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VORTICAL DYNAMICS FOR BOUNDED SHEAR FLOWS PAST A ROTARY OSCILLATING CIRCULAR CYLINDER

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Abstract. *Wwe computationally investigated two bounded laminar shear flows past a periodically rotating circular cylinder and analyzed the wake control of vortex shedding. The shear flows considered in the present study are the Poiseuille flow and Couette flow. The blockage coefficient, B, defined as the ratio of the cylinder diameter to the channel width, was set to be 0.2 and 0.5. The Reynolds number, based on the mean velocity (or undisturbed flow velocity) and diameter of cylinder, was fixed at 50. We studied the variations of vorticity distribution, lift and drag coefficients and vortex flow patterns by varying the period (T) and the peak rotation speed (A) of the cylinder under rotation. General observation shows that the suppression can be achieved only when the peak velocity of rotary oscillation is big, compared to the average speed of the incoming flow. Nevertheless, the proper combinations of the peak velocity and rotary period vary for different blockage ratio and the type of shear flow.*

1 INTRODUCTION

In the study of flow past a non-streamlined bluff body, vortex shedding appears when the Reynolds number reaches beyond some critical value which is usually not big. It is a periodic phenomenon. Therefore, when the shedding is present, both the pressure and velocity fields in the vicinity behind the bluff body oscillate at the vortex shedding frequency. There could be several detrimental effects due to this physical phenomenon. For example, the vortices create alternating low pressure zones on the downstream side of the body and an alternating net force perpendicular to the flow direction results. Naturally, the body is pushed towards the low pressure side which results in body vibration normal to the incoming flow. Vortex-induced vibrations may occur at relatively moderated flow speeds and, hence, the structure itself may undergo a considerable number of stress cycles as time goes on and structural fatigue must be taken into consideration for many practical engineering designs such as bridge [1] and chimney [2]. In addition, the pressure fluctuations also introduce noise. For example, Vortex shedding can be a significant source of noise when an axial flow fan is operated at a lightly loaded condition [3]. Furthermore, a horseshoe vortex is induced in a three-dimensional situation when the cylinder is vertically mounted on a surface. This phenomenon results in, for example, bridge scour which removes sediment such as sand and rocks from around its abutments. It has been known that bridge scour is one of the three main causes of bridge failure [4].

Taking these aspects into consideration, we find that the understanding and suppression of vortex shedding has its own engineering and physical significances. In the past several decades, many studies have been devoted to understanding the physics and mechanism of vortex shedding. Many review papers are available in the literature, reporting the progress of revealing physics in the due course [5-8]. This signifies the complicated nature behind the fascinating physical phenomenon. In fact, there still are new physical features which are often revealed even nowadays.

In the past decade, attention has been paid to the suppression of vortex shedding behind the bluff bodies in order to reduce possible negative effects in various engineering applications. Recently, Choi *et al.* have classified the suppression methods into the boundary-layer control and direct-wake modifications [9]. They pointed out that the boundary-layer control method was only applicable to bluff bodies having a movable separation point. In contrast, the direct-wake modification can be applied to all kinds of bluff bodies. In the following, we will focus on the latter strategy. In the literature, many approaches have been devised to reduce and/or suppress vortex shedding.

The application of a splitter plate located at a base surface or downstream of the bluff body has been a method widely studied in the literature [e.g. 10-13]. The presence of the splitter plate stabilizes the near wake by delaying the interaction of shear layers from the both sides of the bluff body and, therefore, suppress vortex shedding. Another strategy to suppress vortex shedding is due to cylinder rotation. Two possible ways of cylinder rotation include constant rotation and rotary oscillation. In the approach of constant rotation, the rotation motion modifies wake flow pattern and, hence, vortex shedding configuration. Many investigations are available in the literature [e.g. 14-17]. For the rotary oscillation of the cylinder, there are two control parameters, the peak angular velocity and the frequency (or period) of oscillation. Taneda conducted a series of experiments for Re between 30 and 300 [18]. He revealed that if the frequency was high enough, the vortex shedding can be effectively suppressed. Later, employing flow visualization techniques, Tokumaru and Dimotakis carried out experiments at Re = 15,000 and concluded that it was "possible to exercise considerable control over the cylinder wake via oscillatory rotary forcing." [19] These conclusions were confirmed by the theoretical elaboration of Shiels and Leonard [20]. In addition, there are some new findings of the flow physics for different combinations of the two control parameters [21-24].

It is interesting to find that few reports have been devoted to shear flow effect on the vortex shedding suppression, even though shear flows are common in engineering applications, even though shear flow vortex shedding has been rigorously studied in the literature [e.g. 25-26]. In the present study, we study vortex shedding suppression due to cylinder rotary oscillation in shear flows bounded by two lateral walls. Two particular types of shear flows are investigated; they are the Poiseuille flow and Couette flow. The former represents the symmetric flow and the latter asymmetric. The study was carried out computationally. The flow features were also discussed.

