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Flow characteristics and flow-induced forces of a stationary and rotating triangular cylinder with different incidence angles at low Reynolds numbers

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ABSTRACT

In this paper, the problem of two-dimensional fluid flow past a stationary and rotationally oscillating equilateral triangular cylinder with a variable incident angle, Reynolds number, oscillating amplitude, and oscillating frequency is numerically investigated. The computations are carried out by using a two-step Taylor-characteristic-based Galerkin (TCBG) algorithm. For the stationary cases, simulations are conducted at various incident angles of $\alpha=0.0$–60.0° and Reynolds numbers of Re=50–160. For the oscillation cases, the investigations are done at various oscillating amplitudes of $\theta_{\max}=7.5$–30.0° and oscillating frequencies of $F_s/F_o=0.5$–3.0 considering two different incidence angles ($\alpha=0.0^\circ$, 60.0°) and three different Reynolds numbers (Re=50, 100, 150). The results show that the influences of key parameters (incidence angle, Reynolds number, oscillating amplitude, and oscillating frequency) are significant on the flow pattern and hydrodynamic forces. For the stationary cases, at smaller angle of incidence ($\alpha\leq 30.0^\circ$), Reynolds number has a large impact on the position of the separation points. When α is between 30.0° and 60.0°, it was found that the separation points are located at the rear corners. From a topological point of view, the diagram of flow pattern is summarized, including two distinct patterns, namely, main separation and vortex merging. A deep analysis of the influence of Reynolds number and incidence angles on the mean pressure coefficient along the triangular cylinder surface is presented. Additionally, for the oscillating cases, the lock-on phenomenon is captured. The dominant flow patterns are 2S mode and P+S mode in lock-on region at $\alpha=0.0^\circ$. It is found at $\alpha=60.0^\circ$, however, that the flow pattern is predominantly 2S mode. Furthermore, except for the case of $F_s/F_o=2.0$, the mean drag decreases as the oscillating amplitude increases for each Reynolds number at $\alpha=0.0^\circ$. At $\alpha=60.0^\circ$, the minimum mean drag for $F_s/F_o=1.5$ is lower than that for stationary case, and occurs at $\theta_{\max}=15.0^\circ$ (Re=100) and $\theta_{\max}=22.5^\circ$ (Re=150), respectively. Finally, the effect of Reynolds number on a rotational oscillation cylinder is elucidated.

1. Introduction

Flow around a bluff body has been a subject of interest for the past several decades, which is always encountered in engineering applications such as high-rise buildings, long-spanned bridges, ocean structures, heat exchangers, to name a few.

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Periodic forces acting on the body and the vortex shedding may cause structural vibration and fatigue failure of structures among other problems. Hence, suppressing vortex shedding and/or reducing force has received considerable attention.

Some studies on flow past a cylinder with different cross sections have been performed both numerically and experimentally (Bao et al., 2011a; Bearman, 2011; Cheng and Liu 2000; Luo et al., 1994; Norberg, 1993; Sharma and Eswaran, 2004; Sheard, 2011; Sohankar et al., 1997; Williamson, 1996; Yoon et al., 2010; Zdravkovich, 1997). They reported that some parameters, such as the cross-section of cylinder, incident angle and Reynolds number, can give rise to the shift of separation point, resulting in drastic change of flow field and flow-induced forces on the cylinder.

