METHODS FOR THE PREDICTION OF BLADE-VORTEX INTERACTION NOISE

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ABSTRACT

This paper compares aeroacoustic methods for the prediction of parallel blade-vortex interaction noise using data from a specialized rotor test. The test, performed in the NASA Ames 80- by 120-Foot Wind Tunnel, involved a small-scale rotor interacting with a vortex generated by a wing mounted upstream. These data were the focus of a working group that compared a wide range of methods for the prediction of BVI noise. The aerodynamic models include computational fluid dynamics, boundary element, and indicial methods. Acoustic methods include Kirchhoff methods and the Ffowcs-Williams Hawkings approach. The comparisons of computed and measured surface pressure data reveal a number of differences, none of which seem to have major acoustic significance. Comparisons of computed and measured far-field pressures show that BVI acoustics is generally well predicted when the blade aerodynamics are well defined, with more variations being found between the Kirchhoff methods. Within the limitations of the present test, this indicates that BVI noise is reasonably well predicted when vortex parameters (location, circulation, and core radius) are accurately known.

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NOMENCLATURE

c	rotor blade chord, in
C_V	vortex generator chord, in
M_{tip}	rotor tip Mach number
Rotor Azimuth Index	analog of rotor azimuth angle (index value varying 0 to 1024 is equivalent to azimuth angle varying 0 deg to 360 deg)
R	rotor radius, in
r	radial position, in
r/R	nondimensional rotor blade radial position
r_V	nondimensional vortex generator radial core size
U_∞	free stream velocity, ft/s
V_θ	tangential velocity, ft/s
X_m	microphone traverse streamwise position relative to rotor hub, in
x	chordwise position, in
x/c	nondimensional rotor blade chordwise station
Z_v/c	nondimensional vortex generator vertical location relative to the rotor plane.
α_V	angle of attack of the vortex generator, deg
ϕ	elevation angle, measured positive down from rotor plane, deg
Γ	nondimensional vortex strength
μ	advance ratio

INTRODUCTION

Rotor-vortex interactions have been the subject of many experimental, analytical, and computational studies. Most of this activity is motivated by the importance of blade-vortex interaction (BVI) as a major source of rotorcraft noise and vibration problems. BVI is also of basic computational interest because it is a well-defined problem encompassing important numerical issues of rotorcraft aerodynamics. Examples of rotorcraft aerodynamic issues involved in modeling BVI are the computation of vorticity convection, the resulting unsteady loads on an airfoil, and the ensuing pressure waves. The interaction of a rotor blade and a vortex is a much simpler phenomenon than the total rotor/wake environment in which it occurs. This isolated BVI event has been the object of numerous computational methods, ranging from simple, incompressible 2-D analyses to full 3-D, Euler/Navier-Stokes computational fluid dynamics (CFD) codes. Experimental data of comparable simplicity were unavailable because of the difficulty of generating sufficiently clean vortices in a wind-tunnel environment, and also acquiring corresponding loading and acoustic data. These experimental problems have been largely solved by the rotor/vortex-generator approach originally employed by McCormick and later developed into a full aeroacoustic test at the Ames Research Center.[1] The data obtained from this latest test were suitable for evaluating computational models and have become the focal point for the present study by an informal BVI Working Group.

The characteristics of the vortex were not meaured during this test. Most of the methods presented herein used a specified initial vortex form that is derived from a separate, related test by McAlister and Takahashi. The accompanying acoustic methods employ either the acoustic analogy based on the Ffowcs-Williams Hawkings (FW-H) equation or a Kirchhoff approach. Predictions from these methods are compared with data from a near-miss vortex interaction. Head-on (zero miss distance) results are included in Reference 2.

For the present work, some methods were still under active development. Nevertheless, the extensive results obtained to date provide a means to assess the adequacy of the data and also serve as a focus for comparing and summarizing the range of available methods. The methods discussed here constitute probable future aeroacoustic analysis and design tools.

THE BVI EXPERIMENT AND DATA

A rotor model was tested in the acoustically treated NASA Ames 80- by 120-Foot Wind Tunnel for the purpose of studying the isolated, parallel blade-vortex interaction. Figures 1 and 2 show a photograph and a schematic of the experimental set-up. The relevant characteristics of the wind tunnel were described in Reference 3. This experiment used a simple blade geometry and an externally generated vortex to provide an uncomplicated flow environment for computational code validation. This arrangement permitted control of the vortex parameters (strength, sense and location) independently of the rotor state. The rotor was operated at zero thrust, so that the influence of its own wake would be minimized. The vortex/blade separation distance and the vortex sense of rotation were independently controlled by the height and angle of the vortex generator (Fig. 2).

Rotor Geometry

The two-bladed, teetering rotor had a diameter of 7.125 feet. The blades were untwisted with a rectangular planform. The blades employed an NACA 0012 profile with a constant 6-inch chord. The hover tip Reynolds number was approximately one million at a tip Mach number of 0.7. The blades had 60 absolute pressure transducers, 30 on one blade on the upper surface, and 30 on the other blade on the lower surface. The transducers were arranged in three equal chordwise arrays. Figure 3 shows the pressure transducer distributions on the blade. The carbon/epoxy blade structure was very stiff in bending and torsion, which effectively eliminated aeroelastic effects. Full cyclic pitch and collective pitch control were provided through a swashplate. The rotor was operated at zero thrust to minimize self-generated tip vortices. It was always trimmed to zero flapping to enable repeatable control of the blade-vortex miss distance. The rotor rotated clockwise as viewed from above.

