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LES simulation of the effect of yaw angle on VIV response of a 4:1 rectangular cylinder

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SUMMARY:
Three-dimensional large eddy simulation (LES) is carried out to comprehensively investigate the effects of the yaw angle on vortex-induced vibration (VIV) characteristics of a 4:1 rectangular cylinder. Periodic boundary conditions are utilized to minimize the end effect. It is found that the response amplitude and lock-in region for yaw angles β of 5°, 10°, 20° and 30° agree well with their counterparts for $\beta = 0°$. The numerical results demonstrated the validity of the independence principle in the case of VIV, which has not been demonstrated by laboratory tests due to the difficulty in avoiding the end effects. Hence, it is reasonable to assume that the axial component of the velocity can be ignored for the VIV behaviour of the 4:1 rectangular cylinder when the yaw angle is no larger than 30°.

Keywords: rectangular 4:1 cylinder, vortex-induced vibration (VIV), yaw angle

1. INTRODUCTION

In practical applications, engineering structures are not always perpendicular to the wind but often in skew positions. This yawed configuration may lead to more complex three-dimensional flow characteristics and different VIV responses, compared to the perpendicular case. In early research, the independence principle or cosine rule (Hanson, 1966; Zdravkovich, 2003) was proposed to simplify the fluid-structure interaction analysis for inclined cylinders. There has been much fruitful research to validate the independence principle and its scope of application. However, the effects of yaw angle on the VIV of a bridge deck have rarely been investigated. The 4:1 rectangular cylinder is widely considered as a simplified bridge deck since its VIV response and excitation mechanism are similar to those of bluff bridge decks. Wang et al. (2022) experimentally studied its VIV response under different yaw angles. The results showed that the conventional IP theory is inapplicable to the prediction of the VIV response of the rectangular 4:1 cylinder under skew winds. However, experimental research still faces the difficulty of end-effect-free conditions when investigating the flow past a yawed cylinder (Gallardo et al., 2014). To overcome this limitation, large eddy simulation (LES) is exploited here to investigate the effect of yaw angle on VIV response of a 4:1 rectangular cylinder.

2. NUMERICAL MODEL

As in Marra et al. (2015), the width (B) and height (D) of the 4:1 rectangular cylinder are 0.3 m and 0.075 m, respectively. The mesh in the x-y plane is hybrid (Fig. 1), divided into six sub-regions, including one external static region, one intermediate dynamic region, and four rigid regions close to the cylinder. The height of the first grid layer near the wall is 2×10^{-5} m (0.00027D) and then increases with an expansion ratio of 1.15. There are in total 114,176 cells in the x-y plane. The two-dimensional mesh is first rotated about the y-axis (see Fig. 1(b)) by the corresponding yaw angle. Then, the mesh is elongated in the plane to satisfy a 4:1 aspect ratio in its projection onto a plane perpendicular to the z-axis. Finally, it is extruded in the spanwise direction (z-axis) by the appropriate number of layers to obtain the three-dimensional mesh. In this study, the number of spanwise layers gradually decreases from the sub-region near the model to the edge of the computational domain. The finest spanwise grid size in the region closest to the model surface is set to 0.05D. Five yaw angles (β = 0°, 5°, 10°, 20°, 30°) are considered in this study. The spanwise domain length varies from 8D to 10D. Finally, the total number of grid nodes ranges from 9.1 to 11.1 million. A no-slip boundary condition is imposed on the cylinder surfaces, along with a uniform velocity-inlet, a zero pressure gradient-outlet, and symmetry boundary conditions for the front and back domain sides (y-axis); finally, periodic boundary conditions are set on the lateral domain sides (z-axis).

Only the motion in the crossflow y-direction is allowed. The assumed structural dynamic parameters are consistent with the experimental set-up in Marra et al. (2015). The purpose of the simulation is to examine the occurrence of a significant VIV response; the test case with a minimum Scruton number of 1.9 was therefore selected. The governing equations are discretized and solved by the finite-volume code Fluent. Second-order implicit time integration scheme is used for temporal discretization. Second-order upwind scheme and least-square cell-based scheme are used for spatial discretization of the convection term and diffusion term, respectively. The semi-implicit method for pressure-linked equations (SIMPLE) algorithm is used to solve the pressure-velocity coupled algebraic equations. The structural dynamic equation is numerically solved with the fourth-order Runge-Kutta algorithm. The nondimensional time-step based on free-stream velocity and cross-section dimension D is 0.0757, implying approximately 125 samples per vibration period. The statistical convergence of the solution was assessed based on a calculation performed by halving the time step size.

