Comparison of Experimental Blade-Vortex Interaction Noise with Computational Fluid Dynamic Calculations

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Abstract

An experimental study was performed in the NASA Ames Research Center 80- by 120-Foot Wind Tunnel to examine the aerodynamics and acoustics of parallel blade-vortex interaction (BVI). An independently generated vortex interacted with a small-scale, nonlifting helicopter rotor at the 180° azimuth angle. Computational fluid dynamics (CFD) was used to calculate near-field pressure time histories using the Transonic Unsteady Rotor Navier-Stokes (TURNS) code and comparisons were made to two microphone locations in the experiment for several test conditions. Test conditions examined include hover tip Mach numbers of 0.6 and 0.7, advance ratio of 0.2, positive and negative vortex rotation, and the vortex passing above and below the rotor blade by 0.25 rotor chords. Results show that the CFD qualitatively predicts the acoustic characteristics very well, but quantitatively overpredicts the peak to peak sound pressure level in most cases. There also exists a discrepancy in the phasing of the BVI event. An improved vortex model could improve the accuracy of the peak to peak predictions and algorithmic improvements are necessary to make the computations more efficient. Still, this study shows that TURNS has good potential for prediction of simple BVI and could eventually be expanded for more complicated interactions and blade geometries.

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Introduction

Blade-vortex interaction noise is an important and complex noise source in rotorcraft operations due to its particularly impulsive and intrusive nature. As the name implies, blade-vortex interaction (BVI) is the aerodynamic phenomena of a rotor blade encountering a tip vortex. A parallel interaction is typically the most important for acoustics.[1] The purpose of this paper is to (1) better understand parallel BVI, both the physical processes and analytically models; (2) assist in the design of future BVI experiments; and (3) encourage the development and use of reliable simulation codes. These will ultimately lead to the development of quieter rotorcraft.

A two-bladed helicopter rotor model was tested in the acoustically treated NASA Ames 80- by 120-Foot Wind Tunnel to examine isolated, parallel BVI noise. An independently generated vortex, created by a semispan wing mounted vertically in the wind tunnel, interacted with the rotor blades at 180° azimuth. The rotor system was operated at zero thrust to eliminate any self-generated vortices. Pressure transducers on the blades and 7 microphones in the test section measured the pressure changes during the interaction. This experiment used a simple blade geometry and only a parallel interaction in order to compare to simulation codes not yet sophisticated enough to predict more complex flow environments.[2]

The major parameters influencing the parallel, unsteady BVI are the vortex strength,, structure and sense determined by vortex generator angle of attack (α_V), vortex-blade separation distance (Zv), rotor advance ratio (μ), and hover tip Mach number (M_{tip}).[3] The test conditions examined in this study are hover tip Mach numbers of M_{tip} = 0.6 and 0.7; advance ratio of μ = 0.2; positive and negative vortex generator angle, $\alpha_V = +/-12^\circ$; and vortex height above and below the rotor, Zv = +/- 0.25c (Table 1).

The hardware set up in this experiment is similar to that used by Caradonna et al[1] at the Army's Aeroflightdynamics Directorate (AFDD) 7- by 10-Foot Wind Tunnel, although acoustics data was not acquired in that tunnel due to wall reflections. The TURNS code was able to accurately predict the surface pressures and flow environment in the immediate vicinity of the rotor in the Army study.[4,5]

The TURNS code calculates the unsteady, three-dimensional flow and acoustic field using an implicit, structured finite-difference procedure for solving the Euler/Navier-Stokes equations. It combines the vortex fitting method by Srinivasan and McCroskey[6] with a grid that is refined off of the blade in order to directly capture the aeroacoustics of the unsteady interaction of a rotor blade with an isolated vortex, including nonlinear sources and nonlinear propagation. The vortex fitting method is used to accurately preserve the structure of the line vortex as it interacts in parallel with the rotor.

This paper will compare some of the near-field microphone data from the NASA Ames 80- by 120-Foot Wind Tunnel test with TURNS calculations.

