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A study on aerodynamic sound from an externally excited flexible structure in flow

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ABSTRACT

Aerodynamic far field sound generated from an elastic structure vibrating in flow under the influence of external excitation is investigated. A test assembly of a rigid square bluff body with an elastic trailing plate in a steady flow at low Reynolds number and low Mach number is considered. Along with the explicit external harmonic force excitation, the trailing plate experiences excitation from the flow vortices generated from the frontal bluff body. A two-way fluid–structure interaction model is implemented, ensuring a bi-directional coupling between the flow field and vibrating structure. For computing acoustic propagation field, a linearized Euler equation based surface coupling type computational aeroacoustic (CAA) hybrid method is used. A surface source coupling is considered between the flow and acoustic domain and the source term is calculated by unsteady compressible flow computation. The focus of the study is to investigate the effects of additional external forced excitation on the aerodynamic sound generated from a flow-induced vibration of the elastic structure. Several test cases at different external excitation (amplitudes and frequencies) forces are solved and the resultant aerodynamic sound is compared with the case of aerodynamic sound from the structure vibrating in flow in absence of such external excitations. The character of the resultant far field aerodynamic sound is significantly influenced by the harmonic force excitation of the elastic plate. For a certain range of force amplitude, a noticeable effect of reduction in far field acoustic pressure is observed. Dependence of the spectral nature of the acoustic pressure on the parameters of excitation (amplitude and frequency) is discussed. It is also observed that the directivity lobes of far field sound pressure are stretched in the downstream direction in the case of external excitation and their inclination increases with the force amplitude.

1. Introduction

In a noise abatement strategy, an effort is always made to control the noise at the source than in the transmission path. In aeroacoustic study, the sound source lies within the sound propagation domain and, therefore, identification of aerodynamic sound source is a complex problem. The investigation of fundamental mechanism of the generation of aerodynamic sound has long been of great interest in various industries. Aircraft structures, automobiles, wind-turbines, high-speed trains, air-conditioning systems are a few examples of such applications. The aerodynamic performance of these systems is significantly influenced by interactions of vibrating structure and the associated flowing fluid. When the immersed components of such system are flexible, e.g. aircraft wings, turbine blades, automobile bodies (side mirror, rooftop, etc.), air-conditioning ducts, etc., they get excitations from the forces inherent in the system (e.g., from rotating components) as well as from the external flow. Consequently, the coupled system of flowing fluid and vibrating structure (under dual excitation) generates aerodynamic sound in the surrounding medium. In UAVs/MAVs the flexible airfoil wings are subjected to flow-induced vibrations, which eventually influence their aerodynamic performance [1]. In many situations, the performance of mechanical systems is directly linked with the end users comfort level. Thus, efforts are made by the designers to develop a quieter product to satisfy needs of the consumers.

The two major source of aerodynamic sound are the random oscillations of fluid particles in a turbulent flow and the surface pressure fluctuations (on a solid body) caused due to the unsteady vortex shedding. The nature of perturbations within the sound source region is flow fluctuations whereas in the propagation region it is acoustic fluctuations (irrotational). Lighthill [2] proposed an acoustic analogy to solve the aerodynamic sound from a jet flow. The nature of sound source in a jet flow is generally turbulent and so the generated sound has the broadband frequency spectrum. Curle [3] and Williams and Hawkings [4] modified Lighthill's method for a

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Nomenclature

t	time, s
ρ	density of fluid, kg m^{-3}
c	speed of sound, m s^{-1}
u, v	unsteady velocity of fluid along two Cartesian coordinates, m s^{-1}
p	pressure, N m^{-2}
γ	ratio of two specific heats
f_0	flow-induced excitation frequency, Hz
f_e	external excitation frequency, Hz
T	time period, s

Subscripts

0	mean or average components
i	indices

Superscripts

$'$	fluctuating components

Abbreviations

CAA	computational aeroacoustics
FSI	fluid structure interaction
LEE	linearized Euler equation
DRP	Dispersion Relation Preserving
UAVs	unmanned aerial vehicles
MAVs	micro aerial vehicles
R.M.S.	root mean square
LPCE	linearized perturbed compressible equation
PCE	perturbed compressible equation
FFT	Fast Fourier Transform

