Ocean Engineering 139 (2017) 275–286

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Effect of rotating cylinder on the wake-wall interactions

K. Shaafi[a], Sandeep N. Naik[b], S. Vengadesan[b,*]

[a] Delft University of Technology, Netherlands
[b] Indian Institute of Technology Madras, Chennai, Tamil Nadu 600036, India

ARTICLE INFO

Keywords:
Rotating cylinder
IBM
Vortex suppression
Boundary layer flow
Vortex tracking

ABSTRACT

Laminar flow past a rotating cylinder near a plane wall is studied numerically using a second-order accurate immersed boundary method. The wake-wall interactions are investigated in detail, for different wall heights and varying rotational rates. Flow patterns are classified based on the wake structure and the effect of rotation on critical wall heights is discussed for both clockwise and counterclockwise rotation. For the configuration studied i.e. rotating cylinder above a bottom plane wall, counterclockwise rotation of cylinder favors the wake-wall interactions, while clockwise rotation influences in an adverse manner. In addition to conventional analysis, the evolution of the vortical structures in the wake region are examined using Lagrangian analysis of individual vortical structures. The diffusion of the positive vortex shed from the wall facing side of the cylinder is accelerated due to the influence of boundary layer with net negative vorticity. The wall augmented diffusion of positive cylinder vortices is compensated by the creation of secondary wall vortices from the bottom wall boundary layer. Counterclockwise rotation of cylinder increases the shear inside boundary layer resulting in more pronounced diffusion.

1. Introduction

Fluid flow past cylinders in the vicinity of a wall has its applications in designing pipelines laid near the seabed, overhead bridges and other bluff body flows in the vicinity of a plane boundary. This problem has been studied extensively by many researchers because of its various applications in engineering. It also forms the base case for quantifying the effect of confinement on bluff body flows. The plane wall inhibits the development of shear layers and alters the shear layer roll-up from the wall-facing side of the cylinder. Some characteristic phenomena observed in such flows are vortex suppression, decrease in drag force due to the displacement of stagnation point and the pairing of vortices shed from the cylinder with those formed by the boundary layer roll-up. In such flow conditions, apart from Reynolds number, (Re), the non-dimensional gap ratio, (H/D) influences the flow field to a large extent. Here, H is the height of the center of the cylinder from the bottom wall and it is non-dimensionalized by D, the diameter of the cylinder. Fig. 1 shows the schematic diagram along with the nomenclature associated in the present study.

Taneda (1965) was one of the first to study this problem. Experiments were carried out in a water tunnel to visualize the flow behind a circular cylinder near a plane wall using aluminum dust and condensed milk. They found that the compressing effect due to the walls have a stabilizing effect on the cylinder wake. Bearman and Zdravkovich (1978) conducted a similar study and found that regular vortex shedding was suppressed for wall gap ratio H/D $\le$ 0.3. In their experiments the gap ratio was varied between 0 to 3.5 and Re from 2.4 to 4.8×10^4. They noted that the Strouhal number (St) did not vary as H/D was decreased up to H/D = 0.3. Pressure distribution (C_P) on the cylinders and the plane boundary were also investigated. There was a steep decrease in C_P as H/D was reduced and the symmetric distribution of C_P around the cylinder was also distorted. Angrilli et al. (1982) conducted similar experiments and found that St increases with reduction in gap ratio. They attributed it to the proximity of the wall that reduces the space for the formation of vortices. This is contrary to what was observed by Bearman and Zdravkovich (1978). This may be due to the difference in the boundary layer thickness (δ) between the two studies. Grass et al. (1984) also observed a slight increase in St as H/D is reduced. They also reported detached separation regions on the wall in front of the cylinder. They reasoned that this was due to the development of adverse pressure gradient on the bottom plate (or wall). Zdravkovich (1985) examined the variation of forces on the cylinder near a plane wall for $0 \le$ H/D ≤ 2 and $4.8 \times 10^4 \le Re \le 3 \times 10^5$. The lift coefficient was found to increase slightly up to H/D = 0.5 followed by a rapid increase beyond 0.5. Drag force on other hand showed no significant changes as H/D decreased until the cylinder was engulfed in the boundary layer of the bottom wall.