Experimental Set Up

Facilities

The NASA Ames Research Center 80- by 120-Foot Wind Tunnel is part of the National Full-Scale Aerodynamics Complex (NFAC) located in Moffett Field, California. The wind tunnel is acoustically treated with 6 inches of foam on the walls and ceiling and 10 inches on the floor. The maximum velocity in the test section is 100 knots and the axial turbulence intensity is less than 0.5%.[7] This large facility allowed the small-scale experiment to be minimally affected by wall reflections or flow turbulence.

Rotor Geometry

The teetering rotor had a diameter of 7.125 feet and the blades were untwisted with a rectangular planform. The blades had a constant 6-inch chord, NACA 0012 airfoil section and a Reynolds number of approximately one million. One blade had 30 absolute pressure transducers on the top surface and the other had 30 on the lower surface, distributed in three spanwise positions. The blades were constructed of balsa and carbon/epoxy composites to minimize aeroelastic effects. Full cyclic and collective control were provided through a swashplate. The rotor was trimmed to minimum flapping and operated at zero collective to minimize self-generated vortices. Rotation was clockwise as viewed from above.

Vortex Generator

The vortex was generated directly upstream of the rotor by a 18-inch chord, semi-span wing with a NACA 0015 airfoil section. The vortex generator (VG) was mounted vertically in the wind tunnel and could extend or retract vertically to place the line vortex above or below the rotor. Reynolds number for the VG wing was approximately 600,000. Tip vortex strength and structure were not directly measured in this experiment.

Microphones

There were 7 microphones in the test section: 2 in the near-field and 5 in the far field. Only the near-field microphones, designated 6 and 7, are included in this study. Both microphones were located directly below the 88% rotor radius by 12 inches. When the rotor was at 180°, microphone 6 was 8.75 inches in front of the rotor leading edge (near the 193° azimuth location) and microphone 7 was 0.75 inches in front of the rotor (near 181° azimuth).

Illustrations

Figure 1 is an illustration of the experimental set-up and shows how the VG tip vortex interacted with the rotor in a parallel manner. This figure also illustrates the blade-vortex vertical separation distance, Zv, the VG angle of attack, α_V, and the general position of the microphones two rotor chords below the plane of the rotor. Figure 2 is a photograph of the hardware set up in the test section. Figure 3 illustrates the experiment as viewed from above showing the parallel interaction occurring at the rotor quarter-chord position. Figure 4 is a schematic, looking downwind in the plane of the rotor, showing the four test cases studied at the two different hover Mach tip numbers (listed in Table 1). This figure illustrates the vortex sense and location and the induced velocity felt by the blade as a result of the vortex.

Acoustic Data Acquisition and Processing

The Acoustic Laboratory Data Acquisition System (ALDAS)[8] was used for acoustic data acquisition and reduction. Experimental acoustic data were digitized at 1024 points per revolution on a Macintosh-based, four-channel, 12-bit data system. All incoming data were filtered at 10 KHz to prevent aliasing and thirty revolutions of data were acquired for each test condition. The acoustic data were calibrated daily using a pistonphone, and they were time-averaged using the rotor one-per-revolution trigger signal. The result was a one-revolution long, averaged time history in Pascals. The data underwent a thorough review to check for high background noise, corruption due to electrical interference, "self noise" (noise due to airflow over the microphone or other hardware), and for repeatability. The data presented here was found to be acceptable in all of the above criteria.

CFD Model

Governing Equation

The parallel BVI experiment was simulated using the Transonic Unsteady Rotor Navier-Stokes (TURNS) CFD code. The code can be used with either the Navier-Stokes equations or the Euler equations. The choice of governing equations affects the computational time and the level of physics modeled. Blade vortex-interactions rarely results in flow separation so viscous effects are minimal and the Euler equations are able to capture most of the important features. The Euler equations are preferable to simpler governing equations due to the convection of vorticity and compressibility effects that can accompany blade-vortex interactions.

Numerical Algorithm in TURNS

The TURNS code uses Roe upwind biasing with high-order MUSCL (Monotone Upstream Centered Scheme for Conservation Law) type limiting on the right hand side and a LU-SGS (Lower Upper Symmetric Gauss-Seidel) implicit operator is used on the left hand side. (For a full description of the TURNS code, see Reference 9). These features provide higher order accuracy and make the code computationally efficient and robust. For unsteady computations, a second order backwards difference in time is combined with Newton type sub-iterations. This reduces the factorization and linearization errors associated with the implicit scheme and the effects of explicit boundary conditions, and restores the full spatial accuracy of the right hand side.