Vortex Generator

A streamwise vortex was generated directly upstream of the rotor by a vertically oriented, semi-span wing (NACA 0015 airfoil section, 18-inch chord). The Reynolds number for the vortex generator wing was approximately 600,000. The vortex generator (VG) was equipped with a telescoping tip that permitted remote placement of the streamwise vortex at any desired location with respect to the rotor plane. This vertical distance between the vortex and the rotor blade was measured by a stroboscopic video camera. The visualization was performed by ejecting smoke from the tip of the vortex generator and illuminating a cross-section of the vortex with a laser sheet (located at 0.876R). The streamwise distance between the trailing edge of the vortex generator and the rotor blade tip at 180 deg azimuth was 48" or 2.67 VG chords.

Microphones

There were seven, 1/2-inch diameter, microphones located in the test section: two in the near-field and five in the far-field. The microphones were calibrated daily using a standard pistonphone. Both near-field microphones were located 12 inches (2 rotor chords) below the rotor, at the 87.6% rotor radius. Figure 4a shows the location of the near-field microphones 6 and 7 and the far-field traverse position at $X_m = 0$. Figure 4b shows the locations of microphones 1 through 5 on the traverse and their downward angle relative to the rotor hub.

Experimental Test Matrix

The test matrix included a range of hover tip Mach numbers, vortex generator angles, and different vortex locations. Most of the data were obtained at an advance ratio of about 0.2 for each hover Mach tip number by adjusting the flow velocity. Table 1 summarizes the test conditions for which data were acquired. The majority of the computational results in this paper are for a representative single test case. Blade loads and acoustics were computed for Case 1D where test conditions were: hover tip Mach number, $M_{tip} = 0.715$, advance ratio, $\mu = 0.198$, angle of attack of vortex generator, $\alpha_V = -12$ deg, and separation distance between the vortex and the blade, $Z_V/c = -0.25$. This case was chosen because of its simplicity (the blade does not pass through the vortex or its trailing sheet). Additional comparisons were also made (see Ref. 2) with a "head-on" case (Case 1B), where the vortex-blade separation distance was zero.

Acoustic Data

The Acoustic Laboratory Data Acquisition System (ALDAS) was used for acoustic data acquisition and reduction. The data were digitized at 1024 samples per rotor revolution (approximately 34,000 samples/sec) using an external clock signal supplied by a rotor shaft encoder. In the following discussion, unsteady quantities are plotted as functions of the rotor encoder position, referred to as “Rotor Azimuth Index.” An Index of 1024 represents one full revolution of data. The data were acquired on a PC-based, four-channel, 16-bit A/D data system. All incoming data were low-pass filtered at 10 kHz to prevent aliasing errors. Thirty rotor revolutions of data were acquired for each test condition. The data were ensemble averaged based on a rotor one-per-revolution trigger signal.

Blade Surface Pressure Data

A 32-channel, 16-bit digital data acquisition system acquired the 60 channels of blade pressure data in two sets. One transducer was duplicated between the two sets to check repeatability. The data were acquired at 1024 samples per revolution using the external clock signal supplied by the rotor shaft encoder, and anti-alias filtered at 10kHz. Thirty-two revolutions of data were recorded and were ensemble averaged. The data showed good repeatability and there was little degradation by the averaging process. Maximum deviations from the average pressure were small, occurring mainly at the vortex/leading edge impact time. This probably indicates that signal variation is mainly the result of slight vortex wander, which is the small random displacements of the vortex core as it trails downstream.

The resulting averaged data were accessible by a graphics/analysis program that provided displays in the form of either time-histories or chordwise pressure distributions. The data can be filtered to display any desired spectral components. This filtering was useful for eliminating low-frequency variations and biases in the data. For display in the time domain, the lowest four harmonics were filtered out for both the experimental and computed results.

Data Quality

An essential goal of the experimental work was to obtain simultaneous surface pressure and far-field acoustic data of suitable quality for code validation. All of the data were reviewed for data corruption, consistency, and repeatability. One measure of experimental error is the spread of data at each azimuth over all revolutions of recorded data. Using this estimate of error, for blade pressures the maximum error is approximately ±2.5% of the maximum peak-to-peak pressure value. For acoustics, the maximum error is approximately ±5% of the maximum peak-to-peak sound pressure level.

VORTEX STRUCTURE AND MODELING

The computational methods used in the present investigation require a good representation of the vortex structure. The following algebraic vortex core model provided the best overall fit with the measured vortex structure from Reference 4. With this model the tangential velocity equation is expressed in dimensionless form by:

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where r_V is the nondimensional vortex core radius and the nondimensional variables are defined as;

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where the barred values are dimensional and C_v is the vortex generator chord. The working group employed a number of methods to infer the proper values of non-dimensional circulation, Γ, and non-dimensional core radius, r_V, to use in the above model. These methods included curve fitting approaches as well as *a priori* surface pressure computations. (See Reference 2 for a detailed discussion.) These studies led to the non-dimensional circulation of 0.374 and core radius of 0.054; and these values were used in most of the ensuing computations for Case 1D.

