonic pitch, referenced to positive $\theta$, for reference blade passing zero azimuth ($\psi = 0^\circ$), deg
- $\mu$: advance ratio, tunnel flow velocity/$\Omega R$
- $\rho$: air density, kg/m$^3$
- $\psi$: blade azimuth angle, deg
- $\psi_c$: blade azimuth angle selected for $\theta_c$, deg
- $\Omega$: rotor rotational speed, rad/sec

INTRODUCTION

Blade-vortex interaction (BVI) impulsive noise of helicopters is considered a matter of major concern for the acceptability of rotorcraft in densely populated areas and has become an important subject of rotor acoustics research in recent years. The pulse-type noise due to BVI originates from the unsteady aerodynamic interaction between a lift generating blade and the vortex system shed by preceding blades. This phenomenon is generally observed during low speed descent, especially landing approach, and during manoeuvre flight condition, when the
displacements between the rolled-up tip vortices and the rotor plane become extremely small. When BVI occurs, this noise mechanism dominates the noise radiation in the mid-frequency range to which human subjective response is most sensitive.

Earlier experimental work on BVI noise was performed on full-scale and model-scale helicopter rotors in order to determine the rotor operating regimes for BVI (Refs 1-3), the primary parameters affecting BVI noise generation and radiation, as well as the model-to-full-scale acoustic scaling conditions (Refs 4-6). Advancing and retreating side BVI source locations were identified in the first and fourth quadrant of the rotor plane (Refs 7, 8) and were found to be most intense where the blade and the vortex axes are close to parallel (between 45° and 75° and about 300° azimuth angle, respectively).

A BVI noise reduction hypothesis (Ref 9) suggested that decreases in blade lift, vortex strength, and/or increases in blade vortex separation distance at the blade-vortex encounters should help to reduce the effect of BVI on the unsteady blade loads and thus on noise. The technique of higher harmonic control (HHC) of the blade pitch, historically developed for vibration control (Refs 10-13), was thought to be useful for manipulating those parameters. The HHC noise reduction concept is sketched in Fig 1, which illustrates rotor blades undergoing higher harmonic pitch variations. The amplitude and proper phasing of such pitch controls at the azimuthal locations of the most intense BVI encounters and at upstream locations, where the encountering vortex is being generated, would be considered to be important to the noise problem.

![Fig 1 Illustration of noise reduction concept.](image)

The present paper reports on results of a three-nation cooperative model rotor test in the DNW making use of the experience gained by research personnel of the United States, France and Germany during acoustic tests at the Langley Transonic Dynamics Tunnel (TDT), reported in Refs 15 and 16, were quite consistent with the Ref 14 results. The particular prescribed pitch schedule used for HHC was a 4P collective pitch control superimposed on the normal cyclic trim pitch. Uniquely, the acoustic testing was conducted in a heavy gas (Freon-12) flow medium, instead of air, and the reverberant field of the hard wall tunnel test section was used to advantage by choosing a sound power measurement approach. Significant BVI (mid-frequency) noise reductions (5-6 dB) were found for low-speed descent conditions where BVI is most intense. For other flight conditions noise was found to increase with an increase in HHC. On the other side, the mid-frequency noise reductions due to HHC were reported to be accompanied by increased low frequency noise and vibration levels. Similar BVI noise reductions and trends were observed in the three-nation BVI vibration control flight test program on an experimental SA349 Gazelle helicopter (Ref 17).

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EXPERIMENT

Wind Tunnel and Rotor Test Stand

The test program was conducted in the open test section of the German Dutch Wind Tunnel (Deutsch-Niederländischer-Windkanal, DNW) located in The Netherlands. The open configuration employed in this test provides a free jet to the test section of 19 m length. The open test section is surrounded by a large anechoic chamber with a nominal cut-off frequency of 80 Hz (Ref 18). The DLR model rotor test stand, together with the traversing inflow microphone array is shown installed in the DNW open test section in Fig 2. The rotor test stand was housed in an acoustically insulated fiberglass fuselage and was attached to the computer controlled...
hydraulic sting support mechanism. Fuselage and sting were covered with a sound absorptive lining to minimize acoustic reflections. The rotor was driven by a hydraulic motor (100 kW) and controlled by three equally spaced electro-hydraulic actuators providing both conventional (1 per revolution) and higher harmonic (3P, 4P, 5P) blade pitch control. Details of rotor performance and data acquisition/reduction are given in Refs 19 and 20, and are summarized in Ref 21. The data acquisition system acquired about 48 samples per rotor revolution from each of the 64 sensors that allowed data analysis in the frequency domain up to the 9th rotor harmonic.

