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Emerging Computational Tools for Flow Acoustics

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Abstract.

This lecture is a survey of multiple on-going efforts in the United States, largely sponsored by the Office Of Naval Research, that are devoted to the development of prediction methods for flow-generated sound. This research is meant to develop methods that are useful in future engineering applications that could involve complex three-dimensional geometries, high Reynolds number fluid mechanics, flow-induced vibration, and finite Mach number. This paper will focus specifically on development of tools for the calculation of forcing functions and on efforts to systematically validate them in anechoic wind tunnels. The slides that are discussed herein form a complete description of work as currently undertaken at the David Taylor Model Basin of NSWC-CD and its collegiate organizations.

1.0 Introduction.

As currently configured we are focussing on flow dipoles and flow-induced vibration. These methods are being integrated into a prediction system that evaluates the flow, the flow-induced forces on the surfaces, the vibration, and the sound from both flow dipoles and vibration. By necessity, the physics of such problems is multi-faceted and it is useful to develop the prediction system as a modular tool with component algorithms all interconnected by an object-oriented central integration node that imports, interconnects and exports the relevant flow-structural-and acoustic behavior parameters of interest. This tool is necessarily modular with computational components that are newly developed or "borrowed" from other applications. "Other applications" include the use and extension of some methods also being developed under joint NASA and ONR funding. Of many developmental challenges, one of the larger challenges is the definition of flow excitation pressures that either drive a structure or constitute the dipole sources. This lecture will focus on that aspect of our development. Specifically, the essential differences and common areas of aeroacoustics and hydroacoustics will be discussed. The common areas relate to the definition of flow-generated fluctuating pressures on the surfaces; we will discuss these as both narrow band and broadband sources. We will pay particular attention to the experimental verification of components that predict forcing functions. Examples will be given of aeroacoustic measurements of rotor – stator interaction dynamics in compressor elements, and the dipole sound generated by the trailing edges of lifting surfaces. See Slide 2.

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Slide 3 is a partial list of the many organizations and co-investgators that have been contributing to the project as well as to this paper over the last three or four years. As identified in Slide 4, the potential application of the methods that are discussed in this lecture is rather broad. Nearly all the work that is reported in this lecture has been funded by a variety of programs that are or have been overseen by Dr. L. Patrick Purtell of ONR.

As currently modelled in the prediction methods that we will be discussing, the physics of flow induced sound is linearized. This means that flow-acoustic and structural acoustic instabilities are not included in the models. Sources are the result of linearly – driven fluid – structure systems in which the flow sources are unaffected by adjacent surface motion or near – field fluid pressures. Strictly acoustic interactions are included in the form of effects of mean flow convection and structural-acoustic fluid loading impedances. Thus, as listed in Slide 5, the modelling can be modularized, as we will discuss, under the assumptions listed in Slide 6. One of the most important assumptions is that of low-enough Mach number that acoustic loading of the flow sources does not occur. This allows us to use incompressible modelling of the flow, while still considering the complexities of three dimensionality and possible flow – driven surface motion.

2.0 Overview Of The Components Of The Prediction Approach For Low Mach Number.

Slides 7 through 10 provide an outline of the way we have structured the approach to modelling dipole sound from flow–driven surfaces that may be rigid or elastic. If we were to base our approach on the potential benefits of space-time accurate modelling of turbulent flow over rigid surfaces, as made possible with Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES), then we would determine the blocked flow sources and surface pressures that are developed by the flow-surface interaction. The results of such computations would then be used in a pre-processor to the acoustic, or vibro-acoustic, calculation of the vibration or sound. This process is illustrated in Slide 7 which also lists some practical limitations to using it as a general engineering tool. The method has been used by the Stanford group (Moin, Wang) to model trailing edge dipoles and turbulent boundary wall pressure at low wave numbers (Chang, Piomelli). The trailing edge modelling is being verified with detailed flow-acoustic measurement programs at University of Notre Dame (Mueller) and U. Michigan (Ceccio).

