# Active Control of Two-Dimensional Vortex-Induced Vibration of a Circular Cylinder Using a Pair of Synthetic Jets

**Chenglei Wang, Fei Duan and Hui Tang**

**Abstract** This paper presents a study on the control of two-dimensional vortex-induced vibration (VIV) of a single circular cylinder at a low Reynolds number of 100 using a synthetic jet (SJ) pair. To facilitate this study, a lattice Boltzmann method based numerical framework is adopted. While its strength is fixed, the SJ pair operates either in phase or anti-phase over a wide excitation frequency range. The effects of the SJ excitation phase difference and frequency are systematically investigated. Simulation results reveal that both the in-phase and anti-phase SJ pairs are able to mitigate the VIV at higher excitation frequencies, while either the cross-flow or streamwise resonance (associated with large-amplitude VIV) may be induced by the SJ pair at lower frequencies.

**Keywords** Synthetic jet • Vortex-induced vibration • Lattice Boltzmann method

## 1 Introduction

Asymmetric vortex shedding from a bluff body can cause dynamic loading on the associated structure. When the vortex shedding frequency is close to the structure's natural frequency, large-amplitude vibrations may occur, known as vortex-induced vibration (VIV). When this happens, catastrophic failures to the structure may occure. Since this VIV phenomenon can be widely found in engineering practices, such as airplanes, automobiles and offshore structures, it is necessary to attenuate the VIV to protect relevant structures. For years, numerous flow control methods have been used to suppress the asymmetric vortex shedding and VIV, in-

Chenglei Wang • Hui Tang (✉)
Department of Mechanical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China.
e-mail: h.tang@polyu.edu.hk

Chenglei Wang • Fei Duan
School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Republic of Singapore.

cluding passive (no power required) and active (power required) schemes, on which Choi et al. (2008) has given a comprehensive review.

## 2 Problem Description and Methodology

This research studies the active control of two-dimensional vortex-induced vibration (VIV) of a circular cylinder using a pair of synthetic jets. The cylinder is immersed in a uniform flow at a low cylinder-diameter-based Reynolds number, i.e., $Re = U_\infty D/\upsilon = 100$, where $U_\infty$ is the freestream velocity, $D$ the cylinder's diameter, and $\upsilon$ the kinematic viscosity. It connects to two identical springs along the cross-flow and streamwise directions, respectively, as depicted in Fig. 1. Hence, the cylinder can move in the two-dimensional space. In order to mitigate its VIV, a pair of synthetic jets (SJs), represented by the two red line sections in Fig. 1, is implemented along the streamwise direction at the leeward surface of the cylinder. Assuming that the upper and lower SJs operate with the same excitation frequency ($f_{sj}$) and velocity amplitude ($U_{sj}$), their velocities relative to the oscillating cylinder can be defined as

$$u_{sj}^u = U_{sj} \sin (2\pi f_{sj} t + \phi_u) \quad (1)$$

$$u_{sj}^l = U_{sj} \sin (2\pi f_{sj} t + \phi_l) \quad (2)$$

respectively, where $\phi_u$ and $\phi_l$ are the operating phase angles of the upper and lower SJs, from which the phase difference between the SJ pair can be defined as

$$\Delta\phi = \phi_u - \phi_l \quad (3)$$

Normalizing $f_{sj}$ using the natural frequency of the mass-spring system ($f_N$) in fluid gives a non-dimensional SJ excitation frequency ($f_{sj}^*$)

$$f_{sj}^* = f_{sj} / f_N \quad (4)$$

The SJ strength is quantified by a momentum coefficient ($C_\mu$) as

$$C_\mu = 2U_{sj}^2 d / U_\infty^2 D \quad (5)$$

where $d$ is the width of the SJ slots.