2 PROBLEM SETUP AND ITS MATHEMATICAL FORMULATION

2.1 The physical problem

In order to reduce difficulties in computations, we study the effect of two-dimensional shear flows which are bounded in two parallel walls introducing viscous effects to dissipate disturbances induced by the presence of the cylinder. Shown in Figure 1, the shear flow with an arbitrary velocity profile $u(y)$ far upstream passes a cylinder performing rotary oscillation. The channel width is w. The diameter of the cylinder is d. The cylinder is placed symmetrically in the channel and performs a rotary oscillation. Of particular interests in the present study are the incoming flows with a parabolic and linear velocity distribution. The two profiles represent Poiseuille and Couette flows. The former one is driven by a constant pressure gradient and the latter by the constant motion of the upper wall. Ideally, the walls extend upstream and downstream to infinity. For the Poiseuille flow, the velocity distribution can be expressed as

$$\mathbf{u}(\mathbf{x}) = \left[1.5 - 6\left(\frac{y}{w}\right)^2\right]\mathbf{i}, \quad \text{far upstream and downstream} \tag{1}$$

where $\mathbf{u}$ is the nondimensional velocity field, $\mathbf{x} = (x, y)$ the coordinates with origin at the center of cylinder, as shown in Figure 1, and $\mathbf{i}$ the unit vector in x-direction. For the Couette flow, the velocity profile is

$$\mathbf{u}(\mathbf{x}) = \left[2\left(\frac{y}{w}\right) + 1\right]\mathbf{i}, \quad \text{far upstream and downstream} \tag{2}$$

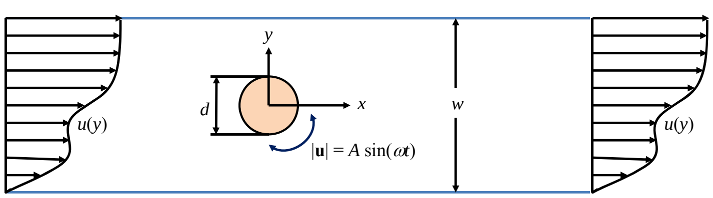


Figure 1. Schematic of the physical problem.

2.2 Mathematical formulation

For the physical problem described above, the unsteady Navier-Stokes equations can be employed for mathematical formulation.

$$\nabla \cdot \mathbf{u} = 0$$
$$\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)\mathbf{u} = -\nabla p + \frac{1}{R}\nabla^2\mathbf{u} \quad (3)$$

where t denotes nondimensional time, p nondimensional pressure field, and R Reynolds number defined as

$$R = \frac{U_{\text{avg}} d}{\nu} \quad (4)$$

in which U_{avg} is the average speed of the incoming flow and ν is the kinematic viscosity of the fluid. In addition, the speed on the cylinder surface can be expressed as

$$|\mathbf{u}| = A\sin\frac{2\pi}{T}t \qquad \text{or} \qquad |\mathbf{u}| = A\sin\omega t \quad (5)$$

where A represents the peak speed of the cylinder in rotary oscillation, T the period of rotary oscillation and ω the ciruclar frequency of rotary oscillation.

There are several paramters which can be defined for the present study. The blockage ratio is defined as

$$B = \frac{d}{w} \quad (6)$$

In the present study, we chose two values for B; namely, $B = 0.2$ and $B = 0.5$, which represent small and medium blockage effects, respectively. The rotary speed ratio is defined as

$$\xi = \frac{A}{U_{\text{avg}}} \quad (7)$$

which is a measure of the local velocity effect around the cylinder. With this definition, Eq. (3) can be rewritten as

$$\frac{|\mathbf{u}|}{U_{\text{avg}}} = \xi \sin\frac{2\pi}{T}t \quad (8)$$

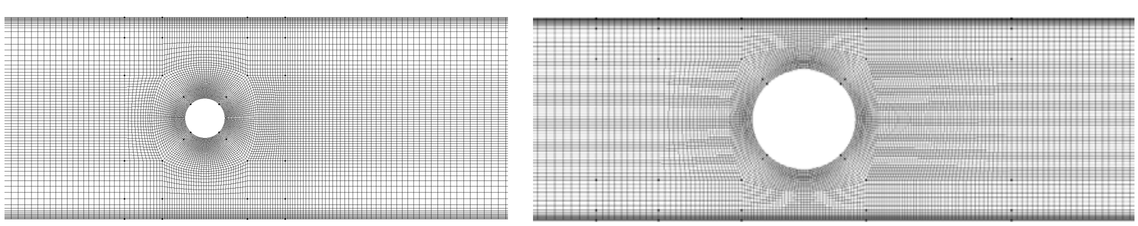
The period ratio is defined as

$$P = \frac{T}{T_s} \quad (9)$$

where T_s is the Kármán vortex shedding period when the cylinder is fixed.