The vortex is introduced and preserved using the vortex fitting method of Srinivasan and McCroskey.[6] The convection of a line vortex in a free stream is a known solution of the Euler equations and can be added to the solution of the rotor blade without a line vortex. The combined nonlinear flowfield will also be a solution of the Euler equations, even though the Euler equations by themselves are nonlinear. The solution of a convecting line vortex in the freestream is subtracted from the combined solution at every time step after the initialization of the vortex into the solution. This reduces the numerical dissipation of the vortex. Such a method is nonlinear and allows for the adequate resolution of the vortex effects even where the grid is very coarse.[10]

Computational Grid

The three-dimensional grid is constructed from a series of two-dimensional hyperbolic C-grids.[4] A finer grid is used away from the rotor blade surface in order to calculate the near-field acoustics, as well as the aerodynamics. BVI noise propagates outward in a circular pattern and the grid is refined in the direction normal to the blade to maintain finer spacing for several chords away from the blade surface.

Specifics for Current Computations

All of the computed solutions using the TURNS code were run in Euler mode which neglects the viscous terms. Limiting is performed in the wrap-around direction to prevent numerical oscillations at shocks. No limiting is done in the normal and spanwise directions in order to better maintain the initial formation and propagation of the acoustics. The flowfield is discretized using 169 points in the wrap-around direction with 121 points on the blade surface, 45 points in the spanwise direction with 23 points on the blade surface and 57 points in the normal direction for a total of over 430,000 grid points.

The flowfield is initialized by computing the quasi-steady solution, without the line vortex, at a blade azimuth of 0°. Since the rotor is symmetrical and set to zero degrees of collective with no cyclical or flapping motions, the computational time is reduced in half by applying symmetry boundary conditions and only calculating one-half of the flowfield. The converged quasi-steady solutions are obtained in approximately 20 minutes of CPU time on a CRAY-YMP C90. The initial unsteady computations, until a blade azimuth of 90°, are also computed without the line vortex on one-half of the flowfield. A time step of 0.25° and three Newton sub-iterations are used at each time step. This requires approximately 30 minutes of CPU time (4.78 seconds per time step).

The line vortex is introduced at the 90° azimuth location, when the vortex is farthest from the rotor blade tip. The vortex is treated as an infinite line vortex that remains stationary as the blade rotates past it. An algebraic core model is used to model the viscous core[11] and the induced velocities in the axial and radial directions are neglected. Since the details of the vortex were not measured during this experiment, all of the calculations use the values of Caradonna et al[1] unless otherwise noted. The vortex strength, $\Gamma = 0.406$, was nondimensionalized based on the freestream velocity and the vortex generator chord, and the viscous core radius of 0.17 was nondimensionalized based on the rotor blade chord. When introducing the vortex, the flowfield is no longer symmetric and the flowfield for the entire blade is calculated. A maximum of five Newton sub-iterations are used at each time step unless otherwise noted. In order to reduce the computational costs, if the residual for a given time step decreases by more than a factor of 50 during the Newton sub-iterations then no further sub-iterations are performed at that time step. Only three Newton sub-iterations are used during most of the calculations except from 184° to 227° where the full five sub-iterations are used. The solution is stopped at an azimuth location of 270°. This requires 13,351 CPU seconds (18.54 seconds per time step) as compared to 10,560 (14.67 seconds per time step) for only using a maximum of 3 sub-iterations.

Results

Comparison of CFD with Experiment

Srinivasan et al performed an initial study with a TURNS predecessor to validate surface pressures and comparisons to the Army 7- by 10-Foot Wind Tunnel experiment found results to match well.[12] Additional calculations were performed by Baeder et al using the TURNS code to examine the flow characteristics calculated off of the blade in the vicinity of the rotor.[4] Now, the TURNS code has been run with the specific microphone locations and test conditions of the 80- by 120-Foot Wind Tunnel experiment.

Figures 5 through 8 compare the experimental pressure time histories with CFD calculations. As stated earlier, all of the CFD calculations in these figures assume that the vortex generator at 12° produces a nondimensional vortex strength, Γ, of 0.406 and a simple algebraic core model with a nondimensional viscous core radius of 0.17.

