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NUMERICAL STUDY OF SOUND GENERATION BY VORTEX INDUCED FLEXIBLE WALL VIBRATION

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Abstract

A numerical viscous/inviscid coupling approach for the calculation of an acoustic field is applied to the case of sound radiation due to unsteady interaction between an inviscid vortex (which models a turbulent eddy) and a finite length flexible boundary. Based on the unsteady hydrodynamic information from the known incompressible flowfield, the perturbed compressible acoustic terms are calculated. Calculated results are compared with analytical solutions obtained by the method of matched asymptotic expansions. Results suggest that the monopole field created by the volumetric flow induced by the vibration flexible boundary dominates the overall acoustic power radiation. The longitudinal dipole directly due to the transverse vortex acceleration is only important when the vortex is moving over the flexible boundary. This investigation verified the applicability of the viscous/inviscid approach to flow structure-acoustic interaction and it is possible to expand the current research to the complicated interaction between flow turbulence and sound in a duct silencer, therefore, to provide information on the future development of low self-noise and efficient duct silencers.

INTRODUCTION

Computational aeroacoustics, which is the science of noise generation and propagation through airflows, is a relatively young discipline compared to other more classical fields of mechanics. Typically, in aeroacoustics the solutions can be grouped into frequency-domain solution and a natural variables (x,t) solution. Within the aeroacoustics field using natural variables, the different approaches can be categorized into three groups.

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The first group makes use of the acoustic analogy. This group of approaches can compute noise directivity on the ground in an economical way, because in the far field the flow is actually uniform. However, all of the acoustic analogies are based on a variety of assumptions such as compact source and low Mach number. Acoustically compact sources (including a vortex) mean that the size of the acoustic source is much smaller than the wavelength of the acoustic waves. In fact, in many practical cases, the wavelength of generated acoustic waves is comparable to that of the vortices. The advantage of numerical simulation is that this compact source assumption is not needed.

The second group of approaches is to make use of direct numerical simulation (DNS), where both the fluid motion and the generated sound are directly computed by means of the Navier-Stokes equations. One of the advantages of DNS is its capability to compute the generation and propagation processes without suffering from restrictions such as low Mach number, high Reynolds number and compactness of the source region. However, from DNS it is difficult to distinguish pressure fluctuations from sound generation as the acoustic perturbations are typically at least 10 times weaker than the corresponding hydrodynamic perturbations.[1]; Furthermore, DNS requires tremendous computational resources and due to limitation of computer resources, it is difficult to compute propagation over long distances and therefore this approach is preferable to study near-field acoustics[2].

The third group of approaches is to make use of acoustic/viscous splitting method that is based on the expansion about incompressible flow (EIF) approach which proposed by Hardin and Pope[3] , and later expanded to compressible and unsteady mean flow by Shen and Sorensen[4] .This approach splits the direct simulation approach into a background flow problem and a perturbation problem, and does not allow for acoustic backscatter into the flow solution. It makes possible computation of aeroacoustic noise generation and propagation by viscous, unsteady, non-uniform flows in complex domains that pose substantial advantage over the first group of methods. Furthermore, compared with the acoustic analogy theories, the sound strength is obtained directly and that it accounts for sound radiation as well as scattering by this approach.[2]. On the other hand, the computing cost required is much smaller than that for the CFD solution of the time-dependent subsonic flowfield. In this paper, this approach is applied to calculate the sound generation by vortex induced flexible wall vibration.

The turbulent air flow inside air conditioning ductwork induces pressure fluctuations on the duct walls, resulting in the vibration of the latter which in turn radiates sound to both the duct interior and the external environment (breakout noise) [5]. Aim to understand the flow-structure-acoustics interaction therefore to provide information for improved duct noise control design, Using asymptotic expansion technique, Tang [6] developed an invisid model to investigate the sound radiated due to the unsteady interactions between a vortex and a finite length flexible boundary in an otherwise rigid wall at low Mach numbers and it is observed that the rate of change of volumetric flow induced by the flexible boundary vibration and the transverse vortex acceleration are two major sources of sound. In this paper, the vortex path and the movement of the flexible boundary will be provided by Tang and the acoustic radiation results calculated by the numerical simulation will be compared to the analytical solution obtained by Tang[6] .

In Tang's model, a vortex is chosen to represent a turbulent eddy and the vortex moves in still air which are in contrast to the real life situation, it becomes extreme difficult to include the mean flow effects using the asymptotic expansion technique but it will be straightforward to extend the present study to nonuniform convective flow. Furthermore, in actual practice, the associated air ductwork conveys turbulent flows from the fans to the interior workplaces. The ducted elements will affect the turbulence thus generated and the propagation of noise. Analytical solution is hard to find for this kind of problem but numerical solution will make it possible to investigate the turbulence-structure interaction. A turbulence modeling technique can be used to a detailed recovery of the turbulent activities in the duct therefore to provide the hydrodynamic terms needed in the acoustic/viscous splitting method and the acoustic radiation will be obtained directly.