The present study was conducted computationally. We employed the commercial software FLUENT6.3 for computation. For each computation, the procedure can be divided into three parts. First of all, the SIMPLE algorithm was adopted for steady flow computation for the flow past a fixed cylinder and a specified Reynolds number. Then the steady solution was employed as the initial condition for unsteady computation for which the PISO algorithm was used. Again, at this stage, the cylinder was fixed. After the stable periodic solution was achieved, the rotary oscillation of the cylinder began and the development of the flow was futher computed.

The meshes for computations were generated by GridgenV15. The computational domain was divided into three regions. Two typical meshes are shown in Figure 2. For the first region, an *O*-grid was generated around the cylinder. Far away the cylinder, a simple *H*-grid with horizontal and vertical lines was employed. In between the simple *H*-grid and the *O*-grid, another set of *H*-grid was generated.



(a) $B = 0.2$ (b) $B = 0.5$

Figure 2. Typical meshes used in the present study.

3 RESULTS AND DISCUSSIONS

A series of computations have been conducted to study the flow phenomena behind the circular cylinder. All the results discussed in this section were obtained based on the following values of parameters: (1) B = 0.2 and 0.5; (2) R = 50; (3) ξ = 0.05, 0.10, 0.20, 0.40, 0.60, 0.80, 1.00, 0.5, 0.5π, π, and 5; (4) P = 0.05, 0.25, 0.33, 0.50, 1.00, and 2.00.

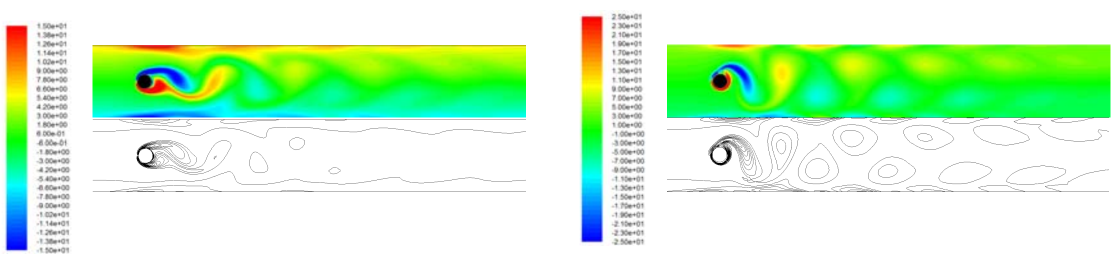
In our computations, the Strouhal numbers when the cylinder is fixed are 0.202 at B = 0.2 and 0.397 at B = 0.5 for Poiseuille flow and St = 0.163 at B = 0.2 and St = 0.371 at B = 0.5 for Couette flow. We can find that the values of St for Poiseuille and Couette flows are significantly different when the blockage ratio is the same. Furthermore, in our computations, we fixed the time step Δt = 0.01.

3.1 Rotary oscillation at P = 1

For the flow at P = 1, the computational results show that more vorticity is generated for different values of B and different shear flows when the value of ξ is raised. Figures 4 and 5 show some typical vorticity distributions in the flow field. Due to symmetry of the Poiseuille flow profile, the vortex shed from the either side of the cylinder is of equal strength; nevertheless, in the Couette flow, the vortex shed from the upper part of the cylinder is stronger than that from the lower part.

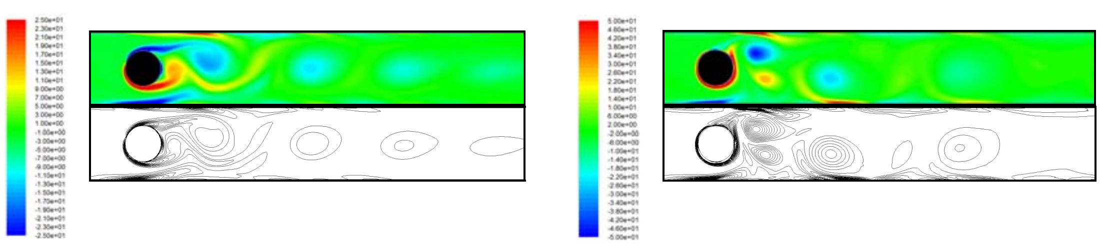
Of course, the vortex dynamics becomes more complicated if ξ is big enough at B = 0.5, compared to those at B = 0.2. For the Couette flow, the two vortices generated at different times may merge into one downstream. Due to the velocity distribution of the Couette flow in which the upper part of flow has a higher speed than the lower part, the vortex shed from the upper part of the cylinder moves faster than the one shed from the lower part. Therefore, the vortex from the upper cylinder merges with the one from the lower cylinder which is generated earlier than the former one.

