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Sensitivity of Helicopter Blade-Vortex-Interaction Noise and Vibration to Interaction Parameters

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An externally imposed vortex is allowed to interact with a rotor, and the effect of variations in individual key blade-vortex-interaction (BVI) parameters on BVI noise and BVI-induced vibratory hub loading is numerically evaluated. The interaction parameters considered are as follows: 1) vortex strength, 2) vortex core radius, 3) blade-vortex miss-distance, 4) angle of interaction in the blade-shaft plane, 5) angle of interaction in the rotor disk plane (parallel vs oblique interactions), 6) spanwise location of the interaction, 7) spanwise length of the interaction, and 8) blade lift at the time of interaction. The results indicate that an increase in miss distance and interaction angle in the blade-shaft plane and a decrease in the interacting vortex strength are most influential in reducing BVI noise and BVI-induced vibratory hub loading. BVI noise and vibratory hub loading were found to be more sensitive to changes in blade-shaft plane interaction angles than disk plane interaction angles, suggesting that introduction of a modest amount of anhedral/dihedral might be more advantageous than introducing comparable amounts of sweep in the outboard regions of the blade. It is also suggested that vibration reductions obtained for the minimum vibration schedule in the HART test result from an increased interaction angle between the blade and vortex in the blade-shaft plane and have little to do with reduced miss distances.

Introduction

IT is well documented that rotorcraft are susceptible to blade-vortex interaction (BVI) in low-speed descent. This occurs when the strong tip vortices dominating the rotor wake strike, or pass in close proximity of, the rotor blades—resulting in impulsive changes in blade loading that produce high noise and vibration. The high BVI noise generated during approach for landing has resulted in strong resistance to the widespread operation of helicopters in densely populated areas. In addition to BVI noise making public acceptance of rotorcraft more difficult, the BVI-induced vibratory loads increase pilot workload, reduce component fatigue life, and increase maintenance costs. Within the past several decades, considerable effort in the rotorcraft community has been devoted toward examining a variety of approaches for the alleviation of BVI. These approaches, which have included passive design concepts (such as advanced tip configurations, trailing-edge spoilers, etc.), active control concepts (such as higher harmonic control and individual blade control), and operational methods, have been summarized in a comprehensive survey article by Yu.[1]

Many numerical studies and wind-tunnel tests examining these methods have shown significant reduction in BVI noise and vibration. Some studies have even attributed the reductions to changes in specific aspects of the interaction, such as increase in blade-vortex miss distance,[2–5] or reduction in interacting vortex strength.[5,6] In many BVI alleviation concepts, a combination of the preceding two factors, as well as others such as change in spanwise location and extent of the blade-vortex interaction and change in the blade-vortex interaction angle (BVI more or less parallel), is present, and it is not clearly evident which of these factors is dominant.

In contrast to examining the effectiveness of various noise-reduction methods (such as active rotor control, passive design, etc.), other researchers have focused on assessing the dependence of the radiated BVI noise levels on the various blade-vortex interaction parameters (for example, see Refs. 7–9). Hardin and Lamkin[7] suggested that BVI noise can be reduced by reducing vortex strength, blade lift, and interaction length, and increasing blade-vortex miss distance. The study was conducted using a simplified version of the low-frequency Green's function approach for aerodynamic noise generation. However, the relative merits of modification of these parameters were not rigorously addressed, and no computations were performed for a real rotor. In 1994 Gallman[8] conducted a computational study of the potential noise reduction from changing certain blade-vortex interaction parameters (specifically, the hover-tip Mach number, blade-vortex miss distance, vortex core size, and obliqueness of interaction) caused by a vortex generated upstream of the rotor disk. In principle, using an externally generated or imposed vortex instead of a self-generated vortex can conveniently allow the variation of a single blade-vortex interaction parameter, without simultaneously influencing other interaction parameters, and consequently allow an examination of the effect of this single interaction parameter on BVI noise and BVI-induced vibratory loading. In Ref. 8, however, when the position of the fixed-wing generating the vortex was moved, the blade-vortex interaction angle in the disk plane as well as the radial location of the interaction simultaneously changed (see Fig. 1). A similar experimental study was conducted in the NASA Ames 80- by 120-foot wind tunnel by Kitaplioglu et al.,[9] where an externally generated vortex was allowed to interact with a nonthrusting two-bladed rotor (to minimize the influence of the rotor's own wake), and the influence of parameters such as vortex-rotor separation distance, vortex strength, and vortex sense (swirl direction) were examined. Although the studies just noted have made an attempt to understand the influence of some of the interaction parameters on BVI noise, there are other important parameters that have not been considered. Further, there is virtually no work focusing on the effects of the blade-vortex interaction parameters on BVI-induced vibratory hub loading.

Focus of the Present Study

The focus of this study is to present a comprehensive analysis of the sensitivity of helicopter BVI noise and BVI-induced vibratory loading to individual changes in the various blade-vortex interaction

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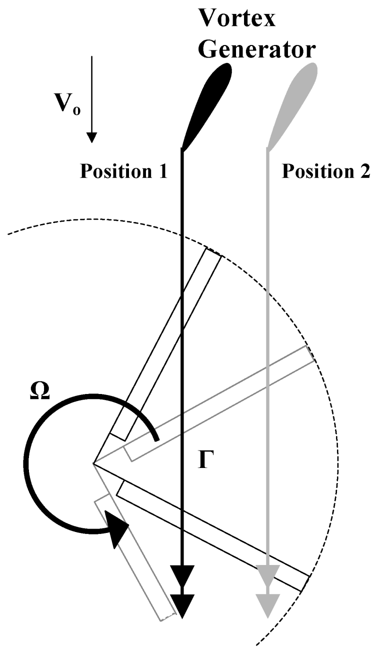


Fig. 1 Blade-vortex interaction studies with an externally generated vortex from Gallman.[8]

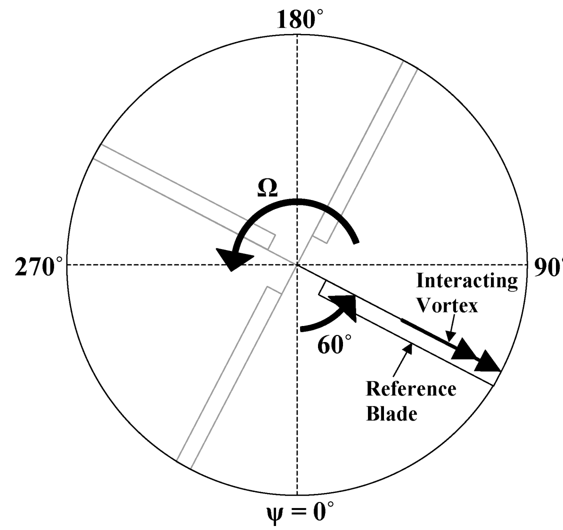


Fig. 2 Baseline blade-vortex interaction geometry.

parameters. The interaction parameters considered are 1) strength of the interacting vortex, 2) vortex core radius, 3) blade-vortex miss distance, 4) angle of interaction in the blade-shaft plane, 5) angle of interaction in the rotor disk plane, 6) spanwise or radial location of the interaction, 7) spanwise length of interaction, and 8) blade lift at the time of interaction. The comprehensive set of results allows a direct comparison of the reductions in BVI noise and BVI-induced vibratory loading achievable by effecting changes in the various blade-vortex interaction parameters, vis-à-vis the effort (the magnitude of change in the parameter) that is required. This, in turn, enables helicopter engineers to make better decisions in terms of which active, passive, or operational strategies they should select and which interaction parameters they should target for manipulation for the most effective alleviation of BVI noise and BVI-induced vibration. For example, with an understanding of the relative influence of change in vortex core size, vortex strength, and blade-vortex miss distance on BVI noise, a decision could be made whether blade-tip design (to increase vortex core size), active rotor control (to decrease vortex strength or increase blade-vortex miss distance), or change in flight path (to increase blade-vortex miss distance) is the most suitable approach for BVI alleviation.

Analysis Method

Numerical results in the present study are nominally based on a model rotor previously examined at NASA Langley Research Center.[10] The four-bladed rotor considered has a 2.856 m diam, a 9.1-cm chord, and a 217.11-m/s tip speed. The present simulations assume a NACA 0012 symmetric airfoil and zero blade twist. The rotor shaft is held vertical, and both the forward velocity and collective pitch are set to zero. The rotating blades are then allowed to interact with an imposed straight-line vortex at $\psi = 60$ deg (see Fig. 2). Although the choice of this azimuthal location is arbitrary for the present configuration (zero advance ratio, shaft tilt, and rotor thrust), strong blade-vortex interactions are known to occur around this region in typical low-speed descent conditions. Thus, simulating an interaction in this region produces a BVI noise "footprint" on an observer plane below the rotor that qualitatively resembles others commonly seen in the literature. As this rotor is nonlifting, it does not produce its own tip vortices, and the present approach of artificially imposing a vortex element makes it possible to vary the interaction parameters as desired and isolate the effects of the various parameters that govern BVI. A self-generated helicopter vortex-wake system, on the other hand, is highly complex, rendering it virtually impossible to quantify the effects of changes in individual blade-vortex interaction parameters. This has been recognized by other researchers as well and was the rationale behind their using an externally generated vortex to study variations in a few interaction parameters.[8,9]

The vortex element interacting with the rotor blade is assumed to have a viscous core of radius r_c, and following Refs. 11 and 12, the tangential velocity v_θ at a distance r from the center of the vortex is given by

$$v_\theta(r) = (\Gamma/2\pi)\left(r\Big/\sqrt{r_c^4 + r^4}\right)$$

Here, Γ is the strength of the vorticity. The vortex core radius r_c is assumed to be 20% of the blade chord, unless otherwise stated. Based on the preceding viscous core/vortex velocity profile model, the inflow at the rotor caused by the interacting vortex is calculated. Blade-element theory is then used to predict the lift on the blade as it traverses around the azimuth. The lift over an individual blade is integrated along the spanwise direction to obtain the blade-root vertical load. Summing the root loads over all of the blades as the rotor undergoes one revolution yields the BVI-induced hub vertical vibratory loading. The lift data are also input into the acoustic code WOPWOP[13] to obtain acoustic pressure time histories at several grid points or "observer locations" on a plane one rotor diameter below the disk. From the acoustic pressure-time histories, the BVI sound pressure level (BVISPL) is calculated by considering the 6th to the 40th harmonics of the blade passage frequency. The BVISPL plots yield the direction of the radiated BVI noise as well as the peak noise levels. Changes in BVI-induced vibratory loading and peak noise levels with changes in interaction parameters are then examined in detail.

