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Aeroacoustics of a Parallel Blade-Vortex Interaction using Indicial Method

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Abstract

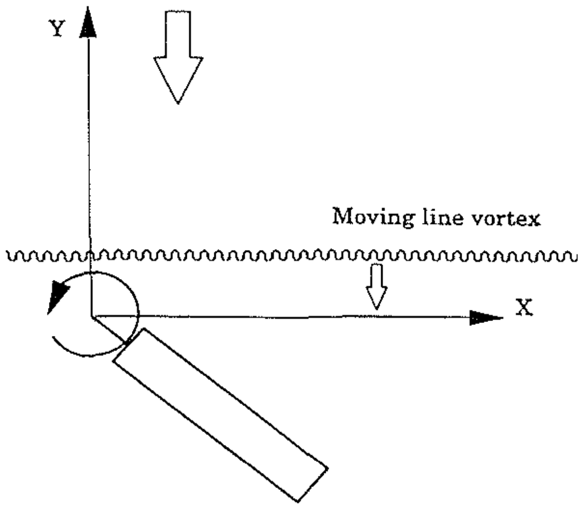
Aeroacoustics of a Parallel Blade-Vortex Interaction (BVI) is investigated using the indicial method. BVI occuring on the advancing blade is modeled as an interaction of a prescribed line vortex of known strength with a rotor blade in forward flight. Indicial method with a general gust function is applied to determine the unsteady aerodynamic lift time history. Acoustic signal at far-field observer locations is calculated using two different integral methods. Accuracy of the indicial method is demonstrated by comparing with the results obtained using the CFD method to predict unsteady aerodynamic lift. Far-field noise is calculated for a range of vortex speed ratios and it is shown that vortex convection speed significantly influences the noise magnitude. Furthermore, it is shown that vortex convection effects can be accurately modeled by using a newly developed general gust function for airfoil penetrating a moving gust.

Introduction

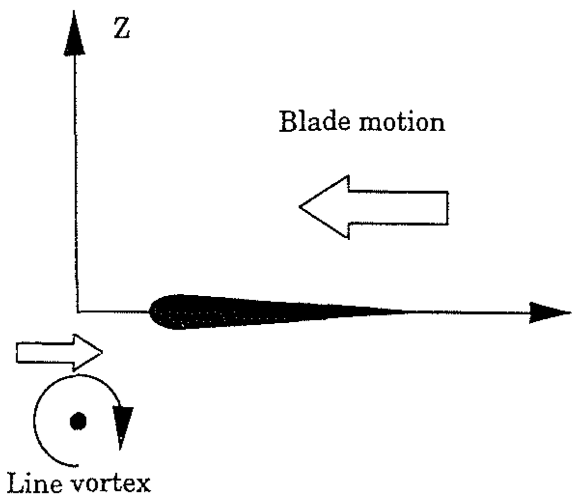
Blade-vortex interactions (BVI) are one of the most important sources of noise for a helicopter. Such interactions occur when the vortices shed by preceding blades induce impulsive changes in angle of attack on the blades and thus produce sharp noise pulses due to high rate of change of blade loading. Although BVI can occur at various locations around the rotor azimuth, the strongest interaction noise usually occurs on the advancing side when the blade is at an azimuthal angle of 70 to 80 degrees. The reasons are twofold: (1) at this point the interaction angle between the vortex and the blade is nearly parallel and the unsteady loading along the span of the blade is in phase; and (2) the Doppler amplification factor is greater for the larger local Mach numbers on the advancing side.

The forward motion of the rotor system in forward flight results in downstream convection of tip vortices that initially follow an epicycloidal pattern. As the tip vortices convect downstream their interaction with the rotor system, as well as mutual self-interactions, results in velocity perturbations which cause tip vortices to move at velocity different than the freestream. The convection velocity of the vortex influences the acoustics of BVI in two ways. One, the unsteady gust field induced by the vortex changes with the vortex convection velocity. For faster moving vortex, the interaction occurs over a shorter interval of time resulting in more impulsive interaction. Secondly, the aerodynamic response of the airfoil section changes. This manifests itself in the change in the coefficients of the gust function.