For engineering application, we currently need approaches that require less computationally-intensive methods than LES and DNS and that provide shorter "turnaround" time. These approaches are built on steady flow Reynolds Averaged Navier Stokes (RANS) solutions, hybridized RANS-Statistical methods or RANS-embedded LES techniques, and 2-dimensional and 3-dimensional Euler methods. We will return to specifics in the flow modelling in later slides, so that we can continue discussion of the overall approach here. As shown in Slide 8, once the surface geometry is defined, the RANS-based prediction can provide models of flow-excitation surface pressure that are based on turbulent kinetic energy and mean velocity profiles (by methods to described later). If needed, the turbulence integral scale can also be derived from the calculation. With a Green's function, or simple transfer function, that is based on a description of blocked sources or surface pressures, we can calculated the sound from the rigid body. If the surface is acoustically compact, this function can be as simple as a calculation of the net dipole force and the well-known relationship for the acoustic dipole. It may also be more complex for extended non compact surfaces or cascades of turbomachinery blades. This would be an approach one would use for the areoacoustics of compressor blades, for example.

The approach that can be used for flow – induced vibration and resulting sound is analogous, as shown in Slide 9. The acoustic functions for sound from rigid bodies are replaced by a Finite Element Model-based approach that develops the sound field as a modal expansion using *invacuo* modes as basis functions. The mode shapes are numerically convolved with the values of blocked pressure. These values are modelled as correlation functions for the flow statistics, that are based on computation, analytical regressions, and models extracted from bodies of experimental data. Often, these descriptions can be as simple as an algebraic step that involves the use of spatial correlation areas and spatial correlation lengths. This is especially the case when wave lengths of vibration and sound are longer than the spatial scales of the flow –induced drivering pressures. Slide 10 brings the aeroacoustic ("direct dipole") sound and the vibration-induced sound together as a superposition of sources.

The common areas of hydro- and aero-acoustics thus involve low Mach number flow dipoles and the definition of forcing functions that describe the magnitudes and spatial scales of surface pressures, as shown in Slide 11. What makes hydroacoustics and aeroacoustics differ is the lack of quadrupole source mechanisms in hyderoacoustics and the general unimportance of vibration and vibration sound in aeroacoustics. Of course, two phase flow noise involving bubbly media and cavitation are also absent in aeroacoustics. The remainder of the lecture will discuss the common areas: the forcing function modelling and verification of predictions, see Slide 11.

3.0 Example Area 1. Rotor- Stator Sound And Interaction Flows Of Turbo-Machinery.

3.1 Response Of Rotors To Inlet Turbulence: Utility Of Simple Strip Theory At Low Mach Number.

Slides 14 through 22 address the verification of prediction models for turbulence ingestion noise. In this work the anechoic wind tunnel at the Hessert Center of the University of Notre Dame under the direction of T. Mueller is being used to produce sound from propellers downstream of rectangular grids, see Slide 19. Strip theory is used to calculate the turbulence induced broadband forcing spectrum. The key element of this modelling is the description of the turbulence spectrum which is nearly homogeneous, see and Wojno et al (2001). Slide 20 shows calculated frequency-dependent radial and tangential correlation lengths of the grid-generated gust. These functions were obtained by integrating the Liepmann spectrum (Slide 16) with coordinate stretching that accounts approximately for slight anisotropy in the radial and tangential directions at the inlet plane of the propeller.

The Slide suggests that about 2 to 3 dB uncertainty may be caused by slight anisotropy alone. Slides 21 and 22 show that the strip theory, the Liepmann spectrum for the turbulence, and measured coefficients for the turbulence wave number spectra provide excellent agreement with measured spectra of sound. The broad humps in the spectra (near 600 Hz for the 10 blade propeller and near 250 Hz and 500 Hz for the 4 blade propeller) are due to blade-blade correlation of the flow - induced forces. This correlation is due to tangential correlation lengths of the inflow turbulence which are at least on the order of the spacing of the blades. This point shall be discussed further below. Slide 23 compares a strip theory of Blake(1986) with that of Martinez (1996). The latter best applies when the radial correlation length of the turbulence is comparable to, or larger than, the length of the blades (here satisfied at low frequencies) and the number of blades is large. Blake's theory is applicable best when the radial correlation length is smaller than the span of the blades (here satisfied at moderate frequencies), but with an arbitrary number of blades.