To obtain the high-resolution BVI airloads, 640 azimuthal stations and 45 radial stations are used. It has been shown that such an azimuthal resolution of nearly half-degree step-size is adequate to accurately capture the impulsive BVI event.[14] Also, for high-aspect-ratio blades in the absence of shock, lifting-line theory produces accurate predictions of far-field BVI noise.[15]

Results

Baseline

The baseline BVI event considered is at an azimuthal location of 60 deg with a vortex parallely intersecting the blade over the outer half of its length ($R/2$ to R, see Fig. 2) with zero miss distance, a vortex core radius of $r_c = 0.2$ chords, and a nondimensional vortex strength $\Gamma/(cV_{\text{tip}})$ of 0.101. This nondimensional vortex strength corresponds to a circulation of $\Gamma = 2$ m^2/s (in the HART program,[2] the strengths of the interacting vortices on the advancing and retreating side varied between 1.1–2.8 m^2/s). The nominal values of the interaction parameters just given are used for all further cases, unless otherwise stated. Figure 3 illustrates the baseline nondimensional

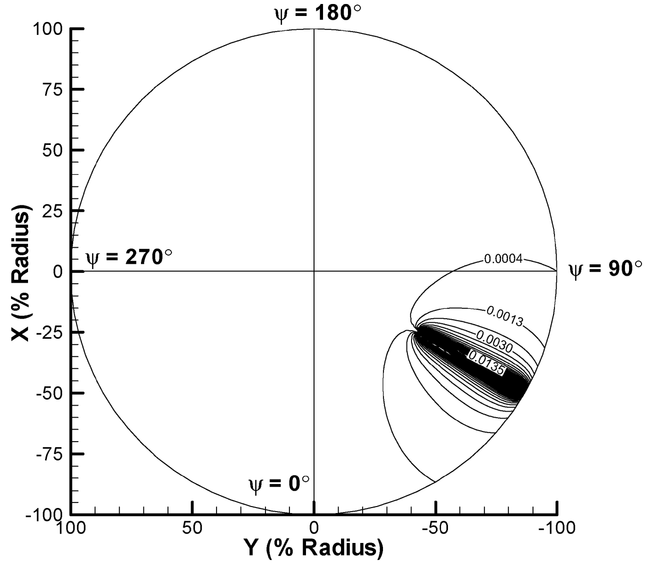


Fig. 3 Baseline nondimensional sectional lift distribution over the rotor disk.

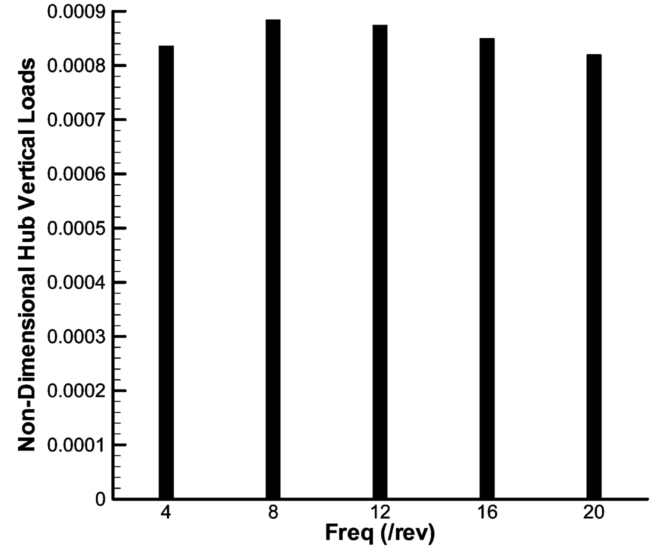


Fig. 5 Frequency spectrum of baseline BVI-induced hub vertical loads.

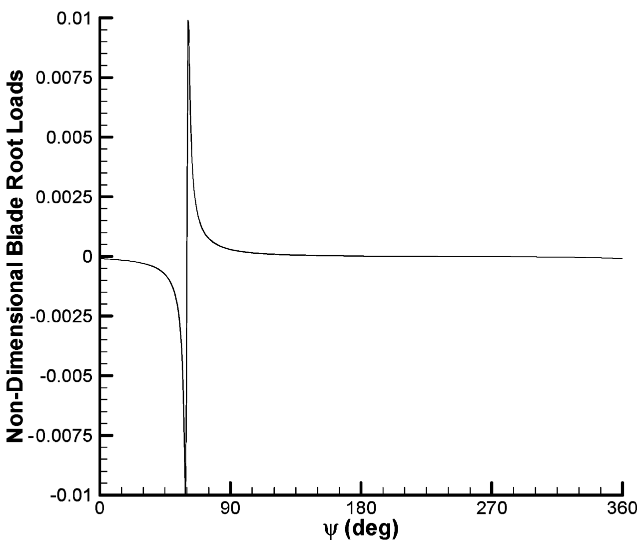


Fig. 4 Baseline blade-root loads vs azimuth [lift integrated along span, nondimensionalized by $\rho acR(\Omega R)^2$].

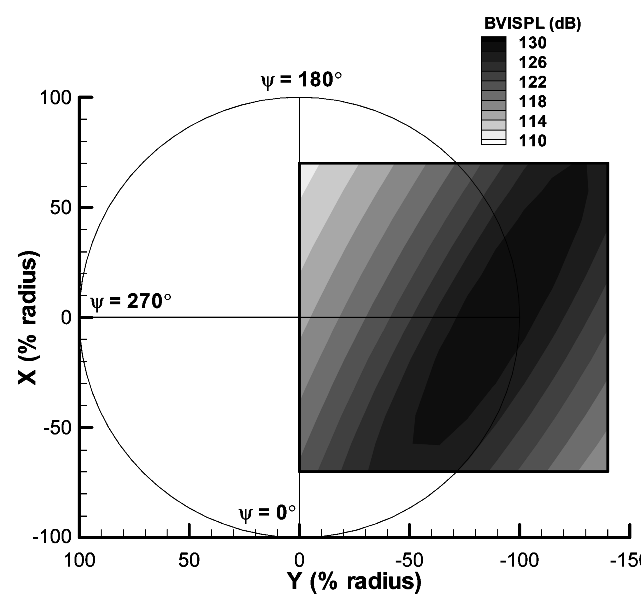


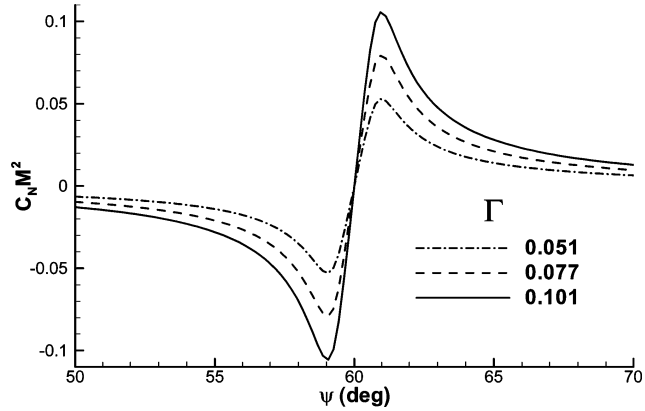
Fig. 6 Baseline BVISPL footprint one diameter below the rotor disk plane.

sectional lift distribution over the rotor disk [nondimensionalized by $\rho ac(\Omega R)^2$]. As the pitch of this uncambered untwisted blade is zero, and the change in inflow as the blade passes the vortex is the only contributor to the angle of attack, the lift distribution appears symmetric about $\psi = 60$ deg. It is also seen that the azimuthal gradients in lift ($\mathrm{d}L/\mathrm{d}\psi$) are largest near the interaction location, and rapidly reduce away from $\psi = 60$ deg. Because of the nature of the interaction, the vertical root loads (obtained by integration of the BVI-induced lift along the blade length) are highly impulsive, as seen in Fig. 4. As a consequence, the BVI-induced vibratory hub vertical loading, obtained by integrating the blade-root loads over the azimuth and summing over the number of blades, is observed to have a very strong higher harmonic content (Fig. 5). The vibratory hub vertical loads are nondimensionalized by the factor $\rho acR(\Omega R)^2$. In fact, the magnitude of the 8/rev component exceeds that of the 4/rev component. There are no steady (zeroth harmonic) loads as the blade generates no lift other than that caused by inflow from the imposed vortex.

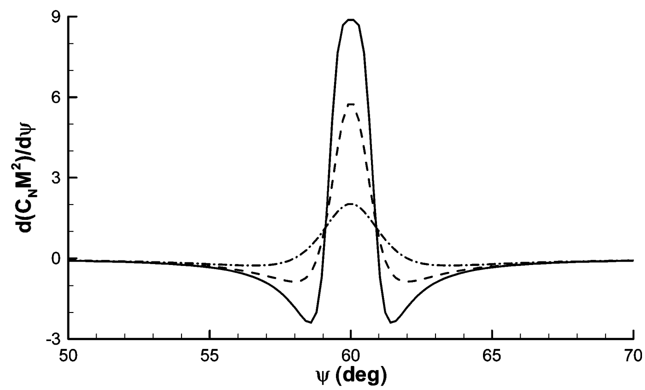
The BVISPL footprint is then examined on an observer plane one rotor diameter below the rotor disk to locate the maximum far-field BVI noise generated in this plane (Fig. 6). The baseline case produces a maximum of 129.5 dB of noise. Though this is significantly larger than normally experienced by a rotor in standard operating conditions, a perfectly parallel interaction occurring over the entire outer half of the blade length with zero miss distance represents an extremely severe BVI event (an idealization, and one of the worst scenarios conceivable).

Interacting Vortex Strength

In this section, variation in maximum BVI noise and the BVI-induced hub vibratory loading is examined as a function of the interacting vortex strength, Γ. The strength of the interacting vortex is one of the easier parameters to control, as it is directly related to the lift on the blade upstream at the time the interacting vortical elements are generated. (This would be over specific azimuthal ranges in the second quadrant of the rotor disk for parallel interactions occurring in the first quadrant). Figure 7 shows the variation of the normal-force coefficient $C_N M^2$ and its azimuthal derivative $\mathrm{d}C_N M^2/\mathrm{d}\psi$ at 75% radius for various nondimensional vortex strength values. It can be deduced that a change in the vortex strength does not affect the azimuthal range over which the effects of the interaction extend, or its fundamental nature, but predominantly results in a change in



a)



b)

Fig. 7 Azimuthal variation in: a) $C_N M^2$ and b) $d(C_N M^2)/d\psi$ at 75% radius spanwise station for different vortex strengths.

