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Numerical Investigation of Sound Generation due to Laminar Flow Past Elliptic Cylinders

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Abstract. Numerical investigation of sound generation due to unsteady laminar flow past elliptic cylinders has been carried out using direct numerical simulation (DNS) approach at a free-stream Mach number of 0.2. Effects of aspect ratio ($0.6 \leq AR \leq 1.0$) and Reynolds number ($100 \leq Re \leq 160$) on the characteristics of radiated sound fields are analyzed. Two-dimensional compressible fluid flow equations are solved on a refined grid using high resolution dispersion relation preserving (DRP) schemes. Using present DNS data, equivalent noise sources as given by various acoustic analogies are evaluated. Amplitudes and frequencies associated with these noise sources are further related to characteristics of disturbance pressure fields. Disturbance pressure fields are intensified with increase in Reynolds number and aspect ratio. Thus, radiated sound power increases with increase in Reynolds number and aspect ratio. Among various cases studied here, minimum and maximum values of radiated sound power are found at $Re = 120$ & $AR = 0.6$ and $Re = 160$ & $AR = 1.0$, respectively. Directivity patterns show that the generated sound fields are dominated by the lift dipole for all cases. Next, proper orthogonal decomposition (POD) technique has been implemented for decomposing disturbance pressure fields. The POD modes associated with the lift and the drag dipoles have been identified. POD analyses also clearly display that the radiated sound fields are dominated by the lift dipole only. Further, acoustic and hydrodynamic modes obtained using Doak's decomposition method have confirmed the patterns of radiated sound field intensities.

AMS subject classifications: 76Q05, 76M20, 76G25

Key words: Computational aeroacoustics, acoustic analogies, aeolian tones, proper orthogonal decomposition, Doak's decomposition.

1. Introduction

Historically, researchers have shown immense interest in analyzing external flows past streamlined and bluff bodies. Some of the important applications can be listed

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as flow past aircraft wings and propeller blades, high-rise buildings, bridge supports, power transmission lines and heat exchanger tubes. Engineers are usually concerned about the flow dynamics and unsteady forces acting on the bodies caused by the fluid motion. Famous collapse of the Tacoma Narrows Bridge attracted significant attention towards vortex induced instabilities, flow induced vibrations and aerodynamic flutter. Apart from imparting unsteady forces to the immersed bodies, time varying nature of the fluid flow also gives rise to sound generation and is often a cause of concern. For example, residents living close to windmill farms are exposed to aerodynamic noise caused by air flow over windmill blades. Thus, one needs to develop a detailed understanding for effects of incoming free-stream velocity and aspect ratio/shape of the body on the generated aeolian tones.

In one of the first experimental work on aeroacoustics, Strouhal [39] reported generation of aeolian tones for flow past a cylinder. Rayleigh [29] and Gerrard [8] subsequently established connection between the vortex shedding behind circular cylinder and radiated aeolian tones. Experiments associated with aeroacoustic problems face significant challenges due to presence of inherent background noise. Lighthill [19] proposed a theoretical approach to estimate aerodynamically generated sound with the help of an acoustic analogy [19, 43–45] Some of the earlier research works [2, 6, 26] used acoustic analogy to predict aeolian tones. Curle [2] further proposed modification in the Lighthill's acoustic analogy to include effects of solid boundaries on the aeroacoustic sound generation. At low Mach numbers, Curle [2] predicted that the dipole sound dominates over the quadrupole sound and the sound associated with the drag force has double the frequency compared to that associated with the lift force. It has been reported that the maximum amplitude of the radiated sound field is at right angles to the flow direction for such low Reynolds number flows past bluff bodies [2, 6, 8, 26] Using the similar acoustic analogy approach, Tam & Hardin [40] and Wang et al. [42] estimated sound generated due to flow past a circular cylinder and a NACA-0012 aerofoil, respectively. Wang et al. [42] found that the quadrupole sound was significantly smaller as compared to that originated due to the lift and the drag dipoles for low Mach number flows. Researchers have also used an acoustic/viscous splitting approach [9, 35] to predict aeroacoustic noise generation at low Mach numbers. In this approach, flow quantities are decomposed into incompressible mean flow component and a perturbation about the mean. Mean flow quantities are first obtained by solving incompressible viscous flow equations and corresponding mean flow information is further used to solve the perturbation equations which provide acoustic quantities in the far field. Hardin & Pope [9] and Shen & Sorensen [35] predicted sound generation by a cylinder kept in an uniform flow using acoustic/viscous splitting method. In contrast to above two approaches, one can use an accurate but computationally expensive direct numerical simulation (DNS) approach [7, 10, 14–17, 21] to predict flow induced sound field accurately. Using DNS approach, Inoue & Hatakeyama [16] computed sound radiated by flow past a circular cylinder in the laminar flow regime, while Mahato et al. [21] computed sound radiated by an equilateral triangular wedge subjected to laminar flows at different angle of attacks. Computations based on the DNS ap-