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Optimization of bluff bodies for aerodynamic drag and sound reduction using CFD analysis

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ABSTRACT

Drag and flow-induced sound reduction on a circular cylinder fitted with splitter plate is numerically studied. The numerical simulations of the cylinder, without and with splitter plate, have been carried out at subcritical Reynolds number (Re) of 97,300 using large eddy simulation (LES). Ffowcs Williams and Hawkings (FW-H) acoustic analogy has been used to calculate the sound field. The length of the splitter plate (H) varies from $0.5D$ to $3D$, where D is the cylinder diameter in simulations. It is shown that both drag and sound levels decrease with increasing H initially and then increase with increasing H. However, the values of H beyond which the drag and sound levels starts increasing with further increase in H are different. This provides a multi-objective optimization problem, which has been studied in this paper using the particle swarm optimization method.

1. Introduction

The aerodynamic sound generated by bluff bodies when exposed to high-speed wind stream is an important problem in various engineering applications such as automobile, bullet train, aircraft etc. (Thomas and Choudhari, 2002). Efficient aerodynamic sound reduction techniques are highly desirable in aircraft industries. The wind drag exerted on high-speed vehicles is closely related to power and hence the fuel consumption. So, the drag force exerted on body and sound emitted to the surroundings are major concerns in many industrial applications.

The flow over a circular cylinder, despite the simplicity of geometry, is a complex and challenging computational problem because of massive flow separation with large-scale vortex shedding, laminar to turbulent transition over part of its boundary, and a turbulent wake with random as well as periodic Reynolds stresses. The vortex structures are very different from the classical vortex street at the subcritical Reynolds numbers, where the three-dimensional effects are significant. The major factors influencing the flow noise are the flow turbulence and velocity fluctuations created due to the boundary layer separation (Bies et al., 1997). From the 1940s' many researchers had carried out computational aeroacoustic analysis of flow past circular cylinders (Hardin and Lamkin, 1984; Casalino and Jacob, 2003; Gloerfelt et al., 2005; Cox et al., 1998; Orselli et al., 2009). The flow-induced sound control methods largely fall into two categories namely, active and passive (Yoo and Lee., 2008; Gad-el-Hak, 2000). The active control method requires a secondary energy supply and an extensive monitoring system. On the contrary, the passive control methods are simple to implement but require an in-depth parametric study. Some of the common methods include splitter plate behind the cylinder, lateral/longitudinal groove and vortex generator. You et al. (1998) numerically examined the impact of a splitter plate on flow noise of a circular cylinder. The splitter plate was found to reduce both the lift force and sound produced by the fluctuations of the lift force. Circumferential variation of sound showed that the generated sound was largely dipolar in nature. The numerical analysis was carried out in two-dimensional grid system for low Reynolds numbers ($Re = 100$ and 160) and with various splitter plate lengths. The cylinder drag also varied significantly with splitter plate lengths, which is also an intriguing observation that has a variety of applications. Apelt et al. (1973) and Hwang and Yang (2007) also studied drag variations of circular cylinders with splitter plates.

Peng et al. (2014) proposed a method to estimate the peak pressure coefficients acting on solid objects in wind. Zhang et al. (2016) conducted LES simulations at $Re = 5000$ to study the impact of shape modification of 2D and 3D circular cylinders on aerodynamic forces. They observed that the 3D spanwise wavy cylinder significantly decreases the forces that act on it. Abdi et al., (2017) investigated a passive flow control method on a circular cylinder at $Re = 100$ by varying the attachment angle and number of splitter plates. Soumya and Prakash (2017) studied the effect of splitter plate on flow characteristics of elliptic

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cylinders of aspect ratios between 0.5 and 1 in the *Re* range of 50–100. Some research works use numerical approaching to understand and enhance the aerodynamic performance using splitter plate (Amiraslanpour et al., 2017; Nakayama and Noda, 2000). Almost all studies with splitter plates either focused on drag reduction or the sound emission at low *Re*. In most industrial applications, however, the aerodynamic sound becomes more significant only for high *Re* flows. Hence, in this paper, a high *Re* (= 97300) flow is treated, where the three-dimensional effects are significant. The numerical results of the drag coefficient and overall sound pressure level of the cylinder are validated with experimental data.

Next, from the LES solutions, we conducted a CFD based single objective optimization coupled with response surface method (RSM) to minimize the flow-induced sound and aerodynamic drag with splitter plate length as the design variable. We identify that the objective functions reach a minimal value at different splitter plate lengths. An attempt has been made to identify the unique splitter plate length for simultaneous minimization of both flow-induced sound and aerodynamic drag using multi-objective optimization (MOO) coupled with RSM. The MOO method is widely used in many engineering applications owing to the development in computing power and the practical applicability (Patil et al., 2011; Li et al., 2016; Shim et al., 2017). Specifically, optimization methodology has also been extended to sound reduction by Kim et al. (2014) and Silva et al. (2017). In the present work, the MOO method is applied to the problem of a circular cylinder fitted with a splitter plate.