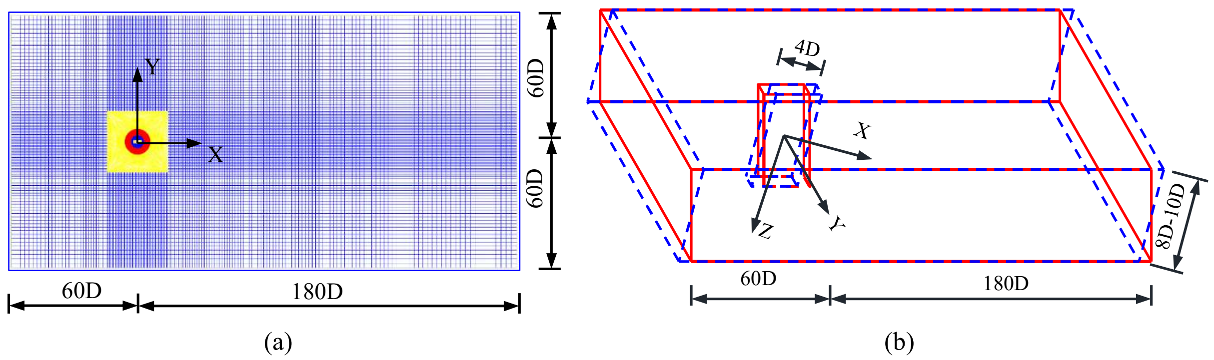


Figure 1. (a) global view of the mesh in the x-y plane; (b) schematic of the computational domain.

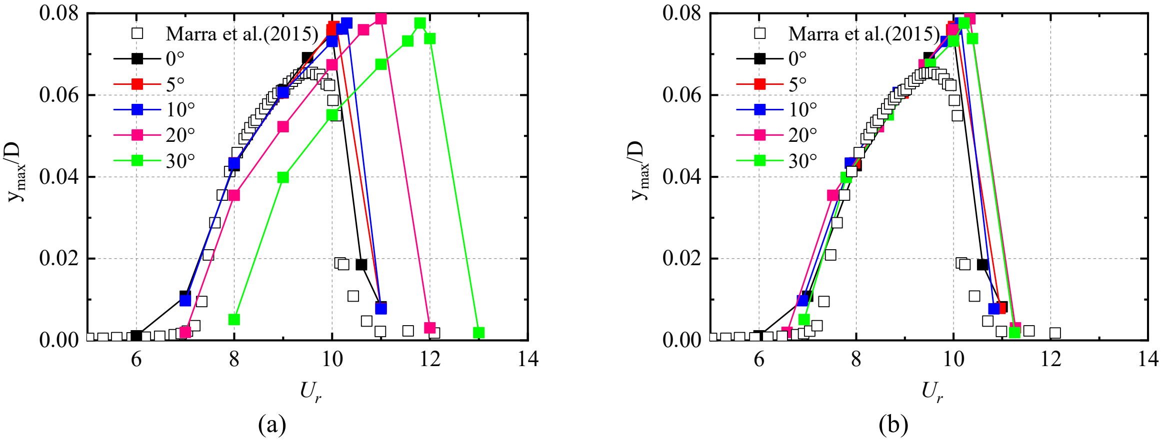


Figure 2. VIV response for various yaw angles: (a) dimensionless amplitude versus reduced wind velocity U_r; (b) dimensionless amplitude versus $U_r cos\beta$.

3. RESULTS

VIV amplitude versus the reduced wind speed is shown in Fig. 2(a) for the various cases considered. For a null yaw angle, the simulation results agree well with the experimental data of Marra et al. (2015) although they exhibit a slightly larger peak vibration amplitude. It is apparent that the maximum dimensionless amplitudes under different yaw angles are very similar and close to 0.08. Nevertheless, with the increase of β, the VIV onset reduced wind speed rises, but the cut-off wind speed increases more, leading to a wider lock-in range. To assess the validity of the independence principle for the considered rectangular cylinder, the VIV responses are plotted versus $U_r cos\beta$ in Fig. 2(b). Then, the results at various wind yaw angles become very similar, both in terms of lock-in range and peak vibration amplitude. Hence, the results of the present simulations suggest that the independence principle is applicable to calculate the VIV response of the 4:1 rectangular cylinder under skew wind.