SUMMARY OF COMPUTATIONAL METHODS

The basis for all the acoustic prediction methods is either an implementation of the FW-H equation or the Kirchhoff approach. Because the latter method requires flow-field data, it is only used in combination with a CFD method. The FW-H approach (without the quadrupole term) requires only surface pressure data and can be used with any aerodynamic method. In general, the computational effort required by the near-field aerodynamics is much greater than that of the acoustics. Furthermore, there are many more aerodynamic than acoustic prediction methods. The contributions are listed roughly in the order of increasing complexity of the aerodynamic model. The various methods and corresponding investigators are summarized in Table 2.

Method 1. Experimental Data Input to FW-H (WOPWOP)
Acoustic predictions were performed at NASA Langley Research Center using measured blade pressures as input to the rotor acoustic prediction code WOPWOP. The measured chordwise blade pressures input were those obtained at the three radial stations (r/R = .772, .876, .946). Acoustic predictions were made for both far-field microphones and near-field microphones.

The WOPWOP code, based on the time-domain Formulation 1A of Farassat predicts rotor thickness and loading noise at a specified observer location.

The noise calculation in WOPWOP divides the rotor blade surface into a number of chordwise and spanwise acoustic source panels. Some variations of computational input were studied. A spanwise grid which matched that of the measured data (from approximately r/R = .75 to r/R = 1.0), was compared to a spanwise grid which extended much farther inboard than that of the measured data (from r/R = 0.3 to r/R = 1.0). The computational spanwise grid was adjusted to locate the measured data at the center of the surface panels. The number of spanwise panels was varied from 10 to 50 between approximately r/R = .75 and the tip (r/R = 1.0) to check for numerical differences that may occur due to grid size. No significant difference in the predicted acoustics was seen. The chordwise computational grid was also varied, from 27 chordwise locations to 54. Again no significant difference in the predicted acoustics was seen. Finally the number of time steps used in the computation was varied from 256 to 1024 time steps per blade passage. The maximum level of the BVI peak for all the acoustic time histories increased by less than 3 Pascals, and the computation time approximately tripled. The final computational grid consisted of 50 radial panels (between r/R = 0.75 and r/R = 1.0), 27 chordwise panels, and 256 time steps per blade passage (1/2 revolution). Linear interpolation of the measured data onto the computation grid was used for the chordwise, spanwise and azimuthal (time) directions. The particular configuration of this BVI experiment (rectilinear vortex and parallel interaction) makes this simple interpolation possible.

Method 2. Indicial Method with FW-H

The indicial approach provides a fundamental method of finding the time-dependent aerodynamic response to a wide range of unsteady flow conditions. The unsteady aerodynamic response to an arbitrary input can be found by Duhamel superposition if the indicial response can be found for a specified unit input, such as a step change in angle of attack or the penetration of a sharp-edge gust. The indicial response in some cases is known analytically, in other cases numerically, and it can also be found experimentally by inverse techniques. If the assumption of linearity of the flow physics over the required range of conditions can be justified, then one advantage of the indicial method is a tremendous saving in computational cost over performing separate flow field calculations. By using certain analytic forms of the indicial response, efficient numerical procedures can be developed to solve the Duhamel integral. Such a method, developed at the University of Maryland, obtains a generalized exponential function that closely approximates the exact two-dimensional solution for lift on an airfoil penetrating a sharp-edged gust in subsonic flow. This allows the unsteady lift for any non-convecting gust field to be computed extremely efficiently. The resulting method can then be applied to obtain the time-varying lift variation on the rotor in response to a specified inflow. For the present application, this inflow is obtained from the tangential velocity induced by the generator vortex. To provide an input to the FW-H equation for the acoustics solution, the predicted unsteady lift over the rotor blade is used to synthesize an equivalent surface pressure distribution using thin-airfoil theory. A novel and very efficient binning technique is used to track the times of emission and reception at the observer locations, thereby preserving the overall efficiency of the approach. Thickness noise effects are incorporated into the acoustics solution using a standard source/sink model.

Method 3. Singularity Method with Cloud-in-Cell Vortex Model (ARHIS), and FW-H (PARIS)

A singularity method, called ARHIS has been developed at ONERA. The method is incompressible and models the interacting vortex as a freely convecting and deforming cloud of vortex elements. Subsonic compressibility effects are included by means of Prandtl-Glauert corrections combined with local thickening of the airfoil. In addition, finite span effects are introduced through an elliptic-type correction of the pressure coefficients. This is the only method used in this paper that models vortex deformation. This particular near-field computation is coupled to an acoustic code, called PARIS, which employs a time-domain formulation of the FW-H equation. The blade is discretized into 10 radial sections.

Two distributions of vortex elements have been used for this study, with the standard values of the circulation and core radius. The first distribution is the only method in this paper that intentionally deviates from the standard vortex model. This model attempts to account for the fact that the vortex is probably not fully rolled up. The model is not axi-symmetric and its outer region roughly emulates a vortex sheet. However, the total circulation is the same as for the standard axi-symmetric vortex. This leads to a maximum induced velocity approximately 14% lower than the maximum velocity induced by the standard model. Computations using this model are referred to as Method 3A. This model has been used because the proximity of the vortex generator to the rotor makes it probable that the vortex is, in fact, not fully developed. In addition, computations are performed using the standard axi-symmetric model and these are referred to as Method 3B. Both of these vortex structures are used only as initial conditions and are subsequently free to deform.