The minimum H/D required to suppress vortex shedding was found

* Corresponding author.
E-mail address: vengades@iitm.ac.in (S. Vengadesan).

http://dx.doi.org/10.1016/j.oceaneng.2017.04.044
Received 28 December 2016; Received in revised form 17 April 2017; Accepted 24 April 2017

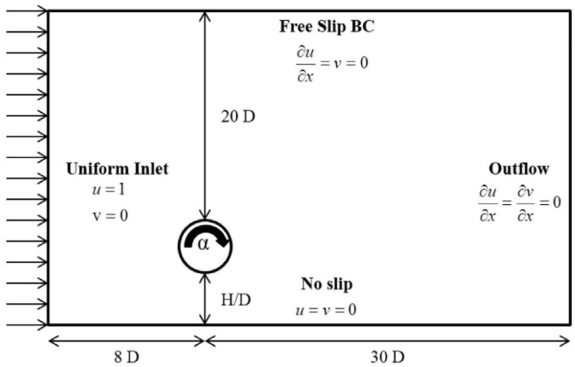

Fig. 1. Schematic diagram of isolated rotating cylinder placed above a plane wall.

to increase with δ in experiments conducted by Taniguchi and Miyakoshi (1990). Experiments were conducted for Re=9.4 × 10^4 and gap ratio was varied from 0 to 3. They suggested that the suppression of vortex shedding at small H/D is due to the cancellation of vorticity associated with the shear-layer on the wall and that shed from the cylinder. They also investigated the effect of boundary layer thickness on the roll-up of shear layers into vortices and noted that as the cylinder came in contact with the boundary layer, vortex shedding ceases. Buresti and Lanciotti (1992) did similar experiments with different types of boundary layers for Re=0.86 to 2.7 × 10^5. They observed vortex shedding for H/D ≥ 0.4, below which (H/D < 0.4) the shedding was suppressed. They too noted that the drag force seems to be dependent more on boundary layer thickness than on H/D. Critical height below which vortex shedding is suppressed was found to increase for incoming flow with the thick boundary layer. For cylinders immersed in the thick boundary layer, separation bubbles are not formed in front of the cylinder and the associated velocity profile is more like shear flow rather than the uniform flow that is observed in other studies with the thin boundary layer. A comprehensive study was carried out by Lei et al. (1999) on the effect of a plane boundary on flow features of flow past a circular cylinder near the wall. Experiments were conducted for Re=1.3 to 1.45 × 10^4 and H/D was varied from 0 to 3. In addition to confirming previous observations, they reported downward lift in thick boundary layers similar to Zdravkovich (1985) and attributed it to the movement of the positive pressure zone and the stagnation point towards the top of the cylinder. They noted that root mean square (RMS) values of lift forces can be used as a quantitative measure to study the suppression of vortex shedding.

Most of the experimental studies were limited to high Re and turbulent wake. One of the first numerical studies for laminar flow was presented by Zovatto and Pedrizzetti (2001). They studied flow between parallel walls and observed that negative vortices separate from the upper side of the cylinder and occupy the lower position in the vortex street, while positive vortices occupy the upper side of the street. They argued that this was due to the walls which repel the wake formation. The cylinder wake is unable to produce any boundary layer separation on the wall. Price et al. (2002) conducted flow visualizing experiments along with PIV and characterized the flow into four different regions based on H/D 0–2). Reynolds number was varied from 1200 to 4960. It was noted that, contrary to the suggestions of Grass et al. (1984) and Taniguchi and Miyakoshi (1990), the two shear layers associated with the wall and the bottom of the cylinder, although of different sign, do not cancel each other. Hindrance to the growth of shear layer was pointed out to be a more prominent reason for vortex shedding suppression. Strouhal number is sensitive at low Re and it increases as Re is decreased.