4. EFFECT OF SPANWISE BOUNDARY CONDITIONS

Regarding the application of independence principle, the current numerical results are not consistent with Wang et al (2022)'s experimental results. However, the end-effect-free condition is difficult to be achieved in the wind tunnel. Thus, the effect of spanwise wall boundary conditions, simulating the wind tunnel set-up, is examined here instead of periodic boundary conditions. The test case with a yaw angle of 30° and U_r = 11.5 is chosen for the comparison. Fig. 3 clearly shows that the cylinder with spanwise wall boundary conditions is stable, even when a large initial condition is imposed. In contrast, when periodic boundary conditions are set at the lateral planes of the computational domain, a notable VIV limit-cycle oscillation is observed. It is therefore proved that the periodic boundary conditions can significantly reduce the effect of the spanwise walls on the three-dimensional flow field around a yawed rectangular cylinder. For this reason, the vibrations observed during wind tunnel tests may be lower than for real conditions, unless the model is sufficiently long.

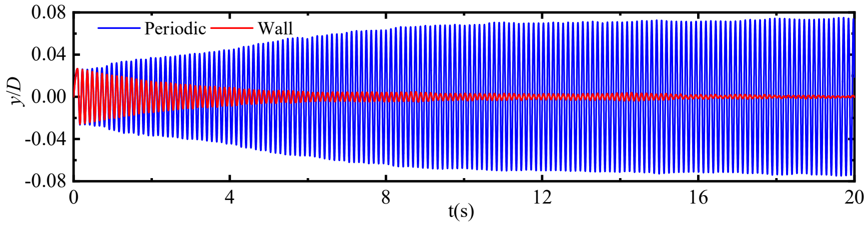
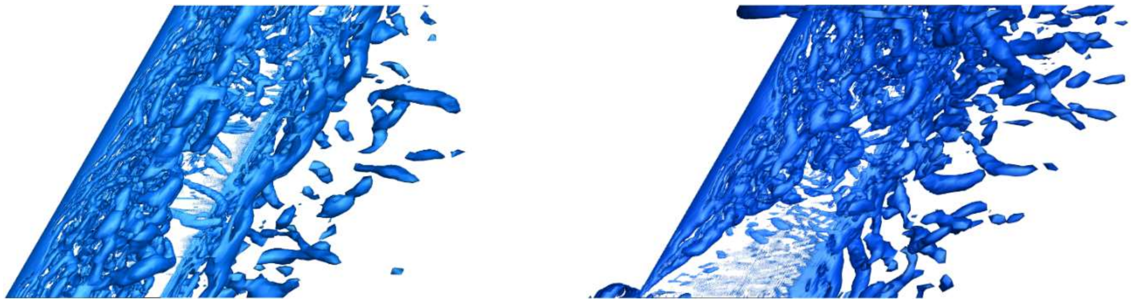


Figure 3. Time-history of displacement for different boundary conditions ($\boldsymbol{\beta} = 30°$, $\boldsymbol{U_r} = 11.5$).



(a) (b)

Figure 4. Instantaneous iso-surface of the second invariant of the velocity gradient tensor (Q = 5000): (a) periodic boundary conditions and (b) wall boundary conditions ($\boldsymbol{\beta} = 30°$, $\boldsymbol{U_r} = 11.5$).

Further, the instantaneous iso-surface of the second invariant of the velocity gradient tensor (Q = 5000) is shown in Fig. 4. Clear differences are found between the two cases in terms of wake features along the span, indicating once again that boundary conditions have a strong impact on the flow around this bluff cylinder. In particular, the effect of wall boundary condition at the upstream end of the cylinder significantly propagates streamwise along the cylinder, whereas flow structures are little influenced by periodic boundary conditions and behave as if the cylinder was infinitely long.

4. CONCLUSIONS

The three-dimensional LES numerical results discussed in this work suggest that the conventional independence principle can predict the VIV response of the rectangular 4:1 cylinder for yaw angles up to 30°, in terms of both VIV peak amplitude and lock-in range. It is also found that, compared to wall boundary conditions, periodic boundary conditions can significantly reduce the effect of spanwise walls on the three-dimensional flow field around a skew rectangular cylinder. It can therefore be concluded that wind tunnel tests can easily underestimate the VIV amplitude under skew wind.

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