The goals of this paper is to verify the applicability to the simplified model of the acoustic radiation by vortex induced by flexible turbulence-structure acoustics and to provide information on the future development of low self-noise and efficient duct silencers.

FORMULATION OF THE PROBLEM

According to the technique proposed by Shen&Shorsen, the compressible solution is decomposed as:

$$u = U + u', v = V + v', p = P + p', \rho = \rho_0 + \rho' \tag{1}$$

where U, V, P, ρ_0 are the background mean flow components which can be obtained analytically or numerically using low-order schemes of computational fluid dynamics; u', v', p', ρ' are acoustic disturbances that are obtained form the numerical solution using high-order schemes in space and time to precisely capture the sound pressure.

Substituting the above equations into the compressible Navier-Stokes equations and neglect the viscous terms, the governing equations for two-dimensional acoustic fields can be expressed as follows:

$$\begin{aligned} &\frac{\partial \rho'}{\partial t} + \frac{\partial f_i}{\partial x_i} = 0, \\ &\frac{\partial f_i}{\partial t} + \frac{\partial}{\partial x_j}\left[f_i \left(U_j + u'_j \right) + \rho_0 U_i \delta_{ij} \right] = 0, \\ &\frac{\partial p'}{\partial t} - c^2 \frac{\partial \rho'}{\partial t} = -\frac{\partial P}{\partial t}, \end{aligned} \tag{2}$$

Where the acoustic co-velocity components $f_i = \rho u'_i + \rho' U_I$

And for a general flow, the sound speed c is given by

$$c^2 = \gamma p/\rho = \gamma(P + p')/(\rho_0 + \rho'), \qquad (3)$$

Where γ is the specific heat ratio.

Note that the only acoustic source coming from the incompressible solution is the instantaneous pressure and the acoustic calculations can thus be started at any time during the incompressible computation. And the calculations begin with the initial fluctuation quantities set as

$$\begin{aligned} \rho' &= 0, \\ u'_i &= 0 \qquad , \\ p' &= p_0 - P \end{aligned} \qquad (4)$$

Where p_0 is the ambient pressure.

NUMERICAL IMPLEMENTATION

In this section, the numerical discretization of the acoustic equations and the boundary conditions will be discussed

Numerical discretization

In this study, the forth-order-accurate central-difference compact scheme[7] , that has low dissipation and near spectral representation of the dispersion relationship, is chosen for numerical approximation of spatial derivatives in the disturbance equations.

$$\frac{1}{4}U'_{i-1} + U'_i + \frac{1}{4}U'_{i+1} = \frac{3}{4\Delta x}\left(U_{i+1} - U_{i-1}\right), \qquad (5)$$

Where $U = \rho', f_1', f_2', p'$, and Δx is the grid step.

At the boundary of computational domain, a third-order-accurate compact scheme biased toward the interior nodes is used [8]:

$$\begin{aligned} U'_1 + 2U'_2 &= \frac{1}{\Delta x}\left(-\frac{5}{2}U_1 + 2U_2 + \frac{3}{2}U_3\right) \\ U'_n + 2U'_{n-1} &= \frac{1}{\Delta x}\left(-\frac{5}{2}U_n + 2U_{n-1} + \frac{3}{2}U_{n-2}\right) \end{aligned}, \qquad (6)$$

Explicit fourth-order Runge-kutta time advancement, which is proposed by Williamson[9] and implemented by Wilson et al.[10], gives low amplitude and phase errors of traveling wave solutions;

$$H^M = S_x \frac{\partial U^M}{\partial x} + S_y \frac{\partial U^M}{\partial y} + a^M H^{M-1}, \tag{7}$$

Where $M = 1,....5$ is the particular stage number; and the coefficients a^M and b^M are given in [11].

Boundary Conditions

Nonreflecting characteristic boundary conditions based on Thompson's technique are used because they are straightforward and easy to apply; no obvious reflections are observed in the computations.

At wall boundaries, the slip condition $u_n = 0$ is implemented, where n indicates the direction normal to the wall, then $f_n = 0$. And the appropriate momentum equation yields: $\partial p'/\partial n = 0$ and the boundary conditions for p' are extrapolated from interior points.

Numerical Results and Discussion

Figure 1 illustrates the schematic of the present study model. A vortex of strength (circulation) Γ is initially located far upstream of the flexible boundary of length L at a distance d above the rigid plane. The initial speed of the vortex, u_{vortex}, therefore equals $\Gamma/(4\pi d)$ and is a direction parallel to the rigid plane. The flexible boundary is at rest initially. The movement of the vortex creates a time varying fluid pressure on this boundary, causing it to vibrate and this vibration eventually gives rise to a fluctuating velocity field, which affects the motion of the vortex. In this study, the vortex movement path and the movement of the vibrating flexible boundary are provided by Tang's solutions[6].

