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Effects of Different Sizes of Cylinder Diameter on Vortex-Induced Vibration for Energy Generation

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ABSTRACT
Vortex-Induced Vibration (VIV) is the turbulent motion induced on bluff body that creates irregular lift forces and results in alternating movement of the body. Vortex-Induced Vibration (VIV) powered system seems a viable idea of alternative source of energy as it has the ability to take advantages of low current speed of water. This work aims to investigate the effects of different sizes of cylinder diameter on VIV system. The study is vital in order to maximize and exploit VIV efficiently to transform the turbulent kinetic energy into valuable source of energy. Five cylinders with the range of 0.25-2.00 inches diameter are tested at water velocity of 0.453 m sec^{-1} to study the behavior of VIV by using a water tunnel facility specifically developed for this study. Results from this experiment indicates that, the 2.0 inches cylinder gives the highest amplitude of oscillation motion that is equal to 0.0065 m within the range of Reynolds number (300<Re<300000). In term of power generated, the 2.0 inches cylinder produces the maximum result of 0.0141 W.

Key words: Renewable energy, turbulence, vortex shedding, vortex-induced vibration

INTRODUCTION

Renewable energy is an energy that originates from resources which are naturally replenished and not exhausted on timescale. It plays a critical role in greening the energy sector by shifting the usage of fossil fuels to renewable energy to minimize the effects of climatic changes and global warming. However, renewable energy technologies exist currently such as solar and wind are unable to meet the demand of continuous sources of energy as the energy based on these sources are directly dependent on the availability of the sun and wind (Goffman, 2008). Besides, several hydropower dams have resulted in ecosystem disappearing under reservoirs.

Ocean which is known as the world's largest storage of energy seems an ideal of alternative source of energy as it can provide continuously an amount of clean energy (Sharma and Sharma, 2013). Electricity can be generated by converting the kinetic energy captured from the ocean current flow using a hydroelectric power generation. However, not all of ocean energy technologies exist currently are suitable due to the normally low current speed.

One possible solution that meets these criteria is a hydroelectric power extraction system based on Vortex-Induced Vibration (VIV) which can generate energy in low speed. Based on previous study done by Bernitsas *et al.* (2006), VIV-powered system has an ability to generate power in the range of current speed 0.26-2.6 m sec^{-1}. Thus, this power generation system is suitable in generating alternative energy for industrial application such as on offshore platform as the typical current ocean in Malaysia is within the range of 0.41-1.18 m sec^{-1} (Yaakob *et al.*, 2006). As the offshore platforms require continuous electrical power driven service to remain operational at all times, VIV powered system seems a great idea in generating alternative energy as it is not only renewable but also environmental friendly.

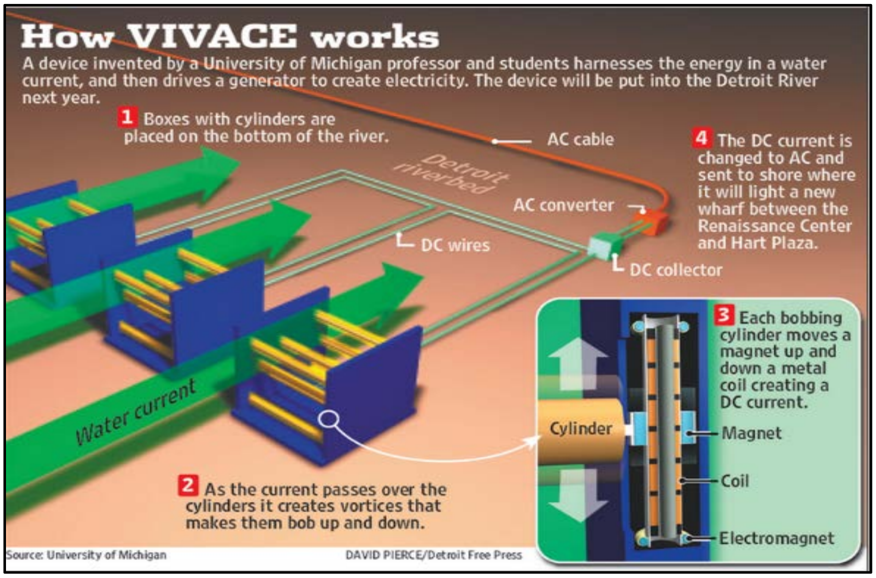

Fig. 1: VIVACE converter operation (Blevins, 1974)

The energy converter device based on VIV is originally designed by Professor Michael Bernitsas from University of Michigan. This VIV powered system which is known as VIVACE works by mounted a cylinder horizontally in a fixed.