One of the focus areas in the recent work is in the development of inversion methods (see Minniti et al (1986))by which we measure the time-dependent pressure response of blades to turbulence to infer the spectrum and correlation lengths of the inflow turbulence. Such approaches are particularly important for applications where the blades may be instrumented and direct flow measurement is not possible. The method is noninvasive and allows the *insitu* rotor dynamics to tailor the flow. Slides 24 through 27 present results of validating the inversion technique in the grid-generated propeller response. In this method, the propeller is instrumented with arrays of pressure sensors that respond to the gust – driven surface pressures on the blades. The sensors are arranged along the chord at a fixed span location and along the span the leading edge near (i.e. at a fixed percentage of local chord) in a "Tee" pattern. Linear airfoil theory is used for inversion; Sears' function for broadband turbulence ingestion and Filotas' function for periodic coherent gusts induced by the time – mean wakes. Slide 25 shows a comparison of the spectrum of the grid-generated turbulence that was developed in the rig that is illustrated in Slide 19. The turbulence wave number spectra are normalized on the mean velocity as a function of the convective wave number normalized on mesh spacing. Three measurements are shown: an average of spectra measured at points by a fixed hot wire anemometer probe, a spectrum measured in the rotation frame by a probe fixed to a blade of the propeller, ant a spectrum that was obtained by inversion of the surface pressure. The inflow had a small-magnitude distortion in the mean velocity that had a time-mean spatial pattern. This component was sensed by both the spinning anemometer and by the inverted surface pressures on the rotating blades and would show up in the spectrum as tones at blade passage frequency; these have not been plotted in Slide 25.

In order to measure the resultant coherent rotor response, a pressure sensor is installed on each blade at the same relative spanwise and chordwise location. The summed pressure at that radius is proportional to and represents the thrust loading, as thrust per unit span, at that radius. The ratio of the spectral density of summed pressure on all B blades to the average of the spectral densities of pressures at all locations on the individual blades is going to be B to B^2 depending on whether or not the gusts at the blades are fully uncorrelated or fully correlated, respectively. We call this ratio the "Array Gain" of the blade row to turbulent inflow because of its analogy to the array gain of signal processing of acoustical arrays in non-isotropic noise fields. In Slide 26, the propeller had 4 blades so the "Array Gain" should be between 4 and 16; the spectrum shown to the right shows that the turbulent flow "Array Gain" is 4 to 8 while the response to tones generated by the steady time-mean inhomogeneities in the inflow approaches 16. The frequencies of these maxima are determined by the blade spacing and the resultant relative velocity of the blades. Thus the peaks are centered just to the right of the blade passage frequency by a ratio U_s/U_θ. The equation on the slide shows how, to first order, the approximate value of the *tangential* correlation length of the incomming turbulence can be extracted from the "Array Gain". The *radial* (or spanwise) correlation length can be extracted from the coherence that is measured between the summed surface pressure and the far field sound. This is illustrated in Slide 27 which shows the redial correlation length of the inflow turbulence as a function of convective wave number normalized on mesh spacing. The correlation length is normalized on the mesh spacing. To compare Slides 20 and 27 we take note of the fact that $\Lambda/M = 1/4$ for the grid that was used. This note taken, we see that the radial correlation lengths aerodynamically measured agree well with that inferred from the coherence between the surface and far field pressures.

The results of these studies show that the use of strip theory at low Mach number gives excellent agreement with the measured response of propellers to turbulence. Blade to blade correlation of the forced response provides enhancements to the spectra of dipole sound. The center frequencies of these peaks are just to the right of the blade passage frequency as determined by the blade spacing and the aerodynamic pitch of the blades. This is because the encounter velocity of the blades with the turbulence is the resultant of the axial and rotational velocity. The results also verify the utility of the inverse technique for measuring the inflow distortions, the turbulence spectrum, and the correlation lengths. In this regard, the inverse method with instrumented blades behaves as a dynamic "probe" whose calibtration factor is the gust response function for the blades. The method can be used to obtain inflow profile surveys in cases that do not premit the installation of invasive probes of Laser probes. To first order the classical Liepmann spectrum provides an adequate "fit" to measured wave number spectrum of the grid-generated turbulence, as expected.

