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Finite Element Analysis of a Fluid Flow Based Micro Energy Harvester

[1]M.S. Bhuyan, [1]B.Y. Majlis, [2]M. Othman, [3]Sawal H. Md. Ali and [1]Shabiul Islam
[1]Institute of Microengineering and Nanoelectronics (IMEN),
Universiti Kebangsaan Malaysia (UKM), 43600 UKM Bangi, Selangor, Malaysia
[2]Ministry of Science, Technology and Innovation (MOSTI),
Federal Government Administrative Centre, 62662 Putrajaya, Malaysia
[3]Department of Electrical, Electronic and Systems Engineering,
Faculty of Engineering and Built Environment, 43600 UKM Bangi, Selangor, Malaysia

Abstract: This study presents multi-physics three-dimensional finite element simulation of a fluid flow based self-excited micro energy harvester. This micro energy harvester is modeled inside a micro fluid channel to convert fluid flow energy into fluid oscillations. Investigations are carried out for the impact of low fluid flow velocity ranging 1-5 m sec^{-1}, associated voltage generation by piezoelectric means and various mechanical analyses to enhance the performance and robust design considerations. The piezoelectric micro cantilever is attached to a D-shaped bluff body. An axial fluid flow and the D-shaped bluff body interaction generate Karman Vortex Street in the wake of the bluff-body. Vortex shedding causes an asymmetry in pressure distribution on the surface of the bluff body which results in time-dependent forces acting on the attached flexible micro cantilever. Due to structural vibrations induced by the uniform and steady fluid flow, periodic strains are generated in the piezoelectric cantilever which converts the strain energy into electrical charge. Finite Element Analysis Software namely COMSOL Multiphysics are used for the Harvester Model and simulation. In a $200\times150\times150\ \mu m^3$ rectangular duct, at 5 m sec^{-1} fluid velocity, the $50\times40\times2\ \mu m^3$ piezoelectric cantilever experienced 3088 Pa stress with cantilever tip displacement around 60 μm. A maximum voltage of 2.9 mV was recorded at 5 m sec^{-1} fluid velocity that is sufficient to drive an ultra-low-power rectifier circuit for a complete energy harvesting system. This study in detail describes the harvester device modeling and finite element analysis in COMSOL. Instead of using ambient parasitic vibration, this Energy Harvester Model directly utilize fluid flow energy to improve harvesting capability. The micro energy harvester self-charging capability makes it possible to develop untethered sensor nodes that do not require any wired connection or battery replacement or supplement batteries. Integration of fluid flow based micro energy harvester device for the autonomous sensor network such as automotive temperature and humidity sensor networks.

Key words: Multi-physics, micro fluig channel, D-shaped, voltage, ultra-low-power

INTRODUCTION

With rapid development of low-power integrated chip technology in the past few years, small wireless autonomous sensor devices, like those used in wearable electronics and wireless sensor networks require miniature energy sources. While the sensor devices have been shrunk to sub-micrometer sizes and have decreased their energy consumptions, the traditional chemical batteries have been restricted by their large size, manufacturing cost, depleted power sources and expense of replacement (Erturk and Inman, 2011). The powering devices usually require a size that is compatible with the specific application, sufficient energy supply and extended lifetime using permanent and ubiquitous energy sources. The research for a sustained energy source for autonomous sensors is activated and developed recently to replace traditional chemical batteries through energy harvesting process (Xu *et al*., 2010). By energy harvesting process, electric energy is captured and stored from ambient environmental sources like solar, thermal, wind and kinetic energy, etc. Most developments in fluid-flow based energy harvesting approaches targeting macro-scale were devoted in optimizing turbine and generator design (Rancourt *et al*., 2007). Scaling down this principle into the micro-scale reflects two important effects. Firstly, the efficiency of the energy harvester conversion efficiency decreases and secondly friction forces increases with

Corresponding Author: Shabiul Islam, Institute of Microengineering and Nanoelectronics (IMEN),
Universiti Kebangsaan Malaysia (UKM), 43600 UKM Bangi, Selangor, Malaysia

decreasing dimensions. Therefore, following rotational energy conversion based principle will fail to optimize energy harvester in micro-scale (Mitcheson *et al*., 2008). In micro-scale, performance of a fluid flow based energy harvester is less efficient due to relatively high viscous drag on the harvester device at low Reynolds numbers and rotating parts mechanical losses (Erturk and Inman, 2011).

