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Combined Experimental and Numerical Investigation of Energy Harness Utilizing Vortex Induced Vibration over Half Cylinder Using Piezoelectric Beams

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Abstract. Energy harvesting technology has the ability to create self-powered electronic systems that do not rely on battery power for their operation. Wind energy can be converted into electricity via a piezoelectric transducer during the air flow over a cylinder. The vortex-induced vibration over the cylinder causes the piezoelectric beam to vibrate. Thus useful electric energy at the range 0.2-0.3V is found which can be useful for self-powering small electronic devices. In the present study, prototypes of micro-energy harvester with a shape of 65 mm x 37 mm x 0.4 mm are developed and tested for airflow over D-shaped bluff body for diameters of 15, 20 and 28mm in an experimental setup consisting of a long wind tunnel of 57cm x 57cm with variable speeds of the motor for different flow velocities and the experimental setup is connected at the downstream where flow velocity is the maximum. Experimental results show that the velocity and induced voltage follows a regular linear pattern. A maximum electrical potential of 140 mV for velocity of 1.1 ms⁻¹ at a bluff body diameter of 15 mm is observed in the energy harvester that can be applied in many practical cases for self-powering electronic devices. The simulation of this energy harvesting phenomena is then simulated using COMSOLE multi-physics. Diameter of the bluff bodies as well as flow velocity and size of cantilever beam are varied and the experimental findings are found to be in good agreement with the simulated ones. The simulations along with the experimental data show the possibility of generating electricity from vortex induced vibration and can be applied in many practical cases for self-powering electronic devices.

INTRODUCTION

As the trend in the electronics industry in the recent years has been the development of faster and complex circuit technologies, low power electronics become more dominant in everyday use .Thus, requirement of reliable power sources in low power electronic components ambient energy harvesting devices become more popular for replacing small batteries .In order to find potential sources for energy harvesting, varieties of energy sources have been investigated. Studies on the possibility of harvesting energy from mechanical vibrations have been conducted widely [1-7] and of which harvesting energy via piezoelectric materials has received most attention[4-7].Piezoelectric materials have been successfully used in various applications, such as in medical, aerospace, nuclear instrumentation ,as a tilt sensor in consumer electronics [8] and in the automotive industry .A number of studies have been reported on the piezoelectric energy harvesting from vortex-induced vibration of circular cylinder[9,10]. For low power electronics, the outcome can be used for designing self-sufficient energy supply system. Whenever a power supply via cable is not feasible and the use of batteries is not desired energy harvested from piezoelectric materials becomes effective. The voltage generated from piezoelectric material can be used in air-ducts to replace batteries required for different sensors in air-condition systems.

Flow induced vibrations are presented in terms of the basic elements: body oscillators, fluid oscillators, and sources of excitation. The sources of excitation when brought about by flow instability, is called instability- induced

7th BSME International Conference on Thermal Engineering AIP Conf. Proc. 1851, 020076-1–020076-7; doi: 10.1063/1.4984705 Published by AIP Publishing. 978-0-7354-1525-6/\$30.00 excitation (IIE) (e.g., alternating vortex shedding from a cylindrical structure).Of all the flow instabilities, the one associated with wakes past bluff cylindrical bodies has received by far the greatest research attention. Body oscillator consists of structural part which is elastically supported to perform linear or angular movements. Instability induced vibration by a flow instability and exciting forced produced through a flow process causes alternating vortex shedding from cylindrical structure. Vortex shedding is an unsteady-flow that takes place in specific flow velocities (according to the size and shape of the cylindrical body). In this flow, vortices are created at the back of the body and detach periodically from either side of the body[10-12]. The frequency of vortex shedding is definite and is related to the Reynolds number (flow velocity, viscosity of fluid, and the diameter of the cylinder). In fluid dynamics, 'Von Kármán Vortex Street' is a repeating pattern of swirling vortices caused by the unsteady separation of flow of a fluid around blunt bodies. When the vortices are not formed symmetrically around the body (with respect to its mid plane), different lift forces develop on each side of the body, thus leading to motion transverse to the flow[13]. For flow over a bluff cylindrical body, the vortex shedding frequency (f_{vs}) is usually expressed in non-dimensional term called the Strouhal number St= f_{vs} D/U_∞, where U_∞ and D is the incoming free-stream velocity and the diameter of the bluff body, respectively.