Indicial method [1,2] with gust function has been shown to be an accurate and efficient method to calculate unsteady lift for BVI. The main advantage of this method is that it is several orders of magnitude faster than the CFD methods. In indicial method, the vertical gust field induced by the vortex is calculated at a point on the airfoil section and the resulting airloads are then determined by Duhamel superposition. Thus, indicial method requires linearity of the flow physics. For rotor blade problem, indicial method is applied in conventional blade element form. The 3-D effects are included using a suitable



(a) Plan View



(b) Side View

Figure 1: Sketch of the computational model for interaction of a line vortex with an isolated rotor blade at 90 degree azimuthal angle.

method like lifting line or lifting surface method. Because of variation in Mach number and speed ratio with both span and azimuth, a general representation of the gust function is required. In this work gust function[3] is extended to make it a function of both Mach number and the speed ratio. The speed ratio, λ for a sharp edged gust is defined as:

$$\lambda = V/(V + V_g) \tag{1}$$

where V is the freestream velocity and V_g is velocity of gust with respect to the freestream. Thus $\lambda < 1$ represents a faster moving gust with 0 corresponding to indicial change in the angle of attack. Similarly $\lambda > 1$ represents a slower moving gust. Typically λ varies from 0.9 to 1.3 for rotor in forward flight.

The main objective of this study is to apply the indicial method with a general gust function to better simulate the effects of vortex convection. Secondary objective is to make a quantitative analysis of indicial methods in determining the far-field noise as the non-linear transonic effects become significant. To this end, a model problem consisting of an isolated rotor blade interacting with a single line vortex of known strength is examined. Far-field noise is calculated for various convection speeds of the vortex to examine the significance of vortex convection effects. In full paper the far-field noise will also be calculated for various Mach numbers to study the non-linear effects.

Figure 1 shows the sketch of the computational model. Plan view shows the rotor rotating in counter-clockwise direction. A line vortex convects in a straight line at a fixed distance below the blade. Velocity of the vortex convection is determined by the speed ratio parameter. The vortex is initialized such that when the blade reaches the 90 degree azimuth the vortex is underneath the quarter chord of the blade.

Approach

Aerodynamics Calculations

The problem of determination of unsteady load distribution over a rotor blade is complex because of two reasons. (1) the feedback effects of the shed vortices. Shed vortices induces downwash over the blade and influences the load distribution accordingly; and (2) the 3-D effects causes reduction in the loads near the blade tip region. The algorithm used in the present study to calculate the unsteady loads is as follows:

At each azimuthal location of the rotor blade the vortex induced vertical gust field is calculated at all span-wise sections. Indicial method is then applied to the gust field to determine the unsteady aerodynamic loads. An equivalent angle of attack for this magnitude of the unsteady aerodynamic lift is calculated by assuming the blade to be operating in a quasi-steady compressible flow. It is to be noted here that the equivalent angle of attack is not equal to the angle of attack induced by the vortex. Application of Weissinger-L method to account for the 3-D effects gives the 3-D losses. Thus, the total unsteady lift on the rotor blade can be determined by subtracting 3-D losses from the lift predicted by the indicial method.

TURNS[4] code is also used for the CFD computations of the unsteady aerodynamic loads. The TURNS code is a finite-difference code to solve Navier-Stokes equations and it has been applied to a variety of helicopter aerodynamic and acoustic problems[5-7]. In this study the viscous effects are ignored and code is used in Euler mode only.