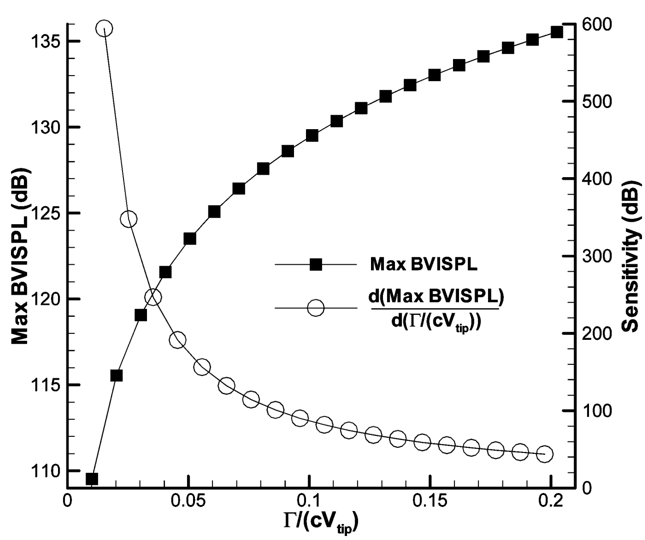


Fig. 8 Max BVISPL and sensitivity vs vortex strength.

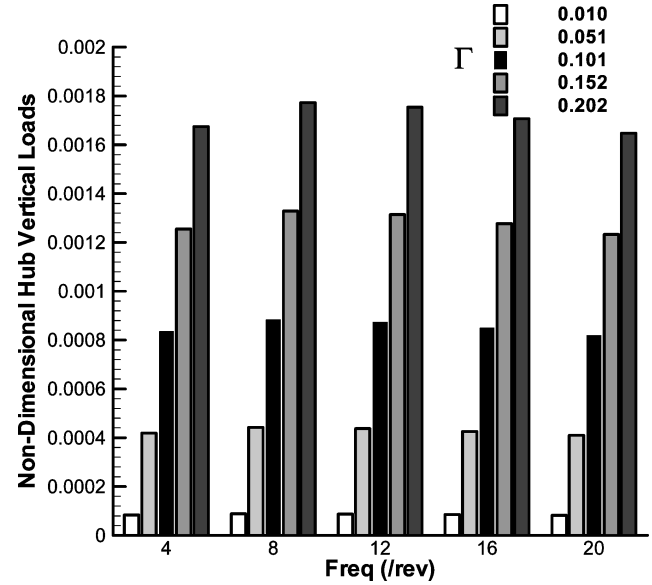


Fig. 9 Frequency spectrum of BVI-induced hub vertical loads for various vortex strengths.

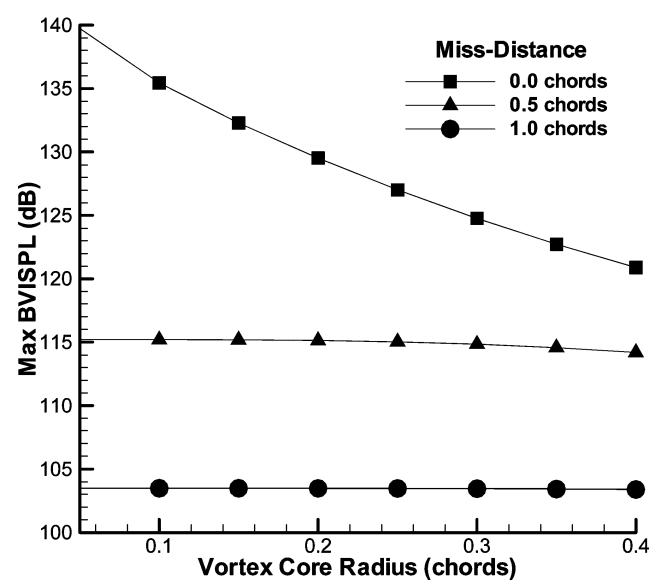


Fig. 10 Max BVISPL vs vortex core radius.

values of peak loading. The variation in peak far-field BVI noise, as a function of vortex strength, Γ, as well as the sensitivity of this noise variation, vs Γ is shown in Fig. 8. From the figure it is observed that the maximum BVI noise reduces with decreasing values of Γ, as expected. The peak noise levels are highly sensitive to changes in Γ when the baseline value of Γ is small, but are less sensitive to changes in Γ when the baseline value is larger. Thus, if the interacting vortex is stronger, much larger reductions in vortex strength Γ are required to produce comparable reductions in peak BVI noise.

Figure 9 shows the BVI-induced vibratory hub loading for several different values of vortex strength. It is observed that variations in Γ change the magnitude of the vibratory loading, but have no effect on the distribution over the different harmonics, as would be expected because only the magnitude of the lift distribution was changed. It is also evident that the magnitude of the loading (at any harmonic) varies linearly with Γ, so that reducing the value of Γ by one-half reduces the BVI-induced vibratory hub loading to one-half of the baseline amplitude.

Vortex Core Radius

A small vortex core radius (tight core) implies higher peak velocities in the vortex, which produces more impulsive changes in blade loading and higher noise intensity when the vortex passes in close proximity to the blade. Variation in peak BVI noise level as a function of vortex core radius is presented in Fig. 10. It is observed that the noise decreases almost linearly with increasing core radius, provided the miss distance between the blade and vortex is small. For larger values of miss distance (typically larger than the vortex core radius), the peak BVI noise levels are insensitive to vortex core size.

Effects of variation in vortex core radius on the BVI-induced hub vibratory loading levels are shown in Fig. 11 for a zero blade-vortex miss distance. It is observed that for a very small core size the

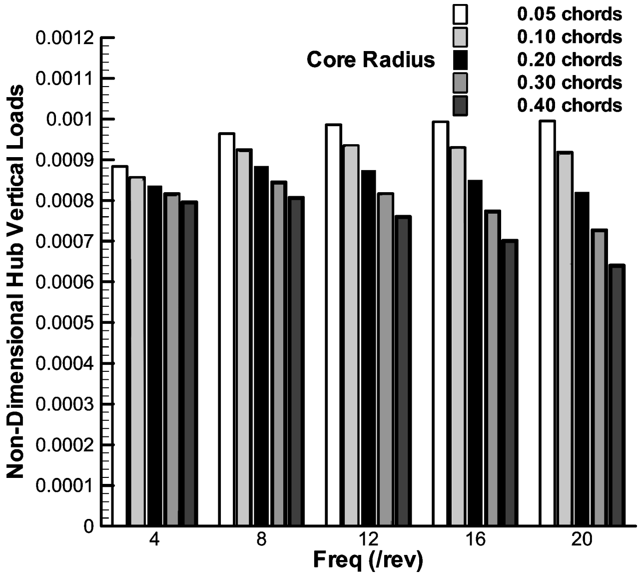


Fig. 11 Frequency spectrum of BVI-induced hub vertical loads for various core radii.

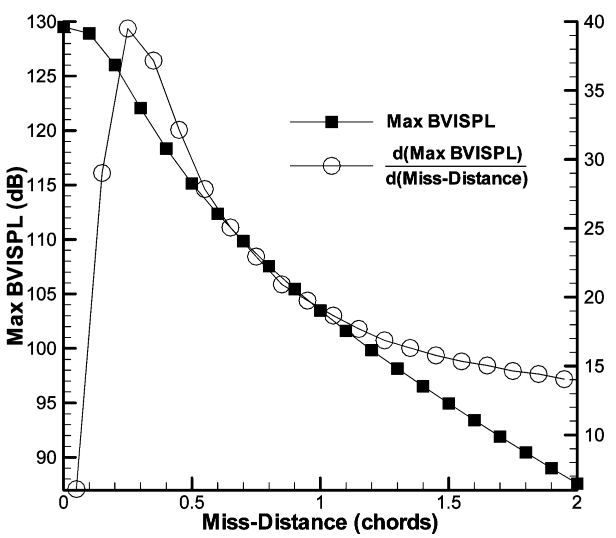


Fig. 12 Max BVISPL and sensitivity vs miss distance.

extremely impulsive nature of the interaction produces hub vibratory loads that have very large higher harmonic content. In fact, for a core radius of 0.05 chords the amplitudes of the harmonics increase from 4/rev up through 20/rev. In general, increasing core radii result in reductions in vibratory load levels, with the reductions being more significant in the higher harmonics.

Blade-Vortex Miss Distance

One of the most important blade-vortex interaction parameters is the separation between the vortex and the rotor blade in the blade-rotor-shaft plane. This is referred to as the miss distance (for example, see Ref. 14). Figure 12 shows the variation in peak far-field BVI noise, as well as the sensitivity of this variation, as a function of the miss distance. It is observed that when the miss distance increases from zero (vortex passing right through the blade) to a value of half a chord, a 14.4-dB reduction in BVI noise is obtained. From the sensitivity curve in Fig. 12, it is observed that except at very small values of miss distance (less than the vortex core radius), the sensitivity of BVI noise to changes in miss distance reduces for increasing miss distances, with low sensitivity beyond a miss distance of one chord. On the other hand, for miss distances smaller than the vortex core radius the sensitivity (change in BVISPL for small perturbation in miss distance) is again small. This implies that as long as the vortex core is intersecting the blade, changes in the separation between

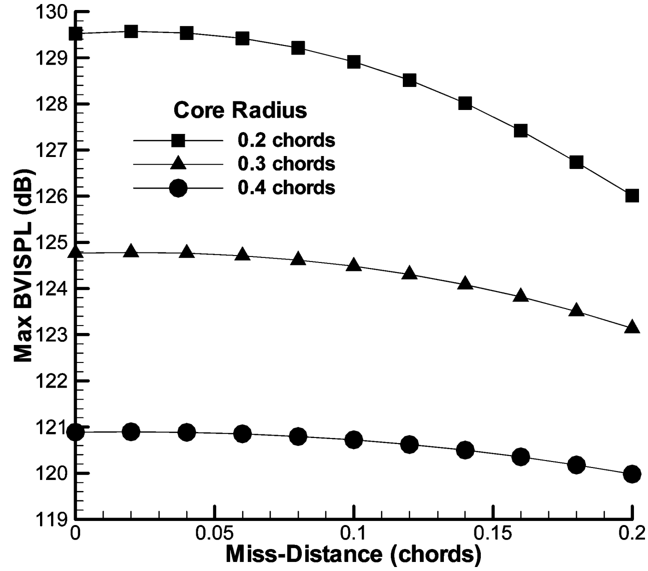


Fig. 13 Max BVISPL vs miss distance (small values of miss distance).