Method 4. Compressible Singularity Method

A three-dimensional boundary element method has been employed at the Boeing Company and Duke University[7]. The aeroacoustic boundary element method is unsteady and compressible, based on the convective wave equation (linearized potential equation), and employs a Lagrangian convection of the vortex. The computation applies the boundary element method using Analytical/Numerical Matching (ANM) in conjunction with Turbulent Core Model vortex dynamics (TCM). ANM is a hybrid scheme combining a low-resolution global numerical computation with a high-resolution local analytical calculation to form a composite solution. ANM avoids the subtlety involved in singular integral equations and their numerical implementation. TCM is based on the fundamental integral conservation laws of the aerodynamic flow field, and offers a flow vortex model which has no empirical free parameters. The current implementation does not include free distortion of the vortex. A Mach number weighting scheme is used to account for blade rotation effects as calculations were not done in a rotating reference frame.

Method 5. Full-Potential CFD Method (FPR) and FW-H (WOPWOP)

The incorporation of transonic, three-dimensional effects requires the discretization and numerical solution of some form of the full flow equations. The potential equations are the simplest such equation set, because they only solve for mass conservation with energy conservation being expressed by the Bernoulli equation. The full-potential CFD code, FPR, has been coupled with the WOPWOP code[9] at Sikorsky in order to predict the far-field acoustics of the BVI. These computations use a compact grid of about 46,000 nodes and proceed in time steps of 0.25 degrees. The grid normal boundaries are about 5 chords from the blade surface. The BVI computations are initiated with a steady solution at an azimuth of 90 degrees and the solution then marches to a final azimuth of 270 degrees.

Method 6. Full-Potential CFD Method (FPX) and Kirchhoff

Near-field modeling of the BVI has also been performed using the FPX code (a later development of FPR) at NASA Ames Research Center. The method uses a density-biased central difference discretization that is solved by an approximate factorization scheme. This code employs a blade-fixed, stacked O- or H-grid, with the former being used for the present application. The passing vortex is modeled by inclusion of its specified flow field (including the vortical core) as a component of the total velocity. This component becomes a forcing function to the equation. The specified vortex-induced velocity component also adds a forcing term to the boundary condition - this term, when used alone, is the well-known "transpiration condition". In the present model, the vortex structure is specified and there is no distortion mechanism. This grid is identical to that used for the Method 5 FPR computations and the solution should also be nearly identical. The main difference between FPR and FPX, for the options exercised for the present computations, is that the former requires approximately twice the CPU time.

The Kirchhoff method is used to compute the far-field noise. The surface integral of the non-linear solution in the near-field gives enough information for the analytical calculation of the far-field. Pressures and pressure derivatives from the near-field CFD calculation are interpolated onto a surface that completely encloses the rotor blades.

A rotating Kirchhoff surface, which has the advantage of allowing the use of the same computational mesh as the CFD calculations is typically located several chord lengths away from, and completely surrounds, the blade surface. The Farassat and Myers formulation[8], which allows both rotation and translation of the Kirchhoff surface, is used for the calculations.

Method 7. Euler CFD Method (TURNS) and Kirchhoff

The structured-grid Euler/Navier-Stokes code, TURNS has been applied at NASA Ames, in combination with a Kirchhoff code.

The TURNS code uses Roe's upwind-biasing in all three directions with a high-order MUSCL-type limiting on the right-hand-side. An LU-SGS (Lower-Upper Symmetric Gauss Seidel) implicit operator is chosen. An early version of TURNS was modified by Baeder and Srinivasan to compute the BVI noise of an isolated rotor blade interacting with an upstream-generated vortex. The vortex is incorporated in a quasi-steady manner using a field velocity approach. This modification also permitted the computation of a perturbation about a specified vortex structure without numerical dissipation. The resulting solution is valid for any interaction where the vortex structure is not deformed. The interaction in this study displayed no obvious viscous features and did not require the full Navier-Stokes analysis. Assuming adequate grid resolution, all nonlinear effects on the acoustic propagation were accurately modeled within the framework of the Euler equations.

Method 8. Euler CFD Method (TURNS)

The TURNS code was used at NASA Ames Research Center and the University of Maryland for a comparison of near field acoustics for eight different test conditions. This method used direct computation to obtain pressure time histories and therefore results were only available for the near-field. These computations were completed prior to the selection of a standard vortex model and used a nondimensional vortex strength of 0.35 and a vortex core radius of 0.05.

Methods 9. CFD Methods (TURNS and FPR) coupled with Kirchhoff and FW-H (WOPWOP).

TURNS was also used at Purdue University to compute the aerodynamic field close to the helicopter rotor. In this contribution, a wide variety of methods were used:

<u>9a.</u> TURNS and Kirchhoff with nonstandard vortex model (vortex strength and core; 0.35 and 0.50)
<u>9b.</u> TURNS and Kirchhoff with standard vortex model
<u>9c.</u> FPR and Kirchhoff with standard vortex model.
<u>9d.</u> TURNS and FHW with standard vortex model

Full potential computations using the FPR code to calculate the blade surface pressure distributions were performed to compare to the Euler results. A Kirchhoff surface which rotated with the blade was used to predict far-field acoustics. Acoustic results using the WOPWOP code are also included.