The energy converter device based on VIV is originally designed by Professor Michael Bernitsas from University of Michigan. This VIV powered system which is known as VIVACE works by mounted a cylinder horizontally in a fixed frame to allow an alternating movement of oscillation body as shown in Fig. 1 (Bernitsas *et al*., 2006). To the authors' best knowledge, the study still lacks of fundamental reasoning as it focuses more on the application side.

Thus, this study aims to investigate the effects of different sizes of cylinder diameter on the behavior of VIV for further enhancement of energy generation system. Previous studies done by Park *et al*. (2013) involved the effects of surface roughness on the surface pressure, flow separation and Strouhal number in order to increase the energy level on VIV system. Moreover, the effects of virtual damper-spring system and shape of oscillation body have been done by previous studies to increase the energy conversion rate (Lee and Bernitsas, 2011; Ball *et al*., 2012). The current work experimentally investigates the effects of different cylinder diameter by using water tunnel facility specially developed for this research to study the potential of VIV.

The VIV is turbulent motion induced on bluff body that creates alternating lift forces on the body and pushing it up and down perpendicular to fluid flow (Hall-Stinson *et al*., 2011). Basically, the behaviour of vortex shedding is affected by flow parameter known as Reynolds number as shown in Eq. 1:

$$Re = (UD)/\nu \tag{1}$$

where, U is the free-stream velocity, D is the cylinder diameter and ν is the fluid kinematic viscosity. In this research, the range of Reynolds number targeted is known as the "fully turbulent vortex street" with Reynolds number in the range of ($300<Re<3\times10^5$) (Blevins, 1974).

Non-dimensional parameter that describes the vortex shedding frequency to the oscillating flow mechanism is known as Strouhal Number, St as shown in Eq. 2:

$$St = (f^s D)/U \tag{2}$$

where, f_s is vortex shedding frequency.

Strouhal number will be used as a constant value in this research as the Reynolds number falls in the middle of constant Strouhal number region which is 0.2 for subcritical flow as shown in Fig. 2 (Techet, 2005).

When the vortex shedding frequency becomes close to the natural frequency of the body, it has the potential to enlarge the amplitudes of bodies' oscillation and generate higher energy levels. This condition is known as "lock in" phenomenon. In order to design energy harnessing device, it is important to study the range of natural frequency that matches with shedding frequency. Reduced velocity, U* is a non-dimensional parameter used to measure vibration of amplitude as shown in Eq. 3:

$$U^* = (1/St) = [U/(Df^s)] \tag{3}$$

According to Williamson and Govardhan (2004), shedding frequency can lock in and shift to match the natural frequency within the range of ($3<U^*<8$).

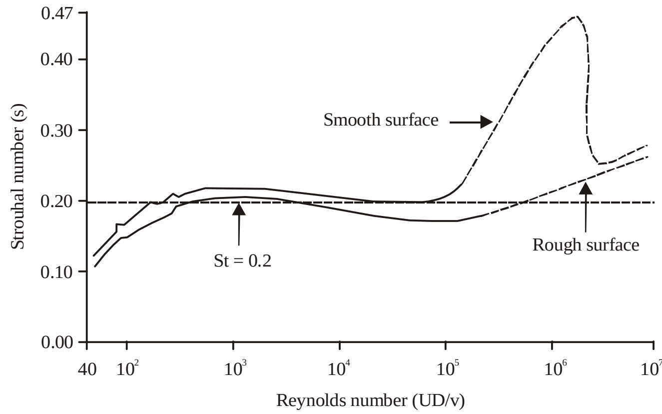

Fig. 2: Strouhal number vs. reynolds number

MATERIALS AND METHODS

Water tunnel: In this section, the design of water tunnel used in this study in order to study the behavior of Vortex-Induced Vibration in water flow. The aims of this custom-made water tunnel is to provide a similar flow speed of ocean current flow in the range of 0.41-1.18 m sec^{-1} for the VIV application (Yaakob *et al*., 2006). So, it is carefully designed to run a steady and uniform flow at the test section for various range of Reynolds numbers as shown in Fig. 3. Basically, the conceptual design of this water tunnel is based on modifications of several water tunnels from the previous studies (Park *et al*., 2013; Hennessey, 2005). Further information on this water tunnel can be referred to Zahari (2014).