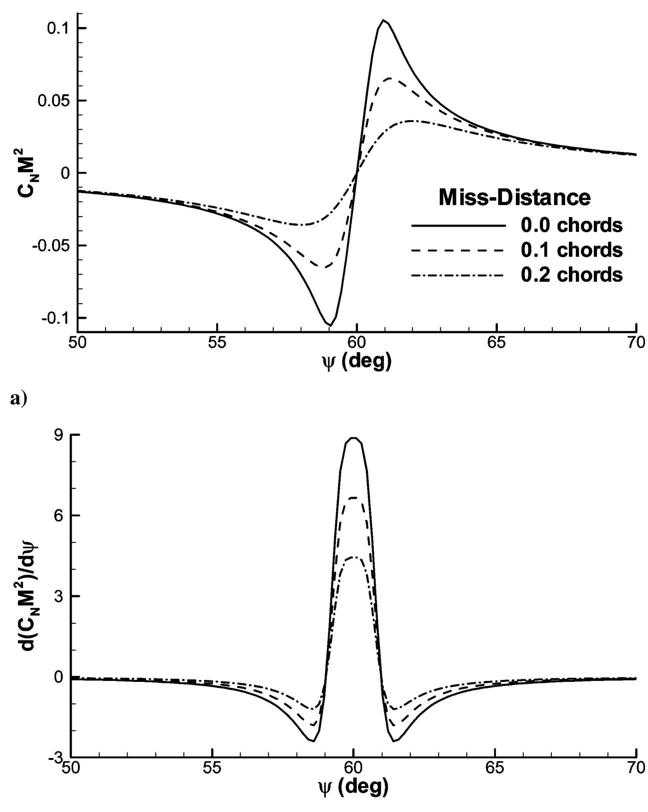


Fig. 14 Azimuthal variation in: a) C_NM^2 and b) d(C_NM^2)/dψ at 75% radius spanwise station for different blade-vortex miss distances.

the vortex center and the blade have only a small influence on BVI noise. In Fig. 13 the variations in BVI noise for small values of miss distance are examined in greater detail. It is again evident that when the vortex core sizes are larger (see the 0.4 chords curve) and the initial miss distances are small modest changes in the miss distance have little impact on BVI noise levels. However, for smaller vortex core sizes (see the 0.2 chords curve) the blade quickly comes out of the vortex core for similar modest increases in miss distance, producing reductions in BVI noise.

Figure 14 shows the variation of the normal-force coefficient C_NM^2 and it azimuthal derivative $dC_NM^2/\mathrm{d}\psi$ at 75% radius, for various blade-vortex miss-distance values. As the miss distance decreases, the peak loading levels increase while the azimuthal interval

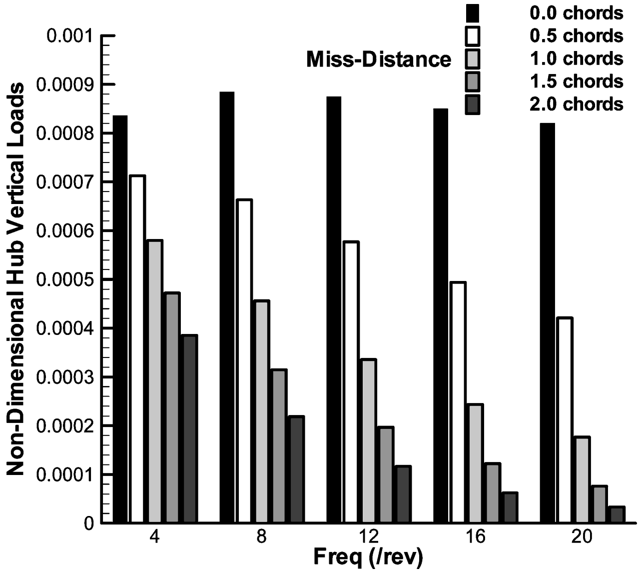


Fig. 15 Frequency spectrum of BVI-induced hub vertical loads for various blade-vortex miss distances.

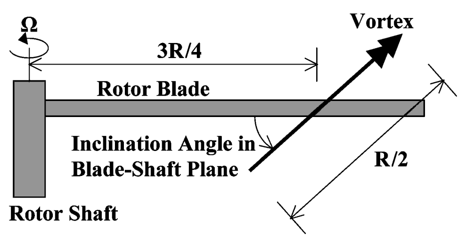


Fig. 16 Vortex interacting with the blade at an angle in the blade-shaft plane.

between the negative and positive peaks are appear to be unaffected, resulting in a more impulsive loading. Figure 15 shows the impact of variations in miss distance on the BVI-induced vibratory hub loads. It is observed that for small miss distances (producing more impulsive sectional loads and blade-root loads) a relatively large portion of the hub vibration energy is in the higher harmonics. As the miss distance increases (and the loads become less impulsive, see Fig. 14), the total hub vibration energy decreases in all the harmonics, with the greatest reductions seen in the higher harmonics.

Blade-Shaft Plane Interaction Angle

For the results presented in the preceding sections, the interacting vortex was contained in the rotor disk plane (zero miss distance) or in a plane parallel to the disk plane (nonzero, but constant miss distance over the blade-vortex interaction length). In this section, the effect of the vortex interacting with the blade at some nonzero inclination angle in the blade-shaft plane is examined, as depicted in Fig. 16 (vortex length is $R/2$ and intersects the blade at a radial location of $3R/4$). The term miss distance, as used in the literature, has little meaning when the vortex is inclined in the blade-shaft plane relative to the blade because the vertical distance between a point on the vortex and the corresponding radial station on the blade will clearly vary with radial position. Figure 17 shows that significant reductions in BVI noise are obtained as the vortex tilts relative to the blade in the blade-shaft plane. For a relative inclination of as little as 10 deg, a significant reduction in peak noise of 7.1 dB is realized. The inclination of the vortex in the blade-shaft plane reduces the BVI noise, as it effectively reduces the interaction length, with regions of the vortex further away from the blade contributing little to the impulsive loads. Also of note is that noise reductions are independent of the sign of the angle in the blade-shaft plane.

Figure 18 shows the BVI-induced vibratory hub loading for various blade-vortex interaction angles in the blade-shaft plane. For a zero relative inclination angle between the blade and the vortex in the

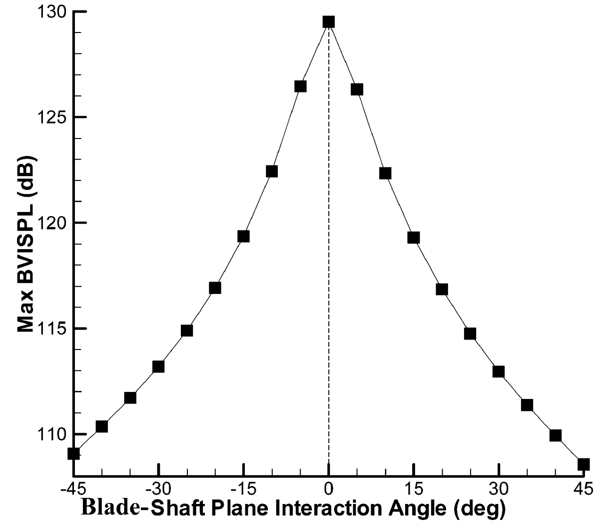


Fig. 17 Max BVISPL vs blade-shaft plane interaction angle.

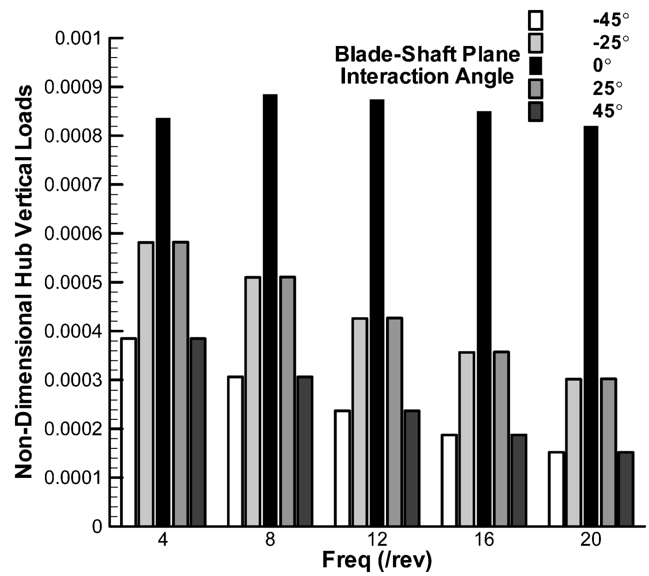


Fig. 18 Frequency spectrum of BVI-induced hub vertical loads for various blade-shaft plane interaction angles.

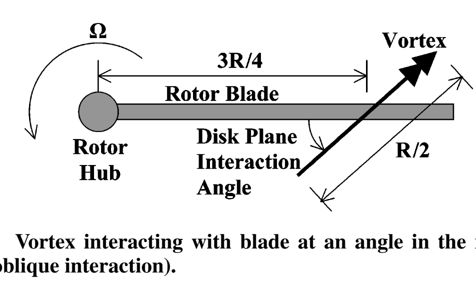
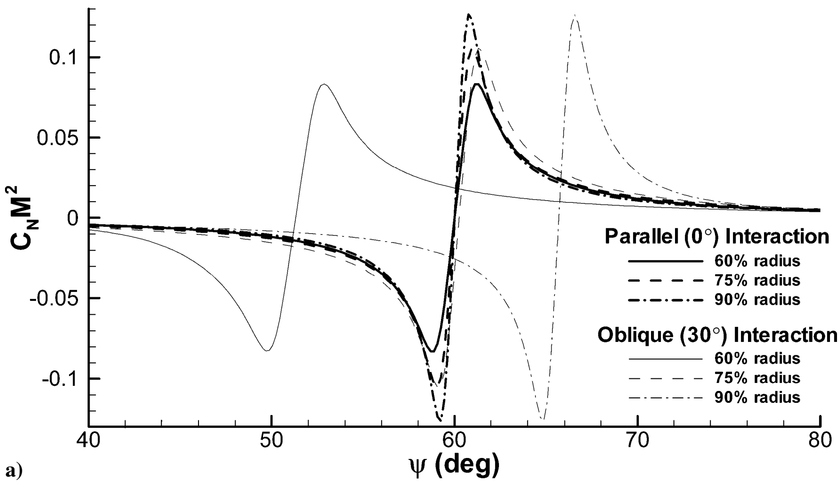


Fig. 19 Vortex interacting with blade at an angle in the rotor disk plane (oblique interaction).