This study only focuses on the effects of SJ frequency ($f_{sj}^*$) on attenuating the cylinder's two-dimensional VIV when the SJ pair operates either in-phase ($\Delta\phi$ = 0) or anti-phase ($\Delta\phi = \pi$). Thus, $f_{sj}^*$ varies in the range of 0.4 to 7, within which various lock-on could be induced (Wang et al. 2017a, 2017b); and the other parameters are fixed as: momentum coefficient $C_\mu = 2.149$, SJ location $\gamma = 50^o$, the cylinder-fluid mass ratio $m^* = \rho_c/\rho_f = 2.55$, and the reduced velocity $U_r = U_\infty/f_N D$ = 5.9. The latter two parameters are chosen in such a way that the cylinder's vibration amplitude is relatively large and difficult to control, as suggested in Du and Sun (2015).

To simulate the two-dimensional flow around the cylinder, two major types of numerical solvers exist in literature. One is the Navier-Stokes equation (NSE) based solver rooting in the continuum assumption at the macro scale, and the other is the lattice Boltzmann equation (LBE) based solver describing the collision and redistribution of collections of particles at the meso scale. In contrast with the NSE based solver, it is much easier to write the code for the LBE based solver and to implement the parallel algorithms, originating from its underlying kinetic theory (Mohamad 2011). Therefore, in this study, the incompressible D2Q9 MRT LBE model, i.e., two-dimensional incompressible multiple-relaxation-time lattice Boltzmann equation model with nine discrete velocities, is employed. The MRT multi-block scheme is applied to enhance the computational efficiency while maintaining sound accuracy. Besides, the interpolated half-way bounce back scheme is incorporated to deal with curved boundaries and the corrected momentum exchange method is employed for accurate prediction of the aerodynamic forces on the cylinder.

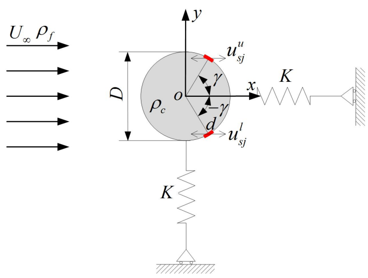


**Fig. 1** Schematic of two-dimensionally oscillating cylinder equipped with a SJ pair. The two red line sections represent the SJ pair, $U_\infty$ the freestream velocity, $\rho_f$ the fluid density, $D$ the diameter of the cylinder, $\rho_c$ the density of the cylinder, $\gamma$ the azimuthal angle, $u_{sj}^u$ and $u_{sj}^l$ the velocities of the upper and lower SJs relative to the oscillating cylinder, respectively, $d$ the SJ width, and $K$ the stiffness of the spring.

Throughout this study, the computational domain is set as 60$D$(length) × 20$D$(width) with a uniform flow flowing from the left to the right at a speed $U_\infty$. The circular cylinder is initially placed on the channel centerline and 20$D$ away from the inlet boundary. Furthermore, the non-reflecting inlet boundary condition is used at the inlet boundary, whereas the homogenous Neumann boundary condition is implemented at the outlet boundary. On the top and bottom walls, the Dirichlet boundary condition is applied with the x-component velocity $U_\infty$ and y-component velocity 0. The SJ actuators are represented by a number of nodes on the cylinder surface, and the time-dependent SJ velocities are realized through enforcing $u_{sj}^u$ and $u_{sj}^l$ on these nodes. The details of the algorithm and its validation can be found in our previous works (Wang et al. 2016a, 2016b).