In order to adjust the volumetric flow rate of the pump to match with ocean current flow, a valve is installed on the pump. Besides, flow guides is positioned at the end of the water tunnel to provide a steady flow within the central channel. Screens have been used on this water tunnel to reduce the intensity of the oncoming turbulence and improved the mean flow uniformity (Mehta, 1985). Submersible pump and piping system is added inside the water tunnel to improve the quality of this water tunnel as shown in Fig. 4.

PVC pipe cylinder: The PVC pipe cylinders are designed for this study in order to examine the potential performance of VIV in low ocean current speed. As the main concern in this research is to investigate the effects of different sizes of cylinder diameter on the behavior of VIV, various cylinders that are 30 cm in length, with 0.25, 0.5, 1.0, 1.5 and 2.0 inches nominal diameters were used as shown in Fig. 5. The cylinders are assumed to be having a smooth surface, therefore giving Strouhal number of approximately 0.2 (Roshko, 1952). The measurement board apparatus is attached at the centre of cylinder to provide a dry platform to measure the displacement, velocity and acceleration of cylinder while the cylinder is submerged in water.

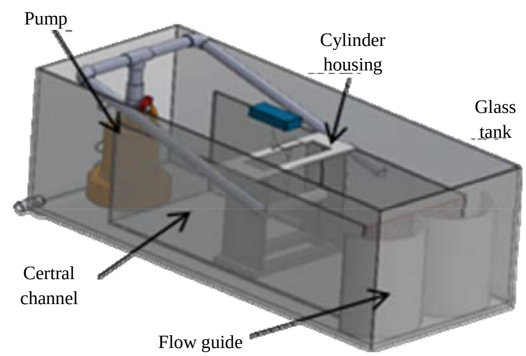

Fig. 3: Water tunnel designed using solid work 2012

The PVC cylinder is attached to the cylinder housing using springs which are connected to the cylinder housing. The top of cylinder housing is cut out for the cylinder visibility and space for measurement platform to oscillate. The combination of cylinder and springs within the cylinder housing is formed "H-shape" as shown in Fig. 6.

Measuring devices

Go! Motion sensor: In this research study, displacement and velocity measurement of oscillating cylinders are vital in order to investigate the effects of different sizes of cylinder on hydrokinetic energy based on VIV. Thus, Go! Motion Sensor as shown in Fig. 7 is used to collect all the data regarding position and velocity of cylinder. This sensor can be connected directly to the computer using the provided cable. It has the features that reduce noise to ensure motion readings are accurate with the resolution of 1 mm.

Open channel flow rate meter: Open channel flow meter is used in this study in order to determine the water velocity inside the water tunnel as shown in Fig. 8. Water velocity is