Furthermore, the effect of the starting time at which the rotary oscillation begins on the development of flow field was also investigated for the case of incoming flow with the Poiseuille profile. The results show that the starting time does have significant influence on the temporary flow development; nevertheless, the long-term stable flow field is not affected. This implies that we are not able to suppress the vortex shedding or vortex street effectively by introducing the rotary oscillation of cylinder at P = 1. In fact, it just strengthens the vortex shedding, rather than diminishes shedding strength.



(a) ξ = 0.2 (b) ξ = 5.0

Figure 3. Vortex shedding at B = 0.2 and P = 1 for Poiseuille flow.



(a) ξ = 0.2 (b) ξ = 5.0

Figure 4. Vortex shedding at B = 0.5 and P = 1 for Couette flow.

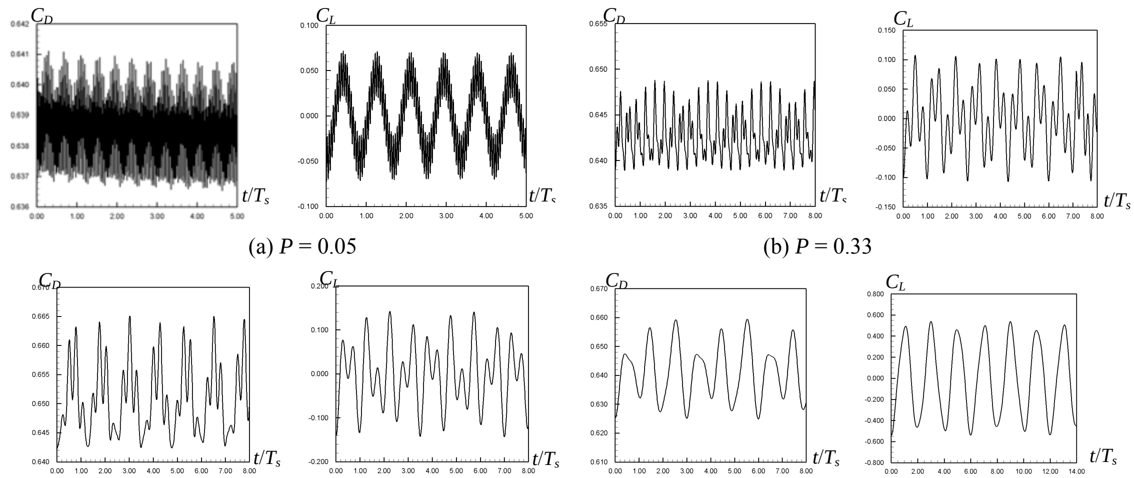
In addition, we also observed the variation of lift and drag coefficients at various values of ξ. The general observation shows that they increase as the value of ξ is raised. Such a trend is more significant for $B = 0.5$.

3.2 Rotary oscillation at other non-dimensional periods

When the rotation period of the cylinder is different from that of vortex shedding, the time-variation of lift and drag forces acting on the cylinder is quite complicated. They are strongly dependent on the peak rotating speeds and rotation frequencies. It is interesting to find that, for the same forcing period, the time-variations of lift and drag have significantly different patterns for different magnitudes of forcing speeds. Similarly, for the same magnitude of forcing speed, the time-variations of lift and drag also exhibit quite different patterns for different forcing periods. Nevertheless, the wake structure is evidently altered with a forced rotation of the cylinder.

Some typical features are shown in Figures 5-8.