Method 10. Euler CFD Method (TURNS) and FW-H

A similar version of TURNS was used at the University of Maryland to predict the far-field pressure with a FW-H acoustic computation. Unsteady computations with ten Newton-like sub-iterations per time step provide second-order time accurate solutions. A FW-H method similar to that of Method 2 was used to calculate thickness and loading noise in the far-field.

DISCUSSION OF AERODYNAMIC RESULTS

Figures 5 through 12 show a comparison of measured and computed azimuthal surface pressures variations for the basic case (Case 1D) using the following five methods (see Tables 1 and 2):

3. Singularity, boundary element with freely deforming vortex (ONERA)
4. Compressible Singularity method, boundary element (Boeing and Duke)
5. FPR full-potential (Sikorsky)

6. FPX full-potential (NASA Ames)
7. TURNS Euler (NASA Ames)

Most contributions to these comparisons include both aerodynamic and acoustic results. Aerodynamics results are not available for all methods (but obviously were performed, since these are required for the acoustics). Method 7 used the same code (TURNS) as methods 8 - 10, and is therefore representative of all the Euler CFD computations for the same values of vortex core size and circulation. Therefore, only Method 7 aerodynamic results are presented in the paper.

Figures 5 - 12 show the pressure time histories at x/c = 0.02, 0.11, 0.40 and 0.83 for the upper and lower surfaces at 88% radius. (Surface pressures at this radius are typical of those seen at all radii.) The curves are offset to separate the different methods. For these methods, chordwise pressure distributions are also shown and compared with the data in figures 13 – 18.

In comparing the data and computations, it is useful to note that wave behavior is evident in the data. The strongest source of waves is the leading edge region. From this region, an upstream family of waves becomes a major part of the acoustic field that is measured in the far-field microphones. A downstream family is also present and is readily seen in the blade instrumentation. In the data shown here, these waves are seen in two ways: (1) in the pressure-time histories, the chordwise sequencing of the BVI pressure-pulse shows a wavefront. A smaller kink in the pressure (following the primary BVI pulse) then results from this front reflecting back from the trailing edge, and (2) in the chordwise pressure distributions, the upper and lower surface pressures diverge momentarily from each other (producing an unusual load distribution) because their rapidly moving downstream wavefronts are of opposite sign. These two features are seen in both the data and (to various degrees) the computations. These wave features can be seen more clearly for Case 1B (the head-on interaction case) in Fig 19, which is a plot of the chordwise distributed transducer time histories at the 88% radial station. For acoustic applications, the primary region to be predicted is near the leading edge, because this is the strongest source. But the subsequent wave behavior seen on the blade surface is a rarely studied aspect of the blade flow (because it is rarely seen). These waves are the source of high-frequency unsteady blade loads and could be useful in evaluating the behavior of the computational methods.

Method 3

Figures 5 - 12 show that the comparison of the 3A results with data is very good from the leading edge to the trailing edge. The main differences with the data are toward the trailing edge (especially on the upper surface) where the computed BVI pulse occurs sooner than that in the data. This probably results from the fact that the computation is incompressible and all signals propagate at infinite speed. The compressibility correction used does not correct phase errors. (On the lower surface, this phase error is not seen at the rearmost chordwise location. This effect is not understood.) These phase errors are of significance to high-frequency airloads, but not for acoustics, which is primarily determined by the unsteadiness at the leading edge. The comparisons at the primary acoustic generation region near the leading edge are very good. For method 3B, employing the standard axi-symmetric initial vortex structure, the comparisons at the leading edge are not as good. This latter computation shows a tendency to overpredict the peak pressures at x/c = .02. In addition, this model also shows greater deviation from the measured pressures at the end of the BVI-induced pressure jump (on both upper and lower surfaces). This deviation is also seen at x/c = .11. However, at the other chordwise locations the comparison is quite good. The comparisons of chordwise pressure distributions (Figures 13 & 14) do not give a clear picture of the difference between the two vortex models. In general, the pressure–time plots are more sensitive indicators of flow differences than pressure – chord plots. Overall, both of the computations used here are quite good with the non-axi-symmetric vortex model producing the better results.

Method 4

Method 4, the compressible boundary element computations using the standard vortex model, shows very good comparison with the upper surface pressure variations at the foremost chordwise locations, except at the conclusion of the BVI-induced pressure jump (very similar to method 3B). Toward the trailing edge, the computed BVI pulse is noticeably broader than that in the data. On the lower surface the peak BVI-induced pressure slightly exceeds the measured value at $x/c = 0.02$, but underpredicts noticeably at $x/c = 0.11$. All other lower surface comparisons are quite good except for the previously mentioned pulse broadening that occurs toward the trailing edge.

The comparison of chordwise pressure distributions, Figure 15, is very good. The separation of upper and lower surface pressures that occurs at the end of the BVI-pulse (caused by pressure waves of opposite sign originating near the leading edge) is seen to be exaggerated in the computations. As indicated in these figures, the surface element density at the trailing edge is quite sparse.