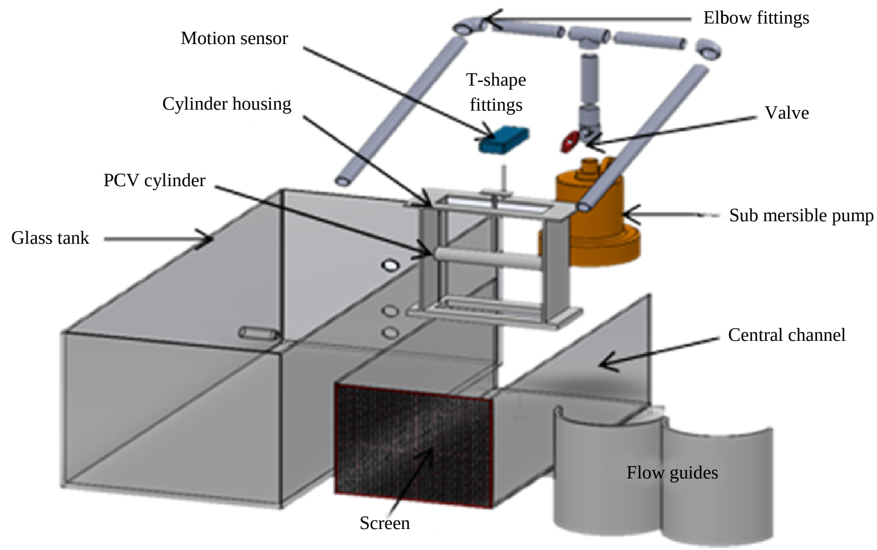

Fig. 4: Exploded view of water tunnel

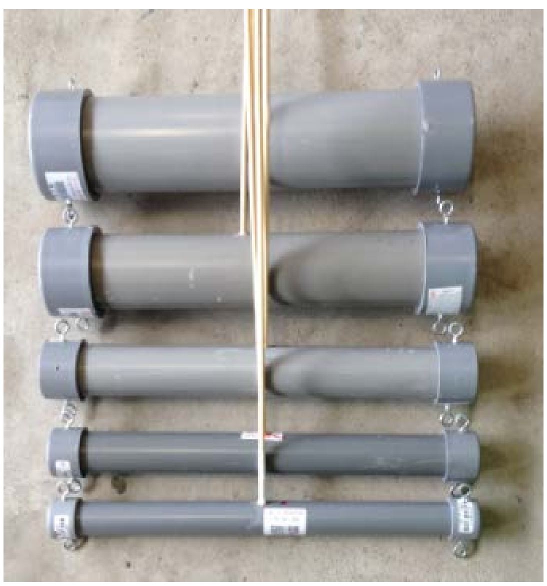

Fig. 5: Various size of cylinder pipe

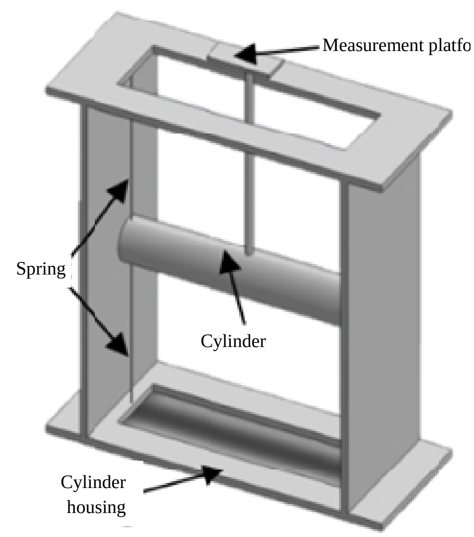

Fig. 6: Cylinder housing and cylinder

vital in this research to ensure the velocity inside the water tunnel is matched closely with the averaged ocean current flow rate. This flow meter is supplied with a dedicated surface display unit and impeller. It can measure the water velocity in the range of 0.046-5 m sec^{-1} with the accuracy 0.01 m sec^{-1}.

Water tunnel is assembled together with measuring device to form a completed open channel tank as shown in Fig. 9. Flow rate meter and motion sensor are used to collect the test data on various sizes of cylinders.

Experimental set-up

Water flow velocity: The ability to sustain a constant flow speed in each trial of cylinder testing is a key factor in order to determine the accurate result. So, the uniform and steady flow inside the test section area are vital in this project. Cengel and Cimbala (2006) stated that, the term steady implies no change at a point with time while the term uniform implies no change with location over a specified region. According to Bernitsas *et al.* (2006), the typical ocean current to generate energy based VIV are in the range of 0.26-2.57 m sec^{-1}. Thus, the flow speed of water need to be obtained in the range of 0.26-2.57 m sec^{-1} and fulfil the criteria of steady and uniform flow as discussed before.

Maximizing VIV through different diameter of cylinder: The goal of this study is to study the effects of different sizes of cylinders on vortex-induced vibration. Details of VIV that are investigated experimentally include amplitude, velocity, natural frequency of cylinders, Reynolds number, power generated, reduced velocity and frequency ratio. In order to study effect of diameter size on VIV, some experiments are required to investigate the characteristic of the cylinders which can produce the highest amplitude of oscillating motion. The parameter varied in this research is the diameter of the cylinder with the constant flow speed. All cylinders are made of PVC pipe with diameter of 0.25, 0.5, 1.0, 1.5 and 2.0 inches are labelled as A, B, C, D and E, respectively. The experiment is conducted in the low-turbulent free surface in the water tunnel constructed. In order to measure the amplitude of the oscillating cylinder, the vernier displacement sensor is used to measure the displacement of the cylinder during experiment. Diameter of cylinder is measured using the calliper and mass is measured using an electronic scale. All other data from this experiment is recorded and derived directly or indirectly from the measured values.