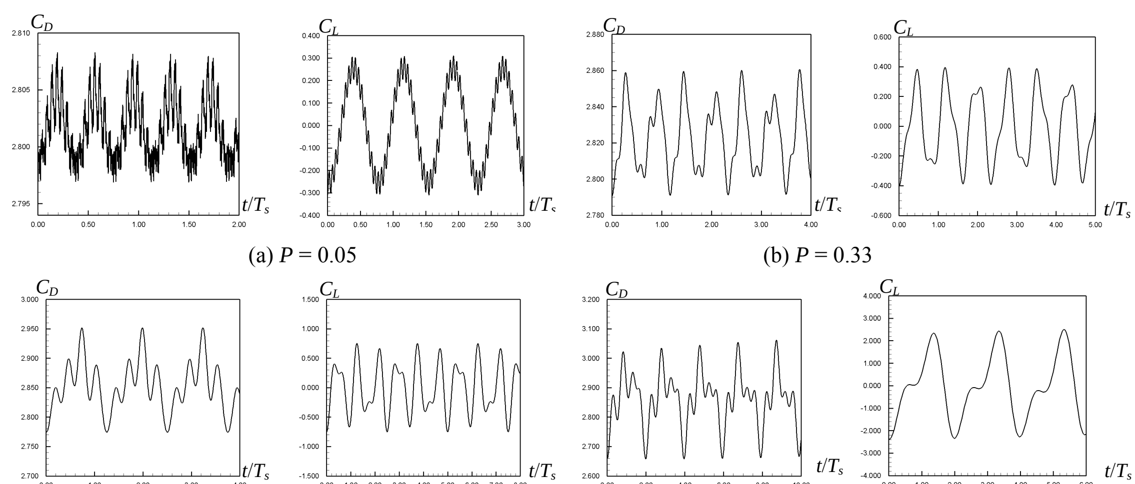
Basically speaking, we find that for all computational cases, the drag and lift coefficients are significantly reduced, compared to those at $P = 1$. For examples, in the Couette flow at $P = 0.05$ and $P = 2.0$, the drag is 26% and 18% less for $B = 0.2$, respectively and 28% and 19% less at $B = 0.5$, respectively.



(a) $P = 0.05$ (b) $P = 0.33$

(c) $P = 0.50$ (d) $P = 2.0$

Figure 5. Variation of drag and lift coefficients at $B = 0.2$ and $\xi = 1$ for Poiseuille flow.



(a) $P = 0.05$ (b) $P = 0.33$

(c) $P = 0.50$ (d) $P = 2.0$

Figure 6. Variation of drag and lift coefficients at $B = 0.5$ and $\xi = 1$ for Poiseuille flow.

In addition, the variation for each case reflects that it is a physical phenomenon combing physics of two frequencies, the vortex shedding frequency and the rotary oscillation frequency. The FFT analysis confirms this. The variations at $B = 0.2$ seem more regular than those at $B = 0.5$. This may be due to the fact that at $B = 0.5$, the blockage effect is more significant which results in a strong interaction between the wall and the flow

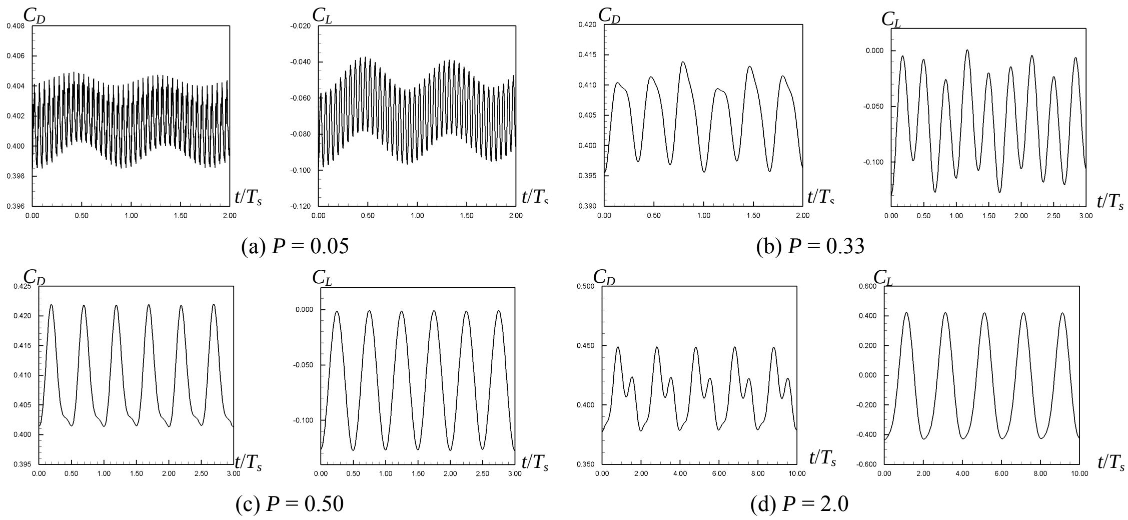


Figure 7. Variation of drag and lift coefficients at $B = 0.2$ and $\xi = 1$ for Couette flow.

