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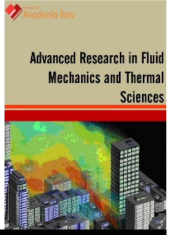

Microwatt Energy Harvesting by Exploiting Flow-Induced Vibration

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ABSTRACT

The green technology approaches by harvesting energy from aerodynamic flow-induced vibrations using a flexible square cylinder is experimentally investigated. The practicability of flow-induced vibration system to supply a sufficient base excitation vibration in microwatt scale is evaluated through a series of wind tunnel tests with different velocities. Test are performed for high Reynolds number 3.9 x 10^3≤ Re 1.4 x 10^4 and damping ratio $\zeta = 0.0052$. The experiment setup is able to replicate the pattern of vibration amplitude for isolated square cylinder with previous available study. Then, the experimental setup is used to study the effect of vibration cylinder in harvesting the fluid energy. A prototype of electromagnetic energy harvesting is invented and fabricated to test its performance in the wind tunnel test. Test results reveal that the harnessed power is corresponding to vibration amplitude flow pattern, but the power obtained is much lower than the vibration amplitude due to the power dissipation at the resistor. The best condition for harnessing power is identified at U_R = 7.7 where the Karman Vortex-Induced Vibration (KVIV) is the largest.

1. Introduction

Flow-induced vibration (FIV) is claimed to cause large number of problems, especially in civil structural design [1] such as risers in marine technology [2], buildings and bridges [3] and heat exchanger tube bundle [4]. Commonly, this FIV is occurring when the structure is analogous to a body supported with a spring-damper system that is then contacting with a fluid flow [5]. The flow pattern found near the body is based on the Reynolds number. When the flow exceeds Reynolds number of 40, unstable separation of fluid flow from the surfaces of the body will cause instability in the flow field [6]. The vortices that is usually fully attached when Re is low appears to detach periodically from the surface of body and this circumstance explains the definition of von-Karman vortex shedding, VKVS. The vortex shedding induces oscillating to the structure that thus generates vibrations. At a

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certain free stream velocity, the vibration frequency is equal to the natural frequency of the structure once the resonance is met. Therefore, there are various studies in developing an effective wake control for suppression of vortex shedding which can be grouped into two: active vibration control [7-9] and passive vibration control [6, 10, 11].

From a totally different viewpoint, an approach to harvest energy from VKVS has been studied in recent years to manipulate and enhance its possibility as a new ideal energy source [12-15]. There are several types of transducer that can be used to convert the mechanical energy to the electrical power such as electromagnetic [16], electrostatic [17] and piezoelectric transducer [18-21]. However, most of the studies have focus on a flexible piezoelectric transducer due to its convenient mechanism to operate the energy harvester system in the optimum condition [22,23]. Studies on different cross section geometries are also have an attention in many years based on the fact that the flow behavior appears on the wake of bluff body will be affecting by the bluff body shape. Basically, the considered shape are circular cylinder, rectangular cylinder, triangular cylinder and square cylinder. But, a square cylinder has been acknowledged more due to its accessibility to the onset of galloping [24-27]. Therefore, the recent studies have shown the interest to improve the fluctuation of the body using a square cylinder in an effort to obtain higher performance of the energy harvester [28].

An electromagnetic induction is literally having a potential to be used as a transducer in exploiting the energy from a relative body motion in the magnetic field, but only gained the interest from limited past studies. Jung and Lee [13] and Jung *et al.,* [29] performed an experimental study on the concept of electromagnetic energy harvesting from a wake galloping. The study found the relation between the harvested energy and the aerodynamic instability (i.e., wake galloping). An approach to experimentally study the galloping oscillations-based electromagnetic wind generator has been investigated by Ali *et al.,* [16] with different cross-section geometries. In the latest study by Maruai *et al.,* [11], different cross geometries are considered and a detached flat plate is placed downstream of the body in the objective to amplify the vibration so that the harvested energy can be amplified. The study reveals that a downstream body with a relevant gap separation are able to magnify the amplitude vibration. Blazewicz and Bies [30] and Ozono [31] are also supported the findings. However, both study by Ali *et al.,* [16] and Maruai *et al.,* [11] did not consider the effect of transducer on the overall performance of the harvested energy where in the actual case, the energy harvester performance may be affected by the installation of the transducer.