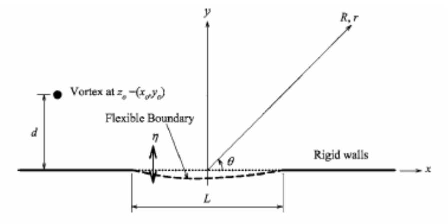


Figure 1- Schematic of vortex induced flexible wall

The incompressible flow potential induced by the moving vortex is

$$\phi_{vor} = \frac{\Gamma}{2\pi}\left[\tan^{-1}\left(\frac{y-y_0}{x-x_0}\right) - \tan^{-1}\left(\frac{y+y_0}{x-x_0}\right)\right], \tag{8}$$

Where Γ is the vortex strength , and (x_0, y_0) , the vortex position is a function of time t and it is given by Tang [6]:

The incompressible flow potential corresponding to the vibrating flexible boundary is given as:

$$\phi_{flex} = \frac{1}{\pi}\int_{-L/2}^{L/2} v \log\sqrt{(x-x_v)^2+(y-\eta)^2}\,dx\,, \qquad (9)$$

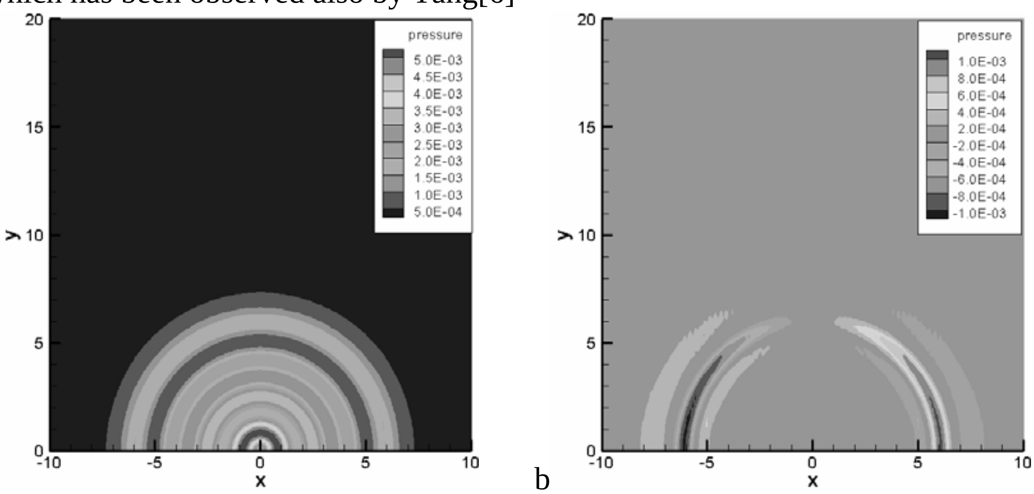
Where (x_v, η) are the location of the points on the flexible boundary and its corresponding vibration amplitude and the values are provided by Tang

The hydrodynamic velocity can be obtained by relationship between velocity and the potential function and the hydrodynamic pressure can be gained by the unsteady Bernoull's equation.:

$$P = p_{ambient} - \rho_0 \frac{\partial}{\partial t}\{\phi(x_0, y_0, t)\} - \frac{1}{2}\rho\left(U^2+V^2\right), \qquad (10)$$

The acoustic field induced by the moving vortex can be obtained by substituting its incompressible hydrodynamic terms to the acoustic disturbance equation 2. So does the acoustic field corresponding to the flexible vibration boundary.

Typical acoustic pressure contours are presented in Fig. 2 for the case of the consideration of the vortex movement only or the case of the vibrating boundary only. It is clear that the pressure contour radiated by the vortex movement is a pattern of a dipole while the pressure contour radiated by the flexible boundary vibration is a patter of a monopole. Furthermore, the sound strength corresponding to the monopole is much stronger than the sound waves radiate by the dipole. In other words, the monopole radiation due to the boundary vibration dominates the radiated sound field, which has been observed also by Tang[6]



a b

Figure 2-Pressure isolines generated by a) flexible vibrating boundary; b) moving vortex

CONCLUSIONS

A computational aeroacoustic technique, which splits Euler equaltions into the hydrodynamic terms and the perturbed acoustic terms is applied this method is applied to the case of sound radiation due to unsteady interaction between an inviscid vortex (which models a turbulent eddy) and a finite length flexible boundary. Based on the unsteady hydrodynamic information from the known incompressible flowfield, the perturbed compressible acoustic terms are calculated. Calculated results are compared with analytical solutions obtained by the method of matched asymptotic expansions. Results suggest that the monopole field created by the volumetric flow induced by the vibration flexible boundary dominates the overall acoustic power radiation. The longitudinal dipole directly due to the transverse vortex acceleration is only important when the vortex is moving over the flexible boundary. This investigation verified the applicability of the viscous/inviscid approach to flow structure-acoustic interaction and it is possible to expand the current research to the complicated interaction between flow turbulence and sound in a duct silencer, therefore, to provide information on the future development of low self-noise and efficient duct silencers

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