Methods 5 and 6

Methods 5 and 6, the full-potential computations, also compare well with the data. The upper surface BVI peak pressure is well predicted. The previously mentioned pressure variation overprediction (at the end of the BVI pulse) also occurs here, but with a much diminished amplitude. The lower surface BVI pressure peak is slightly underpredicted. On the lower-surface, mid-chord region (Figure 10) the computed BVI-induced pressure pulse is much sharper than seen in the data. (Actually all of the computations are somewhat sharper in this region, but the effect is more pronounced with this method at this location.) The pressure pulse that occurs near the trailing edge (Figure 12) is well predicted, but the computations then show another pulse of opposite sign that is not seen in the data. This effect appears related to the passage of the vortex past the trailing edge.

The comparison of computed and measured chordwise pressure distributions (Figures 16 & 17) is quite good. The comparisons at and prior to the peak pressure point are excellent. Following this peak point (index 512) there are more differences from the experimental data and this is seen with many of the other methods as well. The differences at this point result from differences between the computed and actual vortex locations. Since the time derivatives of pressure are very high at this point, these small differences in vortex location cause large differences when viewed in the chordwise distributions. Therefore, the differences seen here are not significant. At index 542, the pressure comparison is very good except at the trailing edge. The difference is more emphasized in Method 5, which is probably because of a larger time step being used. This is probably related to the fixed-wake sheet that is used in all standard potential models (analytical or numerical). One would expect this to also occur in Method 4. That this is not seen clearly with Method 4 may be a result of the sparse grid that is used. The comparisons for the leading-edge region, which is the primary acoustics source, is good.

Method 7

Method 7 is the first of three Euler/TURNS results. The Euler results seen in Figures 5 - 12 appear very similar to the previous full-potential results, with the exception that the mid-chord lower-surface pressures match better with the data and the leading-edge pressures slightly underpredict the pressure peaks. The chordwise pressure variations (Figure 18, index 532 and 542) shows a separation of upper and lower surface pressures (occurring at the end of the BVI-pulse) that is similar to that seen with Method 4. This pressure separation is the result of the downstream passage of opposite-sign pressure waves.

The comparison between Methods 6 and 7 (FPX and TURNS) leading-edge pressure variations provides reasonable substantiation of the deduced vortex circulation value. The general agreement between the methods (especially for the initial part of the BVI) and the good agreement with the data indicate that the deduced standard vortex model is adequate for the present purpose.

DISCUSSION OF ACOUSTIC RESULTS

All of the methods listed in Table 2 provided calculations of the acoustic field. Method 8 provided only near-field results (and is not included here), while Methods 6, 7, and 9A - 9C provided only far-field results. Only the far-field comparisons, represented by Microphone #3, are included in this paper. More complete comparisons can be found in Ref 2. The computed acoustic time histories for the various methods compared to the averaged data are shown in Figures 29 – 30. Only a portion of a full revolution near one of the BVI pulses is shown on each figure.

Method 1

Acoustic integrations, based solely on the three outboard spanwise measurement points, underpredicted the acoustic pressures. This was certainly because of the neglect of inboard contributions to the integral. Subsequent computations assumed that pressure was spatially constant between r/R = 0.772 and 0.3. The resulting comparison with microphone data is shown in Figure 20. The acoustic pressure coefficient is now somewhat overpredicted, but has a good pulse width and shape and constitutes a reasonable comparison. It is clear that this approach is effective and is only limited by the amount of available surface pressure data.

Methods 2, 3, and 4

The results for Methods 2 – 4 are shown in Figures 21 - 23. In the far-field (Microphone 3), Method 2 does very well. Method 3B significantly overpredicts the BVI pulse amplitude. When the non-axi-symmetric vortex model is used in Method 3A, the results are much improved with a good match of the pulse amplitudes in the far-field. Method 4 captures the magnitude of the BVI pulse quite well; however, the pulse width and shape are somewhat distorted.

Method 5

The far-field results for Method 5 are shown in Figure 24 and are in excellent agreement with the data. The pulse amplitude and pulse width, as well as the details of the pulse shape correlate quite well with the data.

Methods 6 and 9C

The results for Methods 6 and are shown in Figures 25 and 28. The results are remarkably similar with the same characteristic large negative pulse as well as under-prediction of the positive pulse. Method 9C also includes a second positive pulse of amplitude roughly one third that of the primary positive pulse. Note that while Method 5 uses an identical aerodynamic computation as Method 6, the acoustic predictions differ considerably.

Methods 7, 9A, and 9B

Methods 7, 9A and 9B are shown in Figures 26 and 27. Methods 7 and 9B both utilize the standard vortex model which results in the same blade pressures. The positive pulse is predicted quite well, while a prominent negative pulse, similar to the one observed with Methods 6 and 9C (full potential + Kirchhoff) and not present in the data, is also present. Method 9A, which utilizes a slightly different vortex model, shows some slight improvement in correlation with data over Method 9B.

Methods 9D and 10

The results for Methods 9D and 10, in Figures 29 and 30, show excellent agreement with data in the far-field. Method 9D shows a slight under-prediction of the first negative peak and a slight over-prediction of the second negative peak, while the positive peak is matched very well.

