Bluff Body Fluid Interactions Modelling for Micro Energy Harvesting Application

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Abstract. In this paper, we have presented a MEMS-based piezoelectric fluid-flow based micro energy harvester. The design and modelling of the energy harvester structure was based on a piezoelectric cantilever affixed to a bluff-body. In a cross fluid flow, pressure in the flow channel, in the wake of the bluff body, fluctuates with the same frequency as the pressure variation caused by the Kármán Vortex Street. This fluctuation of pressure in the flow channel causes the piezoelectric cantilever, trailing the bluff-body, to vibrate in a direction normal to the fluid flow direction. COMSOL finite element analysis software are used for the evaluation of various mechanical analysis of the micro energy harvester structure like, physical the Stress and Strain state in the cantilever structures, Eigen frequency Analysis, Transient analysis to demonstrate the feasibility of the design. Detailed steps of modelling and simulation results of the uniform cantilever were explained. The results confirm the probability of the fluid flow based MEMS energy harvester.

1. Introduction

Energy Harvesting (EH) technology has been explored for more than a decade as an enabling technology to power autonomous systems such as Wireless Sensor Networks (WSNs). WSN are made of several sensor nodes capable of collecting surrounding environmental information (for example, temperature, vibrations, light, etc.), to turn it into numeric data and to send to a base station. Recent widespread development of WSNs allowing real-time monitoring of many application areas like automotive, bio-medical, industrial process, environment etc [1]. All application area demand an economical energy source at micro or nano scale, for continuous operation of the low-powered WSN node. More important demand for the WSN nodes is to avoid the requirement of replacement of finite power stores like primary batteries for autonomous operation. Therefore, considerable academic and industrial research effort is focused on harvesting electrical energy from natural resources such as flowing water, rain, tides, wind, sunlight, geothermal heat and biomass. Global renewable energy
consumption at micror/nano scale is growing very rapidly [2]. Many application areas, such as automotive, transportation, industry and aeronautics, have a strong interest in developing and using WSN to increase their productivity (real-time monitoring), reduce their costs or limit machine downtimes (predictive maintenance). Figure 1 shows the basic modules of an autonomous sensor node with EH module to produce a power range of 10 µW to 100µW, the general power requirement standard for MEMS or NEMS based sensors [3].

![Figure 1. Basic power requirement for an autonomous node and other modules.](image)

When a bluff-body is placed in a fluid flow channel whose direction is perpendicular to the axis of the bluff-body, i.e., in a cross-flow, as shown in figure 2, the bluff-body structure will try to vibrate in a direction normal to the flow direction [4]. This flow induced vibration could be caused by the turbulence generated by the flow around and in the wake of the cylinder. The turbulence represents the random fluctuations of the flow and is not periodic. The turbulence excited vibration can occur at any flow velocity with increasing amplitude, with the increase of the flow velocity and a frequency around the natural frequency of the bluff-body structure. The flow induced vibration could also be caused by the periodic vortex shedding from the bluff-body edge surface. When a vortex is shed from one side of the bluff-body, a pressure difference forms between this side and the other side of the bluff-body causing a net force exerted on the bluff-body in the direction perpendicular to the flow. A vortex shed from the other side causes a force in the opposite direction. Thus the bluff-body is set to vibrate due to the alternate shedding of vortices named as Vortex-Induced Vibration (VIV). The pattern of periodic, alternating vortex shedding that occurs in the flow behind the body is referred as von Karman’s vortex street [5] as shown in figure 2.

![Figure 2. Von Kármán vortex streets forming in the wake of a Bluff-body.](image)

In recent years, harvesting energy from fluid flow has gained increasing interest in the research community. Researchers have developed energy harvesting devices based on fluid induced vibration. Two types of device have been developed; one relies on the conversion of air motion to air steady oscillation, the other on the drag force of the airflow. In the first type of energy harvester’s researchers...
uses Helmholtz resonators to convert airflow motion to steady air oscillation [6]. In the second type of energy harvester, the lift force of the fluid flow causes vibration on a piezoelectric cantilever or magneto-electric component which, in turn, converts kinetic energy of motion into electricity [6]. For vibration based energy harvesting device, it is important to predict the frequency of vibrations at various fluid speeds and thereby identify the desirable resonances between the bluff-body structure and the vortex shedding.

In this paper, we have presented various mechanical analyses for a MEMS-based piezoelectric fluid-flow micro energy harvester. COMSOL finite element analysis software are used for the evaluation of various mechanical analysis of the micro energy harvester structure like, physical the Stress and Strain state in the cantilever structures, Eigenfrequency Analysis, Transient analysis to demonstrate the feasibility of the design. A detailed step of modeling and simulation results of the uniform cantilever is explained. The results confirm the probability of the fluidflow based MEMS energy harvester.

2. Geometrical modelling of the Energy Harvester structure
This section explains the geometric modeling of the energy harvester cantilever structure capable of harness energy from fluid flow. As shown in the figure 3, A piezoelectric film is placed on top of a flexible rectangle, which is located in the wake of a D-shaped bluff body. The COMSOL-multiphysics CAD tools were used to create the 3D composite solid structure, using Boolean operations like union, intersection, and difference of the bluff-bodies. Geometric property range and values are provided in Table 1.