Fig. 7: Go! Motion sensor

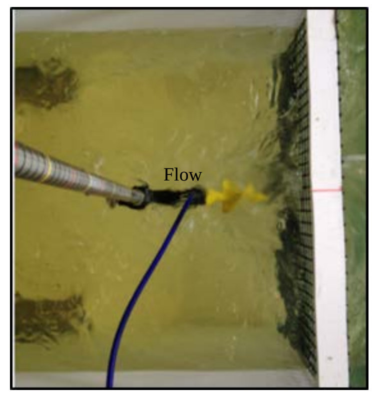

Fig. 8: Flow rate meter inside the water tunnel

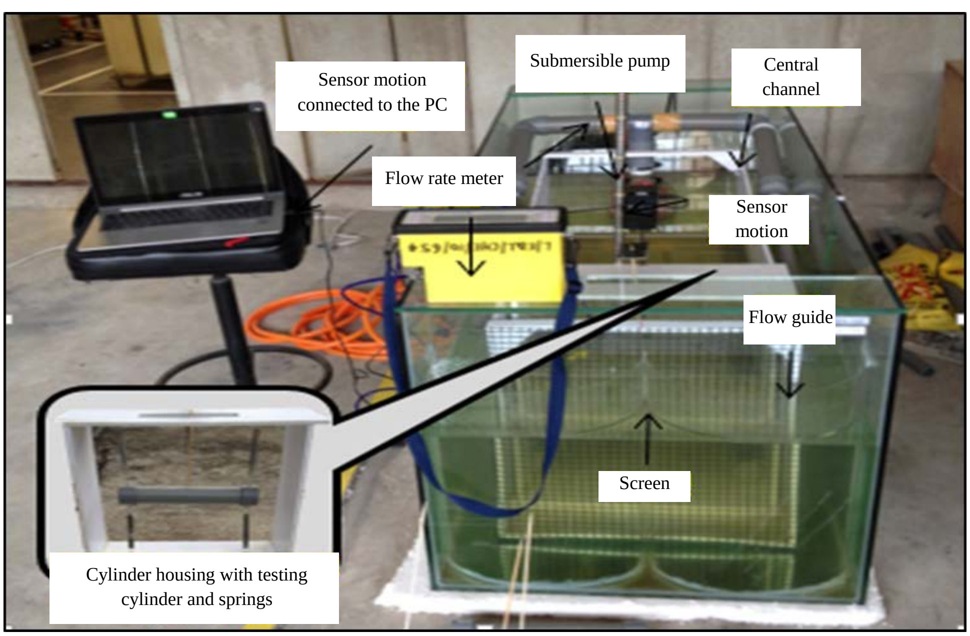

Fig. 9: Assembled water tunnel

RESULT AND DISCUSSION

Water flow velocity: The overall flow velocity data have been recorded and the graph sample number versus velocity in Fig. 10 is plotted to determine the suitable position of tested cylinder within the water tunnel. Figure 11 shows the position of flow velocity along the water depth which is measured inside the water tunnel. By observing the flow rate profiles on this graph, the flow rate test data for top position varies from 0.524-0.564 m sec^{-1}. While for middle and bottom position, it showed a range of flow rates varying from 0.431-0.487 m sec^{-1} and 0.508-0.574 m sec^{-1}. The averaged flow speed of 0.453 m sec^{-1} is used for any calculation in this paper.

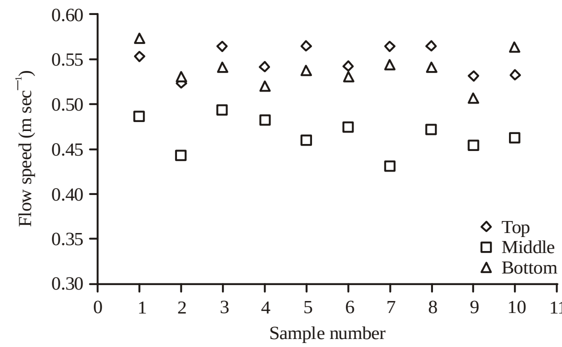

Fig. 10: Graph of sample number vs. Velocity at tested cylinder

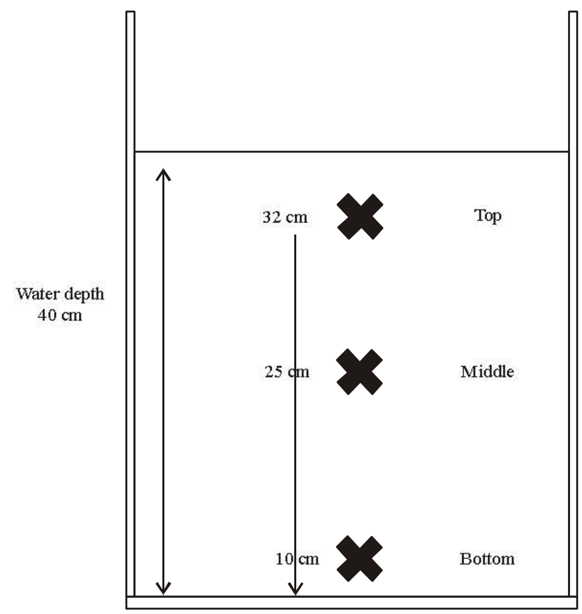

Fig. 11: Position of measured water velocity

Maximizing VIV through different diameter of cylinder

Cylinder amplitude: The corresponding cylinder amplitude was measured and displayed simultaneously on the computer using motion sensor to give an overview of characteristic of VIV through different sizes of cylinder. The result of the cylinder amplitude was shown in Fig. 12 (Zahari and Dol, 2014).

