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Numerical study on aerodynamic characteristics and flow field of a circular cylinder equipped with a C-ring behind

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SUMMARY:
Slender cylindrical structures such as cables and signal poles often experience vortex-induced vibrations. Recently, scholars have developed a novel mitigating measure by equipping a C-ring on the structures, where the C-ring is always behind the cylinder by tail rudder, but the mitigation mechanism is still unclear. To this end, the large-eddy simulation approach has been adopted to investigate the influence of a C-ring on the aerodynamic forces, surface pressure, and flow around a circular cylinder at Re = 1000. Furthermore, to determine the appropriate radii (R) and arc lengths (θ) of the C-ring, various values of R and θ are considered and studied herein. The results indicate that a C-ring can reduce the standard deviation of the lift coefficient by 40%–90%, whereas it has an unremarkable effect on the mean drag coefficient. The C-ring also has a significant influence on the fluctuating pressure coefficients, resulting in a small standard deviation of the fluctuating lift. The spanwise flow on the leeward side of the cylinder under the influence of C-rings with different R and θ can be categorized into three modes. Meanwhile, the C-ring mitigates wind-induced vibrations by enhancing the spanwise flow on the leeward side of the cylinder.

Keywords: Circular Cylinder, C-ring, Aerodynamic Characteristics

1. INSTRUCTION

Slender circular cylinders such as cables and signal poles often experience vortex-induced vibrations, especially in regions that are prone to strong winds. When air flow over these cylindrical structures, large negative pressure resulting in the streamwise drag will be formed in the wake region and alternative vortex shedding contributing to periodic fluctuating lift perpendicular to direction of the flow will be also appeared. Meanwhile, vortex-induced vibration is occurred with large probability once the frequency of the alternative vortex shedding is close to intrinsic frequency of the cylindrical structures. The cylindrical structures encountering vortex-induced vibration with large amplitude are more likely broken and unserviceable.

Passive suppression measures are one of the most effective means to solve this problem of vortex-induced vibration of the cylindrical structures. Installing additional attachments are the commonly used measures for this issue, which can disturb flow field in the wake region and weaken consistency of the vortex shedding, then leading to smaller fluctuating lift. Splitter plate is one of the early vortex-induced vibration suppression measures which have been studied and applied in engineering. Roshko (Roshko, 1954) adopted a splitter plate to prevent interaction of shear layers on upper and lower surfaces of the cylinder to suppress vortex shedding. Unfortunately, installing these mitigating measures is expensive and the related workload is considerable. To address this problem, Ma (Ma et al., 2021) recently proposed a novel cost-effective mitigating measure using a C-ring, which exhibits good vibration suppression. Nevertheless, due to the limited wind tunnel test data, the vibration suppression mechanism of a C-ring is still unclear and requires further study.

With the development of computer performance and computational fluid dynamics (CFD), numerical simulation based on LES approach which has good accuracy is increasingly applied for investigating the flow around a bluff body, and vast amounts of data about flow field can be obtained at a low cost. The numerical simulation based on LES approach is carried out to investigate the influence of a C-ring on the aerodynamic characteristics and flow field of a circular cylinder, as well as to reveal the suppression mechanism of the C-ring.

2. NUMERICAL SETUP

The simulation was performed using the OpenFOAM© code v8.0. The dynamic *k*-equation of LES turbulence model is adopted. Pressure and velocity coupling were solved by the incompressible solver *pisoFoam*, which was implemented using the Pressure-Implicit with Splitting of Operators algorithm based on the factorized finite volume method. A transient, second order implicit Euler method was used for temporal discretization. The Gauss linear interpolation (central differencing) method was applied for gradient schemes. The Gauss linear upwind-based central differencing method was employed for all divergence schemes. The time, gradient, and divergence schemes were approximated with a second order accuracy to obtain an accurate simulation. The residual tolerance for all dependent variables was set to 1×10^{-6}.