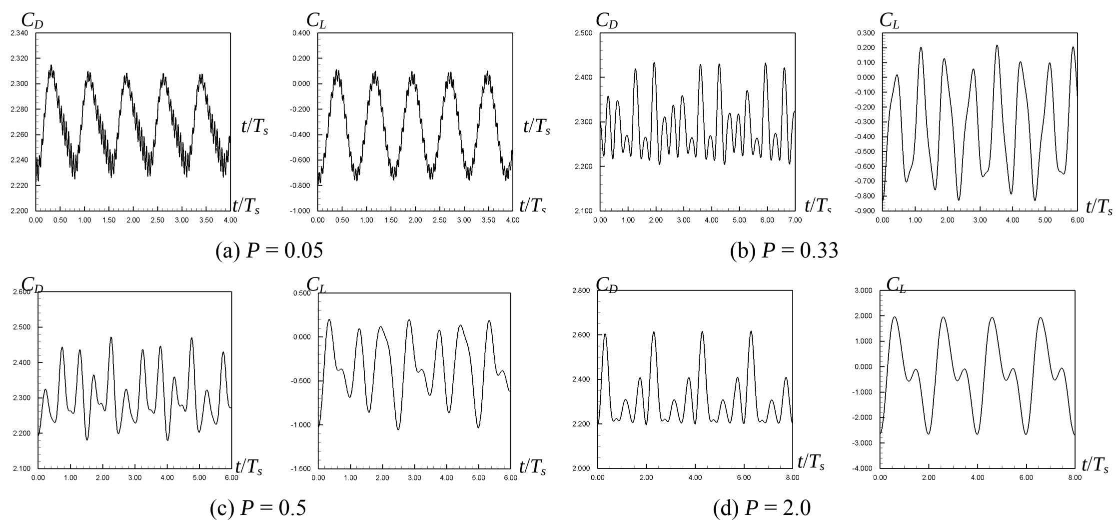


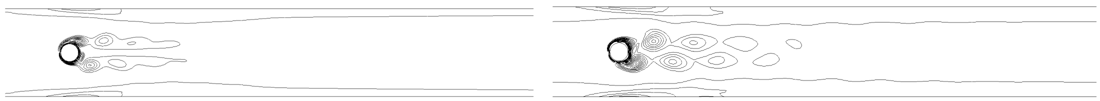
Figure 8. Variation of drag and lift coefficients at $B = 0.5$ and $\xi = 1$ for Couette flow.

3.3 Vortex shedding suppression

In the present study, we find that for a proper combination of peak rotation speed and rotation period, the vortex shedding suppression is possible. Nevertheless, effects of the combination on the suppression mechanism are quite sensible for the shear flow under consideration in the present study.

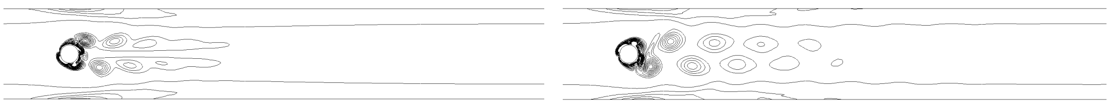
First of all, we find that vortex shedding suppression can be possible when the rotary oscillation is at high peak speed for all cases. And the selection of P should be small, usually less than 0.5. Nevertheless, the suitable values of P depends on the peak speed of rotation which is represented by the value of ξ.

For the case of Poiseuille flow, the computational results show that possible values of ξ for vortex shdding suppresion appear around 0.33, as shown in Figures 9 and 10. It is quite interesting to find that its range is almost fixed regardless of values of other parameters. At $B = 0.2$, the wake which is almost steady is elongated and no vortex shedding appears when $\xi = 0.33$. At $\xi = 0.5$, another scenario is present, in which the shed vortices are quickly dissipated not too far downstream away from the cylinder. When $B = 0.5$, we did not find any case in which the vortex shedding is totally suppressed. The larger value of B results in more complicated flow interaction and the vortices are shed not only from the cylinder but also from the walls. Therefore, it makes vortex shedding suppression more difficult. Nevertheless, Figure 11 shows that the vortices can also be quickly dissipated not far downstream from the cylinder. It is obvious that in this case, some vortices come from the presence of the cylinder and some from the walls. The strength of the latter appears weaker. About 3 diameters downstream of the cylinder, the vortices disappear.



(a) $P = 0.33$ (b) $P = 0.5$

Figure 9. Vortex shedding suppression at $B = 0.2$ and $\xi = \pi$ for Poiseuille flow.



(a) $P = 0.33$ (b) $P = 0.5$

Figure 10. Vortex shedding suppression at $B = 0.2$ and $\xi = 5$ for Poiseuille flow.

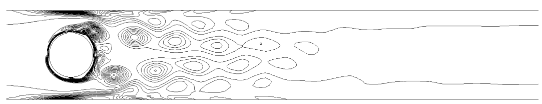
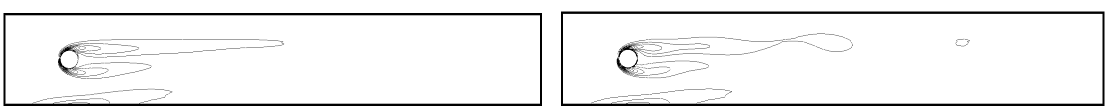


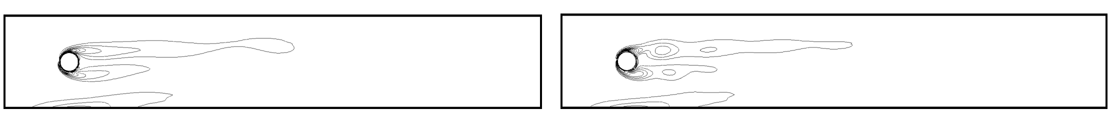
Figure 11. Vortex shedding suppression at $B = 0.5$, $\xi = 5$ and $P = 0.33$ for Poiseuille flow.