## 3 Results and Discussion

The variations of the two-dimensional VIV amplitudes (i.e., cross-flow amplitude $A_y^*$ and streamwise amplitude $A_x^*$) against the excitation frequency of the in-phase ($\Delta\phi = 0$) and anti-phase ($\Delta\phi = \pi$) SJ pair are shown in Fig. 2. Compared to the unforced case where the SJ pair is off, $A_y^*$ can be effectively reduced in two frequency ranges, i.e, $f_{sj}^* < 1.4$ and $f_{sj}^* > 3$, by using the in-phase SJ pair, as shown in Fig. 2a. Within these frequency ranges, the strength of the vortices shed from the upper and lower surfaces of the cylinder can be significantly reduced. The operation of in-phase SJs also results in symmetric wakes as shown in Fig. 3a, which is taken from the case with $\Delta\phi = 0$ and $f_{sj}^* = 1.2$. At frequencies around $f_{sj}^* = 2$, however, $A_y^*$ is augmented, even higher than the amplitude in the unforced case. In this frequency range, the Fast Fourier Transform (FFT) based spectrum analysis for the cylinder's normalized y-displacement ($y_o^*$) reveals that the cylinder's cross-flow oscillation frequency ($f_{vy}^*$) is $f_{sj}^*/2$, one half of the SJ excitation frequency. For instance, in the case with $\Delta\phi = 0$ and $f_{sj}^* = 2$, $f_{vy}^* = f_{sj}^*/2 = 1$, as shown in Fig. 4a. Under this condition, the secondary lock-on occurs. As such, $f_{vy}^*$ is close to the system's cross-flow resonance frequency (around 1), causing the occurrence of cross-flow resonance. As for the streamwise amplitude $A_x^*$, it can be reduced at frequencies greater than about 2 by the operation of in-phase SJ pair, as revealed in Fig. 2b. But it is amplified at $f_{sj}^* < 2$, which mainly stems from the in-phase SJ excitation near the system's horizontal resonance frequency (also around 1). Note that in the case with $\Delta\phi = 0$ and $f_{sj}^* = 2$, FFT is performed over 35 VIV periods, and the sampling rate of FFT is set equal to $35400\Delta t/T_N$, where $T_N$ is the natural period of the mass-spring system in fluid, and $\Delta t$ the unit time step in the LBM-based simulation. Such FFT parameters remain the same in other cases of this study.

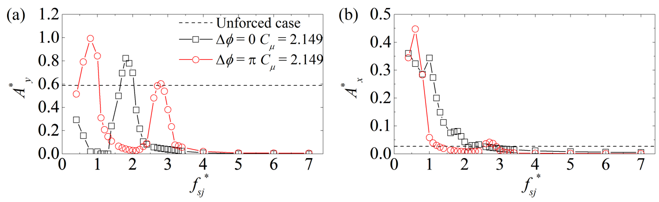


**Fig. 2** The variations of the cylinder's cross-flow and streamwise vibration amplitudes ($A_y^*$ and $A_x^*$) against the normalized SJ excitation frequency ($f_{sj}^*$) when applying the in-phase ($\Delta\phi = 0$) and anti-phase ($\Delta\phi = \pi$) SJ pair for the two-dimensional VIV control.

When the anti-phase SJ pair is applied, significant $A_y^*$ reduction is observed at around $f_{sj}^* = 2$ and $f_{sj}^* > 4$, as shown in Fig. 2a. In these frequency ranges the cylinder's cross-flow oscillation frequency ($f_{vy}^*$) is attracted to the frequency away from the system's cross-flow resonance frequency, and the asymmetric wake is also weakened. This can be confirmed through examining the spectra of the cylinder's normalized y-displacement ($y_o^*$) and instantaneous wake pattern in a representative case (with $\Delta\phi = \pi$ and $f_{sj}^* = 2$), as shown in Figs. 4b and 3b, respectively. On the contrary, the primary ($f_{vy}^* = f_{sj}^*$) and tertiary ($f_{vy}^* = f_{sj}^*/3$) lock-on happen at around $f_{sj}^* = 1$ and 3, respectively, which are evidenced by the spectra of $y_o^*$ in the case with $\Delta\phi = \pi$ and $f_{sj}^* = 1.2$ and the case with $\Delta\phi = \pi$ and $f_{sj}^* = 2.8$, as shown in Figs. 4c and 4d, respectively. Thus, the cross-flow resonance happens as $f_{vy}^*$ approaches 1 or 3, making $A_y^*$ increase a lot in these frequency ranges. Furthermore, the operation of the anti-phase SJ pair at $f_{sj}^* < 1$ allows the development of the system's streamwise resonance, as evidenced by the significant $A_x^*$ increase in Fig. 2b. When $f_{sj}^* > 1$, the anti-phase operation of the SJ pair forces the horizontal oscillation of the system at frequencies away from its natural resonance frequency, so that the cylinder's streamwise VIV is apparently mitigated.

