Flow Separation of a Rotating Cylinder

S. C. LUO, T. T. L. DUONG and Y. T. CHEW

Department of Mechanical Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260

mpeluosc@nus.edu.sg, dthulinh@nus.edu.sg mpecyt@nus.edu.sg

Abstract. The effects of rotating a circular cylinder on the suppression of flow separation were investigated experimentally. Flow separation and vortex shedding were studied by flow visualization to guide the hot-film anemometry measurements that follow. The experiments were conducted for flow past a circular cylinder with an aspect ratio of 16 in a recirculating water channel at Reynolds numbers in the range of 140 to 1000. The rotational to translational speed ratio, α, varied from 0 to 5. The present results show the existence of a critical α value of about 2.3 at which the vortex shedding is suppressed. Below this critical value of α, the Kármán vortex street and separation points are observed. Vortex shedding is deflected and separation points are displaced more and more towards the rotation direction of the cylinder as α increases. Above the critical α value, vortex shedding disappears. The two separation points on the cylinder surface seem to move very close to each other at $\alpha > 2.3$. This issue will also be discussed by analyzing the flow pictures obtained from flow visualization. The flow regime close to the cylinder surface is analyzed at different Reynolds numbers and different values of α to study how the cylinder's rotation affects the flow separation. The effects of rotating circular cylinder to vortex shedding frequency as well as the suppression of vortex shedding and flow separation are studied in order to understand the moving-wall effects in flow separation control.

Key words: flow separation, vortex shedding suppression, rotating circular cylinder, Magnus effect.

1. Introduction

When a viscous fluid flows over a bluff body, flow separation can occur under certain conditions resulting in phenomena such as vortex-induced oscillation, drag increase, lift decrease, wake buffeting, etc. The phenomenon of flow separation has important effects to the bluff body which are associated with the formation of vortices and energy loss in the wake behind the body. The shedding of vortices from the sides of the bluff body then causes fluctuating forces to exert on the body. It is known that to reduce or to eliminate these unfavorable effects, the flow separation should be delayed or even suppressed. In order to effectively control flow separation, different techniques had been introduced to add momentum to the near-wall flow field either passively (based on the design of geometrical configuration, for example disposing slats around the structure [8]) or actively (uses of external power to counteract the adverse pressure gradient, for example using an additional rotating cylinder [9]). In the present study, the influence of the moving-wall effects to the flow separation from a bluff body is investigated when a fluid flows past a rotating circular cylinder.

2. The Experiment

Figure 1 shows the present experimental set-up. A circular cylinder with diameter D = 25 mm and aspect ratio of 16 rotating at angular speed Ω is subjected to an oncoming flow at a free-stream velocity U_∞. Flow visualization is carried out by injecting dye from within the cylinder at Reynolds numbers in the range of 140 < Re < 1000, and the cylinder rotation rate α (cylinder rotational to free stream speed ratio $= \Omega D / 2U_\infty$) of $0 \le \alpha \le 5$. Vortex shedding frequency f and hence Strouhal number (St, $= fD/U_\infty$) are obtained by hot-film measurement in the cylinder wake.

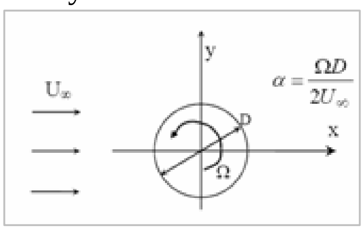

Figure 1. Definition sketch of flow past a rotating circular cylinder.

3. Results and Discussion

The fundamental data in St-Re relationship compared with literatures will be presented first, both as a calibration of the present experimental set-up, and to examine how the cylinder rotation affects the frequency of vortex shedding. Results of stationary circular cylinder (α = 0) are first studied before the more complex rotating cylinder ($\alpha \neq 0$) cases are investigated. After that, some typical pictures obtained from flow visualization will be analyzed to understand the cylinder rotation's effects to vortex shedding process and flow separation.