For the Couette flow, we have somewhat different stories, as shown in Figures 12-16. For the case with B = 0.2, we find that there are more parameter combinations in which the vortex shedding is suppressed. In all cases shown in Figures 12-15, the scenario is the one in which the wake recirculating zones are elongated and are almost steady in time. It is interesting to find that even for smaller values of ξ, the suppression is possible. And at a smaller value of ξ, it appears that the possible range for P is wider. As ξ is raised, the possbile range for P shrinks. And compared to those in Poiseuille flow, Couette flow profile has a better range for the parameters to suppress vortex shedding. However, if the value of B is increased to 0.5, the situation becomes similar to that for Poiseuille flow. This should be attributed to the fact that the interaction between the flow and the wall becomes more stronger and vortex shedding suppression more difficult.



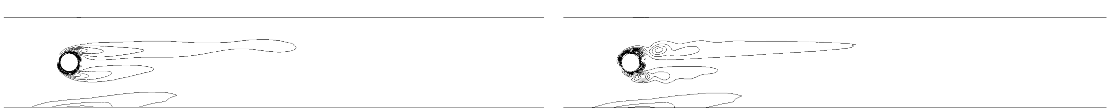
(a) $P = 0.05$ (b) $P = 0.5$

Figure 12. Vortex shedding suppression at $B = 0.2$, and $\xi = 0.2$ for Couette flow.

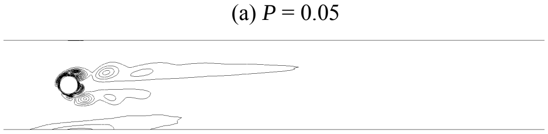


(a) $P = 0.05$ (b) $P = 0.5$

Figure 13. Vortex shedding suppression at $B = 0.2$, and $\xi = 1$ for Couette flow.

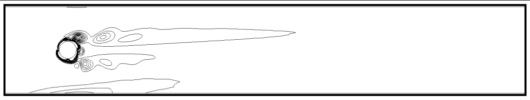


(a) $P = 0.05$ (b) $P = 0.25$

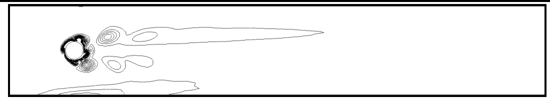


(c) $P = 0.33$

Figure 14. Vortex shedding suppression at $B = 0.2$, and $\xi = \pi$ for Couette flow.



(a) P = 0.25



(b) P = 0.33

Figure 15. Vortex shedding suppression at B = 0.2, and ξ = 5 for Couette flow.

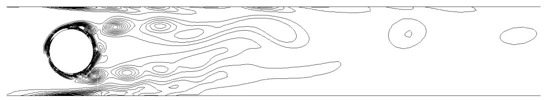


Figure 16. Vortex shedding suppression at B = 0.5, ξ = 5 and P = 0.33 for Poiseuille flow.

4 CONCLUSIONS

In the present study, the physical phenomena about shear flows past a circular cylinder under rotary oscillation are investigated. The imposition of the two walls makes the prescription of boundary conditions physically more rigorous and mathematically easier. However, the two walls also introduce more complicated flow physics due to the interaction of viscous effects from the walls and from the cylinder.

The two particular flows considered in the present investigation are the Poiseuille flow and Couette. Several interesting features have been discussed. Two parameters of cylinder rotations are varied and their effects on vortex shedding suppression were investigated. The results show that suppression of vortex shedding is possible as long as a proper combination of these two parameters is carefully chosen. However, as the interaction between the walls and the flow becomes stronger, it becomes more difficult to suppress the vortex shedding.

In addition, there is a wider range of the two parameters for which vortex shedding is suppressed with a Couette flow profile as long as the wall effects is not strong which is possible when B is small.

5 ACKNOWLEDGEMENTS

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REFERENCES

[1] Mohammadi, M.S. and Mukherjee, R. (2013), *Wind Loads on Bridges*, MS Thesis, Royal Institute of Technology, Stockholm, Sweden.

[2] Giosan, I. and Eng, P. (2000), “Vortex shedding induced loads on free standing structures,” *Structural Vortex Shedding Response Estimation Methodology and Finite Element Simulation*, pp. 1-20.