This manuscript presents the experimental study of a complete energy harvesting system by using an electromagnetic transducer that is utilized from VKVS. The design is targeted for low power consumption applications, such as wireless sensor network (WSN) [32,33] and also for the purpose of health monitoring applications [34,35]. The detail of the experimental setup to measure the velocity, displacement and output voltage are also presented in this paper.

2. Experimental Apparatus and Measurements

Arrangement of the experimental study and the framework that involved in this study are shown in Figure 1. The test section is having a square cross-section and lengths of 0.36 m × 0.36 m and 0.8 m, respectively. The bluff body under investigation is a square cylinder with side lengths D = 26 mm and spanwise length of L = 0.349 mm. The cylinder is hollow and it is supported to the wind tunnel by a steel rod at each end of the cylinder and the length of supported steel rod is 0.105 m length. The steel rods pass through the opening slot on the side walls of the test section and elastically supported by two parallel twin spring plates at both ends outside the wall test section to allow the square cylinder moves in a transverse direction of the incoming airflow. The dimension of the spring plate is 0.5 m × 0.004 m × 0.001 m. To prevent the end effect so that the cylinder will acting as an infinite length, an end plate (circular disk) is used at each of the cylinder end. The experimental conditions are listed in Table 1.

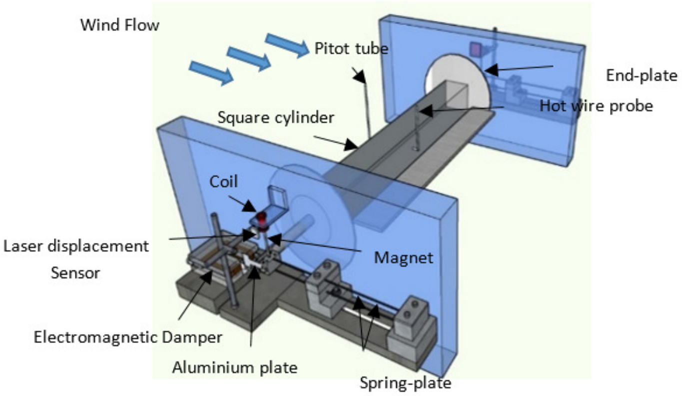

Fig. 1. Arrangement of the experimental apparatus and the system used in this study

Table 1
Experimental conditions

Parameter	Specification
Square cylinder side length, D[m]	0.026
Mass per unit length [kg/m]	0.34
Mass damping ratio,m*	428.15
Spring constant, k [N/m]	1189.75
Logarithmic damping factor, δ	0.0305
Damping ratio, ζ	0.0052
Natural frequency, f_n[Hz]	15.9
Free flow velocity, U [m/s]	2.37-9

2.1 Free Stream Velocity Measurement

The selected device for measuring the air velocity of the airflow is by using the pitot tube. The pitot tube is having ellipsoidal sensing tip (NPL Modified Ellipsoidal Pitot Tube) and it is assembled from a co-axial tubing. This design provides the most accurate velocities measurement for high-velocity flow like is being conducted for this experiment. Pitot tube enables the concurrent measurement of the pressure induced by the moving air particle hitting the tip of the pitot tube and the stagnant pressure of the static air. According to Jr [36], this device able to correct the errors in static pressure reading that is caused by pressure distribution when it is subjected to airflow. Figure 2 shows the basic pitot tube construction with L-shaped that is used in this experiment.

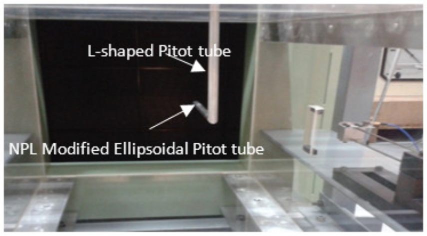

Fig. 2. Basic Pitot tube construction

It should be noted that the pitot tube is physically measuring the pressure generated by the air mass moving around the tip, thus the pressure gauge is required. To obtain the accurate measurement, the sensing tip must be pointed directly into the moving air flow. In addition for a better measurement, the pitot tube is located at the average velocity point in the moving air to reduce the effect of frictional drag due to the pipe wall. The free flow velocity, U is obtained from the Bernoulli's Equation as follows.

Bernoulli's Equation:
Static pressure + Dynamic pressure = Total pressure

$$(P_s + \rho \frac{U^2}{2}) = P_T \tag{1}$$

$$U = \sqrt{2 (P_T - P_s)} / \rho \tag{2}$$

where P_s is the static pressure [pa], P_T is the total pressure [pa], ρ is the density of air [kg/m^3] and U is airflow velocity profile [m/s].