Acoustics Calculations

WOPWOP[8] code is used to calculate the far-field noise. This code is based on the Lighthill's acoustic analogy[9] in the form of the Ffowcs Williams-Hawkings (FW-H) equation[10] including the quadrupole source term. Calculation of the noise contribution from the quadrupole terms is computationally expensive as it require volume integration throughout the flowfield as opposed to the surface integration for the linear acoustics sources. However, an approximation can be made, which is valid for an in-plane observer and utilizes preintegration in the direction normal to the rotor disk. This approximation leads to quadrupole integrals of the same form as thickness and the loading noise. Unfortunately, most intensive BVI noise is radiated in out of plane directions. The far-field noise is also computed using a recently developed boundary integral formulation[11] which does not require the non-penetration condition in the FW-H equations. The errors incurred in making in-plane observer approximation will be shown in the full paper by comparing the results obtained using two methods.

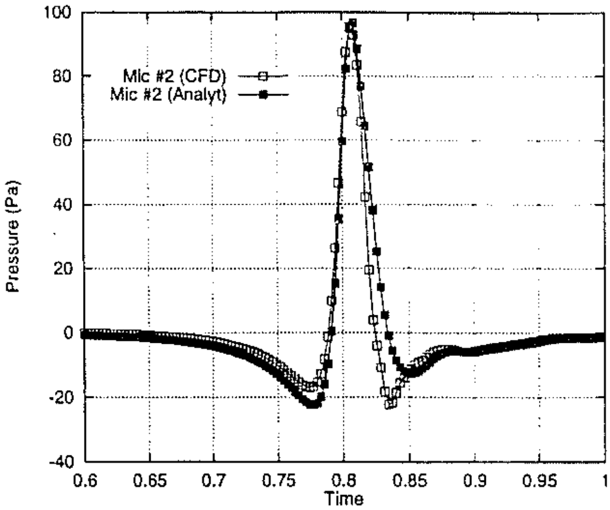


Figure 2: Comparison of acoustic signature for analytical chordwise pressure distribution and the CFD predicted chordwise pressure distribution for BVI at $M_{tip} = 0.71$ and $\mu = 0.2$.

Solution Procedure

Isolated rotor for this study consisted of an untwisted rectangular blade of NACA0012 crossection and aspect ratio of 7.125 to model the rotor system. Blade is assumed to be rigid and operates at a zero collective to minimize the effects of self-generated tip vortex. For interaction at 90 degree azimuth angle, blade is initialized at 0 degree azimuth. A step size of 0.5 degree is used to rotate the blade at each time step.

Once the aerodynamic lift time history is calculated far-field acoustics signature can be determined. For compact acoustics source blade lift time history is sufficient to determine the far-field acoustics signature however for a general source a chordwise pressure distribution over the blade surface is required. This is obtained by using the analytical pressure distribution corresponding to a flat plate in incompressible flow at an angle of attack. This distribution is given by:

$$C_p = \frac{2\alpha}{\pi}\sqrt{x/(1-x)}$$

where x is the distance as a fraction of the chord length from the leading edge and α is the angle of attack.

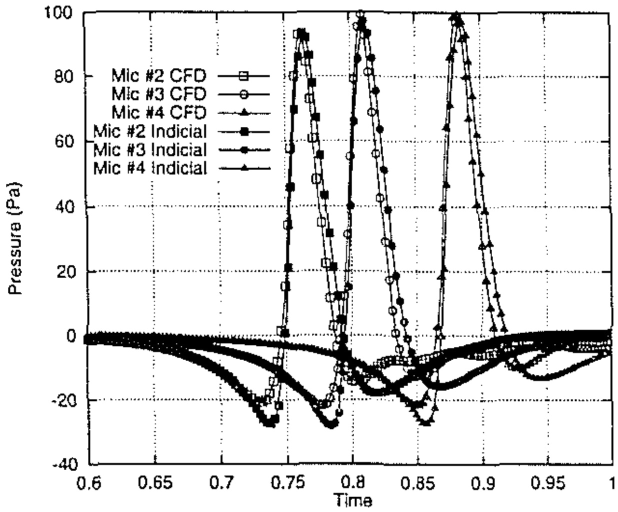


Figure 3: Acoustic signature for BVI at 180° using indicial method and CFD method to calculate unsteady aerodynamic loads at $M_{tip} = 0.71$ and $\mu = 0.2$.

