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Finite Element Modeling of Fluid-Solid-Piezoelectric for Investigating the Ways of Improving the Performance of the Micro Energy Harvester in the Fluid Flow

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ABSTRACT: A coupled fluid-solid-piezoelectric model has been developed by finite element method to study and improve the performance of a micro piezoelectric transducer designed for fluid flow energy harvesting. In this harvester, when the turbulence flow of water passes over a bluff body, the vortex shedding phenomenon occurs and applies a periodical lift force to a piezoelectric beam placed in the downstream region. The resulting oscillations in the piezoelectric beam lead to electrical power generation. Navier-Stokes equations and large-eddy simulation method have been used to describe the fluid turbulence flow, and equations of conservation of linear momentum along with piezoelectric constitutive relations have been employed to obtain solid deformation and electric field intensity. Numerical experiments designed by Taguchi's method have been used to study the effect of different parameters on the harvester performance. The results have shown that using a triangular or D-shape bluff body, and selecting the minimum possible values for the length to height ratio of the bluff body, the distance between the beam and the bluff body, and eccentricity of the beam relative to the bluff body is beneficial for better performance. Furthermore, the shape of the bluff body has been the most influential parameter on the harvester performance.

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1- Introduction

The environmental problems of using fossil fuels have made the generation of clean and renewable energy a serious challenge in the new millennium. In this regard, significant attention has been drawn towards the micro energy harvesters that generate electrical power in the flow of fluids such as air and water. Recently, different techniques have been developed for energy harvesting from the fluid flow. One of these techniques uses the Vortex Induced Vibration (VIV) to convert the flow kinetic energy in the wake of a bluff body to mechanical oscillations of a piezoelectric beam for extracting electrical energy. This method has been studied extensively in the literature. Investigations made by Gu et al. [1], Sun and Seok [2], and Su and Lin [3] are some of the most recent studies to mention. In the present study, a finite element model is developed in the COMSOL software to simulate the coupled problem of the fluid flow, the solid beam deformation, and the piezoelectric effect in a VIV harvester and to investigate the effect of different parameters such as the shape and dimensions of the bluff body and the location of the piezoelectric beam behind the bluff body on the harvester performance.

2- Methodology

The Navier-Stokes equations have been used to model the time-dependent incompressible flow of the fluid in the arbitrary Lagrangian-Eulerian coordinates:

$$\nabla.\mathbf{v}=0 \tag{1}$$

$$\rho_f \frac{\partial \mathbf{v}}{\partial t}+\rho_f \nabla.\left(\left(\mathbf{v}-\mathbf{v}^m\right)\mathbf{v}\right)= -\nabla p+\mu_f \nabla.\left(\nabla \mathbf{v}+\left(\nabla \mathbf{v}\right)^T\right) \tag{2}$$

where ρ_f, μ_f, $\mathbf{v}$, and p are the fluid density, viscosity, velocity vector, and pressure field, respectively. t denotes time, and $\mathbf{v}^m$ is the mesh velocity. For a water flow with $\rho_f = 1000\ \mathrm{kg/m^3}$, $\mu_f = 8.9\times10^{-4}$ Pa.s, and $v_{\mathrm{ave}} = 0.7$ m/s passing over a bluff body of 10 mm diameter, the Reynolds number is equal to:

$$\mathrm{Re}=\frac{\rho_f v_{\mathrm{ave}} D}{\mu_f}=\frac{1000\times0.7\times10\times10^{-3}}{8.9\times10^{-4}}=7865 \tag{3}$$

Consequently, the fluid flow is turbulent and the large

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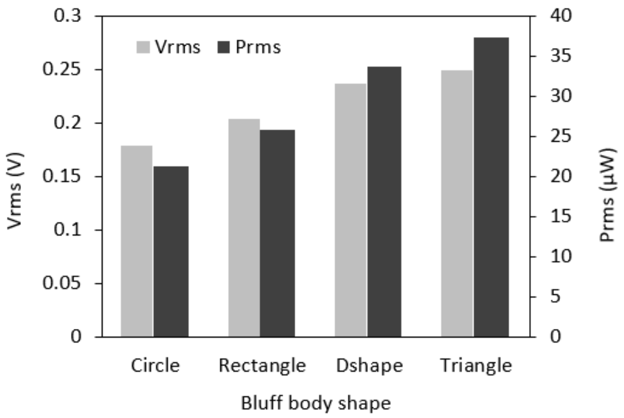