In many of the cases there is a phase shift between the CFD maximum and minimum peaks and those peaks in the experimental data. For $M_{tip} = 0.6$, in cases I and IV , the CFD main BVI event occurs 5° sooner than the experimental results. For $M_{tip} = 0.7$, the same phase shift exists in cases I, II, and IV. The phase shift for both microphones 6 and 7 are the same for all cases. Some degree of deviation in experiment in expected due to data acquisition and experimental set-up, but the consistent 5° is unexplained at this time.

The basic characteristics of the acoustic pressure time histories are matched very well. The CFD predicted waveshapes consistently follow the experimental trends. However, the CFD consistently overpredicts the experimental peak to peak amplitudes by 15-35%. In general the overprediction is smaller for the cases with $M_{tip} = 0.7$ as compared to $M_{tip} = 0.6$. CFD actually underpredicts case I by 2-3% for $M_{tip} = 0.7$.

Experimental and Computational Trends

Peak to peak pressure amplitudes for BVI events appear to follow certain trends and are listed in Table 2. For a positive vortex sense of counter-clockwise (CCW, $\alpha_V = +12°$), microphone 7 is consistently lower in amplitude than microphone 6 even though microphone 7 is physically closer to the event occurring at the 180° azimuth. This is true for the vortex passing both above and below the rotor and for Mach tip numbers of 0.6 and 0.7. For the clockwise rotation (CW, $\alpha_V = -12°$), microphone 7 is higher in amplitude than microphone 6; 10% higher for $M_{tip} = 0.6$ and 20% for $M_{tip} = 0.7$. One possible explanation for this phenomena could be that BVI is highly directive in nature, particularly in the near-field, causing the peak amplitudes to be radiated more laterally than downward.

The passing vortex has tangential velocities that affect the character and magnitude of the BVI noise. For CCW vortex rotation, the peak to peak amplitudes are lower when the vortex is below the rotor; 20% lower for $M_{tip} = 0.6$, 45% for $M_{tip} = 0.7$. This is because the sense of the vortex rotation creates a local velocity on the blade that opposes the freestream velocity, weakening the forces on the blade. Conversely, the CW rotation produces higher peak to peak values for the vortex passing below the rotor due to the addition of velocity on the blade. Figure 4 helps illustrate this trend and pressure amplitude data is listed in Table 2.

Another observation is the pressure changes due to aerodynamic disturbances, often referred to as thickness effects. Figure 9 shows the CFD calculation of thickness effects at the two near-field microphone locations for both tip Mach numbers. (Experimental data of this nature was not available.) Thickness effects always have a predominantly negative pressure time history, whereas the BVI event has both positive and negative peaks. The low-frequency thickness effects occur after the BVI event in the

CCW cases I and III, and before the event in the CW cases II and VI. This is because the BVI sound event travels through space at the speed of sound, but the aerodynamic disturbance travels at the same speed as blade rotation. This implies the pressure disturbance from thickness arrives after the BVI event for microphone 6 since it is farthest away from 180° azimuth angle.

Figure 10 shows the computed pressure time histories at microphones 6 and 7 for the M_{tip} = 0.7 cases I and IV, with thickness effects removed. With the thickness effects removed it is more clearly visible that cases I and IV have pressure time histories that are nearly of equal magnitude and opposite sign. Also, the pressure time histories have a shape that lie between those measured on the surface (with a strong initial peak followed by a weaker second peak of opposite sign) and those in the far-field (with a weak initial peak followed by a very strong second peak of opposite sign with a final weak third peak with the same sign as the initial peak). For cases II and III (not shown) the wave shapes are nearly equal and opposite for the microphone 7 location, but a weaker BVI pulse is observed at microphone 6 for case III.

Examining all eight cases, case III has the weakest BVI pulse for both microphones. Case I has the strongest pulse for microphone 6 and case IV is the strongest for microphone 7. These trends are the same for both CFD and the experimental data.

Discussion

Effect of Vortex Parameters on CFD

It is questionable whether TURNS is accurately modeling the vortex structure, movement and strength. TURNS assumes the line vortex remains undisturbed. This implies it remains undistorted in shape and unwavering in location, which would clearly not be the case in the experiment. The vortex would tend to follow streamlines of the flow environment and would be somewhat distorted by the interaction with the rotor. The rotor itself is effected by the sheet wake of the vortex generator when the wing is positioned to generate a vortex above the rotor.

