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Wall proximity effects on the effectiveness of upstream control rod

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ABSTRACT

Two dimensional flow over a circular cylinder with an upstream control rod of same diameter is simulated in unbound condition and in wall bounded conditions. The cylinders are placed at various heights from the wall and the inter-distance between cylinders is also varied. The control rod is subjected to different rotation rates. It is found that, in unbound condition, rotating the control rod decreases the critical pitch length (S/D_{cr}) and increases the drag and Strouhal number of the main cylinder. In presence of plane wall, the shielding provided by the separated shear layers from the control rod in cavity regime is deteriorated due to deflection of shear layers which results in higher drag and large fluctuation of lift coefficient. However, in wake impingement regime, the binary vortices from the control rod are weakened due to diffusion of vorticity and hence, the main cylinder experiences a lower drag and small lift fluctuations than that of unbound condition. The critical height of vortex suppression (H/D_{cr}) is higher in cavity regime than that of wake impingement regime due to the single extended-bluff body like configuration. The rotation of control rod energizes the wall boundary layer and increases the critical height of vortex suppression. Increasing the rotational rate of control rod decreases the drag force and reduces the amplitude of lift fluctuation. Analysis of the wall shear stress distribution reveals that it suffers a sudden drop at moderate height where the normal Karman vortex shedding changes to irregular shedding consisting of single row of negative vortices. Modal structures obtained from dynamic mode decomposition (DMD) reveal that the flow structures behind the main cylinder are suppressed due to wall and the flow is dominated by the wake of control rod.

1. Introduction

Flow over bluff bodies are encountered in many real time applications. After a critical Reynolds number, periodic vortex shedding occurs from these bluff bodies inducing vortex induced vibrations (VIV). In order to prevent possible structural damage, various types of flow control strategies have been proposed such as upstream stationary control rod, upstream rotating control rod, splitter plate, etc. These flow control devices not only suppress vortex shedding but also reduce the drag to a great extent. However, since the complex vortex dynamics is sensitive to flow conditions, the efficiency of these vortex generator is greatly altered by the incoming flow. One such condition prevailed in more common is wall vicinity, where a bluff body is placed close to a plane wall. In this flow environment, wall boundary layer interacts with the shear

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layers of bluff body and influences the flow behavior. This results in various kinds of wake patterns depending upon the distance between the cylinder and the wall. Since the underlying flow control mechanism of above mentioned vortex generators is the wake interaction of main cylinder with wake of the vortex generator, the efficiency these vortex generators is greatly affected in wall vicinity. Present study investigates the influence of wall vicinity on the effectiveness of upstream control rod.

2. Literature review

Various studies on flow over tandem cylinders (Carmo and Meneghini, 2006; Meneghini et al., 2001; Mittal et al., 1997; Sharman et al., 2005) reports that the drag coefficient and the force fluctuations on the downstream cylinder are reduced when the cylinder is kept in the wake of an upstream cylinder. For small and medium spacing between cylinders, the downstream cylinder experiences a negative thrust since it is immersed in the low pressure region of upstream cylinder wake. Upon further increase of spacing between cylinders, beyond a certain distance, which is referred as critical pitch length or drag inversion spacing, the negative drag experienced by downstream cylinder turns positive and the upstream cylinder starts alternate periodic shedding of vortices. In this regime, force fluctuations are amplified and found to be greater than that of the isolated single cylinder.

The shielding effect provided by the wake of upstream cylinder at small separation distances has been utilized by many researchers as a mechanism for drag reduction and VIV suppression. Igarashi (1997) reported that upstream control rod can reduce drag reduction of a square prism by 50–70%. Lee et al. (2004) studied the effect of a small stationary control rod of different diameters on the flow over circular cylinder and observed a maximum drag reduction up to 25%. Ayyappan and Vengadesan (2008) studied the influence of staggering angle and control rod diameter and found that the drag force and vortex induced vibrations are highly reduced by a rotating control rod of diameter ratio 0.5 placed at a staggering angle of 45°.

Taneda (1965) experimentally investigated the flow over circular cylinder near a plane wall and observed a complete vortex suppression at very close height from the wall. At moderate heights from the wall, single row of negative vortices are shed from the cylinder. Bearman and Zdravkovich (1978) reported that as the cylinder is moved closer to the wall, the front stagnation point of the cylinder is moved downstream along the bottom surface and the wake is deflected away from the wall resulting in a low drag and a positive lift. Lei et al. (2000) studied the influence of wall height numerically using the finite difference method for low and moderate Reynolds numbers and reported that the drag forces as well as the fluctuating force coefficients are reduced at low height from wall. Flow visualization studies done by Price et al. (2002), and numerical studies done by Zovatto and Pedrizzetti (2001) and Dipankar and Sengupta (2005), explained the response of the wall boundary layer to the vortex shedding of the cylinder by generation of weak secondary wall vortices. These wall vortices interact with the positive vortices from the bottom surface of the cylinder and the wake pattern is altered. Sarkar and Sudipto (2010) provided some detailed insights on the wake dynamics, especially the strong coupling between the shear layers from the cylinder and the wall boundary layer. Studies performed by Rao et al. (2011, 2013) confirm that such wake–wall interactions are observed in case of rotating cylinder also. Rao et al. (2011) and Harichandan and Roy (2012) studied the influence of wall proximity on the flow past two tandem circular cylinders and they observed that the wake interference between the cylinders are different from those observed in an unbound condition.

In all the previous studies on flow control by control rod, incoming flow was considered to be uniform at the inlet. But, in many real applications a uniform flow or a controlled flow condition as observed in wind tunnel/numerical experiments does not exist. It is not uncommon for a cylindrical structure to be placed close to a wall boundary layer. As explained above, the presence of wall not only affects the force distribution, the wake of the bluff body is also modified. In such a condition, the wake of the control rod is modified due to mutual interaction of wall boundary layer with the control rod vortices. Since the vortex suppression and the drag reduction by the control rod is due to the interaction of control rod vortices with the main cylinder, the wake–wall interaction may severely affect the efficiency of control rod either in a favorable manner or in an adverse manner. Present study addresses the problem of how this interaction affects the flow control over main cylinder.

3. Numerical methodology

Two dimensional incompressible Navier–Stokes equation is solved in a Cartesian domain using a second order accurate finite difference method. The fractional step method proposed by Choi and Moin (1994) is used for pressure coupling. Boundary condition at the cylinder surface is imposed with the help of immersed boundary method. In context of accuracy, it is advantageous to have orthogonal Cartesian grid near the boundaries where vorticity is created (Dipankar and Sengupta, 2005). Vorticity generating areas in present study case are bottom plane wall, control rod and the main cylinder. A simple Cartesian grid with refined mesh in those areas can capture vorticity with good accuracy. Further, the use of immersed boundary method facilitates handling of complex cylinder geometry without the need of body fitted grid or cumbersome coordinate transformation. The current immersed boundary solver is a variant of continuous forcing approach proposed by Peskin (1972) and further modified by Su et al. (2007). The detailed numerical procedure and standard validation results of the current solver can be found in Sudhakar and Vengadesan (2010, 2012) and Raman et al. (2012).

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