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Flow-induced vibration of a square cylinder and downstream flat plate associated with micro-scale energy harvester

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A R T I C L E I N F O

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A B S T R A C T

The phenomenon of flow-induced vibration (FIV) over a square cylinder at Reynolds numbers, Re = (3.6–12.5 × 10^3) is numerically studied. This current study provides a detailed explanation of the behaviour of transverse motion of square cylinder with the mass damping ratio, $m^*\zeta = 2.48$. The computation of FIV is conducted by numerical simulation based on the Unsteady Reynolds Navier-Stokes (URANS) flow field using OpenFOAM software. The first part of the numerical simulation consists of an isolated square cylinder to validate the solution with previous studies. The computation of FIV with a total number of cells, N = 101,662 have shown a comparable pattern of amplitude curve. The coexistence of vortex-induced vibration (VIV) and galloping is observed for a single isolated cylinder. A downstream flat plate is introduced in the second part of the work. Different gaps separation between the cylinder and flat plate ($0.1 \leqslant G/D \leqslant 3$) are simulated. Based on the amplitude curve against reduced velocities $4 \leqslant U_R \leqslant 20$, four regimes are identified. According to the power estimation, the optimum gap separation is G/D = 0.1. The harnessed power is higher than a single isolated square cylinder while preserving the robustness for the remote harvesting purpose.

1. Introduction

One of many remarkable interests in fundamental physics of fluid, particularly in fluid mechanic, is the flow over a bluff body. It is an important subject especially problem related to buildings and infrastructures. A bluff body is characterized by the significant separated flow associated with vortex shedding occurrence resulting in fluctuating wake when immersed in fluid flow. The flow over a bluff body is frequently referred as a complicated flow as it involves with numbers of flow phenomena such as flow separation, shear layer formation, von Karman street vortex and a highly energetic wake (Matsumoto, 1999). The most prominent feature of flow over bluff body is the development of classic von Karman street vortex that is formed from the vortex shedding (Bearman, 1984). The development of Von Karman Street in the wake of a bluff body leads to a structural oscillation under synchronization condition at which the frequency of shedding is collapsed with the natural frequency of the bluff body. This phenomenon is called flow-induced vibration (FIV), which has been a concern in engineering field since decades ago due to its problematic issue especially towards civil-engineering structures such as tall buildings, chimneys, risers and bridges (Shiraishi and Matsumoto, 1983).

A great amount of attention is received from researchers including (Sarpkaya, 1979), (Bearman, 1984), (Parkinson, 1989), (Blevins, 1990), Williamson and Govardhan (2004) with attempt to reduce and suppress the vibration. However, in these recent years the idea of utilizing this vibration driven by the presence of vortex shedding as the source for energy harvesting purpose has been developed and thus, expanding the demand of in-depth study of the flow-induced vibration mechanism. The rise in micro-electronic devices utilization especially for structural health monitoring expedites the interest in FIV study. The demand of renewable resources with abundant supply and low environmental impact is increasing with the development of micro sensors especially wireless sensor nodes (WSN). According to Kausar et al. (2014) the energy harvesting from natural resources is crucial despite the new and improved battery technology for WSN due to their remote application and high maintenance cost. Therefore, the responsibility to maximize the utilization of ambient resources is important.

Numerous studies have been conducted to prove the feasibility of FIV as a mean of new wind energy harvesting. Jung and Lee (2011) have designed a wind harvester by exploiting the concept of wake galloping for bridge monitoring system. A commercial sensor IMOTE2 is used as a part of bridge monitoring system in Korea. The power consumption for this sensor is about 390 mW and the harvester in their study are successfully generated 370 mW under wind speed condition 4.5 ms^{-1} (Jung

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Table 1
Non-dimensional parameters.

Parameters	Magnitude
Reduced velocity, U_R	6, 8.5, 18
Reynolds number, Re	4.2–10.7 × 10^3
Effective mass ratio, m^*	566.74
Damping factor, ζ	0.0043767
Spring stiffness, k	22379.8
Damping coefficient, c	31.17

Table 2
Grid parameters for considered cases.

Case	A (Fine)	B (Medium)	C (Coarse)
Total No. of Cells, N	101,662	56,316	31,036
Average Cell Size, h_{avg}/D	0.1857	0.2261	0.2758
No. of Cells Near Cylinder, NC	144	84	64

Table 3
Summary of numerical and discretization method.