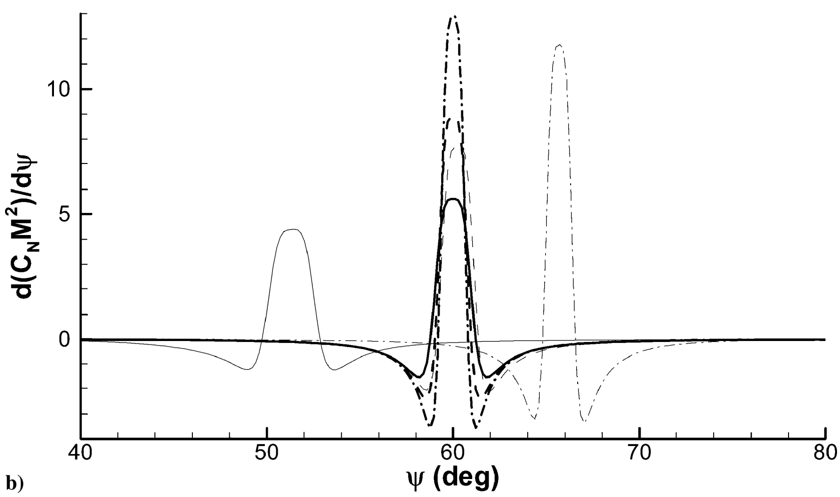
blade-shaft plane (a perfectly parallel interaction), the interaction is very impulsive. Thus, the vibratory loading levels are the highest, and there is a large amount of energy in the higher harmonics. For higher blade-shaft plane interaction angles (increasing vortex tilt relative to the blade in the blade-shaft plane) the effective interaction length is reduced, and the interaction is less impulsive. Thus, the BVI-induced total hub vibration energy (in all harmonics) decreases, with the largest reductions observed in the higher harmonics.

Rotor Disk Plane Interaction Angle

For the results considered so far, the blade-vortex interaction was always perfectly parallel in the rotor disk plane at $\psi = 60$ deg. In this section, the effect of varying the interaction angle between the vortex and the blade in this plane is examined. As seen in Fig. 19,



a)



b)

Fig. 20 Azimuthal variation in: a) $C_N M^2$ and b) $d(C_N M^2)/d\psi$ for different rotor disk plane interaction angles (parallel and oblique interaction).

the vortex of length $R/2$ (from midspan to the blade tip) is rotated in the disk plane about the $3R/4$ point to produce less parallel (more oblique) interactions (the miss distance is set at zero). This causes the blade to interact with the vortex over a longer azimuthal duration. Figure 20 shows $C_N M^2$ and its derivative vs ψ at three different spanwise stations. For a parallel interaction the peaks at the different spanwise stations occur at the same azimuthal location. For an oblique interaction, however, the peaks at the three spanwise stations occur at different azimuthal locations. Because oblique interactions do not focus noise as effectively as parallel interactions,[16,17] the BVI noise is expected to decrease as well. Figure 21 shows the reductions in noise obtained for increasingly oblique interactions. Unlike the inclination of the vortex in the blade-shaft plane, positive and negative angles in the disk plane produce different effects. This is not entirely unexpected because BVI noise is known to be dependent on the type of interaction,[16,17] and positive angles in the disk plane produce a different interaction (moving from inboard to outboard locations along the blade span) from that seen with negative angles (interaction moves inboard from the blade tip). From Fig. 21 it is observed that for small angles between the vortex and blade (less than 10 deg) relatively modest noise reductions are obtained. However, if the interaction becomes more oblique so that the angles between the vortex and blade are in the ±20–25 deg range, then significant reductions in peak BVI noise levels (of over 10 dB) can be obtained.

An increase in the angle between the blade and the interacting vortex in the disk plane could be achieved by sweeping the outboard regions of the blade (either forward or backward). Introduction of a backward blade sweep would produce a positive angle between blade and vortex (for a vortex that would have struck the unswept blade in a parallel manner). Conversely, introduction of a forward blade sweep would produce a negative angle. Figure 21 suggests that if only small sweep angles of 10 deg or less were being considered, a forward sweep (resulting in a negative angle between blade and vortex) would be more beneficial than backward sweep for BVI noise reduction. However, if larger sweep angles (15–25 deg) were permissible, a rearward sweep (resulting in a positive angle between blade and vortex) would produce greater reductions in BVI noise. Other factors, though, such as performance in high-speed flight and aeroelastic stability can play an important role in determining the magnitude and direction of the tip sweep.

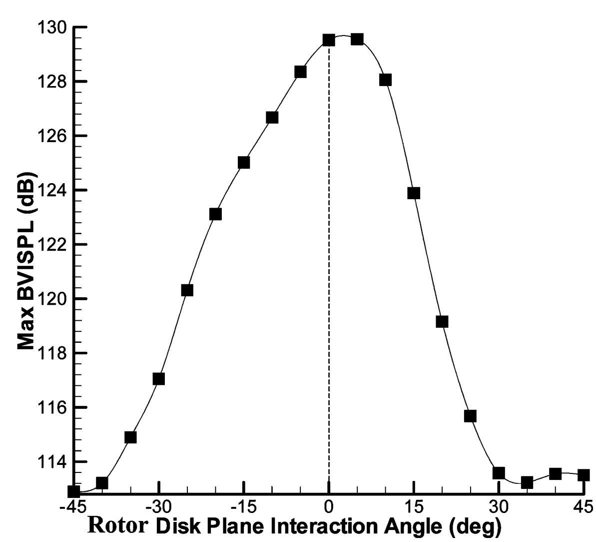


Fig. 21 Max BVISPL vs rotor disk plane interaction angle.

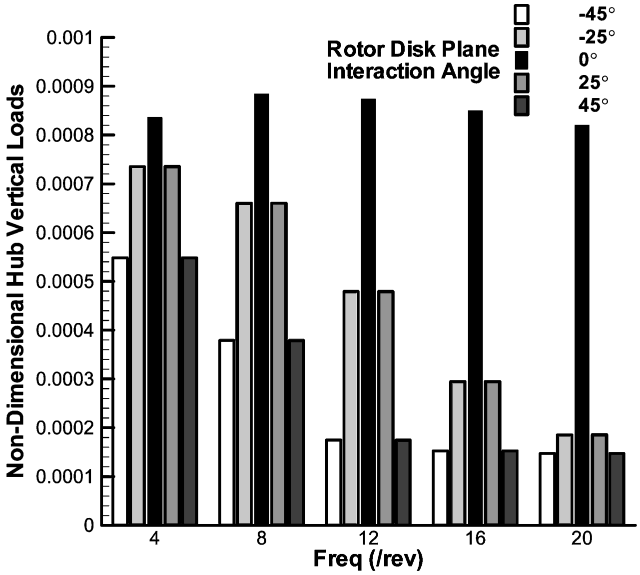


Fig. 22 Frequency spectrum of BVI-induced hub vertical loads for various rotor disk plane interaction angles.

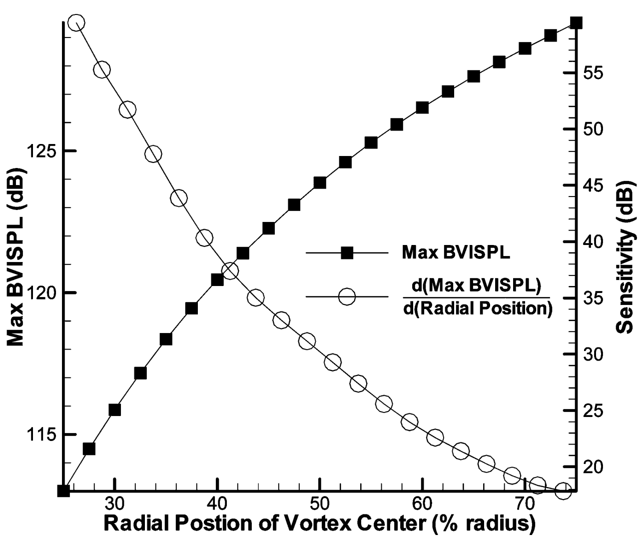


Fig. 23 Max BVISPL and sensitivity vs spanwise location of center of interacting vortex.

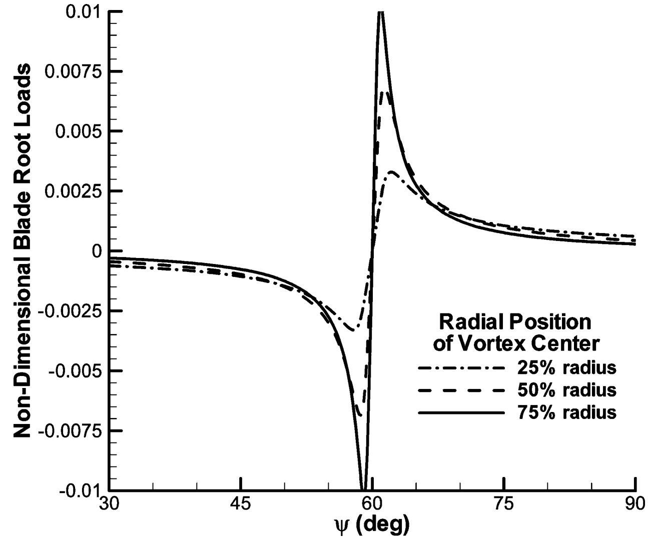


Fig. 24 Blade-root loads vs azimuth for various spanwise locations of center of interacting vortex.

