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Numerical Investigation on Tandem Body Configurations in Prospect to Enhance Low Wind Energy Harvesting

Muhammad Aiman Ahmadi[1], Nurshafinaz Mohd Maruai[1,*], Mohd Fadzli Haniff[2], Ahmad Faiz Mohammad[1], Farah Mohd Redzuan[1], Shahir Mohd Yusuf[3]

[1] Wind Engineering for (Urban, Artificial, Man-made) Environment (WIND) iKohza, Malaysia-Japan International Institute of Technology (MJIIT), UTM Kuala Lumpur, Malaysia
[2] Intelligent Dynamic Systems (IDS) iKohza, Malaysia-Japan International Institute of Technology (MJIIT), UTM Kuala Lumpur, Malaysia
[3] Engineering Materials and Structures (eMast) iKohza, Malaysia-Japan International Institute of Technology (MJIIT), UTM Kuala Lumpur, Malaysia

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ABSTRACT

Fluid-induced vibration (FIV) is one of the alternative techniques for harvesting wind energy. A structure's dynamic response to interacting with a fluid flow is known as FIV. Utilizing flexible micromechanical systems (MEMS) energy harvesters set up with a cylinder that separates the incoming flow into distinct flows, creating vorticity and turbulence, can efficiently convert the kinetic energy of an incoming flow into electrical energy. Through the use of piezoelectricity, which has the potential to transform mechanical energy into electrical energy, it might be transformed into electrical energy. To further optimize the effectiveness of wind energy harvesting, a numerical investigation on bluff bodies was studied in prospect to enhance the low wind energy harvesting. The current study intends to explore the mechanism of flow-induced vibration on the multi-surface bluff body and identify the best position for piezo material on the bluff body which provides the most strain energy. A series of numerical simulations have been conducted to investigate the character of flow-induced vibration and the influence of different geometrical shapes of vibrating cylinders on the harvested power by using Computational Fluid Dynamics, OpenFOAM. Three different geometrical bluff bodies of harvesters are tested to determine which produces the most energy harvesting among square, triangle, and pentagon bluff bodies. Based on the findings from numerical simulation, the square bluff body offers a great amount of strain rate with a peak value of 10076.2 s^-1 at a distance of 42.5 mm. This finding suggests that the design of the square bluff body is more effective in inducing higher strain rates in the upstream cylinder and lower cylinder compared to the triangular and pentagon bluff bodies.

1. Introduction

Wind energy is related to air masses moving with velocities corresponding to pressure gradients from regions of high atmospheric pressure to nearby regions of low atmospheric pressure [1]. Wind energy is safe and clean. Wind energy doesn't release greenhouse gases into the atmosphere like

* *Corresponding author.*
E-mail address: nurshafinaz@utm.my

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coal, natural gas, or oil do. Since wind power is entirely renewable, it will never run out. Wind exists naturally in our atmosphere, thus there are no supply difficulties in the future, unlike traditional fossil fuel supplies, which renew relatively slowly [2]. Due to this, wind energy must be harvested as a backup of power supply in the future.

Fluid-generated vibration is the dynamic reaction of a design structure that engages with a fluid flow (FIV). The flow over a bluff body is complicated because it involves the formation of shear layers, flow separation, and the formation of a von Karman street vortex [3]. Fluid flow is impacted by a bluff body's shape. The establishment of the standard von Karman street vortex is the most prominent feature of flow over the bluff body. Matsumoto and Bearman [3] have discussed vortex shedding in great detail. Boundary layer splitting at specified areas, which may be fixed by geometry in the case of sharp corners or free to move in the case of curved surfaces, is a characteristic of two-dimensional bluff bodies. In the wake of a boundary layer split, vorticity is created. The growth of the flow and the forces exerted on the body are significantly influenced by the behaviour of this vorticity.