The rotor is a 40-percent, dynamically scaled replica of a four-bladed, hingeless 80-105 main rotor. The rotor diameter is 4m, the blade cross section is a NACA 23012 airfoil with the trailing edge modified to form a 5mm-long tab to match the geometry of the full-scale rotor. The rotor blades have a chord length of 121mm, a linear twist of -8°, and a standard rectangular tip. The nominal rotor operating speed was 1050 rpm giving a blade passage frequency (fbp) of 70 Hz and a hover tip Mach number of 0.64. Nominal thrust coefficient was 0.0044. Further details are given in Ref 19. Wind tunnel corrections to the measured geometric shaft angle (\(\alpha\)) for the effect of the finite open jet potential core were calculated with the theory of Refs 22,23. The corrected flow angle corresponding to the full-scale flight condition is referred to as the tip-path plane angle, \(\alpha\).

Acoustic Instrumentation and Data Acquisition

The acoustic instrumentation comprised an eleven-microphone in-flow array mounted on a traversing system (Fig 2) and three in-flow microphones, two of which were mounted on the starboard side (advancing side) of the fuselage and one on the port side (retreating side). The microphones were 1/2-inch pressure-type condensor microphones equipped with standard nose cones. Microphone calibrations were performed with a sound level calibrator on a daily base. In addition, pure tone and white noise signals were recorded on each magnetic tape simultaneously on all channels by signal insertion at the tape recorder inputs. The microphone signals were high-pass filtered at 4 Hz to remove very low frequency content associated with the free jet flow in the open test section.

The microphone array traverse system consisted of a horizontal wing with its span normal to the flow direction, with a useful range in flow direction of 4m upstream, 4m downstream of the rotor hub. The microphones were arranged symmetrically with respect to the tunnel centerline, spaced 0.54m apart, and nominally 2.4m below the rotor hub. The microphone data acquisition/reduction were performed using a vibration isolating mounting. Wing and support struts were covered with an open-cell foam cut in an airfoil section shape. The supporting structure was covered with 0.1m-thick foam lining, and the base was protected with 0.8m foam wedges. In Ref 21 details on control, positioning, and alignment of the array are given.

For measuring the radiated sound field on a large plane (5.4m x 8m) underneath the rotor, an advanced measurement technique was applied, that allowed to reduce the data acquisition time by a factor of about twice the spatial resolution in flow direction compared to earlier measurements using fixed streamwise traverse positions (Ref 21). The new "on-the-fly" data acquisition technique employed a continuously moving microphone traverse with the data acquisition started at preselected streamwise locations. As shown in Fig 3 with a spacing of 0.5m in flow direction, the spatial resolution of the microphone array was 187 measurement points (or about 0.25 m²). The traversing speed was chosen to be very low (about 0.038 m/s) to approximate stationary measurements of the sound field. At each of the 17 streamwise traverse positions the data acquisition was initiated and acoustic data for time periods of 30 rotor revolutions (approx. 1.75s) were acquired simultaneously with rotor and wind tunnel operational data. During this data acquisition period the traverse displacement was...
very small with a marginal change in radiation angle of approximately one degree in major BVI noise radiation directions. Comparisons of instantaneous and averaged time signatures from "on-the-fly" and completely stationary measurements at fixed traverse locations did not show noticeable differences. Therefore, the new data acquisition technique is considered to provide high quality quasi-steady acoustic results in a very efficient way. A typical acoustic data acquisition cycle thus measuring the sound field (Fig 3) comprised: microphone gain adjustments during the downstream travel of the microphone traverse, initiation of the analog recording system, and the measurement of the upstream movement of the microphone array with repeated digital data acquisition at 17 predetermined streamwise locations, giving a total cycle time of about 5 to 6 minutes.

