CHEMICAL ENGINEERING TRANSACTIONS
VOL. 56, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jiří Jaromír Klemeš, Peng Yen Liew, Wai Shin Ho, Jeng Shiun Lim

**ISBN** 978-88-95608-47-1; **ISSN** 2283-9216

DOI: 10.3303/CET1756076

# Wind Energy Harvesting from Wind-Induced Vibration

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Wind power is a clean energy source and alternative to the non-renewable type of energy sources. One of the challenges in utilizing wind energy is to efficiently harvest the wind energy into a usable electrical power, especially in the regions with low wind speed. This study aims to assess the possibility of harvesting wind energy by using the concept of flow induced vibration of a bluff body. A thin flat plate is introduced downstream of the cylinder as a simple but effective passive wind control. Three conditions have been tested to evaluate its effects on wind energy harvesting: isolated cylinder, flat plate with vibrating cylinder and cylinder with vibrating flat plate. The wind-body interaction is simulated using mesh motion technique available in OpenFOAM, an open source code for Computational Fluid Dynamics, while the harvested energy is calculated based on the work done by the single degree of freedom (SDOF) vibrating body. The study found that the vibrating cylinder with flat plate harvests more energy than the isolated cylinder and the fixed cylinder with vibrating flat plate for a relatively wider range of wind speeds. This is due to the generated transverse force on the cylinder is higher than the transverse force generated on the flat plate. The highest energy produced by the vibrating cylinder with a flat plate is $P_{gen}$ = 86.97 mW at reduced velocity, $U_R$ = 11, which is 4 times larger than for isolated cylinder with $P_{gen}$ = 24.50 mW at $U_R$ = 20. For the case of a cylinder with vibrating flat plate, the energy produced is very small with $P_{gen}$ = 0.6972 mW at $U_R$ = 10. The energy produced by the vibrating body is closely related not only to the wind velocity and vibration amplitude but also highly dependent on the rate at which the vibration occurs (frequency) and the phase difference between vibration and the generated force on the body. In the present study, the vibrating cylinder with flat plate appears to be the best configuration to harvest wind energy compared to the other configurations at reduced velocity $U_R$ = (9-11).

## 1. Introduction

The demand for sustainable and renewable energy is escalated with the increasing utilization of electronic devices over the years (Kausar et al., 2014). Nowadays, the deployment of electronic devices especially sensors has become a necessity not only for vehicle systems and medical appliances but also in engineering structures. Structural health monitoring system is one of the most benefited sectors from the advances of technology in these sensors (Balageas et al., 2006). The development of high-rise buildings, bridges, and pipeline risers are equipped with these sensors for their health monitoring purposes. Currently, the main power source for the sensors is the conventional battery, which has finite lifespan. The issue arises from this nature is the cost for maintenance of battery replacement and also the disposal of that used battery is expected to worsen the land and water pollution. Hence, it is important to provide a clean energy to empower these sensors. One of the most promising resource of clean energy with very low environmentally impact is wind energy (Oh et al., 2010).
Wind energy appears as one of the solution to the problem regarding the issues related to reducing the battery usage as the main source power for sensors (Seah et al., 2011). The conventional wind turbine has always been associated with the wind energy harvesting and the miniaturization of it has also been attempted to suit the application of small electronic devices (Howey et al., 2011). This current study, however, intends to introduce another means of harvesting the wind energy, which is from flow-induced vibration. Flow-induced vibration (FIV) is originally one of the undesirable instabilities that concern the aerodynamicist since a decade ago (King, 1977).

Please cite this article as: Mohd Maruai N., Ali M.S.M., Ismail M.H., Mohd Ihsan N.A., Sadzli F.N.H., Salim S.A.Z.S., 2017, Wind energy harvesting from wind-induced vibration, Chemical Engineering Transactions, 56, 451-456 DOI:10.3303/CET1756076

The interaction of flow over an elastic bluff body leads to a significant transverse motion when the natural frequency of the body coincides with the frequency of the motion. Many efforts have been put into suppressing and mitigating this phenomenon as it may cause the destruction of structures (Kawabata and Takahashi, 2013). Due to the advancing technology of sensors the responsibility to maximize the utilization of ambient resources is challenging. Numerous studies have been conducted to prove the feasibility of FIV as a mean of new wind energy harvesting. Intensive studies of FIV from water flow by Bernitsas et al. (2008) have been conducted using a circular cylinder with passive turbulence control. Jung et al. (2011), on the other hand, exploit the concept of wake galloping to harvest the wind energy for bridge monitoring system. Other researchers, which have also exhibit interesting findings in harvesting the energy utilizing FIV are Koide et al. (2011) and Weinstein et al. (2012).