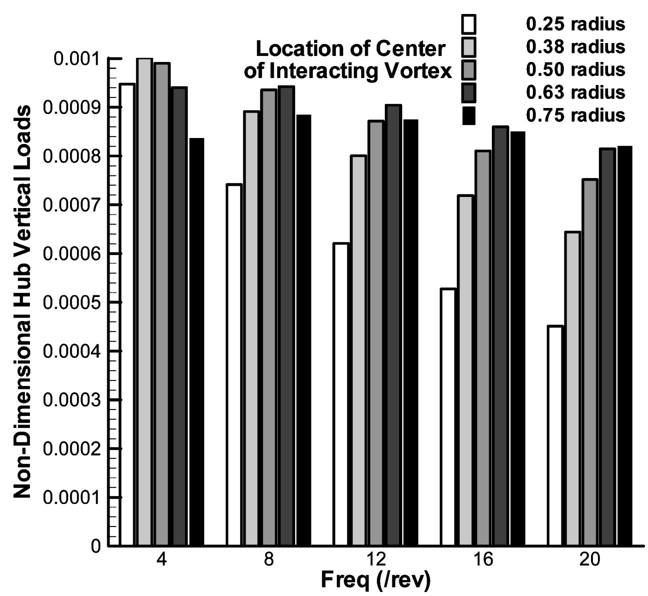


Fig. 25 Frequency spectrum of BVI-induced hub vertical loads for various spanwise locations of center of interacting vortex.

Figure 22 shows the BVI-induced vibratory hub load levels for different interaction angles in the rotor disk plane. Clearly, perfectly parallel interactions occur over very short time durations, are highly impulsive, and produce vibratory hub loadings that are of the largest magnitudes and have a significant amount of energy in the higher harmonics. As the interaction becomes more oblique (occurs over a longer azimuthal interval and is less impulsive), the BVI-induced vibratory hub load levels reduce in magnitude, and the higher harmonic components decrease in prominence.

Spanwise Location of the Interaction

The influence of the radial location of the BVI event on the noise and vibration levels is examined next. For the simulations in this section, angles of the interaction in the blade-shaft and rotor disk planes are again zero, as is the blade-vortex miss distance. The vortex of length $R/2$ was moved in increments along the blade span, from the rotor hub to the blade tip (so that the vortex center traversed from a radial location of $R/4$ to $3R/4$). In Fig. 20b it was already seen that for a parallel interaction in the rotor disk plane, the blade sectional loading at outboard stations is more impulsive in nature, relative to the loading at inboard spanwise stations. Correspondingly, it is observed in Fig. 23 that the peak BVI noise increases as the center of the interacting vortex moves outboard. It is also seen from the figure that the sensitivity of BVI noise to changes in interaction location is greater for inboard rather than outboard interactions. Thus, if a BVI event occurring in the outboard portion of the blade moves slightly inboard, the noise reductions are smaller than those obtained when a BVI event occurring in the inboard portion moved further inboard by a comparable amount.

Figure 24 shows the impulsive blade root loads caused by the blade-vortex interaction occurring at different locations along the span. It is observed that for the inboard interactions the magnitude of the impulsive load is lower, as a result of the lower tangential velocities and the longer duration of interaction. Conversely, the outboard interactions produce very high-intensity impulsive changes in blade-root loads, and these result in significant higher harmonic content in the BVI-induced vibratory hub loading (see Fig. 25). For midspan and inboard interactions, which produce less impulsive blade-root loads, a larger percentage of the vibration energy is in the lower harmonics. In fact, midspan interactions actually produce a larger 4/rev component of BVI-induced vibratory hub loading than do the outboard interactions.

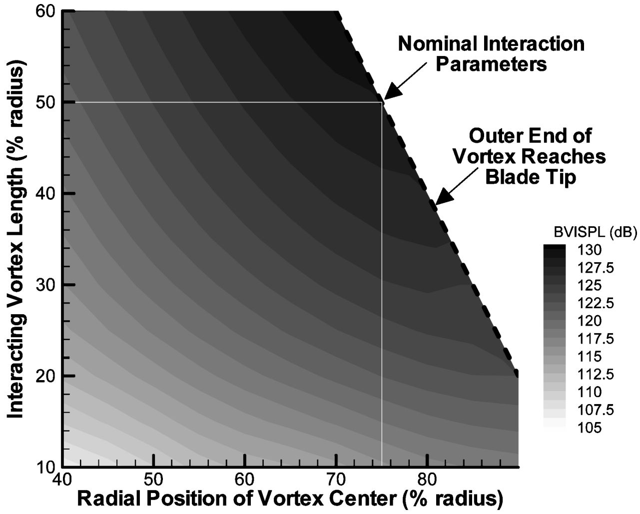


Fig. 26 Max BVISPL vs spanwise location of center of interacting vortex and length of interaction.

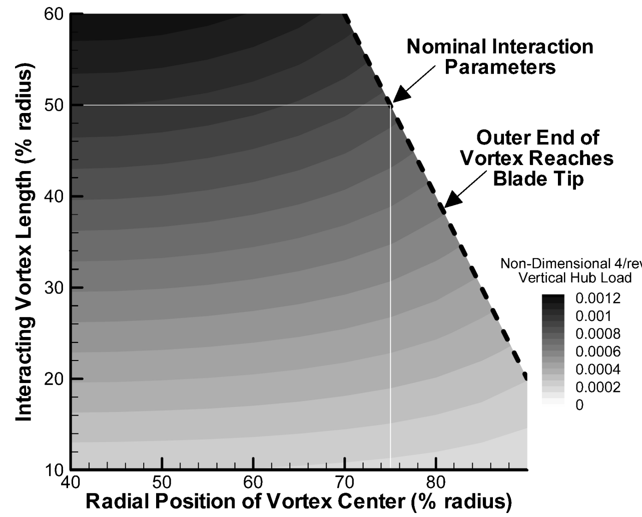


Fig. 27a Nondimensional 4/rev BVI-induced vertical hub loads vs spanwise location of center of interacting vortex and length of interaction.

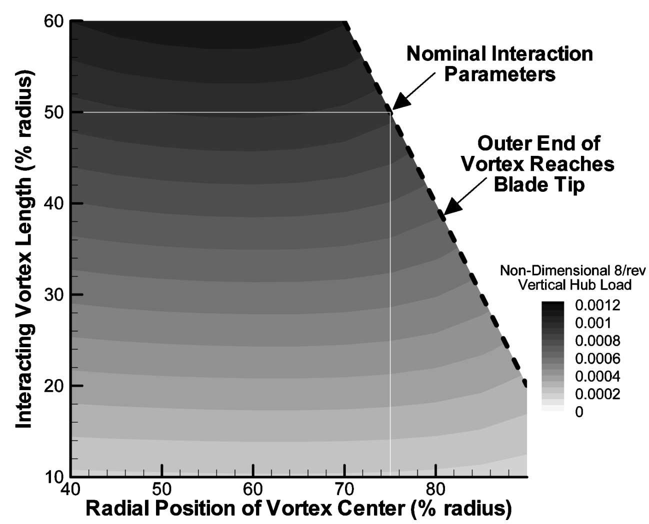


Fig. 27b Nondimensional 8/rev BVI-induced vertical hub loads vs spanwise location of center of interacting vortex and length of interaction.

Spanwise Length of the Interaction

The spanwise length of the interaction is intrinsically tied to the spanwise location of the interaction. When the vortex length is reduced, which portion of the blade is no longer affected by the vortex is as important as how much less of the blade span is affected, in terms of changes to the BVI noise and vibration results. Figure 26 illustrates the change in maximum BVI noise levels with simultaneous variations in these two parameters. If the vortex center is held fixed and its length progressively decreased (moving down lines parallel to the y axis), which is tantamount to reducing the blade area affected by the interacting vortex at the fringes of the vortex, BVI noise levels are seen to reduce. The reductions in noise are qualitatively similar to those seen in Fig. 17, for increasing inclinations of the vortex in the blade-shaft plane. This is to be expected because increasing the inclination in the blade-shaft plane has the effect of reducing the length of the blade affected by the vortex (spanwise length of the interaction), with the fringes of the vortex having reduced contributions. The largest reductions in noise are obtained when the vortex length is reduced and the vortex center is simultaneously moved inboard. This has the net effect of reducing the interaction of the blade with the vortex in the outboard locations, which produce more impulsive sectional loads (Fig. 20b).

Figures 27a and 27b, respectively, show the variation in BVI-induced 4/rev and 8/rev vertical hub loads for variations in the spanwise length of interacting vortex, as well as the spanwise location of the center of the vortex. The vertical hub loads are far more sensitive to changes in length of the interaction than to changes in the spanwise location. Though a reduction in the length of the interaction reduces both 4/rev and 8/rev vibratory loads, it is seen that an inboard motion of the vortex actually increases the 4/rev component and can either increase or decrease the 8/rev component, depending on the length of the interaction. The large reductions in loads observed for reductions in interacting vortex length echo the reductions seen with increase in blade-shaft plane interaction angles (Fig. 18).

Rotor Collective Pitch

All of the preceding results examining the influence of various BVI parameters on BVI noise and BVI-induced vibratory hub loads were obtained for a nonlifting rotor. In the present section the influence of collective pitch (or rotor thrust) variation is examined. A perfectly parallel interaction extending from $R/2$ to R, with zero miss distance, is once again considered. Using hybrid blade-element/momentum theory, an equivalent inflow through the disk is calculated for different values of collective pitch. (Inflow is assumed to be uniform around the azimuth, and a self-generated wake comprising trailing vortices and tip vortices is not considered). Thus, the lift produced on any blade section (at a given radial station) is caused by the resultant angle of attack from the nonzero collective pitch, minus the total inflow angle (comprising a downwash as a result of the lifting rotor and the impulsive change in inflow as a result of the interacting vortex).

Figure 28 shows azimuthal variation in blade lift at $0.76R$ for different values of blade collective pitch setting. It is seen that the total lift increases with blade pitch setting, but the impulsive variation, which produces the BVI noise, is unchanged. The solid line on the graph corresponds to a linear aerodynamic model, and the dashed line corresponds to a model that includes quasi-static stall effects. For the linear aerodynamic model, BVI noise is insensitive to the blade lift (or blade pitch angle). Although the total lift increases with increasing collective pitch values, for higher pitch settings the passage of the vortex caused the blade section angle of attack to exceed stall levels. When a static stall (table look-up) model is used, the impulsive change in lift is reduced, and this actually produces a reduction in BVI noise.