3.2 Cascade Effects And The Influence Of Finite Mach Number On Turbulence Ingestion Noise.

The cascade effects on the response of blade rows to inflow distortions are of interest at low frequencies and moderate Mach number. Two linearized cascade codes are being integrated into our prediction tool: "LINC" and "CASGUST". Both of these codes are being developed at the University of Notre Dame by H.Atassi, see e.g. Abdelhamid and Attassi (2000). They are frequency-domain Euler models for compressible flow and they provide lift response to a specified upstream gust that is defined in three dimensional wave number space. LINC is written for an infinite cascade of unloaded flat blades of vanishing thickness. CASGUST is a compressible flow model of an infinite cascade of blades with arbitrary loading and thickness. Slide 30 shows some integral equations that express the utilization of either of these codes as kernel functions, C(**k**), that provide the spectrum of lift per unit span. One of the spectral models of the inlet gust is the Liepmann spectrum of Slide 16. Figure 31 provides contour maps of $|C(\mathbf{k})|^2$ for each of these codes for a cascade of NACA0012 airfolils at zero mean load and 45° stagger. Both wavenumbers k_1 and k_2 are normalized on half-chord. Superimposed on the contour maps are lines for the various orders of resonances that satisfy the equation

$$k_2 C/2 = \frac{C/S}{2\cos\gamma}\left[2\pi\cdot n-(k_1 C/2)\cdot\left[\tan\gamma\pm\left(\frac{2S\sin\gamma}{C}\right)\cdot\left(\frac{M}{\sqrt{1-M^2}}\right)\right]\right]$$

where M is Mach number, C is chord, S is the nose to nose slant distance along the stagger line, γ is the stagger angle, k_1 and k_2 are the streamwise and stream-normal wavenumbers, respectively, and n is the harmonic order of the interblade phase angle.

At the intersections of these lines the contours show relative maxima which are caused by reinforcements of upward and downward propagating waves. These represent non-propagating acoustic "modes". Slide 32 shows that these regions of acoustic coincidence are also responsible for slight "humps" in the strip theory spectrum of turbulence-induced lift fluctuations. Slide 33 shows that as Mach number is decreased the value of k_1 for coincidence increases, Slide 34 illustrates the associated effect on the spectrum of turbulence-induced lift fluctuations. The "humps" in the spectra shown in Slides 32 and 34 are analogous to those shown in the experimental data of Slides 21 through 23, but not due to the same phenomena. A careful examination of Slide 33 will disclose a series of peaks (dots) in the contours. Note especially those for the LINC calculation. Those dots are singularities that are associated with the inter-blade resonances and they represent the "Array Gain" of infinite values of the infinite cascade that are the result of the coherent summation of lifts on an infinite array of blades. Thus in a cascade of a *finite* number of blades at *finite* Mach number we expect the peaks that are caused by the blade to blade correlation. However, because of the pair of resonance conditions we expect this broadening to be increased over a wider frequency range, but the levels not to be increased. As indicated in Slide 33, as Mach number decreases the two conditions converge to one line at vanishing Mach number.

3.3 Flow Into And Sound Caused By A Stator Behind An Upstream Rotor.

Slides 35 through 40 examine the response of a downstream stator to the wakes of the blades of an upstream rotor. The interaction is due to the time mean wake defects and turbulent flow that is shed. The general experimental setup has already been discussed, here we note the additional strut that represents a two-blade stator. Propellers with 4, 10, and 20 blades were used. Slide 36 gives the general picture of the results, see Lynch (2001), for a complete discussion. The top view on the left is the map of rms turbulence level that is measured downstream of the rotor and at the location of the leading edge of the stator, but without the stator installed. The spectrum of turbulence that is generated by the grid upstream of the rotor is given by the black line. The light blue spectrum is that of the total turbulence in the rotor wake averaged over circumference and including both the blade wakes and the grid-generated turbulence that is passed through the propeller. The spectrum in red is the spectrum of the turbulence the blade wakes only, averaged over the circumference. The spectrum generated by the blade wakes was measured behind the propeller without the grid. The dark blue spectrum is the spectrum of the grid-generated turbulence that is obtained by subtracting the component due to blade wakes from the total circumferentially-averaged spectrum. The illustration on the right simply illustrates the color coding. Careful examination of the data will disclose that the integral scale of the turbulence has been reduced by the action of the propeller. The approximate values of the turbulence integral scale that have been extracted from the spectra are tabulated in Slide 37.