This current study aims to assess the possibility of harvesting the wind energy using a square cylinder and a flat plate, separately or both in tandem. A square cylinder is susceptible to both vortex-induced vibration (VIV) and galloping or pure galloping (Parkinson and Brooks, 1961). The behaviour of FIV is highly dependent on the damping of the body. High damping body excites earlier than the light damped body and has the VIV feature, which appears to be more appropriate for the harvesting purpose. It is very important to be able to harvest energy at low wind speed especially in a country with the tropical climate like Malaysia, which is experiencing average wind velocity 0-2 ms$^{-1}$. A body with relatively high damping ratio is numerically investigated to predict the body excitation that consequently affects the energy extracted from FIV.

## 2. Numerical Approach

In this paper, flow simulations are conducted by an open source software of Computational Fluid Dynamics (CFD), OpenFOAM. The flow is modelled based on the conversion law of mass in predefined volume. The flow solutions are retrieved using the Unsteady Reynolds Averaged Navier-Stokes (URANS) equations. Following Menter (1994) the turbulence model of SST (k-ω) is deployed to determine the stress tensor and consequently the Navier-Stokes (N-S) equations is solved. Here an incompressible air flow is considered. The inlet is set with fixed free stream reduced velocity $U_R$ and zero pressure gradient located 10D upstream of the cylinder. Both upper and lower walls are also set to free stream boundary condition with no slip condition. For isolated case, the outlet is assigned 20D downstream of the cylinder. While for the case with flat plate, the outlet is set 20D downstream to the plate.

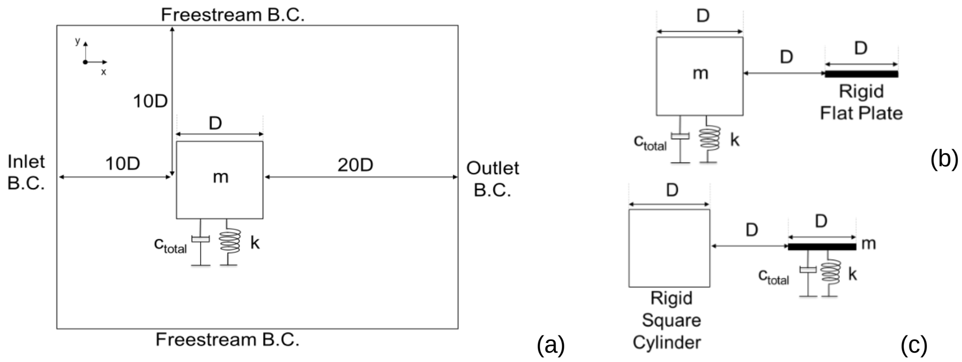



*Figure 1: Sketch of problem geometry a) isolated cylinder in the computational domain b) vibrating cylinder c) vibrating plate.*

The flow simulation is based on the Finite Volume method following Jasak & Tukovic (2006) for automatic mesh motion. This algorithm is opted in this study to properly address the change in shape domain during simulation due to the motion of cylinder. The mesh deformation is according to the point position update and the meshes around the cylinder is deformed based on Laplace smoothing equation. This is to preserve the cell quality near the cylinder due to the motion. The mesh deformation velocity is used to update the new point positions of the mesh distributions:

$$x_{updated} = x_{initial} + u\Delta t \tag{1}$$

Simultaneously, with the newly updated position, the N-S equation and equation of conversion law of mass are solved. The physical parameters designated for this current numerical simulation are presented in Table 1.

