ICWE 16
August 27-31, 2023
FLORENCE - ITALY
16th International
Conference on
Wind Engineering

Effects of oscillation frequency and amplitude on vertical forced vibration for rectangular 5:1 cylinder

Pengcheng Zou [1], Shuyang Cao [2], Jinxin Cao [3]

[1] College of Civil Engineering Tongji University, Shanghai, China, WEzpc@tongji.edu.cn
[2] State Key Laboratory for Disaster Reduction in Civil Engineering Tongji University, Shanghai, China, shuyang@tongji.edu.cn
[3] State Key Laboratory for Disaster Reduction in Civil Engineering Tongji University, Shanghai, China, jinxin@tongji.edu.cn

SUMMARY:
Effects of oscillation frequency and amplitude on vertical forced vibration for a rectangular cylinder with a side ratio of B/D=5 (B: breadth; D: depth of cylinder) are numerically investigated by Large Eddy Simulation (LES) at Reynolds number Re=22,000. The investigation utilizes one series of three-dimensional simulations under forced vibration with various frequency ratios $f_e / f_0 = 0.8 - 1.2$ (f_e : oscillation frequency; f_0 : strouhal frequency) and oscillation amplitudes $A_h = 0.05 - 0.3$ in smooth flow conditions. A good match of mean and fluctuating coefficients between simulations and wind tunnel tests validates the accuracy of simulation. The results show that the oscillation frequency and amplitude of vibration affect the distribution of surface mean and fluctuating pressure, especially the location and value of peaks, revealing the dependence of vortex separation and attachment on vibration parameters. Aerodynamic damping and aerodynamic stiffness are extracted, and discrepancies due to oscillation frequency and amplitude are scrutinized.

Keywords: Large eddy simulation, Vortex-induced vibration, Forced vibration

1. INTRODUCTION

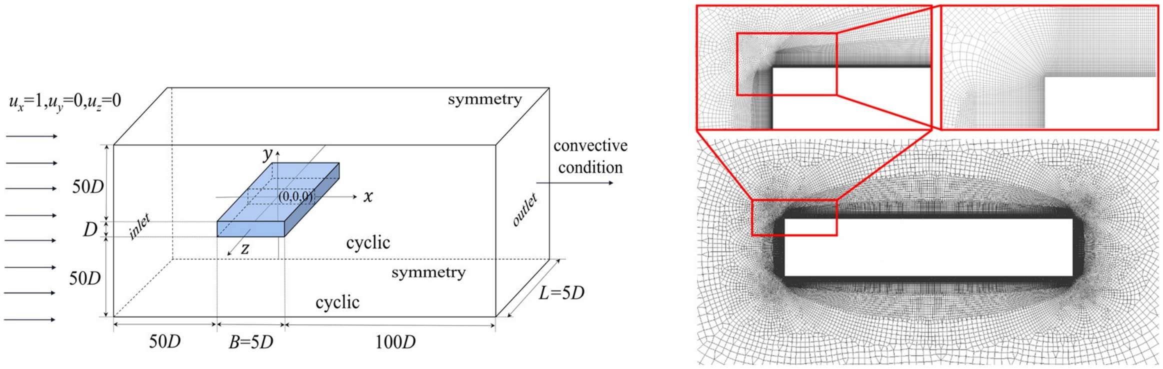
The separating boundary layer flow around a bluff body often results in vortex shedding, which imposes fluctuating crosswise stresses on the body. When the force frequency is close to the body natural frequency, the lock-in or synchronization phenomena takes place, which could lead to vortex-induced vibration (VIV).

Forced vibration wind tunnel test or numerical simulation is one of the methods to study VIV. In the forced vibration test, the body is controlled to have a prescribed motion, typically a harmonic motion with a constant amplitude and frequency, which can be employed to extract oscillation frequency-dependent or amplitude-dependent aerodynamic characteristics, such as aerodynamic damping (Wang and Chen, 2022). Numerical simulations can specify any vibration frequency and amplitude to further study the dependence of aerodynamic force and flow field on frequency and amplitude.

This paper investigates the influences of oscillation frequency and amplitude on aerodynamic characteristics and spanwise correlation of a rectangular 5:1 cylinder at Re = 22,000 under forced vibration and further analyze the relationship between the wind velocity field and pressure field of the vibrating cylinder. Reynolds number is defined as $\mathrm{Re} = U \times D / \nu$, in which U is the upstream flow velocity, *D* is the cylinder depth and *v* is the kinetic viscosity.

2. NUMERICAL APPROACH AND DISCRETIZATION

The PIMPLE algorithm, which combines SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) and PISO (Pressure Implicit with Splitting of Operators) algorithms, is used to solve the discretized equations.