Investigations into the data quality were performed in a pre-test phase by conducting tunnel background noise and reflection tests with all the BVI hardware (except the blades) installed in the test section. Background noise levels were found to typically 20 dB lower in the frequency range dominated by rotor BVI noise. The blast test indicated no extraordinary reflections or any they were typically 15 to 20 dB below the direct signals. The results were quite useful to identify regions where some microphones may be "shielded" by the fuselage. Additional tests with the digital data quality, like tunnel flow quality, rotor performance data, and the steadiness and repeatability of the rotor acoustic data are summarized for a very similar test set-up in Ref 27.

Data Reduction and Analysis

The microphone signals, the blade position reference signal (once-per-revolution signal) and the traverse position signal were synchronously digitized with 16-bit resolution to provide nominal 1024 samples per rotor revolution. This digitizing process was key to the 1024-per-revolution signal of the blade azimuth angle encoder, and provided a sample rate of about 18000 samples per-second with antialiasing filters set at 9 kHz, that gave a useful frequency range between 4 Hz and 9000 Hz. Thirty rotor revolutions of real-time acoustic data were stored on computer disk with subsequent calculation of the averaged power spectrum using Fast Fourier Transform (FFT) software. Several noise metrics were calculated from these on-line results like A-weighted levels, perceived noise levels, and some linear band-pass levels. A useful estimate of the impulsive noise content was the mid-frequency noise level, comprising the acoustic energy from the 6th to the 40th harmonic of the blade passage frequency.

In a similar way a low frequency noise level representing the 1st to the 5th f_p harmonic was calculated. For different metrics, contours of equal noise levels were generated on-line and plotted for the measurement plane. These contour plots indicated the BVI noise directivity pattern and the change in directivity and intensity of the noise radiation when HHC was applied. A reduction of the vast amount of noise data to single noise descriptors was obtained by calculation of an average (mid-frequency) BVI noise level and by determination of maximum mid-frequency noise levels for both advancing side BVI and retreating side BVI. This was accomplished by a search algorithm scanning through the sound field underneath the first, second and third quadrant of the rotor plane for the maximum of advancing side noise radiation and underneath the fourth quadrant for maximum retreating side BVI noise. These single value noise descriptors were found to be very useful to assess the benefits of HHC when changing HHC parameters and/or rotor operational conditions.

The effect of HHC on rotor vibrations was estimated by means of a vibration quality criterion (GF), which was computed on-line from the 4/rev components of the forces and moments of the rotor balance, and which shows minima at the lowest vibration levels.

Rotor Operation

A scheme of the DLR digital higher harmonic control system is shown in Fig 4. Three computer-controlled, equally spaced electro-hydraulic actuators are used to move the swashplate in the desired way, in order to provide conventional pitch motion (collective and cyclic) as well as higher harmonic pitch motion (3P, 4P, 5P and any combination) for a precise blade root pitch control. For this four-bladed rotor, the higher harmonic pitch is achieved by superimposing 4P swashplate motion upon the basic swashplate collective and cyclic (1P) flight control inputs. Collective 4P pitch motion (all four blades pitching simultaneously) was provided as well as pitch schedules containing 3P, 4P and 5P pitch harmonic components, through proper phasing the 4P inputs (Refs 11,12,13). For this test computer-based manual HHC input, i.e. open loop control was used to generate the HHC signals. The system is also designed to operate at closed loop control.
The pitch motion achieved as well as the test procedure can be explained on the basis of Fig 5 which shows a blade pitch angle data versus blade azimuth angle Ψ for a specific advance ratio μ and tip-path-plane angle α, the mean collective (6.0°), for the case shown, necessary to produce the required C_0 and the basic 1P pitch (2.1°) for zero flapping trim with reference to the rotor shaft, were attained as shown. Once performance and acoustic data were acquired for this baseline case, pre-selected HHC pitch was superimposed to generate a deflection of Ψ_c at azimuth angle Ψ_c and data were taken again. Due to the observed only minor variations in thrust coefficient and trim flight condition no adjustments were necessary in mean collective and cyclic pitch. The higher harmonic pitch portion (difference of total and baseline case pitch) is illustrated in Fig 5 (a) for a 4P HHC case.