In the present study, experiments have been conducted to determine the level of harvested power from vortex induced vibrations through a wind tunnel for various diameters of the bluff body and free stream velocities. The periodic of application of the vorticities, which release a mechanical strain upon the beam, effected a generation of electric potential within the piezoelectric layer and enables extraction of electrical energy from the kinetic energy of the fluid. A numerical simulation has been developed and studied using COMSOL multi-physics by performing tight coupled simulation between the fluid flow, structural and electrical components. Fluid Structure Interaction (fsi) along with the electrostatics under solid mechanics multi-physics in COMSOL has been employed to determine the amount of energy harvested via the experimental model. The simulated results were than compared with the experimental data for exploring the potential of the scheme in the self-powering low power electronic sensors in airconditioning systems.

METHODOLOGY

Experiments

Kinetic energy of a flowing fluid can be captured by placing a bluff body in a uniform and steady flow and a piezoelectric beam in its wake. A flexible beam placed in the wake of the bluff body may undergo oscillations due to the passing vortices. The piezoelectric harvester used in the cylinder-wake experiments consisted of a cantilevered composite beam with dimensions of 65 mm x 37 mm x 0.4 mm and with a maximum voltage generation capacity of 5V. The D-shape bluff body was placed inside the wind tunnel and the piezo-ceramic layer was attached to the cantilever beam in the center of the bluff body (Figure 1). For different diameters of the D-shaped bluff body (15, 20, and 28 mm) and different velocities (1.1, 1.5, and 2 m/s), the voltage generated in the layer was measured. The velocity was measured by an anemometer and the uniformity of the wind tunnel was confirmed. The diameters used in the experiment were 15mm, 20mm, 28 mm. Different flow velocities of 1.1 ms⁻¹, 1.5 ms⁻¹, 2 ms⁻¹ have been studied for each diameter separately. The voltage developed in the piezo-ceramic layer was measured by a multimeter having reasonable accuracy varied about \pm 5mv. The D-shape bluff bodies were fabricated from Acrylic plastics and the surface had reasonable smoothness. The schematic figure of the D-shape bluff body along with the piezo-ceramic material is given in Fig 1. The bluff body converted the kinetic energy of the uniform and steady fluid flow to large temporal pressure fluctuations caused by vortex shedding. These pressure fluctuations were then turned into electrical energy utilizing the piezoelectric generator. The experimental procedure is outlined below:

- 1) At least two sets of data were recorded for each diameter and velocity for ensuring reproducibility of the data.
- 2) The D-shape bluff body was placed inside the wind tunnel so that the outside air has no effect on the measurement values.
- 3) The orientation of the setup was confirmed to be horizontal.
- 4) After turning on the airflow through the wind tunnel, sufficient time was allowed for the voltage reading to be stabilized before the measurement were taken.
- 5) As the piezo-ceramic is considerably thin in shape, small deflection may take place after multiple readings were taken. For that reason, initial deformation along with associated electrical potential was recorded to prevent such errors.



FIGURE 1.Schematic view of the experimental setup and D-shape bluff body with the piezo-ceramic material at the center.

Numerical Modeling

The present study is aimed to analyze the possibility of utilizing piezo-electric materials for the fabrication of self-powered low electronic devices. The COMSOL Multi-physics drawing tools are used to create the flow channel and three-dimensional (3D) composite solid objects using different Boolean operations like union, intersection and difference of the bluff-bodies.

The simulations were carried out in COMSOL Multi-Physics following the experimental study that had been conducted for D-shaped bluff body along with a cantilever beam which deflects under the pressure applied as a boundary load due to formation of vortex. Fluid Structure Interaction (fsi) along with the electrostatics under solid mechanics multi-physics was required for this purpose. The displacement of the beam induced strain energy on the beam, which in turns produced electrical energy that can be calculated using electrostatics physics in COMSOL.

The energy harvester model consists of three subdomains: the channels through which the fluid flows is the fluid domain, and the bluff body and the piezoelectric beam in cantilever position are the two solid subdomains. Lead Zirconate Titanate (PZT) piezo-ceramic material used in this model has properties of transverse isotropic material. Such material has same properties in a respective plane and alternative properties in the direction normal to the plane. The stress-charge form had been selected for the constitutive equation. The structural mechanics boundary conditions for this model were that the D-shaped bluff body had been constrained as "fixed" to halt its movement. In contrast, the cantilever, protruding out of the trailing edge of the bluff body was free and experienced a load during fluid flow.