Figure 2 shows the acoustic signature at microphone #3 obtained using the CFD predicted chordwise pressure distribution and the analytical chordwise pressure distribution. X-axis is time as a fraction of time period of rotor cycle. Comparison shows that the peak magnitude of the noise pulse obtained using analytical pressure distribution is in excellent agreement with the noise signature obtained using CFD pressure distribution. In the rest of the paper acoustic signature for CFD method is obtained using the analytical chordwise pressure distribution.

For the purpose of validation of the accuracy of the indicial method BVI noise is calculated at three of the observer locations used in the well known experiment of Kitaplioglu and Caradonna[12]. In this experiment acoustics measurements were made for the interaction of an isolated rotor with an independently generated vortex at 180 degree azimuth angle. The coordinates of the microphone positions, using the same nomenclature to identify observer locations as in the experiment, in rotor radius were :

Microphone Number	X	Y	Z
Mic #2	-3.0	0.0	-1.87
Mic #3	-3.0	0.0	-2.26
Mic #4	-3.0	0.0	-2.80

For the interaction at 90 degree azimuth observer locations were rotated by 90 degree such that observer locations were in front of the rotor disk.

The accuracy of the indicial method is confirmed by calculating the far-field noise for BVI interaction for same parameters as used in the experiment of Kitaplioglu and Caradonna. The acoustic signature is shown for in figure 3. Although not shown in the figure, experimentally measured peak magnitudes are almost same as predicted by both indicial and the CFD method.

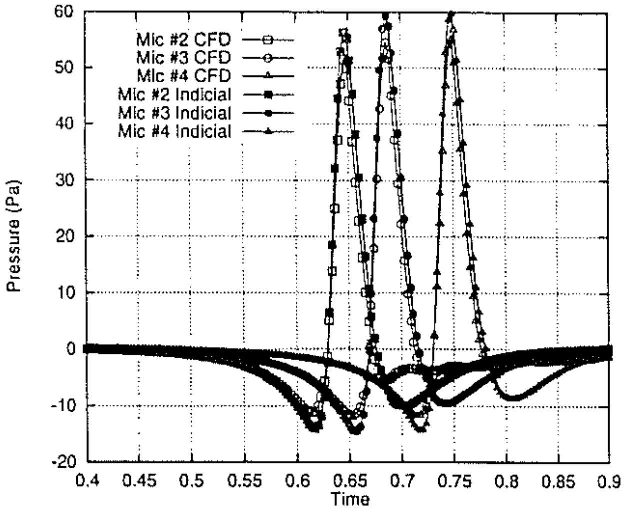
Sample Results

In this section preliminary results are presented for the acoustic signature at three observer locations for BVI computed using indicial method and CFD method for unsteady load calculations followed by the acoustic method. In all these cases, vortex passes one-quarter of rotor blade chord underneath the rotor blade at 90 degree. The non-dimensional vortex strength was 1.05 and core radius of 0.15% of the rotor blade chord. For all the results shown here 15 and 20 elements were used in chord and span direction respectively. Grid independence studies showed that differences in the acoustic signature were indistinguishable even if 10 elements were used in the chordwise direction.