3.1. VORTEX SHEDDING FREQUENCY

For the stationary cylinder, St-Re relationship in mode A (Re<190) and mode B (Re>260) regimes (Figure 2) is achieved. Good agreement is obtained between the present data and the highly cited experimental St-Re curve reported in Williamson [6]. Figure 3 also presents the comparison between the present experimental results and the results obtained from the universal St-Re relation proposed in Williamson and Brown [7] and Fey et al. [2]. The data shows a rather good agreement, except for the transition regime from mode A to mode B regimes where the vortex shedding process is really complicated. The agreement obtained in the comparison presented in Figures 1 and 2 gives some indication of the quality of the present rotating circular cylinder data.

Figure 4 shows an increase in vortex shedding frequency when rotation rate increases. In the present study, from Reynolds number of 600 up to 1000, the Strouhal number seems to reach a constant value at higher Re which is higher for greater rotation rate. This confirms that changing the rotation rate can influence or even control the frequency at which the vortices are shed.

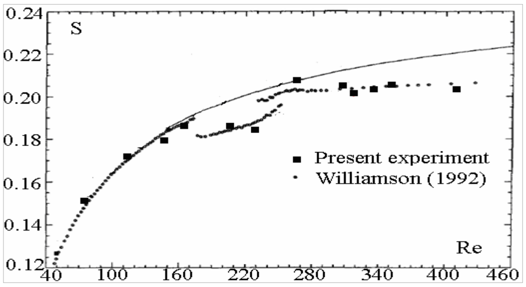

Figure 2. St-Re of stationary cylinder compared with Williamson's St-Re curve [5].

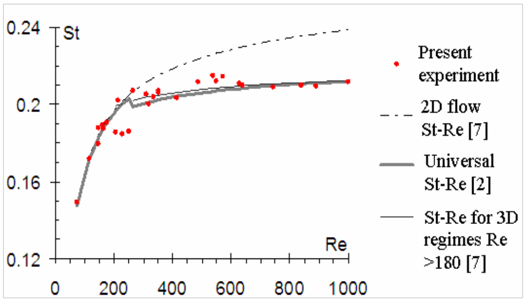

Figure 3. St-Re of stationary cylinder.

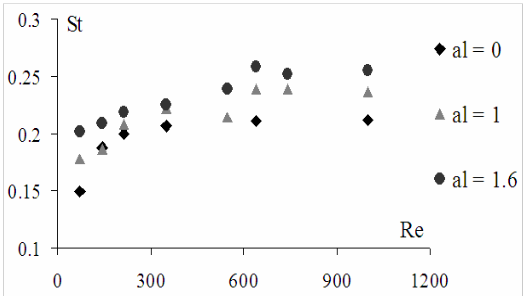

Figure 4. St-Re at different α.

3.2. VORTEX SHEDDING SUPPRESSION

Karman vortex street is observed for stationary cylinder (Figure 5) and the flow pictures match well with those reported in Van Dyke's album [5]. The periodic vortex shedding is also clearly observed for rotating circular cylinder (Figure 6) up to a critical value of rotation rate, α_{crit}, ($\alpha < 2.3$). Above the critical α ($\alpha > 2.3$), regular vortex street is no longer seen, the vortex shedding ceases gradually and disappears as shown in Figure 7. The existence of a critical α is also reported in the literatures ($\alpha_{crit} = 2$ in the computation of Chew et al. [1]; α_{crit} is of 2 and 2.2 at Re of 200 and 1000, respectively, by Ling and Shih [3]). The suppression of vortex shedding at high rotation rate shows that cylinder rotation plays a very important role in controlling the flow process behind the cylinder. Even when the vortex street vanishes, the dye trace in the wake still continues to increase in inclination in the rotation direction as α increases, showing the effect of cylinder rotation on its wake.

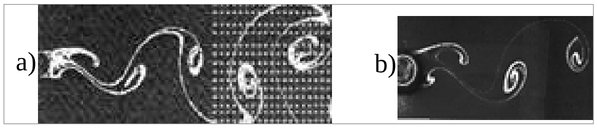

Figure 5. Karman vortex street. (a): at Re = 140 [5]. (b): at Re = 141 (present study).

