Investigation of Vortex-Induced Vibration with Different Width of Two Bluff Bodies in Tandem Arrangement for Energy Harvesting System

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Abstract. Due to imperative of enhancement on Vortex-induced vibration (VIV) energy harvesting as renewable energy sources, dual bluff bodies which are triangle and cylinder in tandem arrangement with different width from each other are studied in terms of total deformation, directional deformation and voltage generated in order to determine the better bluff bodies for the piezoelectric film. This is due to the unsymmetrical wakes pattern, low frequency vortices, and low energy output produced by the system. The length and height of the bluff bodies were fixed to 0.1m and airflow used for simulations was 1.46m/s. The spacing ratio was calculated from 1 to 6 to examine various width between two bluff bodies that will affect the formation of the vortex at the downstream area. From the results, it can be concluded that triangle bluff bodies in tandem arrangement 0.6m from each other have resulted in the highest total deformation and effective voltage generated of 0.47mm, and 3.05mV, respectively. These data indicated the highest ability of energy harnessing. Furthermore, this model results in a consistent flagging direction of the piezoelectric that implying a good energy harvesting system.

1. Introduction
Ocean waves and flow of wind represent potential sources of renewable energy. In the past decade, many researchers have invented various methods to harness this renewable energy into diversifying energy supply in terms of electricity which are essential for a critical area of energy harnessing [1]–[4]. It is crucial to create a useful device that is able to produce electrical energy by harnessing renewable energy because there are a few places that have limitations to reach the electrical power supply. This situation generally applies to offshore platforms or some rural areas. Due to the developments in low power semiconductor technology and wireless system, ambient energy harvesting was found to be an alternative approach to provide power for wireless microsensor networks, thereby able to reduce the need for electrochemical batteries [5].

A potential source for powering wireless sensor networks includes the use of ambient mechanical vibration. Various conversion mechanisms such as electromagnetic, electrostatic, and piezoelectric for harvesting this form of energy have been demonstrated [6],[7]. The piezoelectric element can be
considered an alternative material to harvest macro-scale energy for piezoelectric film devices. Piezoelectric is the most commonly researched among the three transducers because of its size and simplicity. A variety of project research has been done to increase and optimise the output produced from the piezoelectric harvester system [8]–[10].

In order to determine the best bluff body for a piezoelectric film, Kazim et al., [11] have investigated several geometry shapes such as cylinder, square, triangle, D shape, and U shape bluff bodies, in terms of vortex shedding frequency, vorticity, and pressure differences. Airflow used for the simulations was corresponding to Reynolds number of 300, 2000, and 5000. The results showed that the cylinder, triangle, and D shape bluff bodies have a higher value of vortex shedding frequency and Strouhal Number (St). As a result, the triangle bluff body was concluded as the best shape for inducing vortex shedding to piezoelectric film, in which the triangle bluff body was able to maintain the most upper vorticity and pressure difference for all three different airspeeds [11].

To convert mechanical to electrical energy, vortex formation that forms behind a bluff body is exploited to oscillate flexible membranes or beams, which are typically fitted with piezoelectric materials. However, the ability of a piezoelectric element to oscillate at maximum performance is still challenging due to the variety of problems such as wakes pattern formed unsymmetrically behind the bluff bodies, vortices are shed at low frequency compared to the natural rate of the bluff bodies, and low energy output from the harvesting system. Therefore, the principal aim of the project is to investigate the electrical energy output for two different cases, which is by exploiting wakes behind two isosceles triangles and exploiting wakes behind two cylinders in a tandem arrangement. This study presents the development of the 3D models of two bluff bodies in tandem arrangement with a piezoelectric beam placed at the downstream. The effect of width between the dual bluff bodies is then analysed by conducting the transient structural analysis.

2. Methodology
CATIA V5 software is used to create a 3D model of two bluff bodies in the tandem arrangement with the piezoelectric film attached 0.1m behind the bluff body in the downstream area. The piezoelectric film dimension in this project is 300mm in length, 0.51mm in thickness, and 100mm in width. Figure 1 shows the orthographic view of the piezoelectric film with (a) triangle bluff bodies and (b) cylinder bluff bodies, drawn using CATIA V5 software. The sketch was saved as .stp format to make it able to be transported into ANSYS software.