2.2 Vortex Shedding Frequency Measurement

To measure the vortex shedding frequency in the wake of the cylinder, the hot wire probe with a single-wire sensor that is attached to two support needles is used as shown in Figure 3.

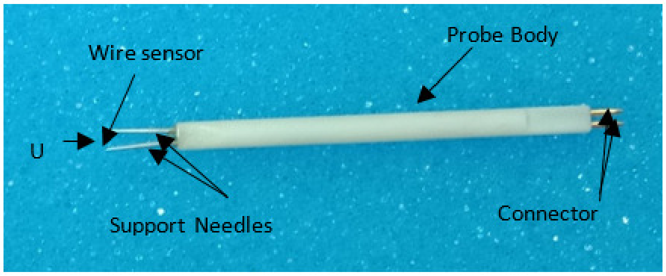

Fig. 3. Hot wire probe with a single-wire sensor type

The position of the hot wire probe in the wind tunnel is similar to Kawabata & Takahashi [37] with x/D = 1.5, y/D = 1.25, z/D = 0.4 from the center of the square cylinder. The two support needles should confront directly into the moving airflow in order to obtain the accurate readings. When the current is passed through the thin wire, heat will be generated. Due to the change in velocity, U, the convective heat transfer coefficient from the electrical package and the wire temperature will change until eventually reach a thermal equilibrium. Afterwards, the signal will be transmitted to the Constant Temperature Anemometer (CTA). CTA is work based on the fact that probe's resistance will be proportional to the temperature of the hot wire and it is capable of measuring the flow and turbulence with low to medium velocity and moderate fluctuation frequencies. The CTA is also equipped with data noise reduction system. For high precision measurement, NI USB-9215 Series is used to build data acquisition and instrument control application using the LabVIEW. Physically, the hot wire measures the stream wise velocity in the wake of the square cylinder. The vortex shedding frequency is obtained by doing a series of power spectrum analysis of the fluctuation velocity. The peak on the spectrum indicates the frequency of the vortex shedding.

2.2 Displacement Measurement

A laser displacement sensor with a diffuse reflective sensing sensor is used to measure the displacement at each end of the cylinder. Data acquisition and data analyzing are conducted using the LabVIEW software with NI USB-9215 Series as an interphase. To find the elastic properties of the system (natural frequency, f_n, logarithmic damping factor, δ and spring constant, K), free damping oscillations are conducted in static air as shown in Figure 4. To calibrate the laser displacement sensor, height gauge is used as signify in Figure 5.

Fig. 4. Free damping oscillation

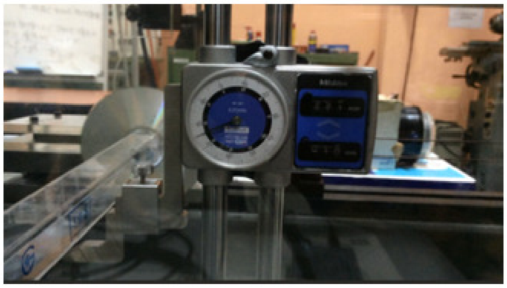

Fig. 5. Laser calibration method by using the height gauge

2.4 Modelling the Energy Harvester System with Electromagnetic Damper System and Electromagnetic Induction

The energy harvester consists of a customized permanent magnet (5 × neodymium, Ø 4 mm × 10 mm) that is glued to the movable square cylinder. The circular coil is fixed above the permanent magnet, thus the position is confirmed to be in the middle of circular coil. Specifications of the coil is presented in Table 2. The method for controlling the vibrations using electromagnetic damper has been investigated experimentally. The width of aluminum thin-plate will be inserted for every 1 mm interval (ΔL_d = 1 mm) into the electromagnetic damper and free damping oscillations in static air is applied to identify the relevant damping factor that is applicable in this experiment. The effect of electromagnetic induction is also has been considered during the free damping test. Figure 6 shows the schematic modelling of energy harvester with electromagnetic damper while Fig.7 shows the equivalent circuit model in this study.