In general, all the methods correlate well with the far-field data, but a number of noticeable differences are seen. The quality of the FW-H acoustic comparisons is directly related to that of the surface pressure comparisons. The CFD methods all compare equally well with the surface pressures and this is reflected in excellent far-field acoustic comparisons. The non-CFD methods also produce very good results, with the indicial method being one of the best. The results from the Kirchhoff methods are more complex. These exhibit a large negative pulse not seen in the data. Moreover, the far-field acoustic results do not correspond as closely with the quality of the surface pressure comparisons. The Euler/Kirchhoff methods (TURNS) produce better comparisons than the potential/Kirchhoff. This may indicate that the CFD far-field accuracy is not simply related to that of the surface solution.

The differences seen here between the Euler and potential/Kirchhoff are not presently understood. It has been verified, for at least one of the potential/Kirchhoff implementations, that these particular solutions are not dependent on the Kirchhoff surface location (for the locations presently used, which ranges from 0.5 to 2.0 chords outboard from the tip). This may not necessary exclude the possibility of an outer boundary condition effect.

Another possibility is that there may be significant differences in the dissipation of pressure waves between these Euler and potential methods. A comparison of Figures 15-18, at time indices 532 and 542, reveal sizeable differences in the previously noted pressure differential between the upper and lower surfaces. The pressure differential for the Euler computation is noticeably larger than that for the potential computation. If these differences carry into the far-field, there could be serious consequences for a Kirchhoff method, which depends on far-field accuracy. Recent progress in Kirchhoff methods may shed further light on these questions. In spite of such questions, it is clear that there is a very good ability to predict the acoustics of parallel BVI.

CONCLUDING REMARKS

This paper has considered a simple parallel BVI interaction and determined that the pressure and acoustic data (together with the inferred vortex model) are a suitable basis for the initial validation of computational models. A user of these data should expect to obtain reasonable comparisons with these blade surface and acoustic data before proceeding on to compute more complex interactions.

Present comparisons with these data use a variety of indicial, boundary-element and CFD methods to predict the aerodynamics and these are combined with FW-H or Kirchhoff methods for predicting the acoustics. Most of these methods employed a common, fixed vortex form and trajectory. All the methods predict the important blade surface pressure characteristic features of the interaction including the initial pressure jump followed by a downstream moving wave that reflects upstream from the trailing edge. This primary pressure jump (which occurs when the vortex is adjacent to the leading edge) is well predicted by all methods in this study. The evident wave behavior in the near-field is unusual and indicates a degree of unsteadiness that far exceeds that found in most flows for which the aerodynamic methods are normally used. Under these conditions it is not surprising that differences do occur in some of the computational results. These differences occur mainly *after* the primary pressure jump, which appears to be the primary event of acoustic importance.

Differences do occur between the various acoustic computations. Generally, excellent results were obtained using the FW-H (for all aerodynamic methods). A greater variability of results was obtained from the Kirchhoff methods. One should note that the present interactions show no sign of nonlinearity (shocks). Higher speed cases involving flow nonlinearity were not performed in this test.

The present comparisons required a vortex model whose structure had to be inferred from a combination of testing (in another facility) and computations. The resulting axi-symmetric vortex model in these comparisons is unlikely to have been a complete description of the actual vortex structure as it interacted with the blades. In fact, one of the present methods did employ a non-axi-symmetric vortex model (in addition to the standard model) and did obtain improved results. At this point it cannot be positively said whether such differences are a result of the vortex model or the solution implementation. Clearly, there is much work to be done in the area of determining the actual vortex structure. These vortex structural considerations are especially important for direct ($Z_v/c = 0$) interactions. The present vortex model gives acceptable results with all methods and should be considered to be, at least, a good starting point for future validation computations based on this data.

One of the most interesting results obtained is the fact that the simplest methods worked so well compared to far more complex models. Of course, the present BVI is intrinsically simple and only acoustic applications are being considered. Full rotor-wake computations wherein loads and performance must be predicted (in addition to acoustics) cannot be expected to yield so easily to the simplest approaches.

Overall, excellent results were obtained, indicating that a significant capability exists to predict the BVI interaction and its acoustic implications. This does not imply, however, that the acoustic problem is solved. In this test the vortex location was well known and the vortex structure was fairly well-defined. In a full rotor computation, these are not known to a great degree of accuracy and the ability to predict these is probably the greatest challenge for the future.

REFERENCES

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McCormick, B. W., and Surendraiah, M., "A Study of Rotor Blade-Vortex Interactions" The 26th Annual Forum of the American Helicopter Society, Washington, D.C., June 1970.

Caradonna, F., Kitaplioglu, C., McCluer, M., Baeder, J., Leishman, G., Berezin, C., Visintainer, J., Bridgeman, J., Burley, C., Epstein, R., Lyrintzis, A., Koutsavdis, E., Rahier, G., Delrieux, Y., Rule, J., Bliss, D., l "A Review of Methods for the Prediction of BVI Noise" AHS Technical Specialists' Meeting, Williamsburg, VA, October, 1997.

Kitaplioglu, C. and Caradonna, F. "Aerodynamics and Acoustics of Blade-Vortex Interaction Using an Independently Generated Vortex" AHS Aeromechanics Specialists Conference, San Francisco, CA, January 1994.

McAlister, K. W., and Takahashi, R. K., "NACA 0015 Wing Pressure and Trailing Vortex Measurements," NASA TP 3151, November 1991.

Watts, M.E., "ALDAS User's Manual", NASA Technical Memorandum 102831, April 1991.