![Figure 1. Isometric view for (a) triangle bluff bodies with piezoelectric film, and (b) cylinder bluff bodies with the piezoelectric film. Dimensions are in mm.](image-url)
The spacing ratio is calculated from 1 to 6 to examine various width between two bluff bodies that will affect the formation of the vortex in the downstream area. The spacing ratio is calculated based on Equation (1) with the width \( w \) and body length \( D \) of the bluff bodies are illustrated in Figure 2.

\[
\text{Spacing ratio} = \frac{\text{width}}{\text{body length}} = \frac{w^2}{D} \tag{1}
\]

**Figure 2.** Illustration of the spacing ratio for the triangle bluff bodies, with \( w = \text{width (mm)} \) and \( D = \text{body length (mm)} \)

After the development of CAD model, the file was imported into ANSYS software. Geometry function in a component system inside ANSYS-WORKBENCH was chosen to open geometry .stp that was created earlier. By referring to the previously published literature, the fluid field was set as 3.0m in length, 1.5 m in width, and 0.5m in height [12]. In this study, the transient structural system is used to determine the dynamic response of piezoelectric film under fluid flow. The oscillations of the piezoelectric film are expected to result in a capacitive build up in the membrane that will produce a voltage source. The fluid flow analysis is used to apply a computational mesh to the piezoelectric film located inside the fluid domain.

The meshing for the surface body is set to triangular mesh with a maximum face size of 0.099m, giving an even and fine overall mesh for the model. To ensure the solution accuracy, additional meshing settings were applied to the model. For instance, the inflation command with a growth rate of 1.2 was used, in which the first layer thickness was set to 0.002m. As a result, the meshing around the bluff body is evenly distributed according to its shape and it has resulted in finer computational mesh around the bluff bodies on the air domain modelled in the unstructured pattern. The mesh skewness is within the recommended value [13]. The inlet velocity used in the simulation is 1.46 m/s with the air density and air viscosity are set to 1.225 kg/m\(^3\) and 1.831×10\(^{-5}\), respectively. The top, bottom, and side walls are set as non-slip wall and the simulation was conducted for 20s simulation time, with the timestep of 0.001s to 0.0001s.

3. Results and Discussion
Transition structural analysis was found to be able to provide a significant amount of data on the behaviour of the piezoelectric film behind the bluff bodies. The vortex-induced vibration that forms behind the bluff bodies is exploited to oscillate the piezoelectric film with a different spacing ratio from 1 to 6. In this study, the flagging pattern of the piezoelectric film was deliberated in transient structural analysis on 3 different categories; total deformation, directional deformation, and voltage generated.
3.1. Total deformation analysis
Total deformation in ANSYS Workbench is used to obtain displacements from stresses where it gave a square root of the summation of the square of x-direction, y-direction, and z-direction. In other words, total deformation is the sum of all directional displacement of the systems. The higher value of total deformation occurs on the piezoelectric film will enhance the ability of energy harnessing. The total deformation and directional deformation data were studied and compared between the two different shapes of bluff bodies. It can be observed that the average total deformation occurs in the piezoelectric element behind triangle bluff bodies are 0.22mm, 0.19mm, 0.17mm, 0.06mm, 0.34mm and 0.47mm for the spacing ratio of 1 to 6, respectively. Meanwhile, average total deformation occurs in the piezoelectric element for the cylinder bluff bodies for the spacing ratio 1 to 6 are, 0.42mm, 0.20mm, 0.21mm, 0.18mm, 0.38mm and 0.05mm, respectively. The overall total deformation for both triangle and cylinder bluff bodies are summarised and graphically illustrated in Figures 3 (a), and (b).

As shown in Figure 3(a), the total deformation value drops as the spacing ratio increase from 1 to 4. However, the displacement value upsurge for spacing ratios 5 and 6 is 0.34mm and 0.47mm. In contradicting with the data collected for triangle bluff bodies, the total deformation within the cylinder bluff bodies is inconsistent, with the highest and lowest values are 0.42mm (spacing ratio = 1) and 0.05mm (spacing ratio = 6), respectively. It can be concluded that the triangle bluff bodies with spacing ratio of 6 was found to have the highest distortion, approximately 0.47mm on the element of the piezoelectric membrane that indicating to have the highest ability of energy harnessing.