*Table 1: Physical Parameters*

| Parameter | Nomenclature | Non-dimensional | Magnitude |
|---|---|---|---|
| Reduced velocity | UR | $U/f_n D$ | 5 - 20 |
| Reynolds number | Re | $U_R D/\upsilon$ | 3.6 x 103 - 12.5 x 103 |
| Total damping factor | ζtotal | $c_{sys}/c_{cri}$ | 0.004377 |
| Scruton number | Sc | $\frac{\pi}{2}m^*\zeta$ | 2.75 |

## 3. Harvested Power from Flow-induced Vibration

### 3.1 Equation of Motion

Flow-induced vibration practically can be modeled based on a single degree of freedom (SDOF) elastic system (Parkinson and Brooks, 1961). Figure 1 represents the sketch of geometry for SDOF elastic system. The dynamic response of this system is described by equation of motion given by:

$$m\ddot{y} + c_{total}\dot{y} + ky = F_y(t) \tag{2}$$

Here m is the total mass of the oscillating structure, k is the spring stiffness, c is the total damping coefficient for an oscillating body, y is the direction of body's motion transverse to the incoming flow and $F_y$ is the total force exerted on the cylinder from air flow in the y direction. When the frequency of vibration is collapsing with the frequency of vortex shedding, the motion of body and the fluid force can be approximated by (Khalak and Williamson, 1999):

$$y(t) = y_0 \sin(\omega t) \tag{3}$$

$$F_y(t) = \frac{1}{2}\rho U^2 DLc_y(t) \tag{4}$$

where $y_0$ is the maximum displacement of body's motion, ω=2πf is the angular frequency, while f is the frequency of vibration.

### 3.2 Energy Conversion

The energy transfer from fluid flow to the elastic system can be defined by the power retrieved from work done unto the body in T vibration. Considering the condition of energy transfer from fluid flow to the cylinder is only eligible when the lift force is in phase with velocity (Assi and Bearman, 2015), the power produced by the vibrating body can be estimated by equating the Eq(2) into Eq(5) as:

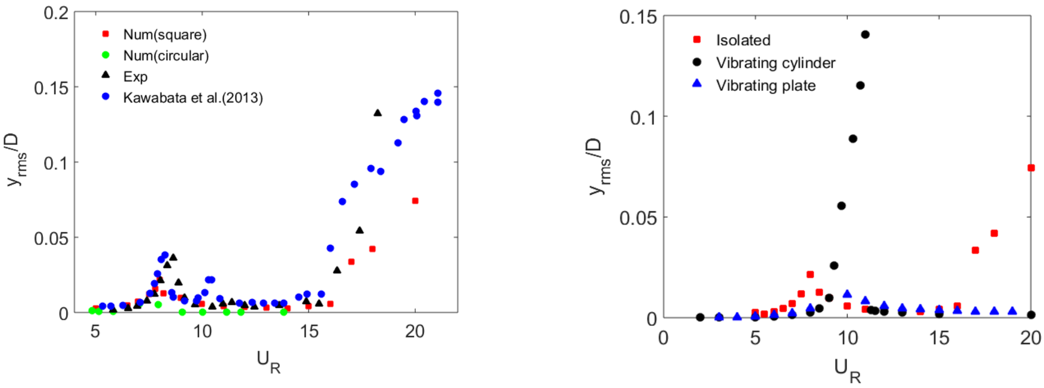
$$P_{gen} = \frac{\int_0^T F_y(t).\dot{y}\,(t)}{T} = \frac{\int_0^T (m\ddot{y} + c_{total}\dot{y} + ky)\dot{y}\,(t)}{T} = 8\pi^3\zeta_{total}m{y_0}^2f^2f_n \tag{5}$$

Here $\zeta_{total} = c_{total}/4\pi m f_n$, $f_n$ is the natural frequency of the body.
Theoretically, the fluid power $P_{fluid}$ can be predicted through the knowledge of Bernoulli's equation for dynamic pressure (Ding et al., 2015). The power of fluid is calculated by multiplying the pressure kinetic head, p with volumetric flow rate, Q. The volumetric flow rate, Q is the product of projected area of flow, which includes the side length and the spanwise length of cylinder. However, it is very important to note that this deduction is made by neglecting the viscous effect and provides the fluid power only for reference purpose. According to Ding et al. (2015), the efficiency of a harvester can be determined by the ratio between the generated power and the power of fluid. Therefore, the efficiency ratio in this particular study is described as $P_{norm}$ and given by:

$$P_{norm} = \frac{P_{gen}}{P_{fluid}} = \frac{P_{gen}}{\rho U^3 DL} \tag{6}$$

## 4. Results and Discussion

The response of an isolated square cylinder is studied prior to the simulation of other configurations. Figure 2(a) shows the validation study of amplitude response for an isolated square cylinder and comparison of numerical finding with experimental measurement and the previous study by Kawabata et al. (2013). The results are comparable, hence confirms the validation of two-dimensional numerical simulation. Two behaviors of flow-induced vibration can be observed from the finding. For 5< $U_R$ <15 a typical VIV response prevails, while beyond $U_R$ > 15 galloping occurred. Besides, series of numerical simulation have been conducted for a circular cylinder for comparison with the VIV response of square cylinder. The magnitude of amplitude response for circular cylinder evidently is very low and did not surpass the amplitude response of the square cylinder. Theoretically, a square cylinder is more appropriate geometry for the harvesting purpose. Figure 2(b) shows the comparison of the amplitude response of the three configurations. The vibrating cylinder with flat plate has significant high amplitude compared to the isolated case and vibrating plate. The root-mean-square (rms) of the transverse amplitude reached the highest at $U_R = 10.3$ with $y_{rms}/D = 0.145$. While for the case of vibrating plate, the vibration is very low and nearly suppressed.




*a) Preliminary study of an isolated cylinder.* *b) Comparison of the three configurations.*

*Figure 2: Amplitude responses of flow-induced vibration.*

The dominant frequency of vibration is determined based on the Fast Fourier Transform (FFT) equation. The results for all configurations are plotted in Figure 3. An abrupt collapse of frequency pattern for the isolated cylinder at $U_R = 15$ confirms the galloping behavior. Starting from that point onwards, the amplitude of vibration is increased significantly (see Figure 2(b)). The lock-in synchronization is well observed within a relatively wider range for vibrating cylinder with a flat plate at $9 < U_R < 11$ as compared to two other cases. Although for isolated cylinder, the lock-in behavior is very remarkable at high velocity but it is important to note that the purpose of this current study is to find the best configuration to harvest the energy from a relatively low velocity. Hence, an isolated vibrating cylinder alone is not competent to harvest useful energy at the low-speed region.

The energy transfer between the fluid force and vibrating body can be assessed by the phase lag between them. Figure 4 shows the phase lag between the displacement of the body and vortex shedding. According to Assi and Bearman (2015), the vibration occurs only when the phase lag between 0º and 180º and therefore the energy transfer is permissible. For vibrating cylinder with a flat plate, the phase lag is increasing with reduced velocity in the VIV lock-in region, while for isolated cylinder the phase lag efficiently increases in the galloping region.

The expected power to be accessible for harvesting purpose from these configurations are calculated based on Eq(5). All results are plotted in Figure 5. The pattern of power response over reduced velocity is in accordance with the amplitude response for VIV response. The accessible power is increased with the reduced velocity, $U_R$ during VIV lock-in synchronization. Vibrating cylinder with plate configuration shows the highest accessible power $P_{gen} = 86.97$ mW at $U_R = 11$. Whereas for isolated cylinder and vibrating plate a very low power is expected to be harvested in comparison with the vibrating cylinder with a flat plate. Figure 6 shows the comparison of harvester efficiency between the three considered configurations.

Based on the amplitude response in Figure 1(b) the accessible power in the galloping region for an isolated cylinder is theoretically anticipated to be higher than during the VIV lock-in. Although it has met the expectation of generating relatively more energy during that region, the efficiency ratio is lower than in the VIV region. Figure 6 has shown that it is more efficient to harvest the energy within the VIV region than galloping for an isolated cylinder. This is also favorable for low wind speed condition due to the nature of galloping, which requires high onset speed (Jung et al., 2011). In contrast, the cylinder with vibrating flat plate has very low potential to generate electricity compared to other configurations. Nevertheless, flat plate has been a popular geometry for the piezoelectric harvester. Owing to its robust shape, the demand for this type of harvester is increasing by year for monitoring purpose (Weinstein et al., 2012). On the other hand, the vibrating cylinder with a flat plate is observed as a good prospect to harvest an ample useful energy for low wind speed condition. This configuration is not only feasible to harvest comparatively more energy but also scores high in efficiency.