Fig 5 Superposition principle of higher harmonic blade pitch: (a) blade pitch angle θ versus azimuth for μ = 0.15, α = 3.8°, C_c = 0.0044 at 4P HHC with θ_c = -1.2° at Ψ_c = 60°; (b) mixed mode HHC schedule (wavelet) with θ_c = -1.4° at Ψ_c = 90°.

The net pitch in general is, due to normally occurring pitch-flap and pitch-lag couplings, not purely 4P collective, but contains small portions of other harmonics as well. The 4P noise data presented in this study are from a 4P like mode, amplitudes and azimuth angle Ψ_c in the first quadrant (0 ≤ Ψ_c < 90°) are obtained from the 4P components (amplitude and phase) of the measured pitch angle FFT analyses. Similar considerations are valid for 3P and 5P pitch schedules with definition of the azimuth angle ranges of 0 ≤ Ψ < 120° and 0 ≤ Ψ < 72°, respectively. Also shown in Fig 5 (b) is the net higher harmonic pitch of a mixed mode case (combination of 3P, 4P, 5P modes) which was designed to form a wavelet with a pronounced negative HHC amplitude at one azimuth location and reduced higher harmonic pitch over a wide range of azimuth angles. This wavelet approach was thought to be a first order approximation of individual blade control (IBC) and would allow an initial estimate of the effect of IBC on noise.

The tests were performed over a range of descent flight operating conditions where BVI is likely to occur with a few level flight conditions. These specific test "flight" conditions were defined by the tunnel reference tip-path-plane angle α and the advance ratio μ. For the data presented, the tip-path-plane angles were corrected (Refs 22, 23) to account for open jet wind tunnel effects to obtain equivalent freestream values. In order to relate the noise results to full-scale flight conditions of a 80-105 helicopter, equivalent descent angles α were calculated based on a simplified force balance of Ref 23. For a few typical BVI test conditions the HHC parameters like mode, amplitude and phase were examined in detail; for a broader range of operating conditions only specific HHC parameters, expected to best reduce BVI noise, were examined.

TEST RESULTS

Change of Noise Characteristics by HHC

The effect of higher harmonic pitch control on BVI noise characteristics in the time and frequency domain is shown in Fig 6. For a "standard" operating condition (μ = 0.15, α = 3.8°) equivalent to a low speed descent at 6° glide slope with minimal BVI noise generation. At part (a) of this figure shifts of mid-frequency noise levels as measured for the baseline case without HHC (center) and for two higher harmonic pitch schedules are compared. Maximum advancing side BVI noise reduction (5-6 dB) is achieved at a nominal HHC schedule of 4-per-revolution, HHC amplitude θ_c = -1.2°, and phase angle Φ = 18° minimum shift (Ψ_c = 53°) as shown in the right hand contour plot with notation 4P/1.2°A/30°Ph, however, at slightly increased retreating side BVI noise intensity. The noise directivity pattern appears also affected by HHC with the radiation lobe directed more towards the upstream direction for this case. Maximum retreating side BVI noise reduction (approx. 6 dB) is obtained for a similar pitch schedule (4P/1.2°A/10°Ph) at a shift of 180° (Ψ_c = 0°; left hand contour plot). In this case advancing side BVI noise is slightly reduced as well.

Related sound pressure time-histories (30 averages) for one rotor revolution and averaged frequency spectra for observer locations at maximum advancing side BVI (part (b)) and at max. retreating side BVI (part (c)) are arranged below the relevant contour plots for easy comparison. For the baseline case without HHC, the center column shows typical advancing side BVI sound pressure pulses of positive polarity and lower retreating side BVI noise pulses of negative polarity and lower amplitude. The related frequency spectra reveal a large number of blade passage frequency harmonics that indicate the dominance of BVI impulsive noise in the mid-frequency range. When HHC is initiated low-frequency loading noise is generated, which is apparent in the noise signatures and spectra, and the intensity of which is increased with HHC amplitude (θ_c).
Fig 6 Effect of HHC on noise contours and BVI noise characteristics for low speed descent case of $\mu = 0.15$, $\alpha = 3.8^\circ$, $\Theta = 6^\circ$, $C_L = 0.0044$, $N = 0.64$; (a) comparison of mid-frequency noise level contours; (b) comparison of advancing side BVI noise characteristics; (c) comparison of retreating side noise characteristics.