Slide 38 provides a study of the sound that is radiated by the stator alone. Two cases are shown: one without the turbulence-generating grid, the other with the turbulence-generating grid. Without the grid, in the so-called "clean" flow, the spectrum is characterized with a vortex-shedding sound, the remaining part of the spectrum is nominally dominated by the facility background. When the grid is installed, the sound levels are increased for frequencies above approximately 400 Hz. The inflow turbulence creates disorder in the vortex shedding so that the vortex shedding peak is reduced in level and broadened. The dark curve with diamond symbols is the sound level that is calculated with a strip theory (see Blake(1986)) and the measured spectrum of the turbulence. Slide 39 shows that the turbulence created by the rotor blade wakes elevates the broadband spectrum for frequencies above 1000 Hz. Slide 36 shows that this is to be expected in this frequency range. The blade tones are due to the interaction of convected mean wakes into the stator. The broadband and narrow band character of the spectrum can be predicted from the measured flow. Finally, Slide 40 shows the stator-generated sound, the rotor-generated sound (the calculation of which was previously discussed with Slide 21), and the measured composite spectrum..

3.4 Distortion Of Convected Vortical Wakes By Swirl.

In turbo-machinery the mean swirl of the mean flow downstream of a rotor causes a relative growth of the vortical wakes that are shed from the stators, see e.g. El-Hadidi et al. (2000). The governing parameter for the evolution of the wake distortions is the radial gradient of the swirl velocity expressed in the dimensionless form of the Rayleigh stability parameter that is defined at the top of Slide 42. The analysis constitutes the solution of eigenfunctions for a linearized Euler equation for the convected modes of the flow. For moderate Mach numbers, say order 0.3, both pressure and vortical disturbances are solutions to the equations of motion; for low Mach numbers the convected vorticity modes are the only relevant solutions since their wave numbers are well-removed from the aclustic wave numbers of the acoustic modes. Thus here we devote our attention to the convected vorticity modes. These wake-driven modes are convected into the downstream stator row and cause blade passage tones that are analogous to those shown previously in Slide 40. The initial conditions are imposed on the problem in the form of a unit-amplitude axial velocity distortion that can be expanded into circumferential harmonics, see Slide 42. Slide 43 shows profiles of axial and radial velocity components along the radius and at a sequence of axial stations downstream of the rotor in a cylindrical duct. For linearly "stable" convection the mean swirl velocity increases with radius and the growing axial velocity-fluctuations grow for a time, but stabilize to a constant value that is somewhat larger than the initial condition. Relatively "unstable" convection occurs when the mean swirl velocity decreases with radius. The convected axial velocity fluctuations continue to grow with distance downstream of the rotor.

This theory is being validated in a measurement program at the Johns Hopkins University under the direction of J. Katz. Slide 44 illustrates the type of data that is being collected using particle image velocimetry. A specially designed test rig was designed by co-workers H.Atassi (UND) and Y.T.Lee (NSWCCD) in order to provide both positive and negative stability parameters. The blades are made of plexiglass and the fluid is a concentrated solution of Sodium Iodide in water to provide an ingeneous method of rendering the blades invisible to the green light Laser. This allows a mapping of the fluid dynamics without shadowing by the blades. The objective is to measure the convected wake harmonics and compare with the predicted values. The measurements will include both mean and turbulent velocities.

3.5 Three Dimensional Effects In Gust Response Of Blade Rows.

In a new direction, we are examining the effects of spanwise variability in three dimensional cascades. Slide 45 is shown the spanwise variation of calculated lift coefficient due to a circumferential harmonic of order m=15 of a transverse gust that is incident on an 8 blade stator. The value of k_2 is m/r and narrowly varies between m/r_t and m/r_h in this problem of coherent gust incidence. Two cases are shown; the left hand side applies to a frequency that is below the cylindrical duct cut-on frequency, that on the right applied to a frequency that is just above the cut-on frequency for plane-wave propagation. In both cases the blades are of zero thickness and unloaded. The strip theory using LINC predicts a duct cut-on mode even when it is not predicted by the three dimensional theory. Above the cut-on frequency of the duct, LINC predicts a second order cut-on mode while the linear three dimensional theory predicts a first order plane wave mode. Outside the near-singularity at cut-on of acoustic duct modes the strip theory gives a good simulation of the three dimensional solution. At very low Mach number, then, we expect that the strip theory as implemented in the preceding Slides will continue to provide suitable solutions.

4.0 Example Area 2: Dipole Sound Of Trailing Edges.

The project is addressing the sound from trailing edges at two levels of computational sophistication. The first approach is a hybrid method that uses steady flow Reynolds Averaged Navier Stokes solutions to calculate the time mean flow everywhere in the domain of interest. Such solutions are now commonly obtained at the Reynolds Numbers and geometric complexity of many engineering applications. They provide turbulent kinetic energy, time mean turbulence dissipation, mean velocity profiles, and surface pressures. Statistical models of the turbulent sources are then used to model surface pressures and analytic functions are used to use these spectra to calculate the trailing edge sound, see Blake, Lee, Zawadzki (1998).