Governing Equations

The governing equations of the fluid flow, the structure, and the coupling between them are as follows:

Structural Equation: The possibly large displacement of the structure is governed by:

$$\rho^{s} \frac{D^{2} y}{Dt^{2}} - \nabla \cdot \left(F \cdot S(u)\right) = \rho^{s} b^{s} \text{ in } \Omega^{s} \times (0, T)$$

$$\tag{1}$$

Where u represents the displacements of the structure, b^s the body forces applied on the structure. S the second Piola-Kirchhoff stress tensor, ρ^s the density of the structure and F represents the deformation gradient tensor.

Fluid Flow Equations: The fluid equations to be solved are the incompressible Navier-Stokes equations in ALE formulation that take the form:

$$\rho^{F} \frac{dv}{dt} |_{\chi} + \rho^{F} . c. \nabla v - 2\mu \nabla . \varepsilon(v) + \nabla \bar{p} = \rho^{F} b^{F} \text{ in } \Omega^{F} \times (0, T)$$

$$\tag{2}$$

$$\nabla \cdot v = 0 in \, \Omega^F \times (0, T) \tag{3}$$

Here v denotes the fluid velocity and p denotes the physical pressure. The fluid density and viscosity is given by ρ and μ , respectively. The fluid body forces are represented by $\boldsymbol{b}^{\rm F}$ and $\boldsymbol{\varepsilon}(\boldsymbol{v})$ represents the strain rate tensor.

Coupling Equations: At the interface Γ , kinematic and dynamic continuity is required. The governing Kinematic coupling equations are:

$$u_{\Gamma}(t) = d_{\Gamma}^{F}(t) \quad \dot{u}_{\Gamma}(t) = v_{\Gamma}(t) \quad \ddot{u}_{\Gamma}(t) = \dot{v}_{\Gamma}(t)$$
(4)

Here $d_{\Gamma}^{F}(t)$ represents the displacement of the fluid mesh nodes at the interface. The dynamic coupling equation takes the form:

$$h^{s}(t) + h^{F}(t) = 0$$
 (5)

Where $h = \sigma n$ signifies the traction vector.

Coupling within Piezo-material: The coupling between the strain and the electric field in piezoelectric material is determined by the constitutive relation:

$$S = s_E T + d^T E \tag{6}$$

$$D = dT + \varepsilon_T E \tag{7}$$

Here, S is the strain, T is the stress, E is the electric field, and D is the electric displacement field. The material parameters $s_{E_i} d$, and ε_T correspond to the material compliance, coupling properties and permittivity, respectively.

RESULTS AND DISCUSSION

A combined experimental and numerical investigation on the possibility of harvesting micro-energy from flowinduced vibration over a piezoelectric cantilever beam placed in the wake of a cylindrical bluff body were conducted in the present study. The effect of flow velocity and the size of the bluff body on the energy harvesting characteristics were examined experimentally for three different wind velocities (1.1, 1.5, and 2.0 m/s) and three different diameters (15, 20, and 28 mm) of the bluff-body. A specifically designed experimental apparatus, consisting of a piezo-ceramic cantilever beam at the end of a D-shaped body connected at the end of a wind tunnel, was used.

The variation of the harvested power with the vibration of the beam within the wake region was investigated. A peak value of about 140 mV was obtained for a bluff body diameter of 15 mm and flow velocity of 1.1 ms⁻¹, as shown in Fig 2(a). With the increment of wind velocity, the harvested energy was observed to decrease almost linearly for specific diameters. The voltage obtained for that specific diameter at velocities of 1.1, 1.5, and 2.0 m/s has values in the range of 90-140 mV. Similar observations have been witnessed for different diameters of bluff bodies. It can also be noted that at higher values of bluff-body diameter, the reduction of generated voltage with an increase in velocity did not follow linear trend as was observed for the smallest diameter of D = 15 mm. For Re<40, St=0, since the wake is symmetric and thus, the Karman Vortex Street is not produced. The wake instabilities initiate vortex shedding at Re>40 with St=0.1. After a laminar shedding regime is passed, the wake becomes fully turbulent with St=0.2 for 300<Re<20,000. If Re is increased further, then St decreases slightly until Re=100,000, at which point the cylinder's boundary layer also becomes turbulent and St increased steadily with increasing Re [14]. Variation of electrical potential with the change of vortex shedding frequency has been shown in the Fig 2(b). It can be seen that electrical potential decreases with the increment of shedding frequency. However, for the smallest diameter of the bluff body, the change is linear whereas in case of the larger bluff bodies the change is exponential with a change in the vortex shedding frequency.