However, low frequency noise is not important from a subjective weighted measure in comparison to the mid-frequencies. Comparison of the BVI impulses, obvious in the sound pressure time-histories, show largely reduced BVI noise signatures for optimum control settings for advancing side BVI and retreating side BVI, respectively. The relevant comparison of the frequency spectra reflect the decrease in mid-frequency noise levels for optimum HHC control settings at increased low frequency noise. In general, the measured sound pressure time histories at a fixed observer location, where strong advancing side BVI is radiated, indicate that variation of HHC phase results in dramatic changes of the BVI waveform shapes. This is shown in Fig 7 for one rotor revolution and constant rotor operating conditions for the "standard" BVI case. For the baseline case without HHC, one strong BVI impulse is seen. With HHC (4P/1.2°A) acti-
Fig 7 Change of BVI impulsive noise wave-forms with HHC phase angle variation at 4P/1.2° amplitude pitch control; acoustic data (except baseline) are high-pass filtered at 200 Hz; rotor condition as for Fig 6 (6°-descent).

vated, multiple BVI waveforms (up to 5 impulses) appear at certain HHC phase angles as well as waveform shapes with one very strong impulse at other phases. Very weak impulses are found at a specific azimuth phase angle \( \psi = 54° \) that corresponds to the optimum noise reduction control phase angle for this HHC pitch mode. Similar trends are observed for other HHC schedules.

The change of HHC phase is obviously changing the interaction geometry (blade position and vortex trajectories) due to the modified blade loading and blade motion. Thus, it appears that in some cases, the blade encounters up to five of the seven vortices, which are present in the first quadrant at this descent condition (Ref 8). At another control phase, it very intensely hits only one vortex, and finally and most desired, the blade seems to miss them all with the effect of largely reduced BVI noise. CAMRAD-JA calculations using a free-wake formulation indicate distinct changes of the interaction geometry when, for a specified HHC pitch schedule, the control phase is changed. The locations, where the vortex system is predicted to cut through the rotor disk (possible BVI source locations) appear to be correlated in a non-linear way with the control phase. This is shown in Fig 8, where the vertical wake-blade displacements (at \( Y/R = 0.87 \)) are plotted vs streamwise position \( X/R \) for the standard baseline case and

Fig 8 Predicted vertical blade-wake displacements for baseline (w/o HHC) and for 4P/0.8°A HHC pitch schedule at different phase angles as seen in a vertical plane parallel to the flow direction intersecting the rotor disk at \( Y/R = 0.866 \). Rotor condition for Fig 6.
4P/0.8°A pitch control at various phase angles. Possible BVI source locations (dZ/R = 0) show substantial changes in upstream and downstream directions. Consequently, the intensity and direction of sound radiation from the acoustic source locations is subjected to similar, apparently non-linear changes, as is seen in the BVI waveforms of Fig 7 for a fixed microphone location.

**Effect on BVI Noise Directivity**

The resulting changes in the noise radiation directivity pattern of the complete sound field underneath the rotor plane is shown in Figs 9 (a) - (d) for the typical BVI "standard" operating case of low speed descent ($\mu = 0.15$, $\Theta = 6^\circ$). To emphasize the more important radiation lobes only the higher noise levels have been plotted. Series of mid-frequency noise level contour plots for different higher harmonic pitch control phase angles are compared to the directivity pattern of the baseline case (part (d)). HHC pitch schedules of 3P/0.8°A (part (a)), of 4P/0.8°A (part (b)), and of 5P/0.8°A (part (c)) are presented with variation of the control phase ($\Psi$) at increments of 30 degrees. The contour plots are arranged in such a way, that the plot with the lowest azimuth angle of minimum HHC pitch ($\Psi$) appears first. Azimuth and control phase angles (based on measured values) are noted on each plot.