In nature, mechanical energy, like wind flow, is a plentiful source of sustainable and renewable energy. Through the use of piezoelectricity, which has the potential to transform mechanical energy into electrical energy, it might be transformed into electrical energy [11]. According to Robbins *et al.,* in theory, mechanical structures induce periodic strains in a piezoelectric material from wind kinetic energy, and the strains instantly produce electrical energy through the material's piezoelectric coupling [4]. Typically, piezoelectric components turn mechanical strain into modest electrical output. These components enable the direct and reverse piezoelectric effects. A piezoelectric crystal naturally produces a weak, undefinable electric output signal for many input sources. The weak output signalcan be effectively applied and modified appropriately [5]. Hence, this study aims to investigate the highest strain rate obtained from three different geometric shapes, namely, triangle, square and pentagon. All of these geometric shapes are configured such that one of its vertex faces the incoming flow. The highest strain rate is expected to produce high energy through the de-crystallization of piezoelectric material.

2. Methodology

This research makes use of the OpenFOAM modelling software. CFD provides codes, which consist of the numerical algorithm to solve the fluid flow problems. The OpenFOAM consists of components involved in pre-processing, solving the problem and post-processing. The pre-processing involves the blockMesh generation, followed by the construction of the computational domain and boundary condition set-up. In the solving part, the solver settings are set. Next, the simulation is performed by solving the equations associated with a particular flow problem. Once the solution is solved, MATLAB software is utilized to perform data analysis and graph plotting. Meanwhile, the flow visualization is analyzed through OpenFOAM software.

Three geometry shapes are considered for numerical investigation to find the best strain rate produced through the interaction of the fore vertex of a bluff body and the incoming flow. In this study, every side of the polygons was set to 1D which is equal to 50mm. To identify the best position, the angle of attack for incoming flow is horizontal to the vertex of the bluff body due to having the flow to attack both sides of the surface. As stated in problem geometry triangular cylinder has an angle of attack of 60° while, a square bluff body has an angle of attack of 45° and a pentagon has an angle of attack of 36°.

The schematic diagram of the computational domain and boundary conditions are shown in Figure 1.The computational domain is constructed with a 31D wide and 21D high. The square cylinder is set tobe 10D from the inlet and 20D from the outlet. To lessen the end wall effect, the outlet was departed from the square cylinder. To avoid the impact of the end wall and to choose a realistic case scenario, the outlet is constructed relatively distant from the body.

