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Effect of aspect ratio of a spanwise sinusoidal profile on the control of turbulent flows around bluff bodies

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ABSTRACT

The deleterious effects of the steady and transient forces on bluff bodies, resulting from turbulent flows, are ameliorated by imposing a spanwise sinusoidal profile (SSP) on their leading edges. Large eddy simulation (LES) is used to elucidate the spatial and temporal details of the flow fields resulting from both square and elongated SSP bluff bodies. Two dimensionless parameters define the geometry of an SSP, namely the wave steepness and normalised wavelength.

In a turbulent flow field, it is observed that an SSP with a wave steepness of 0.2 and a normalised wavelength of 2.4 can result in reductions in the rms drag and lift forces by up to 30% and 95%, respectively. The wakes shed by plain cylinders contain Kármán vortices, however, Kelvin–Helmholtz type vortices form in the upper and lower shear layers of an SSP cylinder.

An SSP imposed on the leading edge of a bluff body elongated in the direction of the flow is found not to be profoundly affected by the aspect ratio. A bluff body with a length-to-height aspect ratio of 5 maintains a highly three-dimensional flow field, and a narrow wake that resembles the characteristics of a streamlined body; this research offers a myriad of industrial applications.

1. Introduction

Many structures such as communication towers, high rise buildings, road vehicles, support pillars, bridges, gates and fences, and louvres, can be generally termed bluff bodies. When bluff bodies are located in turbulent flow fields, they may experience deleterious effects as a result of vortex shedding. Hence, structures may require strengthening or reinforcing, in which case they may still be susceptible to fatigue failure. This approach can be wasteful of materials and perhaps not aesthetically pleasing. An effective solution is to modify the aerodynamics of bluff bodies to produce different, but beneficial wake characteristics that obviate these drawbacks.

There exist numerous methods to achieve control of the flow around bluff bodies, such as attaching helical strakes and bumps to the surface of the structure and also streamlining the body (Bearman and Brankovic, 2004; Kumar et al., 2008; Abeele Van den et al., 2008). However, a drawback of helical strakes is that they can increase drag by up to 10%, and in the case of these devices being attached to a tower, the base bending moments would also increase substantially (Griffin and Ramberg, 1982). Furthermore, streamlining is highly dependent on flow direction. Nevertheless, passive control methods such as these are usually favoured over active control methods, because actuating the flow requires the use of mechanical devices which consume energy and may require maintaining.

An effective passive control method is to modify the leading edge of bluff bodies. Bearman and Owen (1998) incorporated a sinusoidally modulated leading edge and reported reductions in drag of up to 30% that was accompanied by a suppression of vortex shedding. A sinusoidal leading edge not only controls the spatial and temporal features of the flow, but it can produce a near wake in which vortices on the scale of the bluff bodies appear to be absent (Darekar and Sherwin, 2001). Furthermore, as noted by previous authors (Dobre et al., 2006; Bearman and Owen, 1998), a sinusoidally modulated leading edge generally results in flows in the wake of bluff bodies becoming incoherent. As a consequence, it may be expected that this application reduces the temporal variations in the lift force and reduces the mean drag on the bluff bodies.

To date, work has focussed on the phenomena of vortex shedding and flow control around slender bluff bodies, such as circular and square cylinders. However, many industrial applications involve bluff bodies with a large aspect ratio, in which the geometries are elongated in the direction of the flow. In contrast to slender bodies, the flow around an elongated bluff body experiences two types of shear layer interactions: flow separation and reattachment. The shear layers are likely to separate immediately aft of the bluff leading edge, then reattach to the surface of the structure before detaching from the trailing edge as they are shed

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by the body. Modifying the way in which the shear layers behave may enhance the aerodynamic properties of an elongated bluff geometry. However, a problem exists where the effectiveness of a leading edge modification may become attenuated as a result of the decreased proximity of the trailing edge. As a consequence, the vortical structures downstream of the trailing edge are anticipated to become less dependent on the geometry of the leading edge. It is believed that such numerical details of the flow topology around SSP geometries have not hitherto reported in the literature.

The research presented in this paper demonstrates that spanwise sinusoidal profiles (SSPs) have profoundly beneficial effects on reducing the aerodynamic forces on bluff bodies. The reasons for this are investigated firstly by numerically modelling the flow fields generated by square cylinders with and without SSPs imposed on their leading edges. This is achieved by interpreting the vorticity distributions and pathlines of the flow around the bodies, which capture the features of the near wake topology. In addition, time-averaged flow properties are reported. Hence, the current numerical work presented in this paper aims to elucidate the phenomena of the flow field that is associated with this type of passive flow control, and extend on the work of previous studies, such as those of Bearman and Owen (1998) and Dobre et al. (2006). Secondly, the effects of the geometry of the SSP on the coherence of the shear layers and the vorticity field downstream of elongated geometries are investigated. The numerical studies indicate that turbulent flows in the wakes of bluff bodies with SSPs on their leading edges have topologies that are quite different from those generated by plain geometries, particularly in the case of an elongated geometry.