The paper is organised as follows: (1) First, the LES and FW-H acoustic analogy are validated with experiments of Cantwell and Coles (1983), Giedt (1951) and King and Pfizenmaier (2009) for a cylinder without splitter plate at $Re = 97300$; (2) Second, numerical simulations are performed with various splitter plate lengths to compute the drag and flow-induced sound from the cylinder and response surfaces are proposed for both drag and sound level; (3) Lastly, a multi-objective optimization problem is formulated to find the Pareto-optimal frontier of the splitter plate length to minimize both drag and flow-induced sound simultaneously.

2. Computational method

The turbulent flow field around the cylindrical body is resolved by utilizing the LES technique. The filtered mass and momentum conservation equations are:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial(\overline{u}_i \overline{u}_j)}{\partial x_j} = \frac{\mu}{\rho}\frac{\partial}{\partial x_j}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} - \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where, $\overline{p}, \overline{u}_i$ and τ_{ij} are the filtered pressure, velocity and sub-grid scale stress respectively, x_i are the Cartesian coordinates, μ and ρ are the dynamic viscosity and density of the fluid respectively and

$$\tau_{ij} = \rho\left(\overline{u_i u_j} - \overline{u}_i \overline{u}_j\right) \tag{3}$$

The sub-grid scale stresses in the filtered NS equations are unknowns and require modelling which is done by the standard Smagorinsky-Lilly model (Smagorinsky, 1963; Lilly, 1992) based on the Boussinesq approximation (Hinze, 1975) as

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_0 \overline{S}_{ij} \tag{4}$$

where

$$\overline{S}_{ij} = \frac{1}{2}\left[\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right] \tag{5}$$

$$|\overline{S}_{ij}| = \sqrt{2\overline{S}_{ij}\overline{S}_{ij}} \tag{6}$$

The eddy viscosity (μ_0) is modelled as

$$\mu_0 = \rho l_m^2 |\overline{S}_{ij}| \tag{7}$$

$$l_m = \min\left(\kappa d, C_s \Delta^{1/3}\right) \tag{8}$$

where $\overline{S}_{ij}$, l_m, κ, d, C_s and $\Delta$are the strain rate tensor, sub-grid length scale, Kármán constant (= 0.4187), distance to the nearest wall, Smagorinsky constant and volume of the computational cell, respectively. All the computations are performed with a C_s of 0.1, as recommended by Deardorff (1970) and Breuer, (1998).

The finite volume method with the second-order upwind scheme is utilised for the spatial discretization. The SIMPLE algorithm is utilised for the pressure-velocity coupling. An adaptive time-stepping method is used in the paper, where the time steps are adjusted automatically with respect to the truncation error. The time-step is allowed to change in between 10^{-7} s and 10^{-5} s ($= \Delta t$). When the residuals of all variables fall just below 10^{-5}, the solution has been regarded as converged.

3. Acoustic analogy

The flow-induced sound is computed based on the Ffowcs Williams and Hawkings (1969) acoustic analogy with the LES results as input. This equation does not take into account the scattering or reflection of a sound wave due to the presence of any additional hindrance. The wave equation can be written as follows (Orselli et al., 2009):

$$\frac{1}{a_0^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial}{\partial t}\{[\rho_0 v_n + \rho(u_n - v_n)]\delta(s)\} - \frac{\partial}{\partial x_i}\{[P_{ij}n_j + \rho u_i(u_n - v_n) \times]\delta(s)\} + \frac{\partial^2}{\partial x_i \partial x_j}\{K_{ij}H(s)\} \tag{9}$$

where

$$K_{ij} = \rho u_i u_j + P_{ij} - c_0^2(\rho - \rho_0)\delta_{ij} \tag{10}$$

$$P_{ij} = p\delta_{ij} - \mu\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right] \tag{11}$$

$$p' = p - p_0 \tag{12}$$

In the above, s represents the computational domain such that $s = 0$ represents the surface of the body (or the source surface) which is the cylinder surface in the present work; $s < 0$ represents the domain inside the data surface S_B (see Fig. 1) and $s > 0$ represents the unbounded space outside the S_B. Also, p' is the acoustic pressure, ρ_0 is the density of the undisturbed air, ρ is the instantaneous density of the fluid, n_j ($j = 1, 2, 3$) are the components of the unit normal vector pointing outwards from S_B, a_0 is the speed of sound, K_{ij} is the Lighthill stress tensor, $H(s)$ is the Heaviside function, $\delta(s)$ is the Dirac-delta function, δ_{ij} is the Kronecker delta, u_i is the fluid velocity component in the x_i direction and u_n is the fluid velocity normal to the surface $s = 0$ and v_n is the source surface ($s = 0$) velocity (i.e. velocity of S_B) normal to the surface, which is zero in the present case of fixed cylinder. By using the Green's functions of the wave equation, the FW-H approach is turned into an integral form so that it can be solved numerically. This has been discussed in Brentner and Farassat (1998) and Orselli et al. (2009) wherein the thickness and loading noise expressions are given.

4. Multi-objective optimization

The flow chart shown in Fig. 2 describes the optimization procedure