As shown in Figure 1(a), the curvilinear O-type orthogonal grid system, with a diameter of 40D and a spanwise length of 7D, was used as the computational domain. The spanwise length of the C-ring was set to 1D, and it was located in the middle of the cylinder. The thickness for the C-ring is set to 0.01D. To comprehensively investigate the effect of the C-ring on the cylinder and flow field, the spanwise length of the domain with the cylinder was set to 7D. Meanwhile, a grid system using the structured O-type grid meshing strategy with good orthogonality was applied herein to adequately resolve the flow field, as shown in Figure 1(b). The depth of the first grid near the cylinder and C-ring surface was set to an empirical value of 0.008D to obtain a dimensionless wall distance of $y+ \approx 1$. The grid points were clustered near the cylinder, with a grid expansion ratio of less than 1.075 in the radial direction, and the width of the first layer grid was approximately twice the value of the depth. Furthermore, the grid on the surface and side of the C-ring were also clustered with a linear growth ratio of less than 1.075, to adapt to rapid changes in flow field there, as shown in Figure 1(c). The grid numbers adopted for different cases, wherein the R (0.7D, 0.8D, 0.9D, and 1.0D) and θ (60°, 90°, 120°, 150°, and 180°) of the C-ring were varied, ranged from 3.11 million to 4.19 million. The dimensionless time step was set to 5×10^{-3}, which results in a maximum Courant number of approximate 1.

The boundary conditions are as follows: the surface of the cylinder and C-ring were set as no-slip condition; a uniform flow velocity was applied at the inlet boundary; a zero static pressure condition was employed at the outlet boundary, and symmetric conditions were adopted at the two spanwise boundaries.

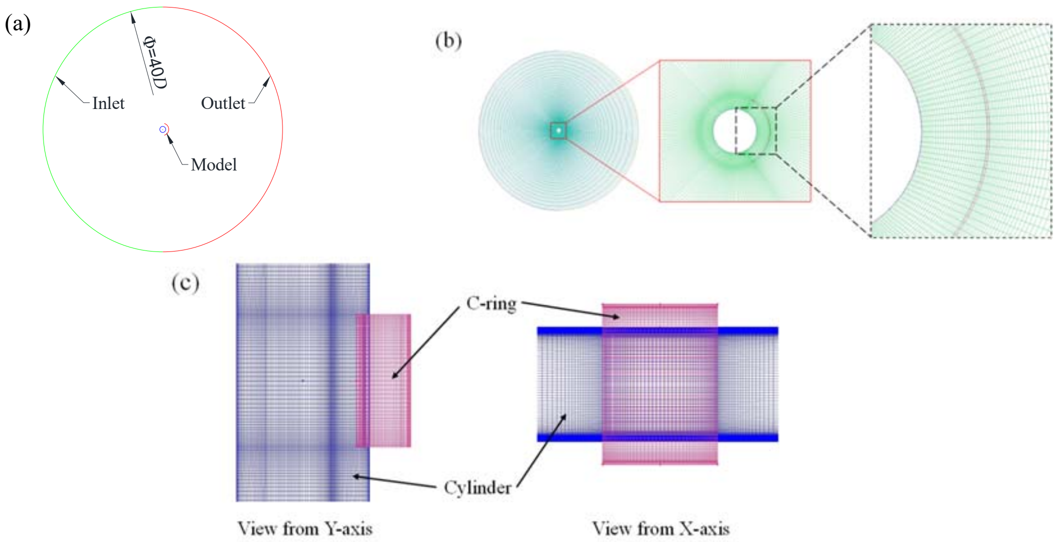

Figure 1. The computational domain. (a) Boundary conditions (front and back are not shown); (b) Grid of the computational domain and close-up view of grids around the model; (c) Local mesh view of the cylinder and C-ring.

3. NUMERICAL VALIDATION

To validate the numerical simulation, the flow over a single circular cylinder with Re = 1000 and 3900 was simulated using the settings described in Section 2. The aerodynamic coefficients obtained from this simulation were compared with those obtained from numerical and experimental methods in previous studies. The comparison of them confirms that the numerical simulation developed herein can provide reasonable and accurate results.

4. RESULTS AND DISCUSSION

The aerodynamic forces, surface pressure distribution, and flow field are comprehensively studied to understand the influence of C-ring on the cylinder and reveal C-ring's mechanism of reducing drag and lift. Some results are illustrate as Figure 2, 3 and 4.