These results appear to contradict previous reports implying that increase in blade lift at the location of the BVI event increases noise and vice versa.[2,7] However, for the simulations in Fig. 28 the vortex was held fixed (as the blade traverses around the azimuth and interacts with it in the vicinity of $\psi = 60$ deg). When the interacting vortex is initially placed at the $\psi = 60$ deg azimuthal location, but

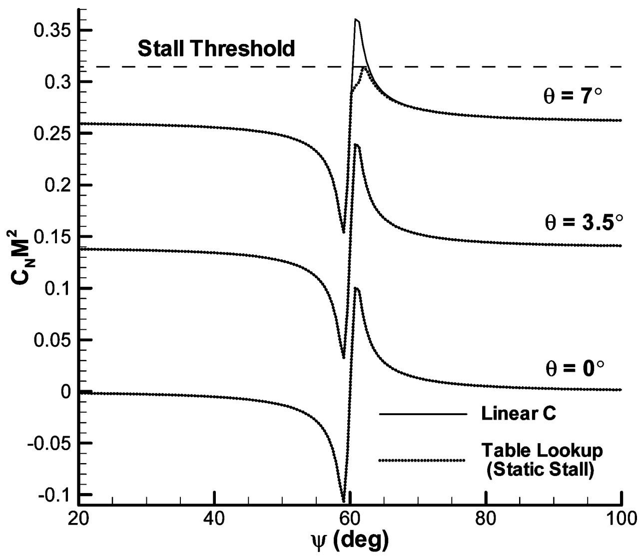


Fig. 28 Blade sectional lift at 75% radius for various collective pitch settings θ.

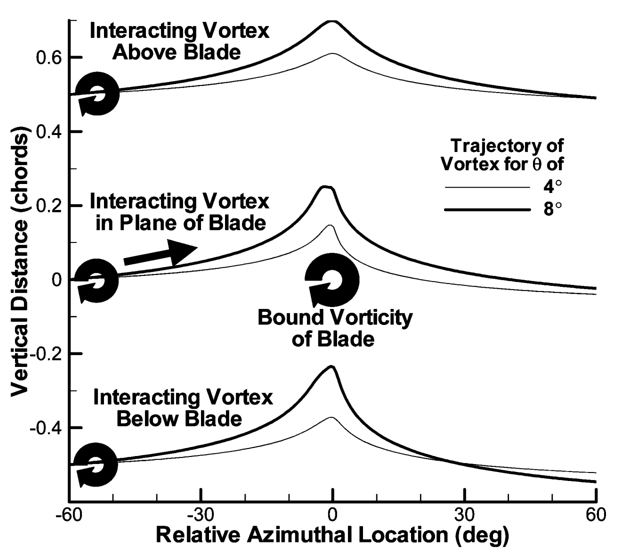


Fig. 29 Interacting vortex trajectories for different initial positions relative to blade and different blade pitch settings.

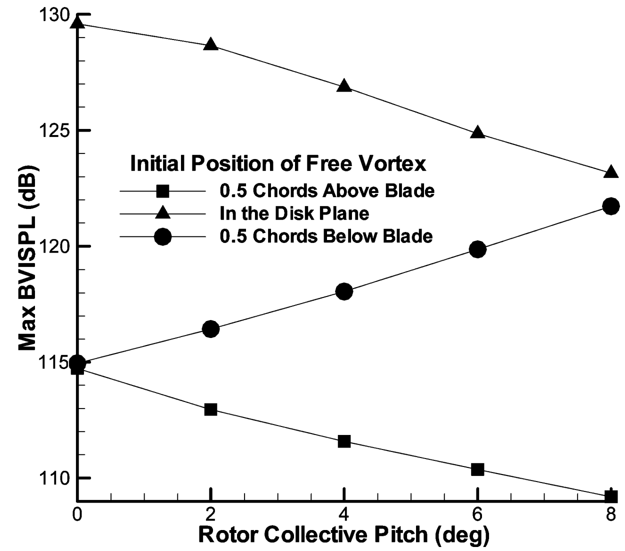


Fig. 30 Max BVISPL vs rotor collective pitch for different initial interacting vortex positions.

is then allowed to convect freely as the lifting blade passes close to it, the results obtained are different. Figure 29 shows the motion of the free vortex caused by the influence of the bound vorticity of the lifting blade. The motion is plotted in blade-fixed coordinates, and the interacting free vortex is shown moving over a range extending from 60 deg before the interaction to 60 deg after. It is seen that the bound vorticity of the blade convects the interacting vortex upward before, and downward after, the interaction. When the free vortex starts below the blade, this effectively decreases the miss distance. The larger the bound vorticity (the greater the blade pitch), the more pronounced is this effect. However, when the free vortex initially starts in the plane of the blade or above the miss distance at the time of interaction, caused by the bound vorticity on the blade, is increased. The results in Fig. 29 suggest that BVI noise can be reduced by locally changing the lift on the blade at the time of interaction through reducing the blade pitch, if the vortex is initially sailing below the blade, or increasing the blade pitch, if the vortex is initially in the disk plane or sailing above the blade. In either case, the resulting increase in the miss distance would be expected to be beneficial from a BVI noise-reduction standpoint. This is clearly seen in Fig. 30, which shows the variation in peak BVI noise with variation in blade pitch for three different initial positions of the interacting free vortex relative to the blade.

However, when a self-generated free wake was considered and local changes in blade pitch around the time of interaction were examined to reduce BVI noise, neither positive nor negative changes in pitch (of varying amplitudes) had much effect on the BVI noise (no results provided). This is because in addition to the bound vorticity (changing whose strength could in principle move the interacting free vortex as explained in the preceding paragraph), the trailed vorticity and the tip vortex of the interacting blade and the rest of the vorticity in the entire rotor wake also influence the movement of the interacting free vortex. For example, an increase in the strength of the bound vorticity (through local change in the blade pitch) would also produce a corresponding increase in the strength of the tip vortex. Although the stronger bound vorticity would tend to convect the free vortex upward, the stronger tip vortex would tend to convect the free vortex downward (inside of the rotor disk), thus negating in part the effect of the change in bound vorticity. Reference 18 has reported that changes in blade flap setting (for the purpose of changing blade lift) around the time of blade-vortex interaction had very little effect on changing the blade-vortex miss distance (the mechanism by which noise reductions would actually have been obtained). On the other hand, no evidence has been presented in the literature that reasonable changes in blade pitch (or lift) around the time of interaction can actually reduce BVI noise, though this idea is frequently suggested.

Comparison of Effect of Various Parameters on BVI-Induced Noise and Vibration

This section examines the comparative reductions in BVI-induced noise and vibratory loading achievable through "moderate" variations in the magnitude of the different interaction parameters considered earlier. The purpose is to compile information that would assist an engineer in deciding which of the parameters it would be most advantageous to attempt to manipulate (resulting in largest reductions in BVI noise and BVI-induced hub vibrations for relatively modest changes in the parameter).

A 50% increase in core radius from a baseline value of 0.2 to 0.3 chords produced a reduction in peak BVI noise of about 5 dB, but little reduction in 4/rev BVI-induced hub vibratory loads. If the spanwise location of the BVI event moved inboard from the tip by about 10% radius (vortex center moving from 75 to 65%), the reduction in BVI noise is less than 3 dB, and the BVI-induced 4/rev vibratory hub loads actually increased. A much larger inboard movement of about 25% radius (center moving from 75 to 50%) would be required to produce a substantial BVI noise reduction, of the order of 7 dB; and such a large spanwise movement of the BVI event might be difficult to achieve. Causing the BVI event to move to a more inboard location (to reduce noise) is unable to significantly reduce BVI-induced hub vibratory loading, and in many cases causes it to increase. A 10% change in the length of the interaction (from 50 to 45% radius) only reduces the BVI noise by 0.3 dB and the 4/rev hub load by about 10%. A full 50% reduction in length results in only about a 5-dB decrease in noise, though it reduces 4/rev vibration by almost 50%. The preceding interaction parameters (vortex core radius, spanwise location of the event, and spanwise length of the interaction) appear to have less effect in reducing BVI noise (for moderate changes in the magnitude of the parameter), compared to some of the other interaction parameters such as blade-vortex miss distance, vortex strength, and the interaction angles in the blade-shaft and the rotor disk planes. Further, they might not even be candidate parameters for change if simultaneous reduction of BVI noise and BVI-induced vibration is desired.

Compared to an interaction wherein the vortex passes right through the blade, a miss-distance value of 0.5 chords reduces the BVI noise by a very significant 15 dB and the 4/rev hub vibratory loading by a more modest 15%. Reducing the interacting vortex strength by a factor of one-half (from $\Gamma = 2$ to 1 m^2/s) decreased the BVI noise by 7 dB and reduced the hub vibrations by 50%. When the angle between the blade and the interacting vortex in the blade-shaft plane increases from zero to ± 10 deg, a 7-dB reduction in noise is observed. When the blade-shaft plane inclination angle increases to ± 20 deg, a 12-dB noise reduction and a reduction in 4/rev BVI-induced vibratory hub loading of around 30% can be achieved. When the angle between the blade and the interacting vortex in the disk plane increases from zero (perfectly parallel interaction) to about ± 10 deg, reductions in BVI noise in the range of only 1 dB to less than 3 dB (depending on the sign of the angle) are observed. However, if the disk-plane angle increases to about ± 20 deg, BVI noise reductions in the range of 6–10 dB (depending on sign of angle) and very modest reductions in 4/rev BVI-induced vibratory hub loading (of the order of 10%) are achievable. Of these four parameters (miss distance, vortex strength, angle in blade-shaft plane, and angle in disk plane) it appears that increasing the miss distance is the most effective in reducing noise, whereas decreasing the vortex strength is most effective in reducing BVI-induced vibratory loading. Reductions in vortex strength might be the best option if simultaneous reductions in BVI noise and vibratory loading are important. Vortex strength might also be the easiest to control by using active methods such as blade pitch variation or flap deflection upstream, at the time of generation of the vortical elements that convect downstream and result in parallel interactions.