The maximum amplitude obtained by cylinder E that is equal to 0.0065 m while cylinder A gives the lowest maximum amplitude that is equal to 0.0035 m. It shows that, the cylinder amplitude generally increases with an increase of cylinder diameter. This is due to the increasing of the Reynolds number, Re and the mass ratio, m*. On the large cylinder, forced movement during their upward motion increase its elastic potential energy compared to small cylinder diameter size. Thus, during the downward motion, energy of the large cylinder contributes to the large displacement and velocity. Reynolds numbers generally affect the peak response of a rigid cylinder to vibrate in a cross-flow (Williamson and Govardhan, 2004). The strength of the vortex shedding increases as the amplitude of oscillation increases. Thus, by increasing the diameter size of cylinder, the Reynolds number increases as shown in Fig. 13. Then, the strength of the vortex can be determined within the range of Reynolds number ($300<Re<3\times10^5$).

Cylinder natural frequency: The values of natural frequency with the constant stiffness of spring for each cylinder were determined using the Fast Fourier Transform (FTT) function built using MATLAB software. Then the frequency ratio was calculated using Eq. 4:

$$f^* = F_s/F_n \quad (4)$$

Frequency ratio is a parameter used to determine the potential of the oscillating body to enlarge their amplitude of oscillation which is known as "lock-in" phenomenon. The "lock-in" phenomenon is a condition when the vortex shedding frequency becomes close to the natural frequency of the body. It has the potential to enlarge the strength of VIV and increase the hydrokinetic energy of body. Thus, when frequency ratio is close to unity, the potential of "lock-in" phenomenon to occur will increase.

Using the natural frequency obtained, the values of reduced velocity, U* was calculated using Eq. 3 to ensure U* values for each tested cylinders are within the range of ($3<U^*<8$) as discussed before. The relationship of frequency ratio and reduced velocity is shown in Fig. 14. Based on the graph plotted, it clearly showed that as the frequency ratio close to one, the reduced velocity will be collected at the centre of the lock-in range. The values of reduced velocity started to move away from the centre of lock-in range as the ratio frequency increased. In this study, the large amplitude of oscillation is obtained by higher diameter size due to the closeness of its natural frequency with shedding frequency which results in frequency ratio close to unity. Thus it showed that, the potential of lock-in to occur increases with the increasing of cylinder diameter.