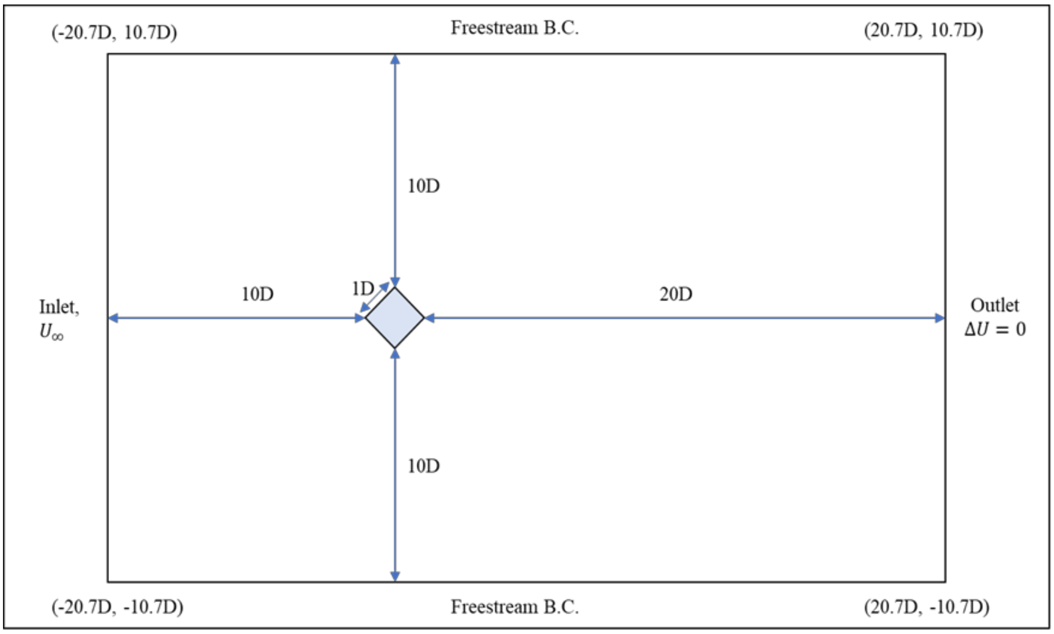


Fig. 1. Schematic diagram of the computational domain and boundary conditions

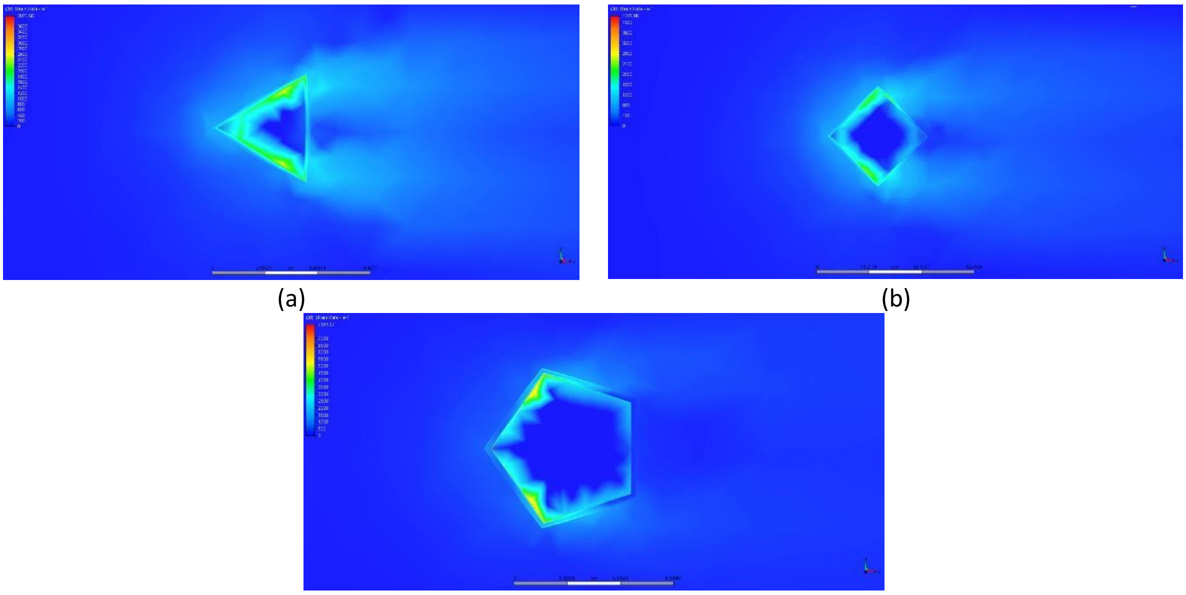
A simple mathematical model of a vibrating system is used to estimate the harvested power in this study. The formulated power is responsible for estimating the power harvested from the flow-induced vibration of three different geometric shapes of the bluff body. The harvested power is shown below

$$T_1 =_{11} S_1 c^E - E_3 e_{31} \quad (1)$$

$$D_3 = s_1 e_{31} -_{33} E_3 \varepsilon^S \quad (2)$$

3. Result and Discussion

The potential position for piezoelectric material is identified based on the highest strain rate obtained from the incoming flow. Figure 2 shows the flow visualization obtained from the interaction of the incoming flow towards the bluff bodies. The strain rate is relatively higher in the vicinity of the fore face of the bluff bodies.



(c)

Fig. 2. Flow visualization of different geometry of bluff bodies (a) triangle (b) square (c) pentagon

Figure 2(a)-(c) presents the flow visualization of fluid flow around the tandem bodies according to the designated geometry shapes. Based on the magnitude of vorticity captured for all cases, it is evident that the highest vorticity magnitude is always discovered at the vicinity of the vertex that is facing the incoming flow. Based on the vorticity magnitude, it can be said that the pentagon is thriving as compared to the triangular and square tandem bluff bodies. Since this observation is vague, further discussion on the strain rate of each geometry shape is important. Strain rate is a parameter to be carefully considered due to its prominent influence towards the generation of electricity by using a piezoelectric material as a transducer for the harvester.