It is noted that the VG chord is three times larger than that of the rotor, producing a tip vortex three times larger and velocity peaks much lower than a rotor-generated vortex would produce. Caradonna et al found the rotor pressure variation to be insensitive to vortex core size in the miss distances used in this study. It was stated that the structure of a trailing vortex from a fixed wing is essentially the same as that from a rotor, therefore the wing-generated BVI has good utility for this investigation.[1]

Kitaplioglu et al found that an increase in vortex proximity (farther from the blade) of a quarter chord, produces a 35% reduction in peak acoustic pressure.[13] It is possible the conditions of the experiment were not exactly symmetric or the vortex equidistant from the blade, which would effect the BVI strength significantly.

McAlister and Takahashi[14] made extensive flow measurements of the vortex strength for a similar NACA 0015 wing. There is some question on what an appropriate value of the nondimensional vortex strength should be, since it was not measured directly in this experiment and could be the source of some error. In the McAlister and Takahashi report, they specify a nondimensional vortex strength of 0.35 for the α_V = +/- 12°. The results for two cases with Γ = 0.35 and M_{tip} = 0.7 are shown in Figure 11. Peak to peak values were reduced by approximately 15% and are listed in Table 2. This greatly improves the quantitative agreement with experiment for case IV. However, case I is now underpredicted by approximately 17%. Although the smaller vortex strength should improve the correlation with experiment for most cases, it is still a source of uncertainty.

It is unclear what effect different vortex core models would have on the near-field pressure time histories. Most investigators determine the vortex strength and core radius to implement in CFD codes by matching the location and magnitude of the maximum tangential velocity of the experiment with those corresponding to the vortex core model. Such a choice guarantees good agreement near the core radius for any chosen model, but different models start producing dramatically different results as one moves away from the core (due to different predicted strengths). As an example, the Sculley vortex model results in tangential velocities far away from the vortex core that are only half of that due to a Rankine vortex[11]. In addition, the models produce dramatically different rates of drop-off in the tangential velocity as one moves radially outward (possibly more important for acoustic noise generation). The determination of which vortex core model is most appropriate could be very important to accurate BVI predictions.

The smaller vortex strength is 86.21% of that used earlier and results in the average change in amplitude (without thickness effects) of 85.21%. This shows a nearly linear relation in the CFD computations. The starred (*) data in Table 2 indicates the value was obtained by multiplying the non-dimensional vortex strength of .406 data by the factor of .8521.

Effect of Newton sub-iterations on CFD

Figure 12 shows the effect of the Newton sub-iterations in the TURNS code. Initially, calculations were made using 3 sub-iterations. It was found that increasing the maximum number of sub-iterations to 5 reduced the peak to peak amplitudes and the oscillations after the BVI event are reduced somewhat. Since a constant time step was used it was expected that the largest errors due to linearization and factorization occur when the vortex is in the vicinity of the rotor blade. There was a need for more sub-iterations during this interval to increase the time accuracy. Increasing the number of maximum Newton sub-iterations past 5 had little additional effect.

Conclusions

This paper presented a detailed comparison of the 80- by 120-Foot Wind Tunnel near-field microphone data with TURNS calculations for a quantitative evaluation of predicted acoustics. The results from the TURNS code correlate well with the experimental pressure time histories in the near field. The results show excellent qualitative comparison, but an overprediction in amplitude and a phase shift in some cases. The most likely cause for discrepancies are deficiencies in the vortex modeling used in the CFD computations. Detailed experiments should be performed to determine the most appropriate and computationally efficient vortex core model for use in CFD and free-wake calculations.

The point of this experiment was not to attempt to model real rotors but to allow for the verification of computational predictions. The larger aspect ratios of real rotors will require increased spatial and temporal accuracy. The spatial and temporal resolutions used in this study were adequate, but algorithmic improvements are needed to make the computations more practical.

Some discrepancies between the near-field experimental and computational data exist, yet the correlation is satisfactory enough that the CFD results could be used as a database to investigate the effects of nonlinearities on the generation and propagation of BVI noise.

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