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Numerical study of adverse pressure gradient generation over a flat plate using a rotating cylinder

Farhana Afroz [a], Muhammad A.R. Sharif [b,*], Amy Lang [b]

[a] East Tennessee State University, Engineering Technology, Surveying, and Digital Media Department, Johnson City, TN 37614, United States
[b] The University of Alabama, Aerospace Engineering and Mechanics Department, Tuscaloosa, AL 35487-0280, United States

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ABSTRACT

Generating an adverse pressure gradient (APG), using a rotating cylinder in the proximity of a plane wall under a laminar freestream flow, is studied numerically in this work. The magnitude of the generated APG is a function of the gap, G, between the cylinder and the wall, and the rotational speed of the cylinder, Ω. The flow in such a configuration is characterized by periodic transient vortex shedding at high Reynolds number. A numerical model for the computation of the transient flow for this configuration is developed using the ANSYS CFD simulation tool. The model is validated against published experimental and numerical data for similar flow configurations and excellent agreement is observed. A parametric study is carried out for different combinations of G and Ω for two different Reynolds numbers of 200 and 1000 to examine the development of the resulting separation bubble due to the generated APG. The mechanism of the boundary layer separation over the plane wall and the corresponding wake dynamics is investigated. Results are presented in terms of the distribution of the pressure coefficient as well as skin friction coefficient along the wall and flow patterns around and downstream of the cylinder in the proximity of the wall. The results of these computations confirm that using a rotating cylinder over a plane wall in a freestream flow is an effective technique to generate a controlled range of adverse pressure gradients.

1. Introduction

The fluid physics of an isolated circular cylinder in a steady freestream cross-flow is well-documented in terms of the vortex shedding phenomenon. When the cylinder is placed close to a plane wall, it introduces additional complexity in the flow. The effect of placing a stationary cylinder of diameter, D, near a stationery plane wall at a gap distance, G, has been studied both experimentally and numerically in some previous works. Experimental study by Bearman and Zdravkovich (1978) revealed that, while vortex shedding was suppressed for lower cylinder-gap to diameter ratios, G/D, the flow separated both the upstream as well as the downstream of the stationary cylinder on the flat plate. Forces acting on circular cylinder placed in the proximity to the wall were measured experimentally for different G/D values by Zdravkovich (1985, 1997). The experimental results showed that the lift coefficient was dependent on the ratio of the cylinder-gap and diameter (G/D), while the drag coefficient was controlled by the ratio of the cylinder-gap and boundary layer thickness, G/δ.

* Corresponding author.
E-mail addresses: afrozf@mail.etsu.edu (F. Afroz), msharif@eng.ua.edu (M.A.R. Sharif), alang@eng.ua.edu (A. Lang).

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A numerical investigation was carried by Lei et al. (2000) to observe vortex shedding suppression of cylinder flow near a plane wall. The minimum value of (G/D) to suppress the vortex shedding was predicted for various Reynolds numbers, Re, based on the cylinder diameter and the free-stream velocity. The gap ratio (G/D) was found to have a stronger effect at higher Reynolds numbers on the vortex shedding frequency. For intermediate gaps $(G/D \geq 0.5)$, the vortex shedding from the circular cylinder was not found to be disturbed by the wall shear layer.

A significant amount of experimental work has been conducted by Price et al. (2002) to observe the fluid flow over a circular cylinder close to a wall for various Reynolds numbers. Two different types of flow visualization techniques, (i) particle image velocimetry (PIV) and (ii) hot-film anemometry; identified four different characteristic configurations based on the gap to cylinder diameter ratio (G/D). For very small gaps $(G/D \leq 0.125)$, the flow in the gap is obstructed or very weak, and the separation of the boundary layer happens both upstream and downstream of the cylinder and irregular vortex shedding occurs. The flow physics for small gap ratio $(0.125 \leq G/D \leq 0.5)$ is almost identical to that for very minimal gaps when the inner shear-layer pairs with the boundary layer of the wall. The flow for the moderate gap ratios $(0.5 < G/D < 0.75)$ is exhibited by the inception of the vortex shedding from the cylinder. For large gap ratios $(G/D \geq 1)$, the wall boundary layer does not separate upstream or downstream of the cylinder.