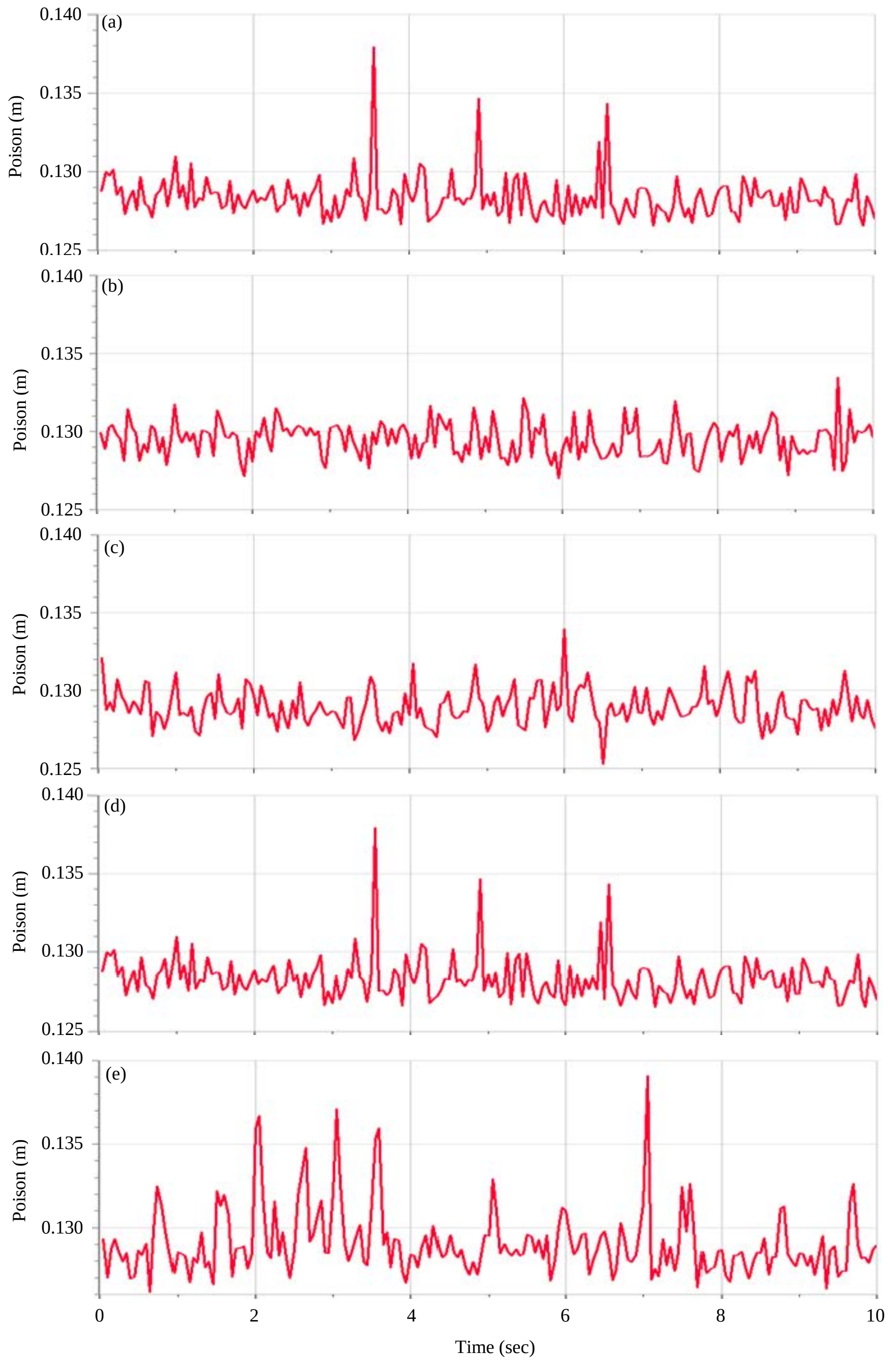

Fig. 12(a-e): Amplitude profiles of different sizes of cylinder, (a) Maximum Amplitude: 0.00315 m, (b) Maximum Amplitude: 0.00325 m, (c) Maximum Amplitude: 0.00430 m, (d) Maximum Amplitude: 0.00570 m and (e) Maximum Amplitude: 0.00650 m

Cylinder power: Based on the cylinder velocity data generated from Logger Lite software, the power of cylinder can be obtained by substituting the velocity of cylinder in Eq. 5. The result of the cylinder power was shown in Fig. 15:

$$P(t) = v(t)\times F_L \sin(\omega t) \quad (5)$$

The maximum power obtained is equal to 0.0141 W which is on cylinder E. For the cylinder A, it gives the lowest maximum power which is equal to 0.0025 W. It clearly shows that as the diameter of cylinder is increased, the maximum power of cylinder increases. So, the power generation of the cylinder will increase.