(a) Computational domain and boundary conditions (b) Mesh near cylinder in x-y plane

Figure 1. Computational domain, mesh system and boundary conditions

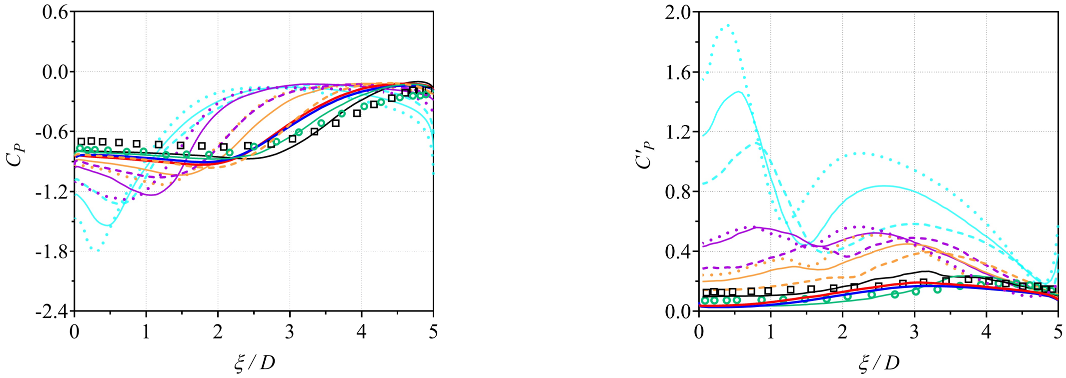
As shown in Figure 1(a), the computational domain is 155*D* in the *x* direction, 101*D* in the *y* direction and 5*D* in the *z* direction with a fixed spanwise resolution of *D*/16. The mesh in *x*-*y* plane is hybrid, with 40 layers structured grid around the cylinder and unstructured grids in the rest area near the cylinder, as shown in Figure 1(b). The first grid near the body surface is given explicitly as $0.1/\sqrt{Re} \approx 6.5\times10^{-4}D$, which yields $y^{+} \approx 0.4$ in the simulation.

3. NUMERICAL RESULTS AND DISCUSSIONS

3.1. Basic aerodynamic feature

Table 1. Comparison of modelling parameters with other studies.

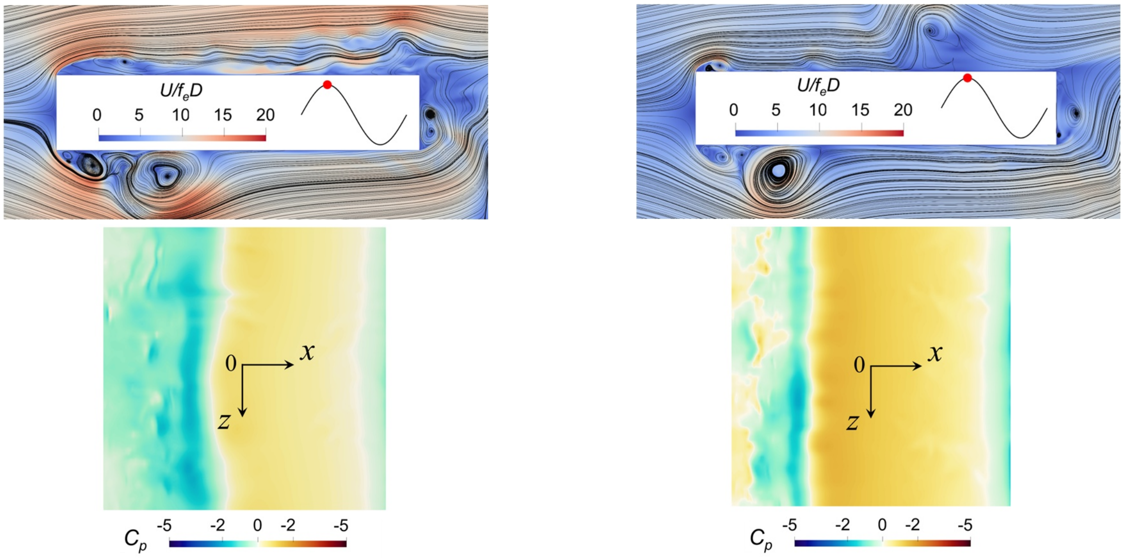
Authors	Method	Re	f_e/f_0	A_h/D	Symbol
Lin et al. (2019)	Exp	50,000	0.281	0.165	○
Jiang et al. (2022)	Exp	101,000	0.060	0.100	□
Bruno et al. (2012)	LES	40,000	*static*		—
Present cases	LES	22,000	*static*		—
			0.28	0.165	—
			0.06	0.100	—
			0.80	0.050	- -
				0.100	- -
				0.300	- -
			1.00	0.050	—
				0.100	—
				0.300	—
			1.20	0.050	· ·
				0.100	· ·
				0.300	· ·



(a) Mean pressure coefficient (b) Fluctuating pressure coefficient

Figure 2. Comparison of the pressure distribution along the surface of rectangular cylinder.