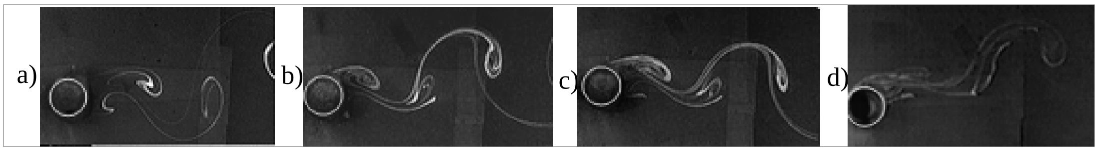

Figure 6. Vortex shedding at Re = 141. (a): $\alpha = 0.4$. (b): $\alpha = 1.4$. (c): $\alpha = 1.8$. (d): $\alpha = 2.3$.

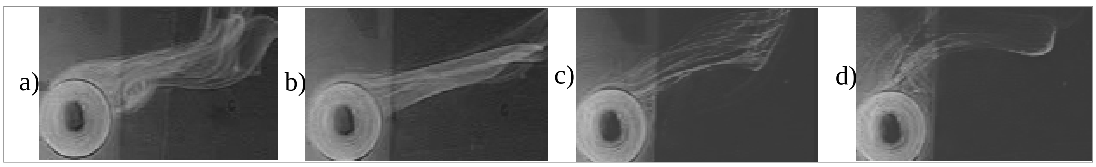

Figure 7. Suppression of vortex shedding at Re = 226. (a): $\alpha = 2.5$. (b): $\alpha = 3$. (c): $\alpha = 4$. (d): $\alpha = 5$.

3.3. EFFECT ON FLOW SEPARATION

When the cylinder is non-rotating ($\alpha = 0$), flow separation occurs symmetrically on both sides of the cylinder causing a large wake behind the cylinder (Figure 8a). For rotating cylinder when the vortex shedding still exists, the two separation points are shifted on the cylinder surface due to the rotation and seem to move closer to each other as α increases (Figure 8). On the side of the cylinder where the surface moves in the same direction with the free stream flow (lower side in Figure 8), additional momentum is injected into the near-surface fluid region, resulting in the delay of boundary separation which can be seen by the displacement of the separation point in the cylinder rotation direction. On the other side of the cylinder, the increase in relative motion between the moving surface and the free stream flow shifts the separation point further upstream. This upstream movement increases with increasing α.

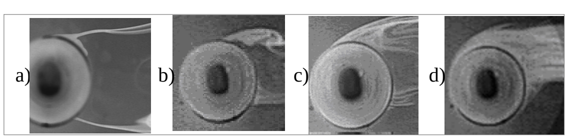

Figure 8. Flow separation (close up view) at Re = 164. (a): $\alpha = 0$. (b): $\alpha = 0.6$. (c): $\alpha = 1.2$. (d): $\alpha = 2.5$.

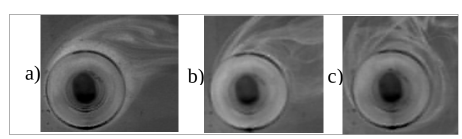

Figure 9. Flow separation at Re = 114. (a): $\alpha = 2.6$. (b): $\alpha = 3.2$. (c): $\alpha = 4$.

Above α_{crit} ($\alpha > 2.3$), the wake appears to become narrower as α increases (Figures 7 and 9) and this could result in a decrease in the pressure drag as well as an increase in the lift force. On the side where the cylinder surface moves in the same direction with free stream flow, the separation seems to be suppressed at high value of α ($\alpha = 4$ in Figure 9) as a large additional momentum is injected to the close-wall flow field to overcome the effects of the adverse pressure gradient. Prandtl, in his experiment [4], also noted that flow separation on one side of the rotating cylinder is completely eliminated when the rotational speed is high.

4. Conclusion

The present study shows that rotating a circular cylinder can result in the suppression of the vortex shedding and elimination of boundary layer separation on one side of the cylinder at high rotation rate. It confirms the existence of a critical α value of about 2.3 at which the vortex shedding is suppressed. Below this critical value of α, the Kármán vortex street and separation points are observed. Vortex shedding is deflected and separation points are displaced more and more towards the rotation direction of the cylinder as α increases. Above the critical α value, vortex shedding disappears.

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