Fig 9 Change in BVI noise directivity with HHC variations for the low speed descent condition of Fig 6; (a) variation of HHC phase at 3P/0.8° amplitude; (b) variation of HHC phase at 4P/0.8° amplitude; (c) variation of HHC phase at 5P/0.8° amp.; (d) baseline.

As compared to the baseline case, strong changes in BVI noise radiation intensity and direction are observed for all HHC pitch schedules (3P, 4P, 5P), when the pitch control phase is varied. In particular, for the 3P pitch schedule (Fig 9 (a)) the minimum HHC pitch azimuth angle $\Psi$ is shifted through the first quadrant and partly
Fig 10 Variation of noise and vibrations with HHC parametric variations for the low speed descent condition of Fig 6; baseline w/o HHC: ---; symbols are for $\theta_r$ = -0.4° (nominal), $\circ$ ; for $\theta_r$ = -0.8°, $\square$ ; and for $\theta_r$ = -1.2°, $\triangle$. (a) - (f) mid-frequency (6 to 40 Hz) max. noise level vs $\psi_c$ at 3P, 4P, 5P control mode; (g) - (i) mid-frequency average noise level; (j) - (l) mid frequency noise level at fixed microphone position (M9 of Fig 6); (m) - (o) low-frequency average noise level; (p) - (r) normalized vibration criterion.

through the second (0° $\leq \psi_c \leq 120°$), when the phase angle is modified from 0° to 360°. Largely increased advancing and retreating side BVI noise radiation is seen at lower $\psi_c$-values (0° $\leq \psi_c \leq 30°$) with a directional change towards the flight direction. At higher $\psi_c$-values (30° $< \psi_c < 70°$), retreating side BVI is effectively reduced at slightly decreased levels of advancing side BVI, which appears more focussed towards the flight track and even extending into the retreating side. At $\psi_c$ values above 70° the directivity patterns become similar to the baseline case with increased advancing side BVI at 70° and 80° azimuth. Effectively reduced advancing side BVI is obtained for $\psi_c$-values about 90° and 100°, at retreating side BVI levels comparable with the baseline case. For the 4P HHC mode (Fig 9 (d)) the azimuth angle of minimum HHC pitch is shifted through the first quadrant (0° $\leq \psi_c \leq 90°$). Again dramatic changes of the BVI noise directivity is observed. Most effective reductions of advancing and retreating side BVI noise (at the order of 4 dB) is obtained for $\psi_c$-values about 80° and 90° (or 0°). At 5P control mode (Fig 9 (c)) the minimum HHC amplitude is shifted through the azimuthal range 0° $\leq \psi_c \leq 72°$ for one complete HHC period. The directivity of BVI noise radiation is similar to the baseline case, however the noise intensity again shows strong variations. Moderate reductions of advancing side BVI noise is measured for minimum HHC pitch azimuth angles of 60° $\leq \psi_c \leq 90°$, at nearly unchanged retreating side BVI noise levels (bearing in mind that the azimuthal range 72° $\geq \psi_c \geq 90°$ is equivalent with 0° $\leq \psi_c \leq 18°$).

At other rotor operating conditions known to generate BVI noise, similar changes of the mid-frequency noise directivity patterns are observed when the HHC pitch schedule, in particular the HHC phase, is varied. At higher HHC amplitudes the directivity changes are even more pronounced.
Effect on Noise Levels and Vibration