3.2. Directional deformation analysis
The directional deformation is the displacement of the system in a particular axis or user-defined direction. In this simulation, directional deformation calculates for the deformations in the z-axis for the given system. The minimum and maximum deflection indicate that the direction of the piezoelectric film flagging toward a positive and negative direction on the z-axis. The displacements in the z-axis will be analysed to examine the flagging pattern of the piezoelectric film. Figures 4 (a) and (b) present the overall directional deformation of the piezoelectric film in the z-axis for all spacing ratios from 1 to 6.
For triangle bluff bodies (Figure 4a), the directional deformation values are 0.28mm, 0.16mm, 0.17mm, 0.06mm, 0.41mm and 0.47mm which is corresponding to spacing ratio from 1 to 6 respectively. This even value of the maximum and minimum amplitude indicates that the flagging direction of the piezoelectric film is consistent in both directions, resulting in a good energy harvesting system. Meanwhile, the directional deformation values obtained for cylinder bluff bodies are 0.42mm, 0.20mm, 0.16mm, 0.18mm, 0.42mm and 0.02mm, corresponding to spacing ratio from 1 to 6 respectively. Nevertheless, Figure 4b shows that the maximum and minimum amplitude values are not even between positive and negative value for spacing ratio 1, 4 and 6. For instance, at the spacing ratio of 1, the maximum value that indicates the deflection in positive and negative z-axis is 0.42mm and 0.27mm respectively. From these values, it showed a big gap between the positive and negative z-axis. The different reading between positive and negative direction displays the flagging direction of the piezoelectric film is not consistent will result in a poor energy harvesting system [11]. The conceivable cause for this result is the airflow distortion due to the cylindrical bluff bodies.

Based on the directional deformation graph, it can be concluded that the triangle bluff bodies with the spacing ratio of 6 is the best distance to use with piezoelectric film. Cylinder bluff bodies with spacing ratio 6 are the least suitable distance for the piezoelectric film for energy harvesting systems.

3.3. Voltage analysis

The bluff bodies that are able to produce the highest value of voltage generated from the piezoelectric film will be chosen as the best bluff body for the energy harvesting system. From the simulation, the sinusoidal waveform of a single-phase AC line flows equally above and below the zero-ground plane, in a pattern determined by frequency and voltage. The higher value of effective voltage will enhance the ability of piezoelectric film for energy harvesting. To compare the overall voltage generated between the triangle and cylinder bluff bodies in each spacing ratio, the average voltage from the piezoelectric film is derived from the root mean square of the peak negative and peak positive crests of those waves. A negative voltage is used to describe an AC condition when the sinusoidal waveform of a single-phase AC line flows equally above and below the zero-ground plane, in a pattern determined by frequency and voltage. Figures 5 (a) and (b) show the overall voltage generated by the piezoelectric film from spacing.
ratios of 1 to 6 for both triangle and cylinder bluff bodies, respectively. Figure 5 (a) and (b) showed that in the early about 0 to 8 seconds, the waveform and frequency of the graph are small and inconsistent due to the early expansion of vortex formation around the piezoelectric film. When the vortex has fully developed and constantly moves with the same air velocity, the waveform of the graph becomes marginally stable with the consistency value of the maximum and minimum amplitude.

![Graphs showing voltage over time for triangle and cylinder bluff bodies](image)

**Figure 5.** The overall voltage generated for (a) triangle and (b) cylinder bluff bodies

From Figures 5, it can be seen that the average voltage produced by the oscillating of piezoelectric film behind triangle bluff bodies is approximately 2.05mV, 1.52mV, 1.83mV, 1.05mV, 2.56mV, and 3.05mV for each spacing ratio from 1 until 6, respectively. Meanwhile, the effective voltage which is produced by the oscillating of piezoelectric film behind cylinder bluff bodies is approximately 2.06mV, 1.52mV, 1.83mV, 1.06mV, 2.56mV, and 0.50mV for each spacing ratio from 1 until 6, respectively.

The highest effective voltage obtained from these data is 3.05mV at the spacing ratio of 6 for a piezoelectric film behind triangle, and 2.56mV for cylinder bluff bodies with the spacing ratio of 5. Based on the piezoelectric effect, the voltage produced by the piezo layers when the piezoelectric film is suffering from the vortex-induced vibration. For the triangle bluff bodies, the piezoelectric energy harvester can produce an output of highest voltage when the distance between the bluff bodies and the piezoelectric film is 0.6m from each other. In this study, the lowest effective voltage produce is 0.50mV with the spacing ratio of 6 for the cylinder bluff bodies.

From the analysis, the bluff bodies that resulted in the highest total deformation, highest directional deformation and highest generated voltage analysis are chosen as the best bluff bodies for this energy harvesting system.
### Table 1. Overall performance for each bluff bodies

| Bluff Bodies | Spacing ratio (m) | Vrms (mV) | Total deformation (mm) | Directional deformation (mm) |
|--------------|-------------------|-----------|------------------------|-----------------------------|
| Triangle     | 0.1               | 2.05      | 0.22                   | 0.28                        |
|              | 0.2               | 1.52      | 0.19                   | 0.16                        |
|              | 0.3               | 1.83      | 0.17                   | 0.17                        |
|              | 0.4               | 1.05      | 0.06                   | 0.06                        |
|              | 0.5               | 2.56      | 0.34                   | 0.41                        |
|              | **0.6**           | **3.05**  | **0.47**               | **0.47**                    |
| Cylinder     | 0.1               | 2.06      | **0.42**               | **0.42**                    |
|              | 0.2               | 1.52      | 0.20                   | 0.20                        |
|              | 0.3               | 1.83      | 0.21                   | 0.16                        |
|              | 0.4               | 1.06      | 0.18                   | 0.18                        |
|              | **0.5**           | **2.56**  | **0.38**               | **0.42**                    |
|              | 0.6               | 0.50      | 0.05                   | 0.02                        |