The effect of blockage was explored by Sahin and Robert (2004) in a 2D numerical study. This problem is similar in the sense that the cylinder is confined both at the top and bottom side of the cylinder by a plane wall. Re was varied from 0 to 280 and blockage ratio was varied from 0.1 to 0.9. They did linear stability analysis and presented neutral stability curves for varying Re and blockage ratio. Chakraborty et al. (2004) presented numerical results on wall effects on the cylinder and reported a functional relationship between Re, drag force and blockage ratio. They observed that drag force increased with a decrease in blockage ratio. Dipankar and Sengupta (2005) reported numerical solutions for flow past non-rotating cylinder near a wall for Re=1200 at H/D = 0.5 and 1.5. The positive vortex shed from the lower half of the cylinder remains attached to the wall, instead of moving downstream for certain H/D values. This tends to separate the flow from the wall and create a low-pressure region just beneath the cylinder as observed in Bearman and Zdravkovich (1978). Inflection points in velocity profile was used to verify the instability in the flow between the cylinder and the wall by Huang and Sung (2007). The authors showed that by using the separation velocity (U_S) in the definition of St rather than free stream velocity (U_∞), the curves collapses into one curve for all Re. Nishino et al. (2007) presented experimental results by keeping the cylinder non-rotating and moving the wall. This ensures that there is no interaction between the cylinder and the boundary layer on top of the wall. They used PIV and surface oil for flow visualization to capture the vortex dynamics. They reported flow features that were similar to previous studies (with boundary layer). They also studied the effects of end conditions on the critical gap ratio.

Most of these studies explore the effect of Re and H/D for a non-rotating cylinder. Very few researchers have studied the effect of rotation on the flow features and the critical height of vortex shedding. Rotation of the cylinder may induce shear layer separation from the plane wall and thus alter the vortex pairing in the wake. Cheng and Luo (2007) studied the effect of rotation on flow past cylinders in the vicinity of the wall for Re=200 and 0 ≤ H/D ≤ 5. They reported that with higher rotation (counter-clockwise), the critical height of vortex shedding increases. Three different regimes were identified based on whether the vortex shedding was regular, irregular or flow was steady.

Recently Stewart et al. (2010) investigated both 2D and 3D flow past a rotating cylinder rolling on the wall. Low Reynolds number flow (Re=20 − 500) were considered for rotation rate ranging from −1 to 1. The transition Re above which the flow becomes three dimensional was found to be highly dependent on α ($=D\omega/2u_\infty$), with positive values of α aiding the transition and negative values of α slowing the transition. Hourigan et al. (2013) have presented numerical solutions for Re=25–750 for different rotation rate at a constant gap ratio of H/D = 0 (roll on the wall). They studied the 3D transition of the flow and reported that rotation of the cylinder near wall suppressed 2D transitions up to Re=750. Experimental investigation of flow past cylinders very close to the wall was studied by Zovatto and Pedrizzetti (2013) using PIV. They divided the flow regime based on the H/D ratio and the vortex shedding associated with those gap ratio. In particular, they investigated the effect of jet-like flow at small H/D ratio and concluded that a that a strong interaction between the lower shear layer completely suppressed the onset of the von Karman vortex shedding.

Rao et al. (2015) studied three-dimensional flow past a rotating circular cylinder for various gap ratios 0 ≤ H/D ≤ 5 and for various Reynolds numbers up to Re=400. Apart from studying different vortex shedding regimes, they also analyzed the effect of plane wall on three-dimensional instabilities using linear stability analysis. The present study aims to investigate the effect of rotating cylinder on laminar boundary layer-wake interactions. Rotation imparts acceleration to the fluid, and depending on the sense of rotation, the flow rate in the gap region may increase or decrease. This has a significant effect on the evolution of vortex structures and alters the critical height of vortex shedding when compared to the non-rotating cylinder. Non-dimensional rotation rate was varied from −1 to 1 in steps of 0.5 and H/D was varied from 0.1 to 3. Apart from conventional analysis such as flow patterns and bulk parameters, we studied the evolution of vortical structures in the downstream wake region using Lagrangian analysis. The insights gained from this investigation, such as accelerated