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Self-sustaining turbulent wake characteristics in fluid–structure interaction of a square cylinder

T.P. Miyanawala, R.K. Jaiman *

Department of Mechanical Engineering, National University of Singapore, Singapore

HIGHLIGHTS

- Confirmed synchronization regimes and wake patterns with recent measurements.
- Assessed 3D wake topology of vibrating regimes against stationary cylinder.
- Quantified spatio-temporal symmetry of Reynolds stress distribution.
- Examined synchronization through TKE evolution in representative control volume.
- Presented self-sustaining process of wake structure development.

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ABSTRACT

We present a numerical study on the fluid–structure interaction of a square cylinder at subcritical Reynolds numbers $1400 \leq Re \leq 10,000$. Variation in spatial and temporal structures during the self-sustaining regeneration cycle are investigated via a three-dimensional Navier–Stokes flow coupled with a freely vibrating square cylinder at relatively low mass ratio. We employ a variational fluid–structure interaction formulation based on the recently developed partitioned iterative scheme and the dynamic subgrid-scale turbulence model. To begin, we assess the response amplitudes, the synchronization regimes and the vortex shedding patterns against the experimental measurements for the flow-induced vibration of a square cylinder at zero incidence angle. Of particular interest is to predict and analyze the synchronization regimes and the associated wake structures for a range of reduced velocity. The vibration of the cylinder provides an avenue for the merging of smaller eddies in the vicinity of the cylinder and there are relatively more clustered spanwise rollers and streamwise ribs as compared to the stationary counterpart. We provide a comparative assessment of Reynolds stress distributions in the near-wake region between the VIV lock-in case and its stationary counterpart. We find that the spatial symmetry of the shearing process in the wake shifts to the temporal symmetry of Reynolds stress when the cylinder is free to vibrate. Consequently, in the vibrating case, the competition between the mean shear growth and damping results in a relatively lower frequency shearing as compared to the stationary cylinder. We introduce a representative control volume in the near-wake region to assess the kinetic energy and enstrophy evolution for the stationary and vibrating configurations. We examine the core reason of the matching of periodic wake frequency with the vibrating cylinder frequency through the development of near-wake flow structures and the kinetic energy evolution. By combining these results with the self-sustained process of coherent vortex structure development, we finally explain

* Corresponding author.
E-mail address: mperkj@nus.edu.sg (R.K. Jaiman).

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the formation of intermediate hairpin-like structures in close proximity to the vibrating cylinder and the absence of them in the stationary cylinder.

1. Introduction

Fluid–structure interaction (FSI) of bluff bodies are omnipresent and have numerous applications in offshore, wind and aerospace engineering. Besides their practical importance, these phenomena offer a fundamental value to flow physics pertaining to vorticity dynamics and wake-body interaction. The asymmetric vortex shedding from the bluff body induces unsteady transverse loads, which in turn may lead to vibrations when the structure is free to vibrate in transverse direction (Blevins, 1990; Paidoussis et al., 2011). These large vortex-induced vibrations can lead to damage and potential risk to the structures, in particular to offshore floating platforms. The present study is mainly motivated by the need to understand and minimize the motion of the offshore structures with square-shaped cross-section. We numerically study the flow past the canonical geometry of square cylinder mounted elastically, whereby the flow is perpendicular to the axis of the cylinder.

Most of the early research of fluid–structure interactions has been carried out for smooth surface based geometries such as airfoils and circular cylinders, rather than a square cross-section with sharp corners. The square cylinder is a bluffer body and has a wider wake as compared to the circular counterpart. The other key difference is that the separation points are fixed at some edges of sharp-cornered configurations, while they are free to move around for the smooth bodies. The location of separation point is a function of angle of attack, which can affect the wake topology and force dynamics of the square cylinder. Owing to this fundamental difference with regard to the sharp corners, a square-shaped bluff body immersed in a flow stream can undergo the combination of both vortex resonance and galloping instability. Apart from the angle of attack α, these FIV instabilities are strongly influenced by four key non-dimensional parameters, namely mass-ratio (m^*), Reynolds number (Re), reduced velocity (U_r), and damping ratio (ζ) defined as:

$$m^* = \frac{M}{m_f}, \qquad Re = \frac{\rho^f U_\infty D}{\mu^f}, \qquad U_r = \frac{U_\infty}{f_N D}, \qquad \zeta = \frac{C}{2\sqrt{KM}}, \tag{1}$$

where ρ^f is the fluid density, μ^f denotes the dynamic viscosity, M is the mass of the vibrating body, C and K are the damping and stiffness coefficients, respectively for an equivalent spring–mass–damper system of a vibrating structure, U_∞ and D denote the free-stream speed and the diameter of cylinder, respectively. The natural frequency of the body in vacuum is given by $f_N = (1/2\pi)\sqrt{K/M}$ and the mass of displaced fluid by the structure is $m_f = \rho^f D^2 L_c$ for square cross-sections, where L_c denotes the span of the cylinder. Around $Re \approx 45$, the flow behind a square-shaped prismatic cylinder becomes unsteady and periodic (Sharma and Eswaran, 2004; Yao and Jaiman, 2017) and vortices are shed alternately from the top and bottom surfaces. The dimensionless Strouhal frequency is $St = f_{vs}D/U_\infty$, where f_{vs} denotes the uncoupled vortex shedding frequency of a stationary cylinder. Likewise the natural frequency f_N and the Reynolds number Re, the mass ratio m^* is an important parameter for flow-induced vibration and it is defined as the ratio of vibrating structure mass M to the mass of displaced fluid m_f. In the present study, we restrict to low mass ratio body interacting with a flowing water stream at small damping value. As reported in the case of circular cylinders (Khalak and Williamson, 1997; Govardhan and Williamson, 2000; Navrose and Mittal, 2013), the VIV alone response can be categorized into three branches, namely initial, upper and lower for low-mass ratio cylinders undergoing VIV at subcritical Reynolds numbers. While the upper branch is attributed to large irregular amplitude patterns at a frequency close to the natural frequency of structure with two oppositely signed pairs of vortices per cycle, the initial branch has a monotonically increasing amplitude with two single counter-rotating vortices per cycle. The third branch has a lower amplitude than the upper branch but comprises two oppositely signed pairs of vortices per cycle. Here, the hydroelastic behavior of noncircular square section is considered with low mass and damping parameters whereby the body can experience combined vortex-induced and galloping oscillations.

Recently, there have been some experimental investigations in Nemes et al. (2012) and Zhao et al. (2014) on the FIV response regimes for the elastically mounted square cylinder in a water channel in the Reynolds number range $1400 \leq Re \leq 10{,}000$. In Zhao et al. (2014), three representative values of the angle of attack (α) were considered to demarcate the synchronization regimes associated with the VIV and transverse galloping. For $m^* = 2.64$, $\alpha = 0^\circ$ case, the classical response of galloping was recovered, whereby the amplitude followed approximately a linear trend with respect to the reduced velocity U_r beyond a certain critical value of the reduced velocity. A narrow VIV lock-in region was observed around reduced velocity $U_r = 4.84$ where the frequency of vibration and the vortex shedding is the same, i.e. 1:1 frequency synchronization was observed. The rest of the cases for $\alpha = 0^o$ was dominated by the galloping response. The second synchronization region was identified in $U_r \in [9, 13]$, with significant contributions of frequency component at three times the vibration frequency to the total lift force and the vortex lift force. The third regime was found around $U_r = 18.0$, which had a single dominant frequency of vibration but the vortex lift spectra showed a significant contribution from the frequency five times the body vibration implying a 1:5 synchronization between the vortex shedding and the vibration.

In contrast to the experimental investigations, there are a few numerical studies on the free vibration of square cylinder with sharp corners (He et al., 2012; Joly et al., 2012; Barrero-Gil, 2009; Sen and Mittal, 2011). In the recent numerical