To provide further insight into the behavior of fluidic energy harvesters, an energy harvester model simulation was developed for simulating the behavior of a piezoelectric beam in the wake of a D-shape bluff body. Analysis was performed to find the magnitudes and locations of maximum stress and electrical potential on the cantilever beam for a particular diameter of the D-shaped bluff body and for a fixed length of the cantilever beam. The geometry of the 3Dbody and the mesh in the fluid domain and the structure are shown in Fig 3(a) and (b), respectively. Tip displacement at cantilever position and associated induced electrical potential at specific velocity are ascertained as the matters of interest. The present analysis consists of identification of the magnitudes and locations of maximum stress and electric potential on the cantilever beam for a wind velocity of 1.5 ms⁻¹ at a bluff body diameter of 15 mm to further corroborate the experimental findings.



FIGURE 2. (a) Piezoelectric voltage (mv) decreased with an increase in the wind velocity, and (b) the variation of piezoelectric voltage (mv) with vortex shedding frequency for various diameters. The material properties were assumed isotropic.

Figure 4(a) shows the cross-section of the flow cannel where the velocity field is expressed as a directional vector. It is evident that the viscous and pressure forces acting as boundary load on the cantilever surfaces cause the cantilever to bend. This bending causes distortion of fluid flow domain too. The color of the streamlines indicates the velocity of the flow and is higher far away from the bluff body. Von-Mises-Stress distribution of beam is shown in Fig 4(b) and as expected, maximum Von-Mises-stress is determined at the fixed end of the beam and the minimum value obtained at the free end of the beam. The color scale shows the magnitude of the displacement.

Due to deformation of the piezo-electric crystal layer attached on the top surface of the beam, an electric potential polarization in z-direction occurs which is proportional to the deformation. This deformation originates an electric potential difference in the piezo-electric crystal as shown in Fig 5. As the present study considered stationary conditions, all the variables showed the steady state solutions. Figure 5 shows that the flow induced an electric potential of maximum 0.16 V across the piezo-electric crystal domain at 1.5 ms⁻¹. This result is comparable to experimental value of 0.14 V. Maximum value of electrical potential is observed the end nearest to the fixed end of the cantilever beam and the minimum one is at the tip of the cantilever beam.

The vertical displacement at the cantilever tip in the z-direction as a function of cantilever length is shown in Fig 6(a). As expected, maximum deflection can be observed at the tip of cantilever beam. Figure 6(b) shows the variation of the electric potential at the piezo-electric cantilever beam along the beam length. Change of electric potential is linear in nature along the beam length as it is directly proportional to the deformation.



FIGURE 3.(a) The geometry of the model, and (b) associated mesh of fluid domain and structure



FIGURE 4.Velocity along the cross section of the wind tunnel after it passes through the D-shape bluff body is shown in (a) for a uniform velocity of 1.5 ms⁻¹ before it passes through, and (b) The Von-Mises-stress distribution along the cantilever beam



FIGURE 5. The generated electric potential (in $Vx10^{-1}$) in the piezo-ceramic cantilever beam. Maximum electric potential is found to occur near the fixed end.



FIGURE 6. The variation of (a) vertical displacement (mm) of the cantilever beam, and (b) Electric potential (V) along the length of the cantilever beam

CONCLUSION

In the present study, that a portion of the kinetic energy of a uniform and steady fluid flow can be converted to electrical energy by placing a cantilevered piezoelectric beam in the wake of a D-shape bluff body has been demonstrated. The addition of the D-shaped bluff-body made significant improvements in vortex shedding

frequency exerting on the cantilever beam. First, we investigated the phenomenon experimentally for a range of geometric and operating conditions and determined the amount of energy that can be extracted through piezoelectric material. After that, a 3D simulation model was developed to find out the relations between the electrical outputs, deformed shapes, Von Mises stress. However, a proper fluid-structure interaction analysis can be challenging for the case of three-dimensional, turbulent flows with flow separation and large structural deformations. In order to simplify our observation, a steady state laminar flow solution with small structural deformations was assumed. The fluid flow induced an electric potential of maximum 0.16 V across the piezo-electric crystal domain at 1.5 ms⁻¹ which was in good agreement with our experimental data of 0.14 V.

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