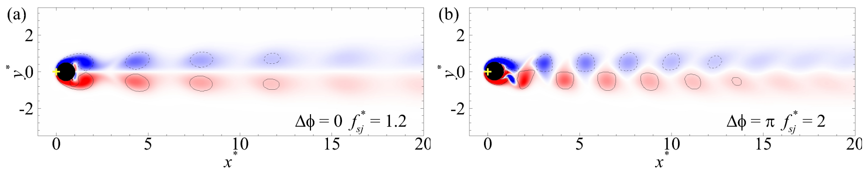


**Fig. 3** Wake patterns for a the case with $\Delta\phi = 0$ and $f_{sj}^* = 1.2$, and b the case with $\Delta\phi = \pi$ and $f_{sj}^* = 2$.

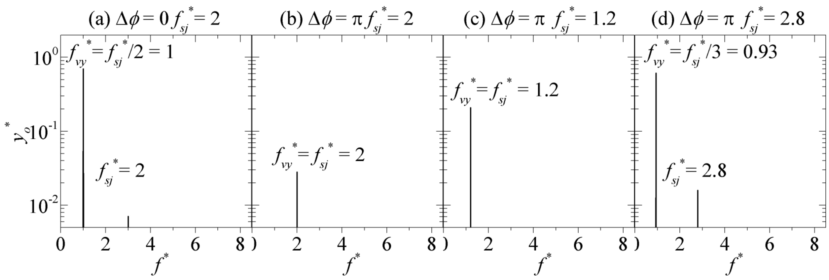


**Fig. 4** Frequency spectra of the cylinder's normalized y-displacement ($y_o^*$) for a the case with $\Delta\phi = 0$ and $f_{sj}^* = 2$, b the case with $\Delta\phi = \pi$ and $f_{sj}^* = 2$, c the case with $\Delta\phi = \pi$ and $f_{sj}^* = 1.2$, and d the case with $\Delta\phi = \pi$ and $f_{sj}^* = 2.8$.

## 4 Conclusions

This paper investigates the effects of a SJ pair on controlling the two-dimensional VIV of a circular cylinder a low Reynolds number of 100. The SJ pair operates either in phase ($\Delta\phi = 0$) or anti-phase ($\Delta\phi = \pi$) with the momentum coefficient fixed at 2.149, and its normalized excitation frequency varies from 0.4 to 7. It is found that the SJ pair is able to suppress the two-dimensional VIV at $f_{sj}^* > 4$ effectively, no matter it operates in phase or anti-phase. However, in the lower frequency range, the cross-flow VIV can be augmented by either the in-phase SJ pair operating at around $f_{sj}^* = 2$ or the anti-phase SJ pair operating at around $f_{sj}^* = 1$ and 3, through inducing the secondary, primary and tertiary lock-on, respectively. As for the streamwise VIV, it can also be amplified due to the induced horizontal resonance, when the in-phase SJ pair operates at $f_{sj}^* < 2$ or the anti-phase SJ pair operates at $f_{sj}^* < 1$.

**Acknowledgements** The authors gratefully acknowledge the financial support for this study from The Research Grants Council of Hong Kong under General Research Fund (Project No.: PolyU 152493/16E).

## References

Choi H, Jeon W, Kim J (2008) Control of flow over a bluff body. Annu Rev Fluid Mech 40:113-139

Du L, Sun X (2015) Suppression of vortex-induced vibration using the rotary oscillation of a cylinder. Phys Fluids 27 (2):023603

Mohamad A (2011) Lattice Boltzmann method: fundamentals and engineering applications with computer codes. Springer-Verlag London, pp 1-13

Wang C, Tang H, Duan F, Yu S (2016a) Control of wakes and vortex-induced vibrations of a single circular cylinder using synthetic jets. J Fluids Struct 60:160-179

Wang C, Tang H, Yu S, Duan F (2016b) Active control of vortex-induced vibrations of a circular cylinder using windward-suction-leeward-blowing actuation. Phys Fluids 28 (5):053601

Wang C, Tang H, Yu S, Duan F (2017a) Control of vortex-induced vibration using a pair of synthetic jets: Influence of active lock-on. Phys Fluids 29 (8):083602

Wang C, Tang H, Yu S, Duan F (2017b) Lock-on of vortex shedding to a pair of synthetic jets with phase difference. Phys Rev Fluids 2 (10):104701