Table 1 shows that the piezoelectric with the utilisation of triangle bluff bodies in tandem arrangement 0.6m from each other has resulted in the highest values of the total deformation and of 0.47mm indicating the highest ability of energy harnessing. Besides, it can be seen that the flagging direction of the piezoelectric film is consistent for both directions, implying a good energy harvesting system. Moreover, this model's effective voltage is 3.05mV, which is the highest amongst another tested model.

The results obtained for the triangle bluff bodies are in good agreement with Kazim et al., [11] that have reported that the spacing ratio 6 gives high VIV response compared to another spacing ratio [11]. Nevertheless, this finding is found to be contradicted to the data obtained for cylinder bluff bodies that have resulted in the lowest voltage generated, total deformation and directional deformation values at the spacing ratio of 6. Despite the worse performance of cylinder bluff bodies at the spacing ratio of 6, the piezoelectric energy harvester can produce an output of high voltage of 2.56mV when the distance between the cylinder bluff bodies and the piezoelectric film is 0.5m from each other.

From the results, it can be concluded that the piezoelectric film placed downstream behind dual triangle bluff bodies is capable of producing the higher value of voltage when compared to the cylinder bluff bodies. The vortex formation created a higher velocity of airflow due to the air distortion when placed behind dual triangular bluff bodies. The high value of total and directional deformation indicates that the piezoelectric film was fluttering in all direction, and therefore, it is able to generate high voltage.

### 4. Conclusion

In the present work, the commercially available CFD software, ANSYS Workbench was used to investigate the output performance of the piezoelectric film in energy harnessing for two different cases, which is by exploiting wakes behind two isosceles triangle and exploiting wakes behind two cylinders bluff bodies. The different spacing ratio of 1 to 6 was examined, and the results are analysed based on the total deformation, directional deformation, and voltage generated. From the results, it can be concluded that the utilisation of triangle bluff bodies with the spacing ratio of 6 have resulted to the highest voltage generated and highest total deformation values of 3.05mV and 0.47mm, respectively. The high value of effective voltage and total deformation indicates the high ability of piezoelectric film to harvest energy.
References

[1] Hussain A, Arif S, and Aslam M 2017 Renewable And Sustainable Energy Reviews. 71 12-28.
[2] Evangelos M, Georgia M, Panayiotis D, Vasileios A, Demetris K and Vasiliki K T 2017 Energy Procedia. 125 415-424.
[3] Saeed K, and Pasquale F. F., 2020 Enrico A., Carbon. 162 604-649.
[4] Li W, Ching T W, and Chau K T, 2017 Appl. Energy. 208 878–888.
[5] Arms S, Townsend C, Churchill D, Galbreath J, and Mundell 2005 S Proc. SPIE 5763, Smart Structures and Materials 2005: Smart Electronics, MEMS, BioMEMS, and Nanotechnology
[6] Safaei M, Sodano H A, and Anton S R 2019 Smart Mater. Struct.113001 (62pp).
[7] Wei C and Jing X 2017 Renewable and Sustainable Energy Reviews. 74 1-18.
[8] Panthongsy P, Isarakorn D, Sudhawiyangkul T, and Nundrakwang S 2015 12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), Hua Hin 1-6.
[9] Jiang W A and Chen L Q 2014 J. Sound Vib. 333 4314-4325.
[10] Wang H Y, Tang L H, Guo Y, Shan X, and Xie T 2014 J. Zhejiang Univ. Sci. A. 15 711–722.
[11] Kazim M N F M, Rasani R, Nuawi M Z, Harun Z, Hau Y K, and Majid M S A 2019 J. Adv. Res. Fluid Mech. Therm. Sci., 55 249-263.
[12] Kazim M N F M, Rasani R, Abd Rahman A A, Nuawi M Z, Harun Z, and Amin N A M 2019 IOP Conf. Series: Materials Science and Engineering. 705 012023.
[13] Aziz N A, Amin N A M, Majid M S A, Belusko M, and Bruno F, 2018 Applied Thermal Engineering. 1431085-1092.

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