Kitaplioglu, C. and Caradonna, F. "A Study of Blade-Vortex Interaction Aeroacoustics utilizing an Independently Generated Vortex" AGARD Symposium, Berlin, Germany, October 1994.

Ffowcs Williams, J.E. and Hawkings, D.L., "Sound Generation by Turbulence and Surfaces in Arbitrary Motion," Philosophical Transactions of the Royal Society, Vol. 264A, 1969, pp. 321-342.

Farassat, F. and Myers, M.K., "Extension of Kirchhoff's Formula to Radiation from Moving Surfaces," Journal of Sound and Vibration, Vol. 123, No. 3, 1988, pp. 451-461.

Brentner, K.S., "Prediction of Helicopter Rotor Discrete Frequency Noise" NASA TM 87721, October 1996.

Farassat, F.; and Succi, G.P.: "The Prediction of Helicopter Rotor Discrete Frequency Noise" Vertica, Vol. 7, No. 4, 1983, pp. 309-320

Leishman, J.G., "Subsonic Unsteady Aerodynamics Caused by Gusts Using the Indicial Method" Journal of Aircraft, Vol. 33, No. 5, Sept.-Oct. 1996.

Leishman, J.G., "Aeroacoustics of 2-D and 3-D Blade Vortex Interaction Using the Indicial Method" The 52nd Annual Forum of the American Helicopter Society, Washington, D.C., June 1996.

Leishman, J.G., "Acoustic Focusing Effects During Parallel and Oblique Blade Vortex Interaction" Journal of Sound and Vibration, Vol. 221, No. 3, April 1999, pp. 415-441.

G. Rahier, "Modelisation de l'interaction profil tourbillon en fluide parfait et application au rotor d'helicoptere" La Recherche Aerospatiale (with abridged version in English), No. 4, pp. 241-252, July 1995.

P. Spiegel, "Prevision et analyse du bruit emis par un rotor principal d'helicoptere en presence d'interactions pale-tourbillon" ONERA Publication 1996-1, February 1996.

Rahier, G., and Delrieux, Y., "Influence of Vortex Model in Blade-Vortex Interaction Load and Noise Predictions," American Helicopter Society Technical Specialists' Meeting for Rotorcraft Acoustics and Aerodynamics, Williamsburg, VA, October 1997.

Epstein, R.J., Rule, J.A., and Bliss, D.B., "A Novel Method for Calculating Two-Dimensional Blade Vortex Interactions," AIAA Journal, Vol. 35, No. 5, May 1997.

Rule, J.A. and Bliss, D.B., "Prediction of Turbulent Trailing Vortex Structure for Rotorcraft Blade-Vortex Interaction," Proceedings of the 51st Annual Forum of the AHS, Fort Worth, Texas, May 1995.

Tork, M. and Berezin, C., "Aerodynamic and Wake Methodology Evaluation Using Model UH-60A Experimental Data," Journal of the American Helicopter Society, Vol. 39, No. 2, April 1994.

Bridgeman, J.O., Ramachandran, K., Caradonna, F.X., and Prichard, D.S., "A Computational Analysis of Parallel Blade-Vortex Interactions Using Vorticity Embedding," 50th Annual Forum of the American Helicopter Society, Washington, DC, May, 1994.

Strawn, R.C., Biswas, R., and Lyrintzis, A. S., "Computation of Helicopter Blade-Vortex Interaction Noise with Kirchhoff Methods," IMACS Journal of Computational Acoustics, Vol. 4, No.3, Sept. 1996, pp. 321-339.

Srinivasan, G. R., and Baeder, J. D., ``TURNS: A Free-Wake Euler/Navier-Stokes Numerical Method for Helicopter Rotors,'' AIAA Journal, Vol. 31, No. 5, May 1993, pp. 959--962.

Srinivasan, G. R., ``A Free-Wake Euler and Navier-Stokes CFD Method and its Application to Helicopter Rotors Including Dynamic Stall,'' JAI Associates Inc., TR 93-01, November 1993.

Baeder, J. D., and Srinivasan, G. R., "Computational Aeroacoustic Study of Isolated Blade-Vortex Interaction Noise," presented at the AHS Aeromechanics Specialists' Meeting, San Francisco, CA, January 1994.

McCluer, M. S., "Helicopter Blade-Vortex Interaction Noise with Comparisons to CFD Calculations," NASA Technical Memorandum 110423, December 1996.

Lyrintzis, A. S., Koutsavdis, E. K., and Strawn R. C., "A Comparison of Computational Aeroacoustic Prediction Methods," Journal of the American Helicopter Society, Vol. 42, No.1, Jan. 1997, pp. 54-57.

Xue, Y. and Lyrintzis, A.S., "Rotating Kirchhoff Formulation for 3-D Transonic Blade-Vortex Interaction Hover Noise," AIAA Journal, Vol. 32, No. 7, July 1994, pp. 1350-1359.

Khanna, H. and Baeder, J.D., "Coupled Wake/CFD Solutions for Rotors in Hover," 52nd Annual Forum of the American Helicopter Society, Washington, DC, June 1996.

Singer, B.A., Brentner, K.S., Lockard, D.P., and Lilley, G.M., "Simulation of Acoustic Scattering from a Trailing Edge," Journal of Sound and Vibration, Vol. 230(3), February 24, 2000, pp. 541-560.