Each geometry has been simulated and the average strain rate for each geometry is plotted in Figure 3. Based on Figure 3, It can be observed that the pentagon bluff body consistently has the highest strain rate across all distance values. The strain rate values for the pentagon are generally higher than those of the square and triangle bluff bodies. The square bluff body has strain rate values that are lower than those of the pentagon bluff body but higher than the triangle bluff body. It falls in between the other two shapes in terms of strain rate values. The triangle bluff body has the lowest strain rate values among the three shapes, consistently lower than both the square and pentagon bluff bodies.

To determine which shape of the bluff body has the best strain rate for the upstream cylinder, we can compare the peak strain rates achieved by the triangular, square, and pentagon bluff bodies. Among the provided data, the square bluff body has the highest peak strain rate of 10076.2 s^-1. In comparison, the triangular bluff body reaches a peak strain rate of 9123.225 s^-1, while the pentagon bluff body reaches a peak strain rate of 7743.03 s^-1.

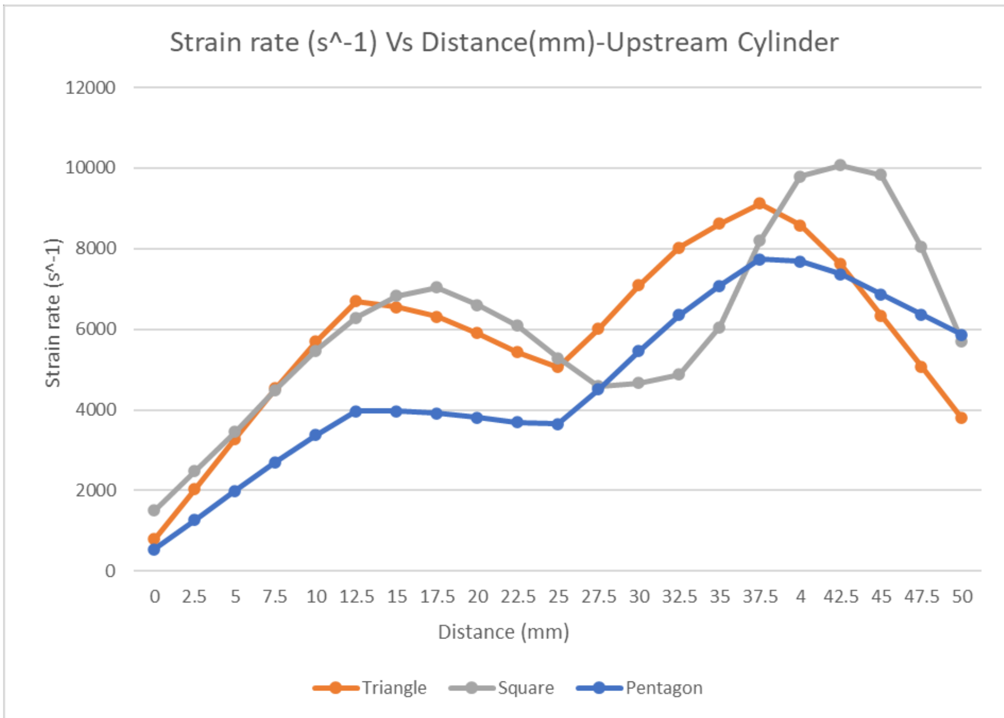


Fig. 3. Average strain rate for different shapes of bluff body at downstream cylinder

4. Conclusion

The utilization of open-source computational fluid dynamics software called OpenFOAM contributes to the success of this current study. The prevalent flow for this problem is in a streamwise direction, which is confirmed by the findings of prior pertinent research, hence the two-dimensional domain example was chosen. Based on the results obtained from the previous study, the configuration of a square cylinder is said to be the most reliable geometric shape to produce the maximum energy. The results of harvested power are predicted to be different and to be increased when there is an attackof angle to the bluff body instead of a flat surface or 0° of attack of angle.

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