The mid-frequency noise level contours and noise characteristics as well as the noise directivity patterns shown, have indicated strong variations due to changes of the HHC parameters. The more clearly shown are the low operational pitch control variations affect rotor noise and vibrations, the general trends and the noise reduction potential of HHC are illustrated in Figs 10 (a) - (r), which show the results of the noise parametric variations and allow a quantitative evaluation of its effects. Selected noise evaluation measures (mid-frequency, low-frequency) and a vibration criterion are plotted for different HHC modes (3P, 4P, 5P) and HHC amplitudes (θ = -0.4°, -0.8°, -1.2°) versus rotor azimuth angle of minimum HHC amplitude (Ψ). The data for the baseline case without HHC corresponding to the standard (8° descent) rotor operating condition, is indicated on each plot by a dashed line. Advancing and retreating side maximum, mid-frequency noise levels have been determined from the measurement plane underneath the first to the third quadrant and underneath the fourth quadrant, respectively. The spatial average mid-frequency noise levels for 3P, 4P and 5P HHC, respectively. Effective noise reductions but also increased noise levels are seen for all three control modes. For 3P and 4P HHC the larger control pitch amplitude (0°) produces the larger noise reductions. For 3P HHC noise reductions (order of 6 dB) are obtained for minimum HHC pitch in the range of 40° ≤ Ψ ≤ 50° and 90° ≤ Ψ ≤ 100°. At 4P HHC the minimum noise is found at 50° ≤ Ψ ≤ 60° and again for Ψ = 90° (or 0°). At 5P HHC smaller noise reductions (almost independent of HHC amplitude) are observed at a wider azimuth range of 70° ≤ Ψ ≤ 100°. Comparative noise reductions and similar trends are seen for advancing side BVI as shown in Figs 10 (d) - (f). Maximum reductions (approx. 6 dB) are found at Ψ = -1.2° for 3P at Ψ = 50° and for 4P at Ψ = 90° (or 0°). Moderate reductions are found at about Ψ = 80° (3P) and about Ψ = 40° (4P). 5P Control appears to be less effective and respectively for 5P HHC control results (Figs 10 (a), (d) and (b), (e)), it is obvious that the azimuth angles Ψ (or equivalent the control phase angles) for effective noise reductions are slightly different for advancing side and retreating side BVI. This implies that both noise sources cannot be simultaneously controlled in an optimal way by HHC for the considered test case.

The spatial average mid-frequency noise levels (part (g)-(i)) representing the BVI noise of the complete measurement plane, therefore indicate somewhat less reductions (order of 3 dB). Also, it appears that average mid-frequency noise can be effectively reduced at moderate HHC amplitudes (e.g. θ = -0.8°) with the minimum HHC amplitude at about Ψ = 90° for each control mode. The mid-frequency BVI noise levels for a fixed upstream microphone location (mic 9 at X/R = -0.75), chosen to receive maximum advancing side BVI noise radiation at the baseline case (part (j)-(l)) show similar trends as for the maximum advancing side BVI (see part (a)-(b)) except for 5P control mode where larger reductions are obtained, possibly an effect of directivity changes due to HHC.

The BVI noise measured by the fuselage and by the inflow-traverse microphones is due to the observed directivity changes subjected to substantial changes of the degree of correlation.

Spatial averaged low frequency noise levels are presented in Figs 10 (m)-(o). Compared with the baseline case, they are largely increased with application of HHC, distinctly growing with HHC amplitude. The highest levels are observed at 4P control (plus 15 dB at 1.2° amplitude), the lowest at 5P (7 to 8 dB). It is important to note, that on the subjective A-weighted dB scale, the low frequency noise is not of concern compared to the mid-frequency BVI harmonics for example, the blade passage frequency of 70 Hz must be attenuated by at least 25 dB on the dBA scale, when compared with the mid-frequency (BVI) harmonics.

The vibration quality criteria calculated from the 4P components of the six-component balance forces and moments and normalized to the baseline case vibration parameters are presented in Figs 10 (p)-(r). Inertial forces due to the accelerating masses of the swashplate, blade root hardware, actuator pistons, and other control hardware used to produce the HHC pitch motion have been compensated (inertial effects removed) by proper calibration. In general increased vibration levels are seen at reduced BVI noise control settings and lower levels when mid-frequency noise is increased. This is quite consistent with the findings in Refs [14, 16, 17]. The larger the HHC amplitude the higher are the vibration levels. However, for 3P pitch control a number of control settings are found for simultaneous noise and vibration reduction (see parts (a, g and p)). Also, the absolute vibration levels do not appear prohibitive in this low speed descent flight regime, where the application of HHC for noise reduction would be most effective. Furthermore, the mixed mode HHC may offer a possible solution of reducing BVI noise without increasing vibrations. As shown in Fig 11, for 3P pitch control a 3P and 5P HHC schedule at -1.4° amplitude (see wavelet of Fig 5) with minimum HHC pitch at Ψ = 0° a mid-frequency noise reduction of 4:5 dB is achieved at only 50% increased vibration level. A separate paper reporting on further investigations into the HHC effect on vibratory loads in the fixed and rotating frame at optimum noise reduction control is planned.

