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Effects of streamwise gust amplitude on the boundary layer of two tandem circular cylinders

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SUMMARY

Herein, three-dimensional large eddy simulations are conducted with the aim of investigating the effect of sinusoidal streamwise gust amplitude on the boundary layers of two tandem circular cylinders in a subcritical state, where the Reynolds number $Re = 10^3$ and the center-to-center space L between the two cylinders is fixed at 3.5 times the cylinder diameter D. And the sinusoidal streamwise gust is set as $U = U_0 (1 + A_R \sin 2\pi f_u t)$, where A_R is the velocity amplitude ratio, U_0 is the mean flow velocity, f_u is the frequency of the gust, and t is time. To better understand the effect of streamwise gust amplitude on the boundary layer of the two tandem cylinders, the flow structure, flow separation, and boundary-layer thickness. The results show that the flow structure around the cylinders is sensitive to A_R and two different flow patterns are identified. The separation point θ_s of boundary layer changes with the switch in flow pattern. Additionally, the boundary layer thickness δ decreases with increasing A_R.

Keywords: tandem circular cylinders, sinusoidal flow, boundary layer

1. INTRODUCTION

The fluid flow over cylindrical structures is a prevalent phenomenon in engineering fields such as adjacent tall buildings, parallel cooling towers, bridge piers, and wind turbine towers, and they have thus attracted significant research attention. The problem of a pair of cylinders that are placed in tandem has been widely studied in the past decades. Most previous studies have focused on two tandem cylinders subjected to a uniform oncoming flow, and it was found that the Reynolds number *Re* and spacing ratio *L/D* were two key parameters affecting the flow around two tandem circular cylinders (Zdravkovich, 1987; Carmo et al., 2010; Alam, 2014). However, in many practical applications, the oncoming flow contains unsteady components. To analyse the effect of an unsteady oncoming flow, a few studies have been conducted on an isolated airfoil or cylinder under a sinusoidal streamwise gust (Cao and Li, 2015; Ma et al., 2021).

As reviewed above, some studies have investigated the effects of sinusoidal flows on a single cylinder or the effects of *Re* and *L/D* on two tandem cylinders subjected to a uniform oncoming flow. To our knowledge, no study has investigated the effect of a sinusoidal oncoming flow over two tandem circular cylinders; the wake and aerodynamic forces of sinusoidal and uniform oncoming flows are expected to differ. This study aims to understand the effects of sinusoidal streamwise gust on the flow structure and boundary layer around two tandem cylinders. The velocity of the sinusoidal streamwise gust is set as $U = U_0\,(1 + A_R \sin 2\pi f_u t)$ with $A_R = 0$ (uniform flow), 0.05, 0.10, 0.20, and 0.25. The spacing ratio between the two cylinders is fixed as $L/D = 3.5$ and the Reynolds number based on D and U_0 is set as $Re = 1 \times 10^3$., which is corresponding to a critical state (Zhou et al., 2019).

2. BOUNDARY CONDITION

The computational domain size is 45D, 20D, and 4D in the x-, y-, and z-direction, respectively. For the inlet boundary, a sinusoidal streamwise gust with a velocity of $U = U_0\,(1 + A_R \sin 2\pi f_u t)$ is applied. Here, the mean velocity U_0 = 10 m/s and the oscillation frequency f_u = 0.5 Hz. The velocity amplitude ratios considered are A_R = 0, 0.05, 0.10, 0.20, and 0.25, where A_R = 0 corresponds to a uniform oncoming flow. At the outlet, the convective boundary condition and fixed value of the pseudo-pressure $p = 0$ are applied for the velocity and pressure, respectively. Furthermore, a symmetric boundary condition is adopted for the top and bottom surfaces of the computational domain, and a periodic boundary condition is employed for the two side surfaces. Finally, the no-slip wall condition is applied on the surfaces of the two cylinders.

3. FLOW STRUCTURE

Fig. 1 displays the contours of instantaneous spanwise vorticities at the midspan plane of the cylinders for each A_R. Two major flow patterns are distinguished:

Reattachment pattern: At A_R = 0.05 and 0.10, the shear layers separating from the upstream cylinder develop are similar to those in a uniform flow (A_R = 0.00), where both the upper and lower shear layers attach on the downstream cylinder. Simultaneously, a pair of counter-rotating vortices is generated in front of the downstream cylinder. In the wake of the downstream cylinder, the reattached shear layers shed alternate vortices, affording a Kármán vortex street.

Co-shedding pattern: For A_R = 0.20 and 0.25, alternate vortex shedding occurs in the gap between the two cylinders. The shear layers from the upstream cylinder roll up into vortices. Here, the upstream-cylinder shear layers are not as long as those in the reattachment flow and the vortices in the gap alternately impinge onto the downstream cylinder. This results in the formation of binary vortices in the wake of the downstream cylinder. Therefore, alternate vortex-shedding occurs in both the gap between the two cylinders and wake of the downstream cylinder, which is similar to the flow structure with $L/D \geq 4$ under a uniform oncoming flow.

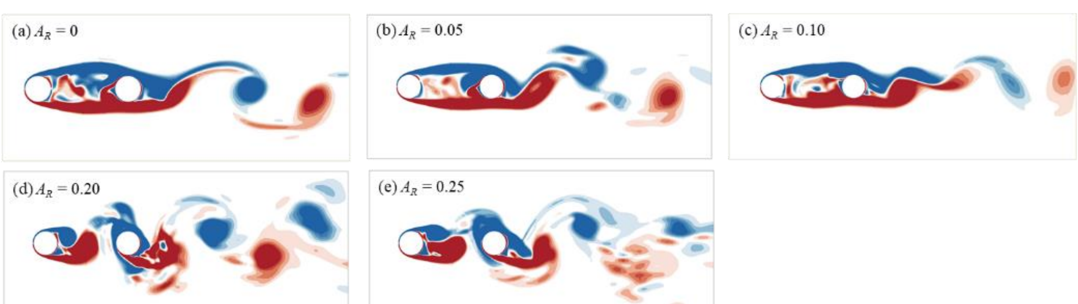

Figure 1. Instantaneous spanwise vorticity structure at the midspan plane.