![Figure 3](image)

Figure 3. Schematic of MEMS piezoelectric energy harvester designed for flow-induced vibration.

| Table 1. Geometric property range and values |
|---------------------------------------------|
| PZT Length (L)                              | 58µm  |
| PZT Width (W)                               | 50µm  |
| D shape Diameter (D)                        | 40µm  |
| Thickness PZT                                | 2µm   |
| Thickness Stainless Steel                   | 1µm   |

3. Mechanical analysis of the Energy Harvester
The EH device depicted in the above figure 3 is part of a support mechanism and is subjected to both mechanical and electric loads. In this section, we have presented different analysis steps and results, to carry out a detailed mechanical analysis of the EH structure using MEMS Structural Mechanics Module. To specify the EH model’s physics, we have defined material properties in ‘Subdomain
Setting’ and ‘Boundary Setting’ dialog box’s, such as constraints, external forces and effects (such as mechanical constraints or loads), voltages, and temperatures etc.

3.1. **Subdomain Setting conditions of the EH structure**

In the Subdomain Setting the structural steel domain is an isotropic material model (the bluff-body and the lower part of the cantilever structure), and the PZT structure which has a length of 58µm, width 50 µm and thickness of 2 µm is Lead ZirconateTitanate (PZT-5H). Both properties with values are provided in Table 2.

| Description               | Quantity | Value/Expression | Unit | Description               | Quantity | Value/Expression | Unit |
|---------------------------|----------|------------------|------|---------------------------|----------|------------------|------|
| Young’s Module            | E        | 2.0e11           | Pa   | Young’s Module            | E        | 200e9            | Pa   |
| Poisson’s Ratio           | v        | 0.33             | -    | Poisson’s Ratio           | v        | 0.33             | -    |
| Density                   | ρ        | 7500             | Kg/m³| Density                   | ρ        | 7850             | Kg/m³|
| Thermal expansion coeff.  | a        | 1.2e-5           | 1/K  | Thermal expansion coeff.  | a        | 12.3e-6          | 1/K  |

**Table 2.** Material property range and values.

3.2. **Boundary Setting conditions of the EH structure**

The boundary conditions resulted from the working conditions of the energy harvester model shown in figure 4. For the mechanical part a constraint of zero movement on the bluff-body has been considered. The cantilever part of the EH structure with the PZT substrate module (length of 550 mm, width 50 mm and thickness 5 mm) remain free to vibrate in response to a applied load on the free end of the cantilever beam. A distributed load is applied of 3.106 N/m² in the z-direction on the PZT upper face.

![Figure 4](image)

**Figure 4.** The MEMS EH geometry together with fixed constraints symbols (red arrows) and load symbols on the cantilever (blue arrows).
3.3. Static Analysis
A static analysis has no explicit or implicit time dependencies. It corresponds to the steady state of a transient analysis with constant (in time) boundary conditions and material properties. The purpose of this analysis is to find the magnitudes and locations of the maximum strain, stress, and electrical potential on the cantilever beam when an external static load is applied to the beam’s free end, compare it with the material’s yield strength, and to check that the deformation of the cantilever is within the limits of the design criteria. Figure 5 shows the maximum stress calculated with Von Mises criteria determined in the left side of the beam (in the vicinity of the clamping side with the D shaped Bluff Body) and the minimum value in the right side of the beam. Table shows the Von Mises effective stress calculation for different load, and using the Point Evaluation feature, obtained the deformation of a point on the geometry. The largest displacement occurs at the tip where the load is applied.

![Figure 5. Maximum stress with Von Mises.](image)

| Fz  | Von Mises Stress [Pa] | Z-displacement [µm] |
|-----|-----------------------|---------------------|
| 3e6 | 3.8185e9              | 8.765783            |
| 2e6 | 2.545667e9            | 5.843855            |
| 1e6 | 1.272833e9            | 2.921928            |
| 0.5e6| 6.364167e8            | 1.460964            |

3.4. Eigenfrequency Analysis
An Eigenfrequency analysis finds the undamped eigenfrequencies and mode shapes of a model sometimes referred to as the free vibration of a structure. The eigenfrequency analysis is carried out to determine the natural frequency of the EH structure, and therefore, setting up the excitation frequency of the dynamic load in the time-dependent analysis. The purpose of the eigenfrequency analysis is to find the first 6 modes of frequency of the cantilever beam and their corresponding shape of deformation. These modes of frequency values are used later in finding the beam’s damping factor, and in setting the excitation frequency that makes the beam vibrates near its resonance and, therefore, gives maximum electrical potential. The values of the modes of frequency are illustrated in the following
Table 4 shows the corresponding deformation shapes for the highest and the lowest eigenfrequencies of the EH model.

| Mode | Eigen frequency (Hz) |
|------|----------------------|
| 1    | 7.629872e5           |
| 2    | 2.030683e6           |
| 3    | 4.65233e6            |
| 4    | 7.11031e6            |
| 5    | 7.459217e6           |
| 6    | 8.491459e6           |

Figure 6. The highest and the lowest eigen mode of the EH model.

3.5. Transient Analysis

This type of analysis solves for the transient solution of displacements and velocities as functions of time [8]. The purpose of this analysis is to find the transient response of the EH model from a harmonic load during the first five periods shown in figure 7. Figure 8 shows the displacement of the cantilever tip in the z-direction on the loaded face. The excitation frequency is set to 7.629872e5 Hz, which is between the first and second eigenfrequency found in the eigenfrequency analysis.
Figure 7. Slice plot of the von Mises stress shows the last time step on the MEMS EH structure at 0.0036s.

Plot graph in figure 8 shows quantitative view of the time evolution of the cantilever displacement.

Figure 8. Displacement in the z-direction at a tip point on the loaded face.

4. Conclusion
In summary, we reported various mechanical analysis results of a MEMS micro energy harvester to extract energy from the Kármán Vortex Street behind a bluff body using COMSOL FEA software [7]. These results will be compared with the experimental results of the fluid-flow based EH, presently under development at our lab. The initial results confirm the probability of the fluidflow based MEMS based energy harvester and necessary optimization directions.
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