In this work, the bluff body has a leading edge of height, *D*, and spanwise sinusoidal profiles imposed on the leading edge have a wavelength, λ, and a wave height, ω. In geometries studied in this work, it is found that the proximity of the SSP leading edge to the trailing edge does not profoundly influence the control of the flow field. As a result, the flow field and wake of an elongated SSP body resemble characteristics of a streamlined body. The presence of an SSP greatly reduces the energy of vortices shed by a bluff body.

2. Computational model and numerical method

2.1. Governing equations

Numerical simulations are performed using a double precision large eddy simulation (LES) turbulence model incorporated in FLUENT (ANSYS, 2009). The time-dependent incompressible Navier–Stokes equations take the spatially filtered form

$$\frac{\partial \bar{u}_i}{\partial t} = -\frac{1}{\rho}\left(\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \bar{\tau}_{ij}}{\partial x_j}\right) - \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\upsilon \frac{\partial \bar{\sigma}_{ij}}{\partial x_j}\right), \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \tag{2}$$

where $\bar{u}$ and $\bar{p}$ are the filtered velocity and the pressure, and $\bar{\sigma}_{ij}$ and $\bar{\tau}_{ij}$ are respectively, the viscous stress and the sub-grid scale (SGS) stress; ρ and υ are the density and the kinematic viscosity of the fluid, respectively. The filtered momentum equations explicitly resolve the large scale turbulence, while the small scale turbulent structures are modelled (Shah and Ferziger, 1997; Versteeg and Malalasekera, 2007; Wilcox, 1993). A second-order accurate bounded central differencing scheme is employed for the momentum discretisation. In addition, a pressure-implicit with splitting of operators (PISO) scheme is used for the pressure–velocity coupling between the momentum and continuity equations. The stress components are modelled using a Boussinesq eddy-viscosity approximation, such that

$$\bar{\tau}_{ij} = \frac{1}{3}\bar{\tau}_{kk}\delta_{ij} - 2\mu_t \bar{S}_{ij}, \tag{3}$$

where

$$\bar{S}_{ij} \equiv \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right). \tag{4}$$

In Eqs. (3) and (4), the term $\bar{S}_{ij}$ is the local rate of strain tensor of the resolved flow. The variables $\bar{\tau}_{kk}$ and μ_t represent the isotropic component of the sub-grid scale stresses and the turbulent sub-grid scale viscosity, respectively. The Smagorinsky–Lilly model (Smagorinsky, 1963) is used to determine the subgrid turbulent viscosity, such that

$$\mu_t = \rho L_s^2 |\bar{S}|, \tag{5}$$

where

$$|\bar{S}| \equiv \sqrt{2\bar{S}_{ij}^2}, \tag{2a}$$

$$L_s^2 = \min(\kappa d, \quad C_s V_c^{1/3}). \tag{2b}$$

L_s is the characteristic mixing length of the sub-grid scales, and C_s is the Smagorinsky constant. The variables κ and d represent the von Kármán constant and the distance from the cylinder surface, respectively. A fixed value for the Smagorinsky constant, C_s, equal to 0.1 (Liang and Papadakis, 2007; Lam and Lin, 2008; Sohankar, 2008; Lam and Lin, 2009) was used to determine the turbulent viscosity. Deardorff (1970) and Breuer (1998) found that this value of the Smagorinsky constant provides accurate results when large scale fluctuations in the transitional flow exist near wall boundaries.

2.2. Computational domain and boundary conditions

The full computational domain for the numerical simulations is presented in Fig. 1. The domain is a rectangular prism that conforms closely to that employed by Shah and Ferziger (1997), Krajnovic and Davidson (2002), Saha et al. (2003) and Sohankar (2008) for the simulation of flow over a square cylinder. Taking the dimension of the bluff body as *D*, and the flow direction as left to right, the domain extends from the surface of the body a distance of 7*D* both upstream and in the vertical directions, and a distance of 15*D* downstream; the width of the domain is 7λ, where λ is the wavelength of the SSP. The domain is chosen to contain a sufficiently large region downstream of the geometry for the accurate development of the wake. The domain also ensures that any blockage effects due to the upper and lower boundaries in the

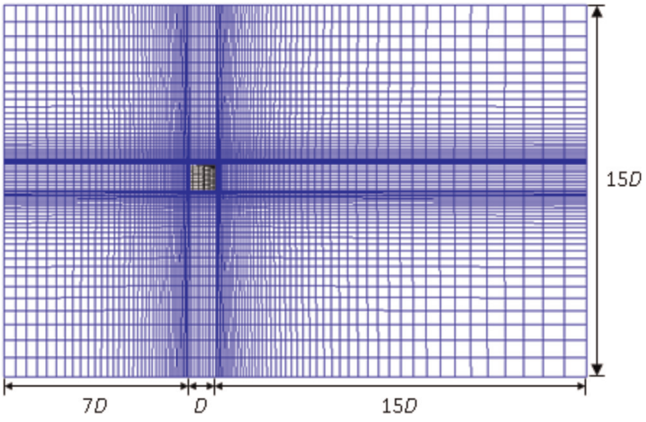

Fig. 1. Computational domain.