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Brief Communication

Vibrations of a cylinder in a uniform flow in the presence of a no-slip side-wall

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A R T I C L E   I N F O

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A B S T R A C T

A circular cylinder placed in a uniform flow, and that spans the entire length between two side walls, may experience either parallel or oblique vortex shedding depending on the end conditions. It was shown by Mittal and Sidharth (2014) that the spatio-temporal periodicity of the oblique vortex shedding results in constant-in-time force experienced by the cylinder. On the contrary, parallel vortex shedding leads to fluid force that fluctuates with time. The free vibrations of a circular cylinder, in the presence of a wall, are investigated. For comparison, computations with end walls, where a slip condition on velocity is specified, are also carried out. The Reynolds number, based on the diameter of the cylinder and free-stream speed of the flow, is Re = 100. The initial condition for the free vibrations is the fully developed unsteady flow past a stationary cylinder with oblique shedding. It is found that as the amplitude of vibration of the cylinder builds up, the vortices shed from the cylinder align with its axis leading to parallel shedding. The response of the cylinder is associated with two branches: initial and lower. On the lower branch, the response of the cylinder is virtually identical from two- and three-dimensional computations. The flow as well as the response is different on the initial branch and outside the synchronization regime. Forced vibrations confirm the phenomena.

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1. Introduction

The flow past a circular cylinder has been widely investigated. For example, the reader may refer to the reviews by Williamson (1996), Bearman (1984), Berger and Wille (1972) and Zdravkovich (1997). It is associated with rich dynamics of the flow over a wide range of Reynolds number. The Reynolds number is defined as $Re = UD/\nu$, where U is the free-stream speed, D is the diameter of the cylinder and ν is the coefficient of kinematic viscosity. The steady flow past a circular cylinder becomes unstable beyond $Re \sim 47$ via Hopf bifurcation (for example see the work by Kumar and Mittal 2006a,b). After an initial linear growth, the flow achieves a state of limit cycle due to the non-linear processes (Verma and Mittal, 2011). The alternate shedding of vortices results in fluctuations in pressure and the von Karman vortex street (Williamson, 1996). In the classical configuration of the vortex street, for a nominally two-dimensional cylinder, the axes of the shed vortices are parallel to the axis of the cylinder. This is referred to as *parallel shedding*. It has been observed in several laboratory experiments that the vortices can also be shed at an oblique angle to the axis of the cylinder (Berger and Wille, 1972; Tritton, 1971; Gerich and Eckelmann, 1982; Williamson, 1989). This is referred to as *oblique shedding*.

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The present study is restricted to the situation when the cylinder spans the entire distance between two parallel walls. The case of a finite cylinder with free ends has not been investigated in the present work. It has been a subject of several earlier studies (for example, Zhao and Cheng, 2014; Sumner et al., 2004).

Mittal and Sidharth (2014) investigated the flow past a cylinder at $Re = 100$. They showed via linear stability analysis that there exist a vast number of unstable eigenmodes for the $Re = 100$ flow past a cylinder, each corresponding to a certain angle of oblique vortices. The parallel vortex shedding is one of the many possible states and is associated with the largest growth rate. They demonstrated the spatio-temporal periodicity of the oblique vortex shedding and showed that the drag and lift experienced by the cylinder, over integral spanwise wavelength of the cylinder span, are steady. In contrast, the unsteadiness in the forces is quite large in the case of strictly parallel shedding. Usually, the unsteady force in the transverse direction, with respect to the free-stream, is much larger compared to that in the in-line direction.

It is well known that unsteady aerodynamic forces arising from vortex shedding from a bluff body may lead to vibrations (Bishop and Hassan, 1964; Feng 1968). Free vibrations are often associated with resonance/synchronization/lock-in, wherein the vortex shedding frequency matches the oscillation frequency of the structure (Khalak and Williamson 1997,1999). There have been numerous efforts in the past to study the lock-in phenomena associated with a vibrating circular cylinder. For a comprehensive review of lock-in and various other aspects of vortex-induced vibrations (VIV), the interested reader is referred to articles by Bearman (1984, 2011), Sarpkaya (2004), Williamson and Govardhan (2004) and Wu et al. (2012). VIV of structures is of relevance in various engineering situations. For example, in wind-induced vibrations of electric transmission cables, vibrations of heat exchanger tubes, vibration of chimneys, tall buildings/towers and bridges.