Discretization	Scheme
Temporal discretization	2nd order backward scheme
Convection term	3rd order QUICK scheme
Viscous term	2nd order unbounded Gauss linear differencing scheme
Pressure-velocity coupling	PIMPLE
Turbulence model	URANS SST (k-ω)

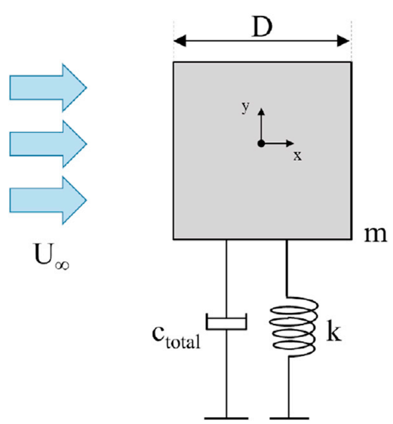

Fig. 1. Sketch of problem geometry.

and Lee, 2011). Besides that, an intensive study of FIV from water flow by Bernitsas et al. (2008) have been conducted using a circular cylinder with passive turbulence control. The state-of-art Vortex-Induced Vibration for Aquatic Clean Energy (VIVACE) are designed and patented in 2008, which utilized the vortex-induced vibration to convert ocean current energy into electricity (Bernitsas et al., 2008). Other researchers, which have also exhibit interesting findings in harvesting the energy utilizing FIV are Koide et al. (2013) for river monitoring system and Weinstein et al. (2012) for Heating, Ventilation, and Air Conditioning (HVAC).

Owing to the advancing technology of supercomputers, the flow-induced vibration phenomenon can be assessed through numerical simulation decently. Several approaches have been suggested by previous study to predict the behaviour of flow past a flexible circular and square cylinder (Murakami and Mochida, 1995)(Murakami et al., 1997)(Ji et al., 2011)(Sewatkar et al., 2012)(Tang et al., 2013)(Ding et al., 2015). Therefore with aim to exploit the energy extracted from FIV, the geometry opted in this study is a square cylinder. In general, a square cylinder regards as a simple geometry in engineering structure, thus it is important to study the principal properties of the flow on the cylinder (Ali et al., 2009). Square cylinder has a fixed separation point making it susceptible to both vortex induced vibration (VIV) and galloping (Davenport and Novak, 1976)(Nakamura, 1993). Earlier study by Parkinson and Brooks (1961) of two model square cylinders with different structure damping shows contradict behaviour. According to them, pure galloping occurs only to the model with low structure damping ($\zeta = 0.00152$) while for the latter case ($\zeta = 0.0062$) vibration happens only for a while and reoccurs at higher wind velocity with higher amplitude of vibration. This explains the findings from (Kumar and Gowda, 2006), (Amandolèse and Hémon, 2010) and (Barrero-Gil and Fernandez-Arroyo, 2013), which have been experimentally investigated the flow-induced vibration associated with the square cylinder. Nevertheless, the square cylinder is quite a challenging problem to resolve due to its complicated character of flow impinging, separation and also the response of vortex shedding in the wake (Murakami and Mochida, 1995). This conflict usually leads and resulted in small discrepancies of analysis.

Discrepancy or inaccuracy of numerical solution occurs due to the difference computational code used for the numerical simulation and variation of machine performance. In order to overcome this issue, an upgraded CPU resources is required for a high accuracy turbulence model, for example, large-eddy simulation (LES) (Murakami and Mochida, 1995). Nevertheless, this would contribute to the increased of computational cost and time. According to Ali et al. (2009) the inaccuracy of solutions may also happen because of the difference in generating the mesh grid. Based on their DNS simulation of a rigid cylinder, for a well refined mesh grid the discrepancy between the solution and Richardson extrapolated value is significantly reduced when compared to a coarser mesh grid (Ali et al., 2009). Hence, in order to obtain a precise solution to the flow-induced vibration issue without compromising the computational cost and time, the grid refinement study is an adequate alternative.

Unlike the conventional mechanical vibration, flow-induced vibration accumulates relatively lower vibrational motion and technically produces only small scale energy. As a consequence of the limitation, many studies have initiated to explore the advantages of passive vibration control. One of the most efficient method of flow control for bluff bodies is by modifying the wake interference. Liu (2015) has suggested a new approach by inducing the boundary layer transition which resulted in the amplification of FIV using a patented flow disturbance device (FDD). FDD is introduced at a frequency within the boundary layers frequency range so that the fluctuation flow is enlarged and could produce more energy by imitating the turbulent flow feature from a transitional flow feature (Liu, 2015).

Another exceptional work is discovered by Bernitsas and Raghavan (2011) to enhance the vortex-induced motion (VIM) with presence of surface roughness control (SRC) on a bluff body. The patented work introduced SRC as the means to amplify the vibrational amplitude and extend the synchronization range. The distribution and location of SRC on bluff body are varied to achieve the robustness of harvester (Bernitsas and Raghavan, 2011). Meanwhile, Ding et al. (2015) also introduced a cylinder with a passive turbulence control (PTC). Based on their numerical study using Computational Fluid Dynamics (CFD) software, PTC has successfully prolonged the upper branch of VIV and obtain a developed galloping within a relatively reduced velocity at the optimal location. Koide et al. (2013) on the other hand, have prevailed that a downstream strip plate in cruciform arrangement managed to expand the working velocity for harvester in natural rivers. Therefore, to initiate an enhanced vibration amplitude, a downstream flat plate is introduced in this study.

The objectives of this current study are:

1. To investigate the effects of downstream flat plate to the FIV for different gap separations.