[3] Longhouse, R.E. (1977), “Vortex shedding noise of low tip speed, axial flow fans,” *Journal of Sound and Vibration*, Vol. 53, pp. 25-46.

[4] L.J. Prendergast, L.J. and Gavin, K. (2014), “A review of bridge scour monitoring techniques,” *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 6, pp. 138-149.

[5] King, R. (1977), “A review of vortex shedding research and its application,” *Ocean Engineering*, Vol. 46, pp. 141-171.

[6] Bearman, P.W. (1984), “Vortex shedding from oscillating bluff bodies,” *Annual Review of Fluid Mechanics*, Vol. 16, pp. 195-222.

[7] Williamson, C.H.K. (1996), “Vortex dynamics in the cylinder wake,” *Annual Review of Fluid Mechanics*, Vol. 28, pp. 477-539.

[8] Matsumoto, M. (1999), “Vortex shedding of bluff bodies: a review,” *Journal of Fluids and Structures*, Vol. 13, pp. 791-811.

[9] Choi, H. Jeon, W.P. and Kim, J. (2008), “Control of flow over a bluff body,” *Annual Review of Fluid Mechanics*, Vol. 40, pp. 113-139.

[10] Bearman, P.W. (1965), “Investigation of the flow behind a two-dimensional model with a blunt trailing edge and fitted with splitter plates,” *Journal of Fluid Mechanics*, Vol. 21, pp.241-255.

[11] Roshko, A. (1955), “On the wake and drag of bluff bodies,” *Journal of the Aeronautical Sciences*, Vol. 22, pp.124-132.

[12] Yao, Y.F. and Sandham, N.D. (2002), “Direct numerical simulation of turbulent trailing-edge flow with base flow control,” *AIAA Journal*, Vol. 40, pp. 1708-1716.

[13] Sudhakar, Y. and Vengadesan, S. (2012), “Vortex shedding characteristics of a circular cylinder with an oscillating wake splitter plate,” *Computers and Fluids*, Vol. 53, pp. 40-52.

[14] L. Prandtl, L. (1961), *Collected Works*, edited by W. Tollmien, H. Schlichting, and H. Görtler, Springer.

[15] Tanaka, H. and S. Nagano, S. (1973), “Study of Flow around a Rotating Circular Cylinder,” *Bulletin of JSME*, Vol.16, pp. 234-243.

[16] F.H. Barnes, F.H. (2000), “Vortex shedding in the wake of a rotating circular cylinder at low Reynolds number,” *Journal of Physics D: Applied Physics*, Vol. 33, pp. L141-L144.

[17] Kang, S., Choi, H., and Lee, S. (1999), “Laminar flow past a rotating circular cylinder,” *Physics of Fluids*, Vol. 11, pp. 3312-3321.

[18] Taneda, S. (1978), “Visual observations of the flow past a circular cylinder performing a rotary oscillation,” *Journal of the Physical Society of Japan*, Vol. 45, pp. 1038-1043.

[19] Tokumaru, P.T. and Dimotakis, P.E. (1991), “Rotary oscillation control of a cylinder wake,” *Journal of Fluid Mechanics*, Vol. 224, pp. 77-90.

[20] Shiels, D. and A. Leonard, A. (2001), “Investigation of a Drag Reduction on a Circular Cylinder in Rotary Oscillation, *Journal of Fluid Mechanics*, Vol. 431, pp. 297-322.

[21] Wu, J.M., Mo, J.D. and Vakili, A.D, (1989) “On the wake of cylinder with rotational oscillations,” *AIAA Paper*, No. AIAA-89-1024, 1989.

[22] S. Baek, S., H.J., and Sung, H.J. (1998), “Numerical simulation of the flow behind a rotary oscillating circular cylinder,” *Physics of Fluids*, Vol. 10, pp. 869-876.

[23] Furukawa, H. (2003), “Vortex structure and periodicity of disturbances in the wake of a rotationally oscillating cylinder,” *Journal of the Physical Society of Japan*, Vol. 72, pp. 1092-1097.

[24] Thiria, B., Goujon-Durand, S., and Wesfreid, J.E. (2006), “The wake of a cylinder performing rotary oscillations,” *Journal of Fluid Mechanics*, Vol. 560, pp. 123-147.

[25] Maull, D.J. and Young, R.A. (1973), “Vortex shedding from bluff bodies in a shear flow,” *Journal of Fluid Mechanics*, Vol. 60, pp. 401- 409.

[26] Lei, C., Cheng L., Armfield, S.W., and Kavanagh, K. (2000), “Vortex shedding suppression for flow over a circular cylinder near a plane boundary,” *Journal of Fluid Mechanics*, Vol. 27, pp. 1109–1127.