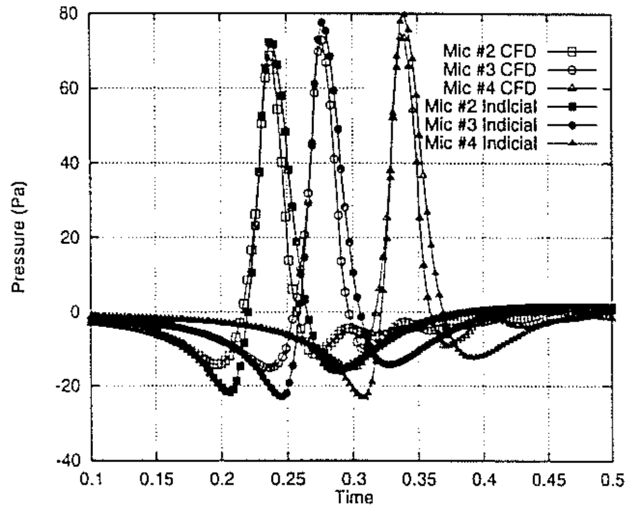
Figure 4 shows the noise level for parallel BVI occuring on advancing blade and at 180 degree at same locations relative to the rotor in rotor fixed frame. Results obtained using CFD are also shown to further validate the accuracy of the indicial method. It can be seen that the interaction occuring on advancing blade results, for reasons mentioned previously, in about 30% higher peak noise amplitude for the same flight conditions.

Figure 5 shows the acoustic signature for BVI at three microphone locations for interaction at $M_{tip} = 0.60$ and $\mu = 0.2$ for two different vortex speed ratios. It can be readily observed that indicial method predicts peak amplitude accurately for all the cases. For $\lambda = 0.9$, which represents faster moving vortex, peak amplitude is about 20% higher than the peak amplitude obtained for $\lambda = 1.1$.

Figure 6 shows the acoustic prediction for BVI interaction by using the stationary gust function. Stationary gust function is function optimized for sta-

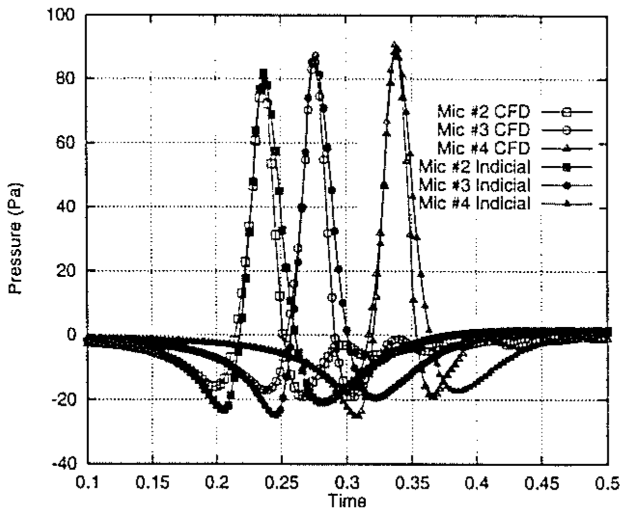


(a) $\Psi = 180°$

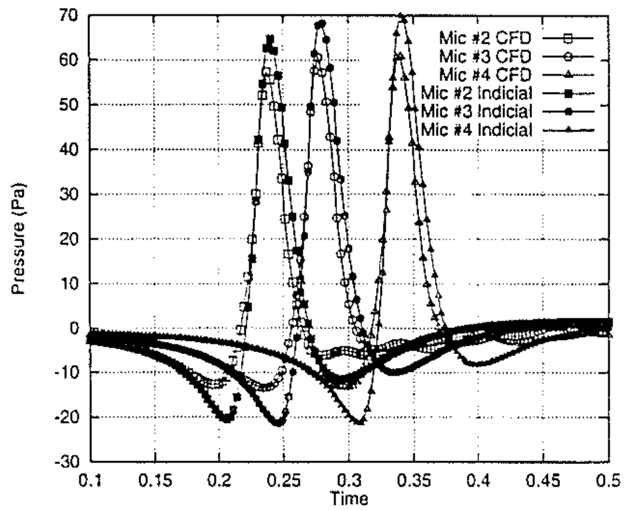


(b) $\Psi = 90°$

Figure 4: Far-field acoustic signature for parallel BVI interaction at $\Psi = 180°$ and $\Psi = 90°$ for rotor in forward flight at $M_{tip} = 0.6$ and $\mu = 0.2$.