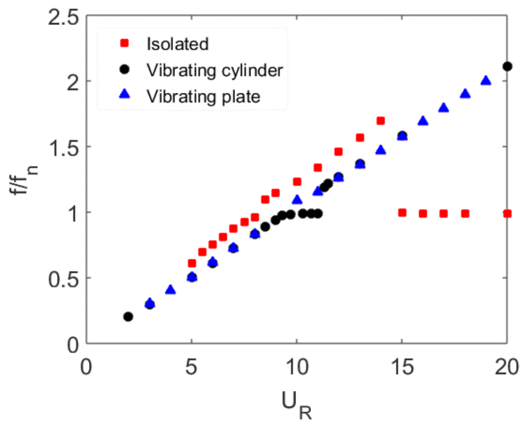



*Figure 3: Variation of the dominant frequency of vibration.*

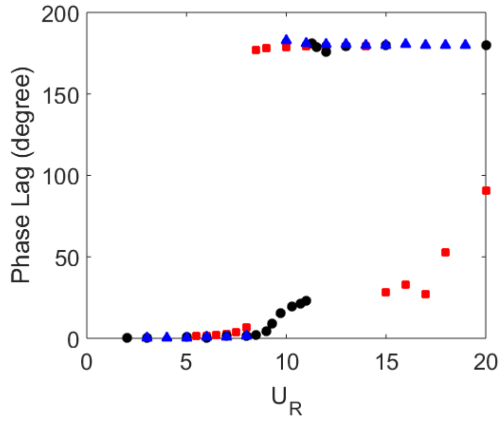



*Figure 4: Variation of phase lag between the displacement of the body and lift coefficient.*

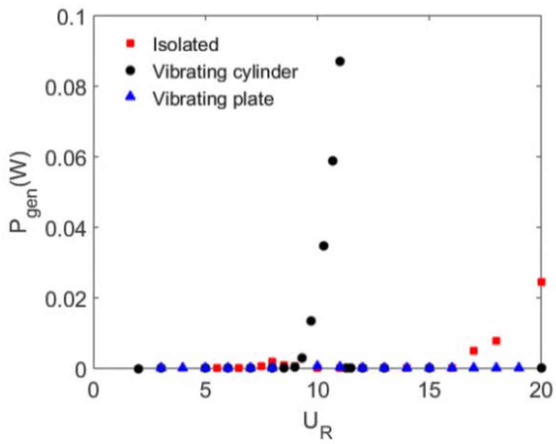



*Figure 5: Comparison of generated power.*

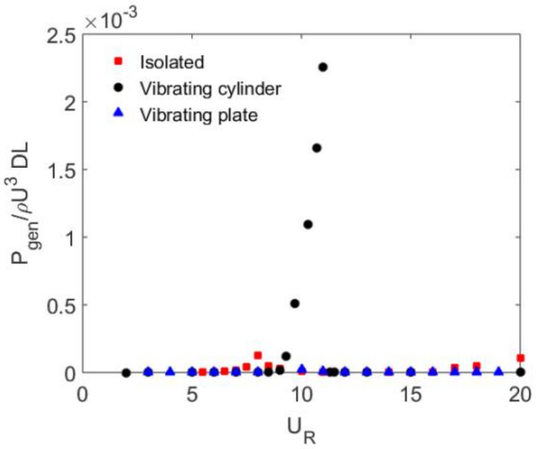



*Figure 6: The efficiency of harvesters.*

## 5. Conclusion

Currently, thanks to the development of sensors and micro devices, the industrial sector has starting to shift the power resources from chemical battery to a better and cleaner energy. This type of energy not only sustainable with low environmental impact but also could help with the reduction of maintenance cost. This study aims to promote the utilization of energy from flow-induced vibration. Flow-induced vibration occurs due to the interaction of flow with an elastic body. Numerical simulation has been performed to investigate the dynamic response of the elastic body over a range of reduced velocity. The cases considered in this current study are an isolated vibrating square cylinder, vibrating square cylinder with a downstream flat plate and rigid square cylinder with the vibrating plate. The power, which is expected to be harvested from this interaction, is calculated based on the equation derived from the simple harmonic equation. Vibrating cylinder with downstream flat plate can harvest relatively more energy within a wider range of reduced velocity compared to other configurations. The highest energy produced by this configuration is at $U_R$ =11 with generated power of $P_{gen}$ = 86.97 mW. On the other hand, both isolated cylinder and vibrating plate can harvest very low energy.


### Acknowledgments

This research was financially supported by Malaysia Ministry of Higher Education (MOHE) under Fundamental Research Grant Scheme (FRGS) project of Universiti Teknologi Malaysia PY/2015/05383 and TWAS 13-272 also High Performance Computer (HPC) Universiti Teknologi Malaysia for the use of their supercomputer facilities. The first author would like to acknowledge Universiti Teknologi Malaysia for the receipt of Ph.D scholarship.

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