Figures. 2(a) and 2(b) compare the spanwise-averaged distributions of mean and fluctuating pressure coefficients, C_P and C'_P, around the rectangular 5:1 cylinder surface with data in the literature (ξ is the distance from the leading edge along the cylinder surface) and Table 1 lists the comparison of the modelling parameters between the present and other studies. The present results of both static and vibrating cylinders agree well with responding simulations (Bruno et al., 2012) or experiments (Jiang et al., 2022; Lin et al., 2019), which proves the accuracy of numerical simulation. With the increase of A_h or f_e / f_0, the position of the negative pressure peak in Figure 2(a) and the fluctuating pressure peak in Figure 2(b) move towards the leading edge, but the single peak of fluctuating pressure transform to double peak, in addition, the peak value of mean pressure decreases while the peak value of fluctuating pressure increases, gradually.



(a) A_h / D= 0.3, f_e / f_0 = 0.8, $2\pi f_e t = \pi/2$ (b) A_h / D= 0.3, f_e / f_0 = 1.2, $2\pi f_e t = \pi/2$

Figure 3. Instantaneous streamlines with reduced velocity and corresponding lower surface pressure.

Instantaneous streamlines and reduced velocity around the cylinder located at the positions of extreme value of oscillation are illustrated together in Figure 3. When the rectangular cylinder vibrates to the position of extreme displacement point, main vortices exist at the leading edge on the opposite side. The existence of leading edge vortices seems to lead to a negative pressure zone at the corresponding position of the bottom surface, and the zone seems to shrink with the increase of f_e / f_0 from 0.8 to 1.2.

The estimated aerodynamic damping H_1^* and aerodynamic stiffness H_4^* are plotted in Figs. 4 and 5 and they are are divided by the maximum of its absolute value respectively for dimensionless, where the frequency ratio dependence is evident. For aerodynamic damping H_1^*, the smaller amplitude shows a stronger dependence on the frequency ratio and the peaks of $A_h / D = 0.05$ and 0.1 are located at the position where the frequency ratio $f_e / f_0 = 0.8$. The aerodynamic stiffness H_4^* is less affected by the increase of frequency ratio, showing a slight downward trend in general.

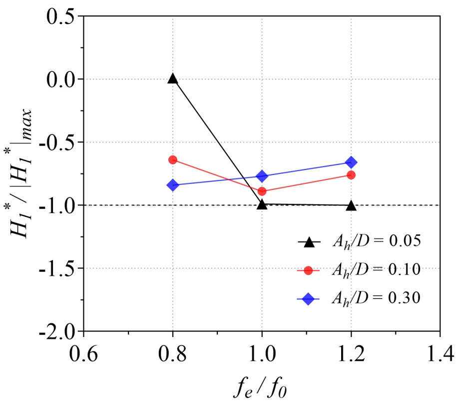


Figure 4. Aerodynamic damping as a function of f_e / f_0 and A_h / D.

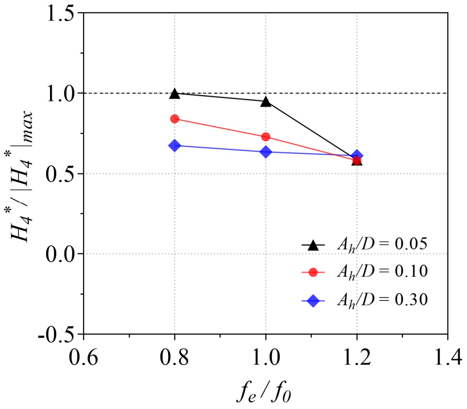


Figure 5. Aerodynamic stiffness as a function of f_e / f_0 and A_h / D.

4. CONCLUSIONS

The vibration frequency and amplitude have obvious influence on the surface pressure distribution, especially the value and position of the peaks. The existence of leading edge vortices seems to lead to a negative pressure zone on the cylinder located at the position of extreme displacement point.

ACKNOWLEDGEMENTS

The research described in this paper was financially supported by the National Natural Science Foundation of China (NSFC) Grant NO. 52078382 and the State Key Laboratory of Disaster Reduction in Civil Engineering Grant NO. SLDRCE19-A-01.

REFERENCES

Bruno, L., Coste, N., Fransos, D., 2012. Simulated flow around a rectangular 5:1 cylinder: Spanwise discretisation effects and emerging flow features. Journal of Wind Engineering and Industrial Aerodynamics, 13th International Conference on Wind Engineering 104–106, 203–215.

Lin, S., Wang, Q., Nikitas, N., Liao, H., 2019. Effects of oscillation amplitude on motion-induced forces for 5:1 rectangular cylinders. Journal of Wind Engineering and Industrial Aerodynamics 186, 68–83.

Jiang, H., Li, S., Li, J., Su, Y., Li, Z., Liu, J., 2022. Effect of vibration on the aerodynamic behavior of a 5:1 rectangular cylinder. Journal of Wind Engineering and Industrial Aerodynamics 225, 104995.

Wang, Y., Chen, X., 2022. Extraction of aerodynamic damping and prediction of vortex-induced vibration of bridge deck using CFD simulation of forced vibration. Journal of Wind Engineering and Industrial Aerodynamics 224, 104982.