Table 2
Coil specifications

Coil type	Parameters	Specifications
Copper	No. of turns, N_t	400
	Resistance, [mΩ]	0.49
	Inductance, L [H]	0.00837
	Wire diameter d_w [mm]	0.4
	Outer diameter coil, d_o [mm]	20.7
	Inner diameter coil, d_i [mm]	14.9
	Height of coil, h_c [mm]	40
	Total wire length, L_w [m]	9.61

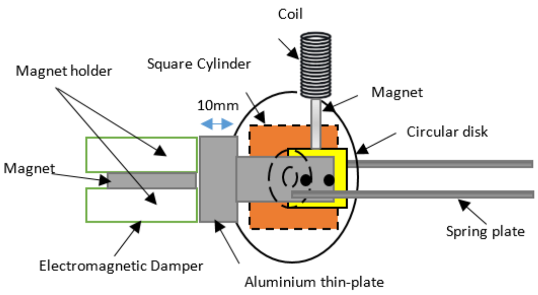

Fig. 6. Schematic modelling of energy harvester with electromagnetic damper

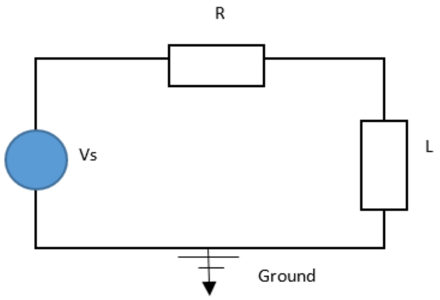

Fig. 7. Equivalent circuit model

2.5 Mathematical Modelling

In this part, a mathematical modelling for experimental power [P_e] is introduced as follows.

- Resistance [R]

$$R = \rho L_T / A \tag{3}$$

where R is electrical resistance of coil[Ω], ρ is resistivity of the copper coil in [Ω·m], L_c is the length of coil [m] and A is the cross-sectional area of coil [m^2]

- Power [P_e]

$$V_{emf} = IR \tag{4}$$

Hence,

$$I = V_{emf} / R \tag{5}$$

Substitute I value into the power equation,

$$P = VI \tag{6}$$

where P is the power output [W] and V is the emf voltage. Noted that the V value is obtained from the experimental result.

3. Experimental Result

In a series of experimental studies of flow-induced vibration, the square cylinder is flexible and it is subjected to wind stream velocities within 2.37 m/s to 9 m/s that is corresponding to wind speed velocity in Malaysia [38]. The equivalent reduced velocities [$U_R = U\ f_n / D$] is determined in the range of 5.5 < U_R < 19.5. The study has been conducted similar to Ismail *et al.,* [10]; Maruai *et al.,* [11]; Kawabata *et al.,* [37]. Therefore, a comparison are made to validate the experimental setup as listed in Table 3. The square cylinder side length (D), effective mass ($m_{e)}$, and spring stiffness (k) have chosen to be consistent with the previous studies and were kept as close as possible for this validation purposes.

Table 3
Damping factor calibration

Physical parameter	Kawabata *et al.,* [37]	Ismail *et al.,* [10]	Maruai *et al.,* [11]	Current study
Square cylinder side length, D [m]	0.0260	0.0260	0.0260	0.0260
Effective length [m]	0.3150	0.3150	0.3150	0.3150
Effective mass, m_e [kg]	0.11	0.15	0.15	0.12
Mass ratio, m^*	585	587.56	587.56	428.15
Spring stiffness, k [N/m]	1181	1173	1173	1189
Logarithmic damping factor, δ	0.027	0.0275	0.0275	0.0305
Damping ratio, ζ	0.0047	0.0047	0.0047	0.0052
Natural frequency, f_n [Hz]	16.5	14.2	14.2	15.9
Scruton number, Sc	35.1	32.3	32.3	26.1
Free flow velocity, U [m/s]	1.8-16.5	2.37-9	2.37-9	15.92.37-9

For flow across an isolated square cylinder with one degree of freedom, there are two types of flow-induced vibration are predicted, Karman vortex-induced vibration (KVIV) and galloping. The current study is able to replicate the vibration behavior with reduce velocities as predicted by Sarpkaya, [39] when the regions of KVIV is occurred at lower branch velocity region while galloping is at higher branch velocity region. However, the occurrence of the peak vibration in the KVIV region is shifted to earlier reduced velocity compare to the other studies due to the different value in damping ratio (ζ) as shown in Figure 8.