Slides 47 and 48 outline the overall conditions and analytics of the method. The challenge is to use the RANS solutions to develop the surface pressure spectrum and correlation scales that are identified in the Slide 48. We currently use the model of pressure fluctuations that involves the mean shear turbulence interaction (MST) sources in the turbulent boundary layer. A recent large eddy simulation (Chang, Piomelli, Blake(1999)) suggests that the turbulence-turbulence (TT) interaction pressures are proportional to the mean shear turbulence (MST) interaction pressures. THus, calculation of the total spectrum may be based on the calculation of the MST component with a small multicative constant correction. In the RANS-Statistical approach, the modelling of fluctuating wall pressure is as sketched in Slides 49 through 52. In essence, RANS solutions are used for the local time mean turbulence intensity and mean shear across the boundary layer on the three dimensional surface. Analytical functions with empirical coefficients are used to express the local statistics of the pressure sources. These functions are used for the wave number spectrum of vertical component turbulent velocity fluctuations, the length scale for those spectra, and a function that describes the turbulent velocity correlation in at different wall-normal coordinates. Examples of these are shown in Slides 53 and 54. This modelling was first tested to cakculate a locally homogeneous wall pressure field statistics in the plane of the surface. Slide 55 illustrates how well the modelling accounts for pressure fluctuations beneath a turbulent boundary layer on a flat plate. Slide 56 shows that the calculated sound level that is obtained with these spectra and with the equations on Slide 48 agrees well with measurements.

In a related study that is being conducted at the Center for Turbulence research at the Stanford University, Large Eddy Simulation is being used to calculate the sound from trailing edge flow. Slides 57 and 58 respectively give maps of the turbulent Reynolds stresses in the vicinity of the edge and a series of wall pressure spectra. The calculated wall pressure spectra are compared with measured values in Slide 58. Slide 59 shows the calculated spectrum of far field sound compared with measurements made on a similar airfoil in the Anechoic Flow Facility at NSWCCD in the mid 1970's (See Gershfeld, Blake, Kniseley (1988)). Several limitations prevail regarding the comparisons shown here between calculation and measurement. There were no flow measurements with which to define the boundary conditions for the simulation which could only examine the turbulence in a control volume situated near the edge. Time mean surface pressures were not measured at enough locations on the experimental airfoil to determine the mean lift on the surface. Radiated sound measurements did not accompany the flow measurements. Thus a combined computation and verification measurement program is being undertaken on a new lifting surface in a combined program at NSWCCD, the Stanford University, the University of Notre Dame, and the University of Michigan. Two dynamically-similar flow models will be examined experimentally and computationally in air and in water. LES, and RANS-Statistical model predictions will be made of the wall pressure statustics, flow induced dipole sound, and surface vibration. All calculations will be consistent in the flow-source modelling that is used. Measurements will include mean and turbulent flow, surface pressures in air and water, flow induced vibration in water, and flow induced trailing edge sound in air. As facility constraints permit, details of acoustic source physics will be obtained with which to test the flow modelling. In essence, this program will test the complete computational framework that is laid out in Slides 5 through 11.

We anticipate that these are the first steps in developing and verifying the prediction of edge-related flow dipoles using some mix of RANS Statistical method and LES-based acoustic predictions. We are just beginning to consider ways of modelling the flow dipoles of tip flow (see Slide 60), flaps, and lift augmentation flows.

5.0 Conclusion.

With the development of modern computational resources, we are having considerable success in calculating the flow-induced sound and flow-induced vibration in many engineering applications. The focus presented here has been on the prediction of flow-induced forcing functions for aeroacoustic dipoles and flow-excited vibration. The latter is of interest in hydrodynamic applications. While computations that are based on LES and Direct Numerical Simulation are possible for some idealized and special-purpose applications, hybrid methods are being developed for near term engineering applications.

Experimental verification of each step in the prediction process has been and is being given major consideration. Systematic verification that involves the use of signal processing techniques, substitution experiments, and special – purpose models are all being integrated in an program of development of prediction techniques.

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