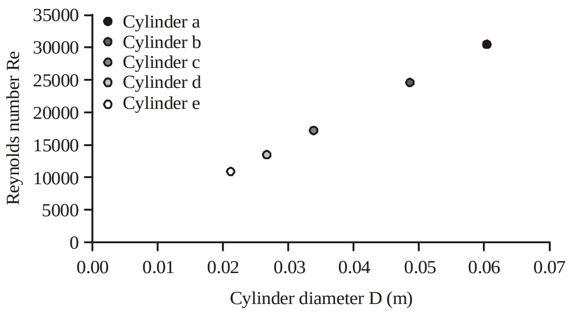

Fig. 13: Graph of cylinder diameter vs. reynolds number

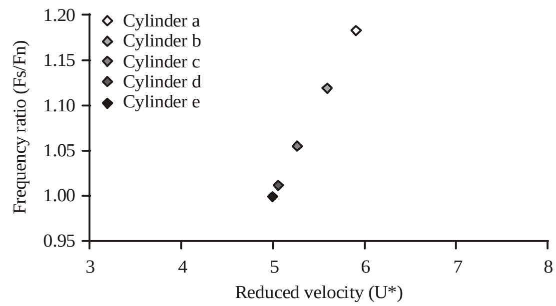

Fig. 14: Graph of frequency ratio vs. reduced velocity

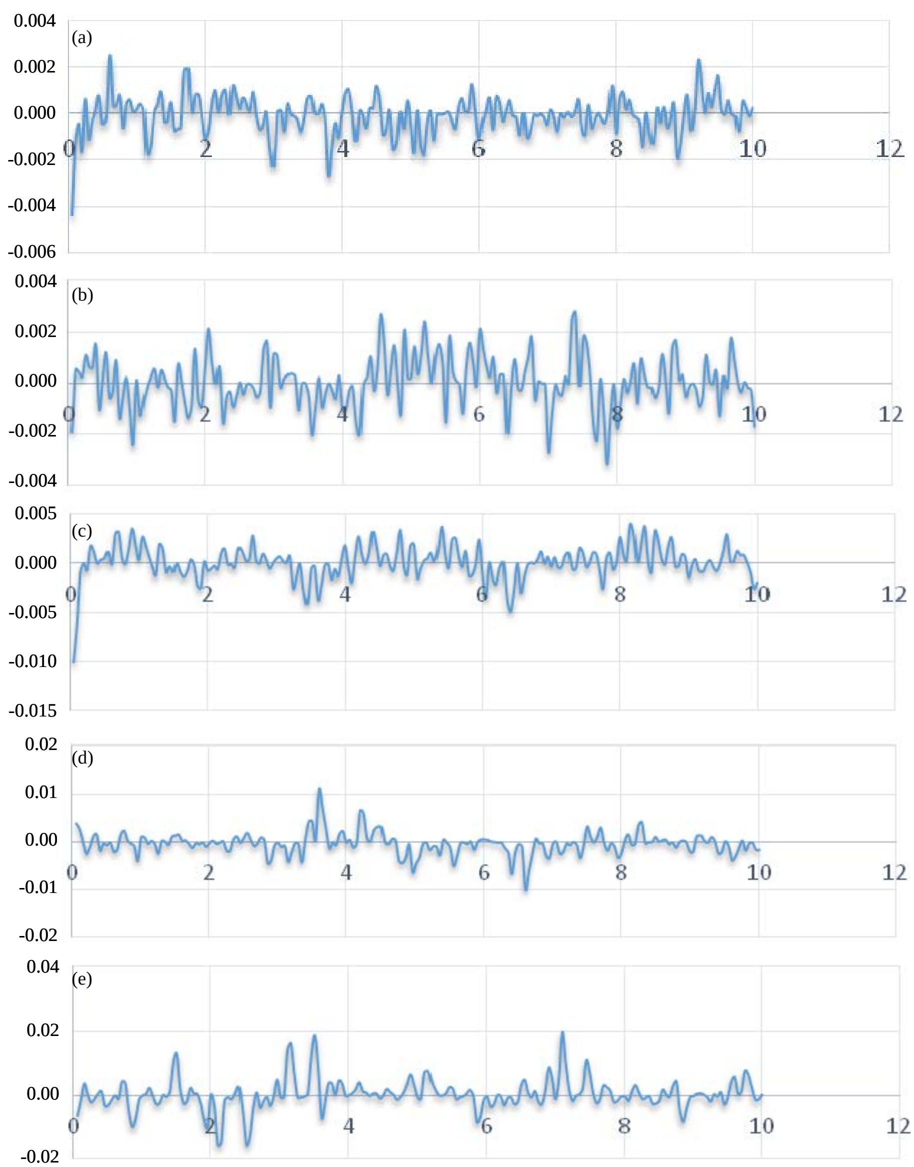

Fig. 15(a-e): Power profiles of different sizes of cylinder, (a) Maximum power: 0.0025 W, (b) Maximum power: 0.0032 W, (c) Maximum Power: 0.0045 W, (d) Maximum power: 0.0120 W and (e) Maximum Power: 0.0141 W

CONCLUSION

The vortex induced vibration of a rigid, circularly and smooth surface cylinders with different sizes of diameter was investigated experimentally within the range Reynolds numbers (300<Re<300000). From the experiment, it can be concluded that, as the cylinder diameter is increased, the energy levels produced on the cylinder increases. The suitable size of oscillation body is vital in the designing of VIV converter to generate higher energy as VIV is a viable solution of the current energy extraction problem for industrial application.

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