Fig. 1. effect of the bluff body shape on the harvester performance

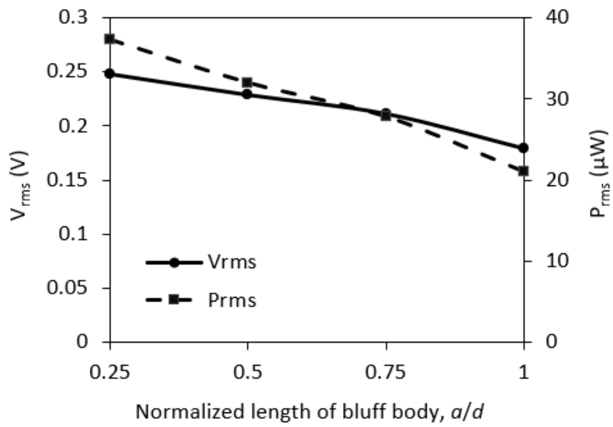

Fig. 2. Effect of the length to height ratio on the harvester performance

eddy simulation method has been employed for its simulation.

The law of conservation of momentum is used for characterization of the solid structure behavior:

$$\rho_s \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla . \boldsymbol{\sigma}_s + \rho_s \mathbf{b}_s \tag{4}$$

In this equation, ρ_s is the solid density, $\mathbf{u}$ denotes its displacement vector, $\mathbf{b}_s$ represents the body force vector, and σ_s is the Cauchy stress tensor.

Generally, the piezoelectric effect is expressed in the strain-charge form given by:

$$\boldsymbol{\varepsilon} = \mathbf{s}_{\mathbf{E}} \boldsymbol{\sigma}_s + \mathbf{d}^T \mathbf{E}_p \tag{5}$$

$$\mathbf{D} = \mathbf{d} \boldsymbol{\sigma}_s + \boldsymbol{\varepsilon}_{\mathbf{T}} \mathbf{E}_p \tag{6}$$

where ε is the strain tensor, $\mathbf{s}_{\mathbf{E}}$ represents the elastic compliance tensor at the constant electric field, $\mathbf{d}$ is the coupling matrix (charge constants) of the piezoelectric, $\mathbf{E}_p$ denotes the electrical field strength, and $\varepsilon_{\mathbf{T}}$ is the permittivity tensor. The Lead Zirconate-Titanate/ Polydimethylsiloxane (PZT-PDMS) piezoelectric material is employed in this study the properties of which are presented in Table 1.

The shape of the bluff body, its length to height ratio, the distance between the beam and the bluff body, and eccentricity of the beam relative to the bluff body are the parameters

Table 1. Properties of the piezoelectric material

Property	Density (kg/m^3)	Compliance (1/Pa)	Charge coefficient (pC/N)	Relative permittivity
Value	3000	10^{-7}	3000	10

investigated in this study. Four different levels have been considered for these four parameters. Consequently, an orthogonal array of L16 should be used for Taguchi's based design of experiment [4].

3- Results and Discussion

The root mean square of the harvester output voltage and electrical power are presented in Fig. 1 for different shapes of the bluff body. Based on this figure, the maximum voltage and power are generated by harvesters with triangular, D-shape, rectangular, and circular bluff bodies, respectively.

The harvester output voltage and power are shown in Fig. 2 for different length to height ratios of the bluff body. According to this figure, increasing the length of the bluff body leads to a decrease in the harvester output voltage and power.

Similar diagrams have also been obtained for the remaining two parameters and it was observed that by increasing the distance between the beam and the bluff body, and the eccentricity of the beam relative to the bluff body the amount of voltage and power generated by the harvester decreases.

4- Conclusions

In this paper, the finite element method modeling was employed to study and improve the performance of a micro energy harvester which uses the piezoelectricity effect to harvest energy and generate electricity from the vortex shedding phenomenon in the fluid flow. It was observed that the maximum amount of the harvester output voltage and power is obtained by triangular and D-shape bluff bodies. Moreover, by decreasing the bluff body length to height ratio, the distance between the beam and the bluff body, and the beam eccentricity, the output voltage and electrical power are reduced. Furthermore, the bluff body shape is the most influential parameter on the harvester performance, while the length to height ratio, the distance between the beam and the bluff body, and the beam eccentricity are the next influential parameters, respectively.

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