In contrast to the studies of the flow past a circular and square cylinder, there are limited studies that focus on a triangular cylinder immersed in a uniform flow. Numerous works have investigated the effects of wind direction and cross-sectional shape on the flow past a triangular cylinder at high Reynolds number (Alonso and Meseguer, 2006; Alonso et al., 2012; Camarri et al., 2006; Iungo and Buresti, 2009; Johansson et al., 2005). Furthermore, many researchers have put emphasis on both the flow field and heat transfer characteristics of a triangular cylinder placed in a channel with confined flows (Abbassi et al., 2001; Alawadhi, 2013; De and Dalal, 2007; Srikanth et al., 2010). In addition, De and Dalal (2006) presented a study of two-dimensional flow over an equilateral triangular cylinder with varying Reynolds numbers ($10 \le \mathrm{Re} \le 250$) by means of the numerical method. Their emphasis is placed on the effect of Reynolds number on the flow topology when $\alpha = 60.0^\circ$. Bao et al. (2010) reported the numerical study of flow over an equilateral triangular cylinder with different incidence angles at two different Reynolds numbers ($\mathrm{Re} = 100$ and 150).

On the other hand, rotary oscillating motion can bring about changes to the flow characteristics behind the bluff body and the forces on it. So far, most of the research on the flow past a rotary oscillating cylindrical structure has been conducted for a circular cylinder (Baek and Sung, 1998; Cheng et al., 2001a, 2001b; Chew et al., 1995; Nazarinia et al., 2009; Williamson and Roshko, 1988) rather than a prismatic cylinder. Filler et al. (1991) presented the experimental study of the shear layer separating from a circular cylinder subjected to small-amplitude rotational oscillation at different frequencies. Lu and Sato (1996) investigated the flow field and force characteristics over a rotationally oscillating circular cylinder for various oscillating amplitudes and frequencies at $\mathrm{Re} = 200$, 1000 and 3000. They pointed out that the influences of the oscillating amplitude and frequency on the forces acting on the cylinder are significant. Du and Dalton (2013) also reported that rotary oscillation of the cylindrical object could change the flow characteristics and forces on the object at both low and high Reynolds number.

Limited research can be found relating to the flow past an oscillating triangular cylinder (Alawadhi, 2013; Alonso et al., 2012; Srigrarom and Koh, 2008; Wang et al., 2011). The numerical simulations of two-dimensional flow around a triangular cylinder subjected to vertical oscillating motion in a channel were carried out by Alawadhi (2013). Alonso et al. (2012) investigated the transverse galloping of cylinders with six different triangular cross-sections and found the incident angle greatly affects the occurrence of the hysteresis phenomenon. Srigrarom and Koh (2008) and Wang et al. (2011) presented the self-excited rotational oscillation on isolated and tandem triangular cylinders, respectively.

As far as known to us, a comprehensive investigation on the effects of Reynolds number and incident angle on flow characteristics and flow-induced forces on a stationary triangular cylinder, as well as the effects of oscillating amplitude and oscillating frequency on the flow past a rotational oscillation triangular cylinder has not been done yet.

In this paper, by employing the TCBG method, the flow over a triangular cylinder is computationally investigated, which has important fundamental interest in both physics and engineering application. The aim is to explore the effects of Reynolds number Re and incident angle α on the flow patterns and pressure on the triangular cylinder for stationary cases and to investigate the effects of oscillating amplitude and oscillating frequency on the flow characteristics and hydrodynamic forces on the triangular cylinder for oscillation cases.

The paper is structured as follows: the governing equations and TCBG algorithm are given first, followed by detailed validations. Then, the computational results for the flow over a triangular cylinder are discussed and explained in detail: the influences of Re and α on the flow topology and pressure distribution on a stationary triangle and the flow past a rotationally oscillating triangle. Finally, some conclusions are provided.

2. Numerical method and description of the problem

2.1. Numerical method

2.1.1. Taylor-characteristic-based Galerkin (TCBG) scheme

For the incompressible viscous fluid flows, the governing equations can be written in the dimensionless form as follows:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}} \frac{\partial^2 \tau_{ij}}{\partial x_j \partial x_j}, \tag{1}$$

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{2}$$

where u_i and p are i-component velocity and pressure, $\mathrm{Re} = \rho U_\infty D/\mu$ represents the Reynolds number, D, ρ, U_∞, μ denote characteristic length, fluid density, characteristic velocity, and dynamic viscosity constant, respectively. The deviatoric