bluff body in the flow. The bluff body in the flow creates periodic shedding of shear layer and consequently, due to the surface pressure fluctuations, a tonal aerodynamic sound (aeolian tone) is radiated in the medium. In the case of tonal aerodynamic sound generation from the flow over a bluff body, the intensity of sound is M^{-2} (M is the Mach number) times more than the broadband sound generated by the turbulent eddies alone [3]. Therefore, the computation of tonal aerodynamic sound at low Mach number flow is important. Hardin and Pop [5] proposed a linearized Euler equation (LEE) based hybrid method, which gives an independent treatment to nonlinear flow field and linear acoustic propagation. In the past, fundamental problems of flow-induced sound from a rigid bluff body viz; airfoil, cylinder, square block, half cylinder, plate etc. have been studied [6–9]. Ali et al. [10] have investigated a case of low Reynolds number flow over a square cylinder with a trailing rigid plate. Calculation of the flow-induced sound for different lengths of the trailing plate has shown that the presence of rear plate influenced the aerodynamic sound generation. Sudhakar and Vengadesan [11] have studied the vortex shedding characteristics of a circular cylinder with an oscillating hinged rigid plate attached at rear side of a cylinder. They used a two-dimensional Navier–Stokes equation, and a comparative study of change in flow field by using fixed and oscillating trailing plate have been attempted.

The problem of flow over a flexible body involves fluid–structure interaction, which can be solved either by one-way or by two-way coupling between the fluid and structural dynamics. From the flow dynamics perspective, significant work has been published on investigation on the flow field considering coupling between fluid and structure. The problem of oscillating bluff body, viz. cylinder, square block, sphere, etc., in the cross flow stream is widely studied in the past [12–14]. In these work, both flow-induced and forced oscillations have considered. In past few decades, the problems of distributed mass structures as cantilever beam, etc. have also been taken up. Fujarra [12] have studied the flow induced vibration of a flexible structure. Lee and Lee [15,16] have proposed an immersed boundary technique based numerical method and solved a problem of flow over a vertical flexible plate. Tang et al. [17] have studied the flutter phenomenon of a two-dimensional cantilever flexible plate placed under an axial flow stream. They discussed about instability and post critical behavior of the plate. Campos et al. [18] have carried out numerical and experimental investigations for an unsteady flow problem of flapping flexible flat plate wings. Lately, Gomes [19] have studied a two-dimensional FSI induced swilling motion of a coupled structure of a rigid cylinder and a trailing flexible plate. The cylinder is free to rotate on its axis and an end mass is attached at the tip of cantilevered plate. Recently Lee and Lee [20] have presented a computational analysis of a flapping flexible plate in the still fluid. They investigate the effect of flexibility on propulsive velocity. In all the mentioned work, mostly, the source of vibrations is the vortex-induced forces, whereas the studies for externally excited structure are very few. Additionally, the focus of research was either on the development of a numerical method (for exploring the fluid–structure coupling) or to solve the flow dynamics. In addition to that, investigations from the point of view of aeroacoustic study are very limited in the literature. However, in many engineering applications such as wings of an aircraft and blades of a wind turbine etc., the immersed flexible structure experiences both flow-induced forces and excitation from other sources. Therefore, study of a FSI problem of externally excited flexible structure in flow is important from both the flow dynamics and aeroacoustics point of views.

In the available literature, a few research works have addressed the sound generation from the flexible structure. Wu and Maestrello [21] studied the acoustic and dynamic response of an elastic structure under the turbulent boundary layer excitations. Similarly, work related to sound generation from a flexible body under the boundary layer excitation has been reported in [22–24]. In these works, excitation to the elastic structure is provided using a mathematical model of pressure field obtained from the boundary layer study, although the effects of structural deformation on the fluid pressure distribution is not accounted. In a systematic study considering two-way fluid–structure interaction (FSI), Schafer et al. [9] investigated the flow-induced sound from a thin flexible membrane of fixed–fixed end condition.

It is necessary to understand the complex physics of generation of aerodynamic sound from the flexible structure under the influence of flow. A basic study in this regard has been carried out by the authors recently [25], wherein the effects of structural flexibility on aerodynamic sound generation have been explored. A low Reynolds number and low Mach number flow over a cantilevered flexible plate has been considered and a comparison of the far field aerodynamic sound generated by rigid and flexible structure has been reported. Such flexible structures can also be under harmonic/periodic external excitation. Far field aerodynamic sound radiated from such structures under external excitation has not been investigated [9,19–21].

A thorough analysis of aerodynamic sound generation from an externally excited flexible structure in flow is important and is attempted in this paper. The prime objective of the study is to investigate and understand effects of forced vibration of elastic structure on the flow induced far field sound. For this purpose, a two-dimensional numerical investigation of aerodynamic sound generation in a case of flow over a force vibrating flexible plate