A vortex-induced instability mechanism occurring in the incompressible wall shear layer has been proposed by Sengupta et al. (2003). According to this theory, instability arises when a convecting vortex of finite-core comes into contact with an underlying shear layer and results in unsteady flow separation. Experimental flow visualizations of Price et al. (2002) were compared with the numerical investigation of Dipankar and Sengupta (2005) who explained the vortex induced unsteady flow behavior using vorticity dynamics. In the case of smaller gap ratio, two vorticity fields interact significantly and, as a result, the fluid flow over the wall suffered unsteady separation upstream and downstream of the rotating cylinder. When the gap ratio was increased, main vortex-induced instability was observed close to the cylinder surface accompanied by a very insignificant instability to the flat plate shear layer.

An experimental investigation was conducted using digital PIV by Wang and Tan (2008) to visualize the flow behavior in the near wake region of a circular cylinder as it was placed in fully established turbulent flow in the vicinity to the flat plate. The results depict that, the wall-effect on cylinder wake was negligible for the gap ratios (G/D) over 0.8. For gap ratios ranging between 0.3 and 0.6, the wall boundary layer is intermittently disrupted by the shed vortices from the bottom side of cylinder. The evolution of shed vortices for two representative cases, small gap ratio $(G/D=0.2)$ and intermediate gap ratio $(G/D=0.6)$, revealed that the shed vortices moved downstream parallel to flat plate.

Harichandan and Roy (2012) numerically investigated the behavior of the vortical wake created by square and circular cylinders (non-rotating) placed in a boundary-layer flow formed over a plane wall at Reynolds numbers of 100 and 200 and the gap ratio was varied from 0.1 to 2. It was observed that the gap ratio strongly influences the onset of vortex shedding from the cylinder and the frequency of vortex shedding for wall proximity flows were higher than those for corresponding unconfined flows.

An interesting numerical study was done by Zovatto and Pedrizzetti (2001), where a stationary circular cylinder was placed between the walls of a plane channel and at different distances from the wall of the channel. Within the unsteady regimes, when the circular cylinder was positioned far away from one wall, the vortex shedding produced a similar pattern of von Karman vortex path, even if the confinement because of the channel walls produced a reversal of the position of vortices. But placing the cylinder very close to the wall behaved as a blockage on the surface with a high resistance. The two different layers of reverse vorticity got separated from the rotating cylinder and the flat plate, and generated a pair of vortex sheets that dissipated during the reciprocally induced stretching and eventually developed into a von Karman vortex sheet with a distinctive row of same-signed vortices.

The flow physics over a circular rotating cylinder, located close to a wall moving at the same velocity of the free stream, was numerically studied by Huang and Sung (2007). The moving wall caused the gap-flow to be accelerated at a much higher rate compared to that of the stationary wall. As a result, vortex shedding was produced even at small gap ratios compared to the stationary wall case.

The wake dynamics for flow passing over a rotating cylinder is much more complex than the flow passing over a stationary cylinder. This phenomenon is of immense interest due to its potential applications in flow control. Modi et al. (1991) described how flow past airfoils could be controlled by increasing lift by placing a hollow rotating cylinder not only at the leading or trailing edge but also on the upper surface of the airfoil. It is also useful for performance improvement of aircrafts by reducing drag and suppressing vortex resonance as noted by Modi (1997). A detailed computational study of flow dynamics of rotating cylinder was conducted by Mittal and Kumar (2003), and results showed the termination of vortex shedding with the increase of rotation speed. When the rotation rate of cylinder is increased, a positive vortex is developed in the vicinity of the upper cylinder surface, and as the vortex increased in size, it moved outward and far from the cylinder. As a result, it caused the whole wake to deflect upward and a reduction of the cross-stream width of the wake occurred. Moreover, the cause of the flow stability with the increase of the rotation speed was also explained in that study. As the rotation speed increases, the vorticity strength also increases which accompanies the increase of the thickness of the area of closed streamlines near the cylinder, and this results in a stable flow.

When the rotating cylinder setup is placed to the proximity of a plane wall, much complexity arises in vortex shedding and wake development compared to that of a stationary cylinder. The resultant flow dynamics differs from that of a standalone rotating or stationery cylinder. There are only a few studies performed to visualize the flow around a rotating cylinder within the vicinity of a wall. Cheng et al. (2006) numerically studied a two-dimensional incompressible flow using