Although it is widely accepted that more oblique, rather than parallel, interactions produce less BVI noise, the results in this paper indicate that a small increase in the angle between the blade and the vortex in the blade-shaft plane is much more effective in reducing the BVI noise than a comparable increase in the disk plane angle. This point is reinforced in Fig. 31, which shows contours of constant peak noise levels vs variations in blade-shaft plane as well as rotor disk plane interaction angles. Clearly, changes in the blade-shaft plane angle produce greater reductions in BVI noise for modest changes in the value of the parameter than do changes in the rotor disk plane angle. Increasing the blade-shaft plane inclination angle has the added benefit of reducing vibration. From Fig. 32, reductions in BVI-induced 4/rev vertical loads are far greater for inclinations in the blade-shaft plane than inclinations in the rotor disk plane. This would suggest that anhedral or dihedral (which can potentially affect the interaction angle in the blade-shaft plane) could be more effective in alleviating BVI than blade sweep (which seeks to affect the interaction angle in the rotor disk plane).

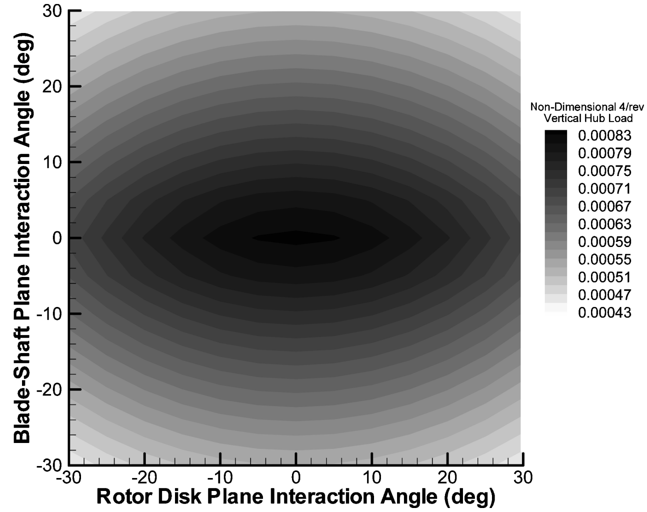


Fig. 32 Nondimensional BVI-induced 4/rev hub vertical loads vs interaction angles in the rotor disk and blade-shaft planes.

The preceding comparisons point towards an increase in miss distance and interaction angle in the blade-shaft plane and a decrease in the interacting vortex strength as the most influential of the parameters considered for reducing BVI-induced noise and vibration.

Minimum Vibration Case in the HART Test

Researchers reporting the results of the HART test,[2] and several others subsequently examining higher harmonic blade pitch control (HHC) for BVI alleviation, have indicated that the HHC schedule that produced minimum vibration decreased the miss distance, relative to the baseline, and an adequate explanation has not been provided to date for this observation. However, the results in the present study show that smaller values of miss distance produce larger, not smaller, BVI-induced hub vibratory loading (see Fig. 15). Resolving this question requires taking a closer look at the HART data and in particular the geometry of the interacting vortices, relative to the blade, for both the baseline as well as the minimum vibration cases (see Figs. 33a and 33b). It is seen that although the vortices pass through the blade for the minimum vibration case, they have a very large inclination in the blade-shaft plane (compared to the baseline case). From Fig. 18 it was observed that such an increase in inclination would indeed produce significant reduction in BVI-induced hub vibratory loading. Thus, it is hypothesized that for the HART minimum vibration case it was a larger blade-shaft plane angle that resulted in lower vibrations. Furthermore, it should be reiterated that it is somewhat misleading to use the concept of miss distance in reference to vortices that are significantly inclined relative to the blade in the blade-shaft plane because every point will have a different miss distance from the blade. The miss distance concept is useful only when vortices are generally contained in planes parallel to the rotor disk plane.

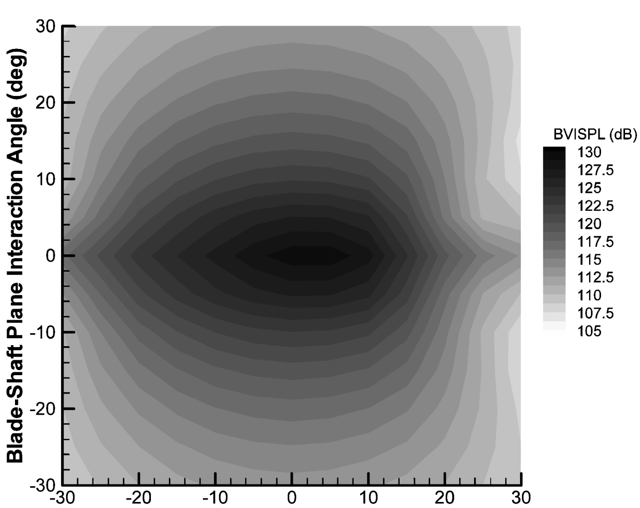


Fig. 31 Max BVISPL vs interaction angles in the rotor disk and blade-shaft planes.

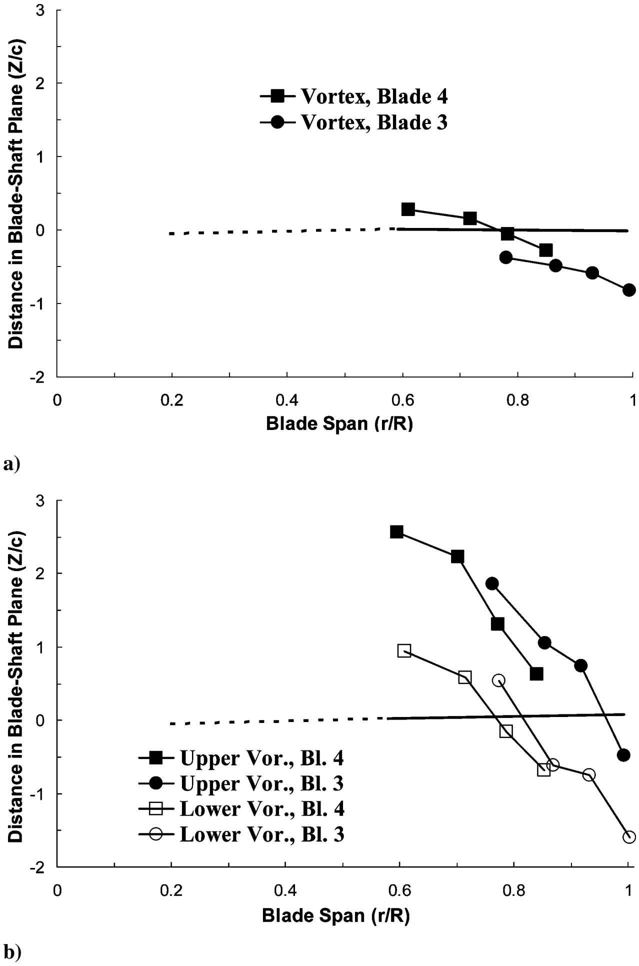


Fig. 33 HART test[2] blade-vortex interaction geometry in blade-shaft plane for a) baseline and b) minimum vibration HHC inputs.

Conclusions

This paper comprehensively examines the influence of various blade-vortex interaction parameters on BVI noise and BVI-induced vibratory hub loading. An externally imposed vortex is allowed to interact with a rotor and key interaction parameters such as vortex strength, core radius, the blade-vortex miss distance, the spanwise location of the interaction, the angles between the vortex and the blade in the blade-shaft plane and the disk plane, and finally the blade lift at the time of interaction are varied. The corresponding reductions achieved in BVI noise and BVI-induced vibratory hub loading are evaluated. From the results presented in this paper, the following conclusions can be drawn:

1) Reduction in vortex strength Γ reduces the peak BVI noise. Larger noise reductions (for a given reduction in Γ) are obtained when the baseline vortex strength is moderate to low. Reduction in BVI-induced vibratory hub loading is directly proportional to reduction in vortex strength.

2) Increasing the core radius reduces BVI noise provided the miss distance is small (less than the core radius, so the blade is intersecting the vortex core). For larger miss distances (that place the blade outside the vortex core) change in core radius has little effect on the peak BVI noise. For moderate baseline values of vortex core radius, reduction in core radius has little effect in reducing BVI-induced vibratory hub loading.

3) As long as the vortex core is not passing through the blade, increase in miss distance has a dramatic effect on reducing BVI noise. The largest reductions in BVI noise are observed when the initial miss distance is small, whereas the reductions for comparable increases in miss distance are smaller than when the initial miss distance is larger (beyond one chord length). Increased miss distance reduces both the overall amplitude of the BVI-induced vibratory hub loading as well as the higher harmonic content.

4) Modest reductions in BVI noise can be obtained as the event moves to a more inboard location and decreases in length. A more inboard interaction can actually increase the amplitude of the 4/rev BVI-induced vibratory hub loading slightly, although the percentage of vibration energy in the higher harmonics reduces.

5) Even a modest inclination (10–20 deg) of the vortex relative to the blade, in the blade-shaft plane, can produce large reductions in BVI noise, as well as BVI-induced vibratory hub loading. Inclination in the blade-shaft plane also reduces the percentage of vibration energy contained in the higher harmonics. This suggests that introducing modest amounts of anhedral or dihedral at the blade tips might be attractive.

6) Inclination of the vortex in the disk plane, from a more parallel to a more oblique orientation, also reduced the BVI noise. However, only very modest noise reductions ($\sim$2–3 dB) are obtained for small inclination angles (of up to 10 deg). Even for larger inclination angles, the noise reductions are smaller than those caused by comparable inclinations between the blade and vortex in the blade-shaft plane. This suggests that forward or backward sweep of the outboard regions might be less effective than blade anhedral/dihedral. The noise reductions are dependent on the sign of the inclination angle. Reductions in BVI-induced vibratory hub loading are also smaller than those caused by inclination in the blade-shaft plane.

7) When the blade pitch is changed but the interacting vortex is held fixed relative to the blade, there is only a change in the steady component of lift, but no change in the impulsive lift. However, when the interacting vortex is free to move, the bound vorticity of the blade causes it to convect upward. By increasing the blade pitch, the magnitude of the bound vorticity increases, and so a vortex that is passing below the blade gets pulled toward it by the bound vorticity and a vortex in the disk plane or above the blade gets pushed further upward and away from the blade. In practice, however, it is difficult to achieve noise reductions by changing the blade lift around the time of interaction as the effect of the change in bound vorticty is negated by other influences such as the change in tip vorticity of the blade.

8) The results in the present study suggest that the notion that the miss distance reduced for the minimum vibration case in the HART test is misleading. The angle between the vortex and blade in the blade-shaft plane was significantly increased for the minimum vibration case, and the results in this paper suggest that such an increase could indeed be expected to produce a reduction in BVI-induced hub vibration levels.

Acknowledgments

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