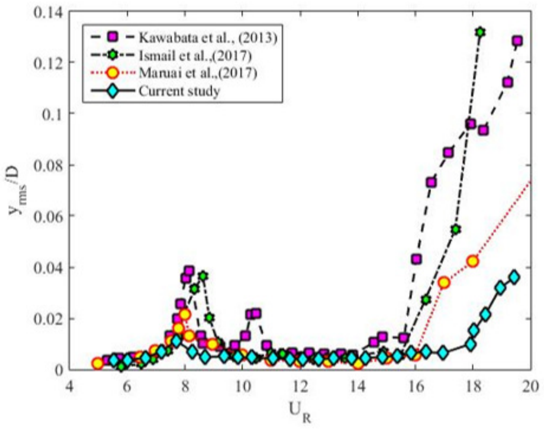

Fig. 8. RMS transverse amplitude with reduced velocity, U_R

3.1 Power Harnessing

From the results presented in Fig. 9, the power harnessed by the electromagnetic converter from flow-induced vibration is calculated using the equation 3-6. It shows that the harnessed power flow pattern is equivalent to the amplitude ratio *($\mathbf{Y_{rms}/D}$)* and this theory is supported by Maruai *et al.,* [11]. According to the data, the ideal U_R to harness the power is at U_R = 7.7 which is in the Karman Vortex Induced Vibration region. The power identified at that particular U_R is about 5.224 mW after the value of resistor and inductance has been considered. The determined power value across the U_R is observed between 0.3265 mW-73.47mW within $5.5 \leq U_R \leq 20$.

In Figure 10, three different frequencies are plot in the same graph for $\boldsymbol{U_R}$ = 7.7. Apparently, the PSD analysis shows that the energy frequency is the lowest among the three frequencies. Thus, the harnessed power is expected to loss due to the resistor that is equipped in the circuit or through the mechanical devices during the vibration.

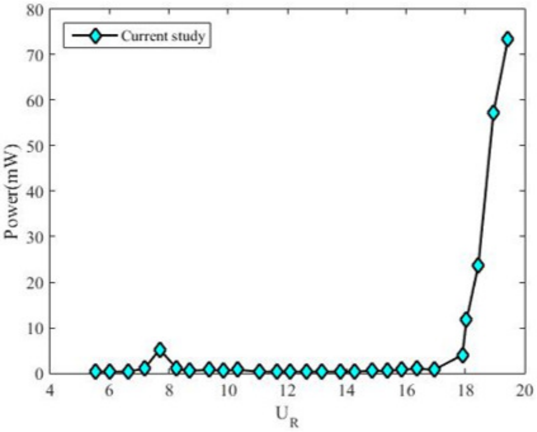

Fig. 9. Power against $\mathrm{U_R}$

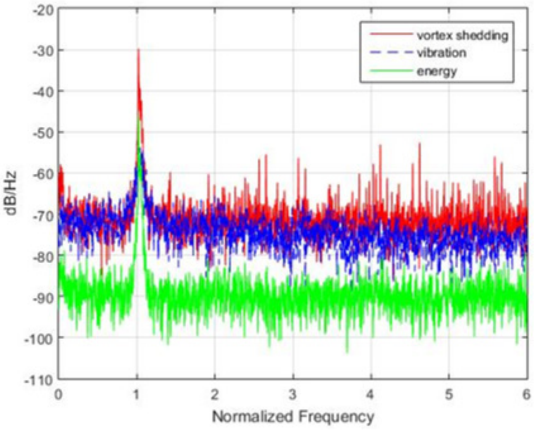

Fig. 10. PSD at $\mathrm{U_R}$ = 7.7

4. Conclusions

In this paper, the feasibility study of flow-induced vibration for generating a green technology is extensively investigated. In order to design the portable energy harvester based electromagnetic transducer, the characteristics and mechanisms of various aerodynamic instability have been studied clearly before approaching the next step which is to design the energy harvesting device that is appropriated to test under the wind tunnel. As seen from the test results, the average generated power can be obtained in the range of 0.3265 mW-73.47mW under the wind speed 2.3 – 9 m/s. However, the ideal wind speed to harness the power is obtained at wind speed 3.3 m/s which is equal to U_R = 7.7. For this proposed device, the electromagnetic induction can be easily increased, thus more power can be produced with the right configuration. Therefore, the advantages of the proposed energy harvesting device is promising and it could be effectively used as a power supply for powering up low power electronic devices like the wireless sensor network under the moderate wind conditions.

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