4. BOUNDARY LAYER

The study of the boundary layer is a good direction for analyzing the effects of the streamwise sinusoidal gust on the flow mechanism. Prandtl (1904) believed that the influence of viscous force could not be ignored in thin layers near the wall and a considerable velocity gradient exists along the normal direction of the wall in this thin layer, which is called boundary layer. The separation of this boundary layer leads to the departure of the main flow from the bluff body and the formation of vortex-shedding in the wake zone. Thus, the separation and the thickness of the boundary layer are studied to get an in-depth understanding of the effect of streamwise sinusoidal gust on the flow structure around two tandem cylinders.

4.1. Separation point

The separation point is obtained from time-mean skin friction distributions on the cylinder surfaces. The relationship between separation angle θ_s and A_R is shown in Fig. 2. The θ_s for the upstream cylinder in the reattachment pattern (A_R = 0 – 0.15) remains around 92°, which is close to the separation angle of a single cylinder in the uniform flow ($\theta_s \approx$ 95º, Cao et al. (2010)). With increasing A_R, θ_s for the upstream cylinder grows to 95.4º for A_R = 0.20. On the other hand, θ_s on the downstream cylinder stays in θ_s = 126º - 135º in the reattachment pattern and suddenly drops to θ_s = 99.8º in the co-shedding pattern with A_R increasing to 0.20, which is similar to the result of the two flow patterns in the uniform flow (Zhou et al., 2019). This result suggests that a larger A_R of 0.20 and 0.25 that can lead to the co-shedding pattern could significantly advance the shear layer separation point of the downstream cylinder and thus enhances the flow instability.

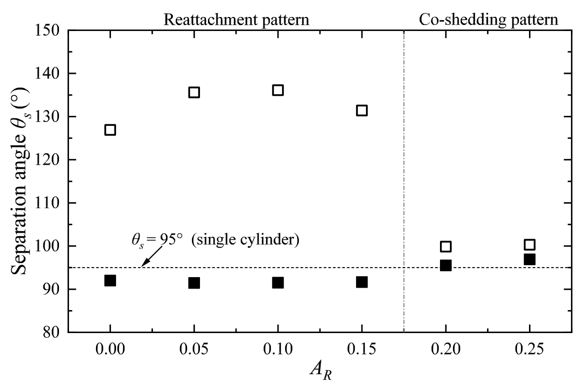

Figure 2 Variations in separation angle θs with A_R.
Solid symbol: upstream cylinder; Open symbol: downstream cylinder.

4.2. Thickness of boundary layer

Fig. 3 presents the thickness of boundary layer of the upstream cylinder. The thickness of the boundary layer δ is defined from the surface of the cylinder to the point where the tangential velocity equals $0.99U_e$, where U_e denotes the maximum value of the tangential velocity. As shown in Fig. 3, δ increases with θ, resulting from that the closer to the separation point, the more unstable the boundary layer is and the higher the boundary layer is raised by the recirculation zone behind the separation point. However, a larger A_R of 0.25, which could also make the boundary layer more unstable, as shown in Fig. 2, would rather suppress the thickness of the boundary layer. It can be seen that the rate of increase of the boundary layer with θ and the thickness δ decrease with A_R, indicating that A_R might reduce the thickness of the boundary layer while also weakening the intensity of the recirculation zone.

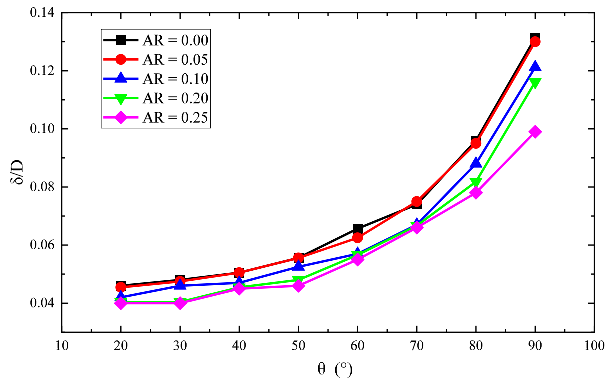

Figure 3. Thickness of the boundary layer of upstream cylinder for different A_R.

5. CONCLUSIONS

Herein, three-dimensional large eddy simulations are conducted with the aim of investigating the effect of sinusoidal streamwise gust amplitude on the boundary layers of two tandem circular cylinders in a subcritical state, where the Reynolds number $Re = 10^3$ and the center-to-center space L equals 3.5 times the cylinder diameter D. The results show that the flow structure around cylinders is sensitive to A_R. As A_R changes, the reattachment pattern ($A_R \leq 0.15$) mutates to the co-shedding pattern ($A_R \geq 0.20$). Moreover, the boundary layer is also sensitive to flow pattern. As flow pattern switches with A_R, the separation point of upstream cylinder maintains at 95º, while the separation point of downstream cylinder drops dramatically from 126º - 135º in the reattachment pattern to around 100º in the co-shedding pattern. Additionally, the boundary layer thickness δ decreases with increasing A_R, and so does the rate of increase of the boundary layer with θ.

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