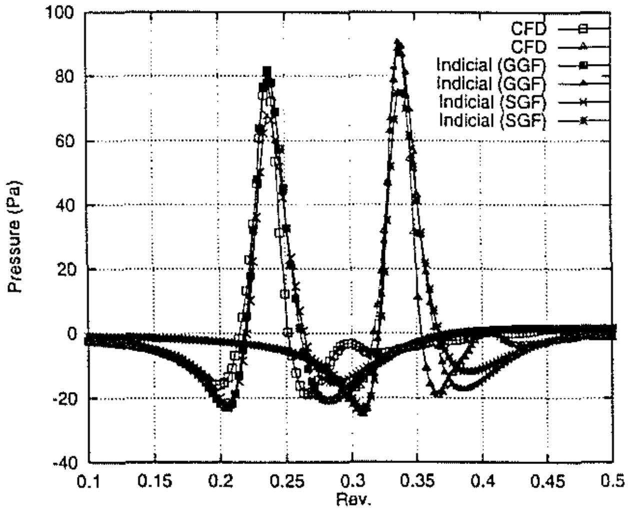
(a) $\lambda = 0.9$



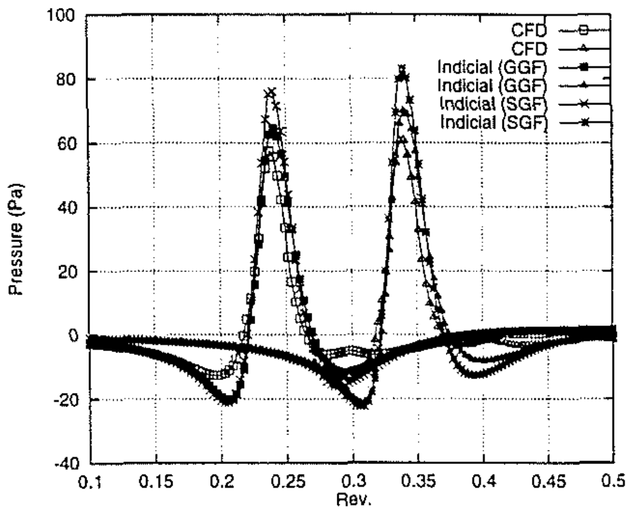
(b) $\lambda = 1.1$

Figure 5: Far-field acoustic signature for various speed ratios of the vortex convection velocity for rotor with $M_{tip} = 0.6$ and $\mu = 0.2$.

tionary gusts only. Thus it is function of only Mach number. However, the effects of vortex velocity on the unsteady gust field are accurately modeled. Results obtained using CFD and the general gust function are also shown for comparison. It can be observed that for a faster moving vortex the acoustic peak amplitude is underpredicted while for a slower moving vortex it is overpredicted. It is interesting to see that stationary gust function predicts higher peak magnitude for a slower moving vortex. The stationary gust function fails to even predict the trend of increasing amplitude of noise with increase in the speed of vortex convection



(a) $\lambda = 0.9$



(b) $\lambda = 1.1$

Figure 6: Acoustic signature obtained using general gust function (GGF) and stationary gust function (SGF) for BVI at $M_{tip} = 0.60$ and $\mu = 0.2$.

Projection for the full paper

For the full paper, acoustics signature will be calculated at higher tip Mach numbers to investigate the importance of the non-linear aerodynamics. The acoustics computations presented in the abstract are obtained by making the in-plane observer approximation for the quadrupole terms to reduce the computations costs. The validity of this assumption will be examined by computing the acoustics using the Kirchhoff-FWH formulation. Time permitting, indicial method will also be applied to rotor blades of non-rectangular planforms to study the accuracy of the indicial methods for the rotor blades of arbitrary shapes.

Conclusion

Far-field noise of a parallel BVI on the advancing blade is calculated using the indicial method with a general gust function. It is shown that indicial method can be used to accurately predict far-field BVI noise. It is also shown that vortex convection speed has significant influence on the peak amplitude of the far-field noise and use of general gust function allows indicial method to capture this effect accurately.

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