In the laminar regime the cylinder response consists of only two branches: initial and lower. Mittal and Singh (2005), Singh and Mittal (2005), Prasanth and Mittal (2008), Prasanth et al. (2006, 2011), and Navrose et al. (2014) conducted a series of studies for various aspects of free vibrations in the laminar regime. They demonstrated that the transition between the initial and lower branch of cylinder response is hysteretic on either extremity of the lock-in regime. The two branches are associated with different vortex modes of vortex shedding. It is 2S on the initial branch. On the lower branch, the *C(2S)* mode is observed. In the 2S mode, a single vortex is shed, alternately, from each of the upper and lower side of the cylinder during every cycle of cylinder oscillation. The *C(2S)* mode is a modified version of 2*S* mode wherein the vortices of the same sign, downstream in the wake, coalesce.

In this effort, we investigate the flow past a vibrating cylinder in the presence of a side wall. The no-slip condition on the velocity on the side wall is known to induce oblique vortex shedding in the flow past a cylinder (Berger and Wille, 1972; Tritton, 1971; Gerich and Eckelmann, 1982; Williamson, 1989). Mittal and Sidharth (2014) showed that oblique shedding past a stationary cylinder is associated with spanwise periodicity. As a result, unlike in the parallel shedding, the fluid force on a segment of the cylinder consisting of an integral number of spanwise wavelengths of the oblique waves does not vary with time. A question that arises is that what would be the nature of free vibrations of the cylinder in the presence of a side wall with no-slip condition on the velocity? The investigation is restricted to the laminar regime at $Re = 100$. Computations are carried out for free as well as forced vibrations of the cylinder. To further understand the results for free vibrations, computations are also carried out for forced vibrations with varying amplitude and frequency.

2. Problem set-up and computational method

A cylinder of aspect ratio $AR = 400$, resides in a hexahedral domain. The x-axis is along the free stream flow while the z-axis is aligned with the axis of the cylinder. The cylinder occupies the entire span of the domain. Experiments carried out on stationary cylinder of relatively large aspect ratio at $Re = 100$, in the past, show that the vortices in the wake form a chevron pattern and posses symmetry about the x–y plane at mid span (Williamson, 1989). Taking advantage of the symmetry, only one half of the span is simulated and symmetry conditions are applied at the mid-span. The origin of the coordinate axes lies along the axis of the cylinder and on that face of the computational domain where the no-slip condition is applied on the side-wall. The upstream and downstream boundaries are located at a distance of 25D and 50D, respectively from the axis of the cylinder. The height of the domain is 100D; this results in a blockage of 1%. Uniform flow is prescribed at the upstream face of the domain. At the outflow boundary the stress vector is set to zero. To promote oblique shedding, no-slip condition on the velocity is specified on one of the end walls ($z=0$) for $x/D \geq -L_p$. Symmetry conditions are prescribed on this boundary for $x/D < -L_p$.

Behara and Mittal (2010) carried out a study of oblique shedding in the presence of a no-slip side wall for a stationary cylinder for $60 \leq Re \leq 150$. Computations were carried out for various values of the aspect ratio of the cylinder and the upstream location of the end-wall where the no-slip condition on the velocity is specified ($-L_p$). For the $Re=100$ flow they found that the flow consists of two cells along the span: end and central. The end cell is close to the no-slip wall while the central cell occupies the remaining span. The vortex shedding frequency and the oblique angle of vortices are approximately constant along the central cell. For a fixed L_p, the spanwise extent of the end cell seems to be unaffected by the aspect ratio of the cylinder. For $L_p = 5.0$, the spanwise length of the end cell is 20D, approximately. An increase in L_p causes an increase in the boundary layer thickness on the side wall at the location where the flow approaches the cylinder. This, in turn, leads to an increase in the angle of oblique vortices as well as the spanwise extent of the end cell. In the present work, we have carried out computations for $L_p=5.0$. The aspect ratio of the cylinder ($=400$) has been chosen so that the end cells, one close to each of the two no-slip walls, occupy only about 1% of the span. Indeed, these choices of parameters for the domain result

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