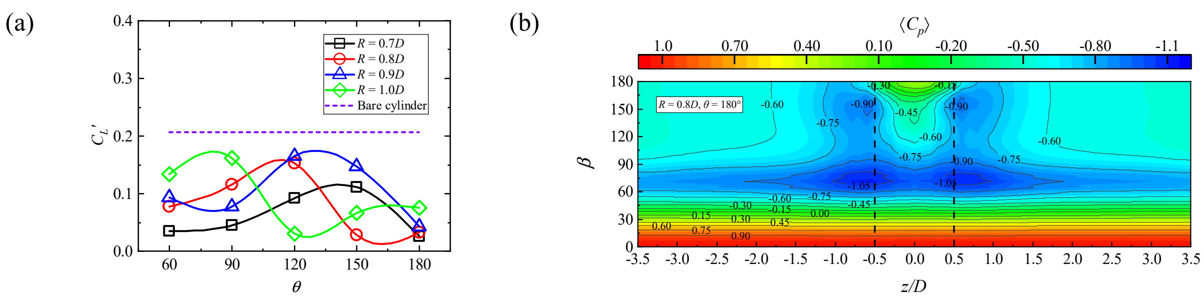

Figure 2. Fluctuating lift coefficients (a) and surface pressure distribution (b).

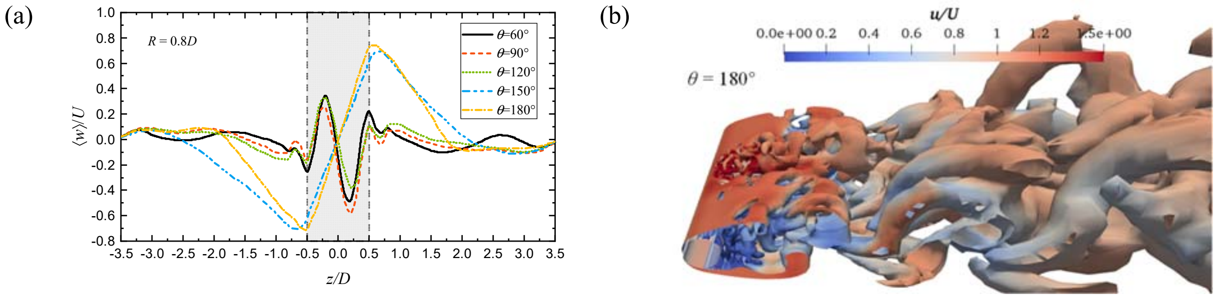

Figure 3. Spanwise velocity behind the cylinder (a) and instantaneous isosurface of $Q = 0.001(U/D)^2$ (b).

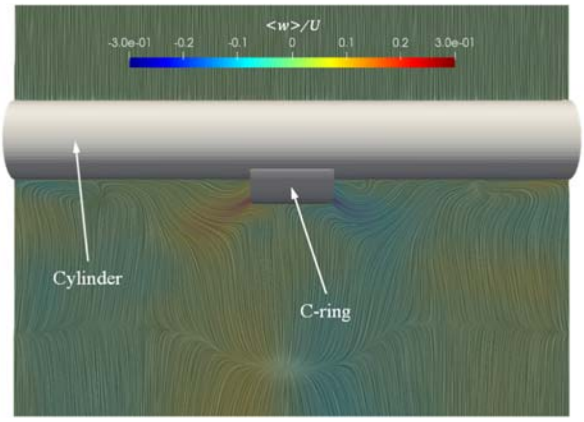

Figure 4. Mean streamlines and mean lateral velocity field at x-z plane, where $R = 0.8D$ and $\theta = 120°$.

5. CONCLUSIONS

The C-ring significantly influence the mean drag coefficient and the fluctuation of the lift coefficient of the cylinder. The C-ring substantially reduces the standard deviation of the lift coefficient by 40%–90%, and the mean drag coefficient of the cylinder with the C-ring ranges from 85% to 115% of that of the bare cylinder. The effect of the C-ring on the surface pressure can be categorized into two modes based on the time mean base pressure. The C-ring also has a significant influence on the fluctuating pressure coefficients, resulting in a very small standard deviation of the fluctuating lift. The spanwise flow on the leeward side of the cylinder can be categorized into two modes. Meanwhile, those on the leeward side of the C-ring can be categorized into three modes. The C-ring generates smaller vortices with higher irregularity along the spanwise direction. The C-ring enhances the spanwise flow on the leeward side of the cylinder, resulting in a small fluctuation in the lift.

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