Variation of Flight Condition

Descent angle variation:

The isolated effect of descent angle change, or equivalently, variation of the tip-path plane angle on the mid-frequency, maximum advancing side BVI noise level and the effectiveness of HHC to reduce those levels were presented in Fig 12. Ψ was changed in increments of 0.5° and all other test conditions were held constant. Baseline case levels are compared with results of a specific and effective HHC pitch schedule of 4P/0.8°/180°Ph (Ψc = 0°). The baseline cases...
Variation of advance ratio:

As the advance ratio increases, the noise level decreases. At high advance ratios, the difference in noise level becomes negligible.

CONCLUSIONS

1. This model rotor wind tunnel study clearly demonstrates the benefit of HHC to reduce BVI impulsive noise over the range of descent conditions where BVI noise is most intense. Highest mid-frequency noise reductions (locally more than 6 dB) are measured at low speed descent condition (similar to the noise certification landing approach). More limited or no noise benefit is seen for flight conditions outside the intensive BVI range.

2. The detailed acoustic in-flow measurements in the anechoic environment of the DNW
open test section reveal large changes of the BVI impulsive noise characteristics and noise directivity patterns with HHC variations (especially phase variations).

(3) Mid-frequency level contour plots show reductions of advancing side and retreating side BVI maximum noise levels of similar magnitude (about 6 dB) for specific HHC pitch schedules, however, at different HHC phase angles. The noise reductions correspond to the interaction locations in blade pitch at specified azimuth angle regions between 40° and 90° (adv. side BVI) and between 270° and 300° (retr. side BVI). 3P and 4P HHC modes are more effective than 5P. The largest reductions are obtained at the largest HHC amplitude (θ = -1.2°). Spatial averaged mid-frequency noise reduction (3-4 dB) is somewhat less due to noise directivity changes.

(4) The use of HHC produces increased low frequency loading noise, which however appears to be of minor concern when a subjective A-(or NDV)-weighted measure is considered. Also, vibrational loads increase, especially at HHC schedules most beneficial for BVI noise reduction. But the levels do not appear prohibitive in the low speed flight regime, where the use of HHC for noise reduction would be most effective. Finally, a number of control settings are found for simultaneous noise and vibration reduction.

(5) The mixed mode HHC wavelet approach tested does not significantly improve BVI noise reduction, however, may have a potential to combine both, BVI noise reduction and low vibration levels.

(6) Rotor simulation results (at 5° azimuthal resolution, Ref 14) give some evidence that BVI noise reduction is due to decreased blade loading in the azimuthal regions of the first and fourth quadrant (specified in (3)) where strong BVI is known to occur. Nothing definite can be said about the influence of vortex strength, since it is predicted to be partly increased and partly decreased. Blade-vortex displacements are definitely affected by HHC and evidently represent a dominant factor in the BVI noise reduction. A high resolution air load code (4° 1° azimuth) may provide a better insight into the occurrences.

(7) Individual blade control (IBC) is seen to be a highly desirable control capability, that could be used to tailor the blade pitch schedule to local azimuth ranges, such as regions where tip vortices are shed and where blade-vortex interactions occur, and thus to try to combine low vibrational loads with optimum noise reductions on the advancing and retreating side simultaneously.

(8) For effective noise reduction at variable descent flight conditions different HHC schedules are necessary, that suggest the use of an adaptive closed-loop control algorithm with the need for representative feed back signals from fuselage and/or blade mounted sensors.

(9) Non-intrusive local wake and blade position measurements (e.g. use of LDV) are strongly recommended in order to determine both, the blade-vortex displacements generated by HHC and the tip vortex strengths during BVI. Finally, blade surface pressure measurements would make-up the set of information necessary to improve the understanding and modelling of the effect of HHC on BVI noise generation and reduction.

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REFERENCES