Investigation on flapping piezoelectric cantilevers attached to a bluff-body was carried out (Pobering and Schwesinger, 2008). Vortices generated behind the bluff body drove the vibration on the piezoelectric cantilever. A voltage of 0.83 V was achieved at airflow velocity of 35 m sec^{-1}. However, this flow speed is far greater than the velocity usually encountered in a Heating, Ventilation, and Air Conditioning (HVAC) duct and simulation was limited to two-dimensional analyses. A three-way coupled interaction simulation taking into account aerodynamics, structural vibration and electrical response of a piezoelectric generator in unsteady flow was carried out, however the power outputs were insufficient for running a wireless sensor node specially in HVAC flow speed regime (Akaydin *et al*., 2010). Operation at very low fluid flow velocities, about 1 m sec^{-1}, a micro energy harvester requires very low-friction to avoid mechanical losses. Compared with the small turbine and generator design, fluid flow driven piezoelectric energy harvester based on flapping or vibration are more attractive in principle because they do not involve any rotating part and without electromagnetic induction. In the case of energy harvesters that use parasitic vibration of infrastructures as input ambient energy, usually use the parasitic vibration of bridge, building, pipeline, machinery, automobile and so on (Zhu *et al*., 2010). In this study, fluid like air or water instead of parasitic vibration is used to induce Flow Induced Vibration (FIV) phenomenon in a piezoelectric micro cantilever attached to a D-shaped bluff-body. When fluid flows over the slender micro cantilever, it generates mechanical vibration. Kinetic energy in fluid flow offers a relatively high energy density in combination with high availability. Applying FIV in the micro cantilever, the high stiffness characteristics of Micro-Electro-Mechanical Systems (MEMS) utilized natural frequency of several kHz (Liu *et al*., 2011). Flowing fluid pressure loading sensitivity on the micro layered cantilever is investigated through Finite Element Analysis (FEA) software namely COMSOL Multiphysics (COMSOL, 2008). Simulations using different application modes in COMSOL is carried out to investigate various mechanical analysis of the MICRO energy harvester. The mechanical outputs of the modeled energy harvester are used to evaluate its performance. Design guidelines are presented in detail following simulation results. Based on the FEA, the effects of the piezoelectric film dimensions, the fluid pressure applied to the harvester and types of piezoelectric layer on the output voltage of the harvester can be investigated.

A complete mathematical description of the behavior of a piezoelectric structure immersed in a fluid flow presented with the three-way coupling between the fluid dynamics phenomena, its structural response and the energy harvester generator electrical behavior. Consideration of the mutual interaction between these three domains ideally requires an aero-electromechanical model of the system, i.e., a coupled solution of the system of the governing equations of the fluid flow, the structural dynamics and the associated electrical field. The goal of this study is to introduce a new fluid flow based micro energy harvester, predict its performance through electromechanical modeling. The development of a fully coupled model to predict the aero elastic forces is left for a subsequent future study.

IMPLEMENTATION PROCESS OF THE ENERGY HARVESTER IN COMSOL

Figure 1 shows the line drawing of the model, the basic principle by which the harvester operates. In this model, fluid is flowing through a rectangle micro channel. Fluid enters through the inlet with a fully developed laminar flow velocity profile, passes over the D-shaped bluff-body and leaves through the outlet. The beam, the D-shaped bluff body attached to micro cantilever beam in

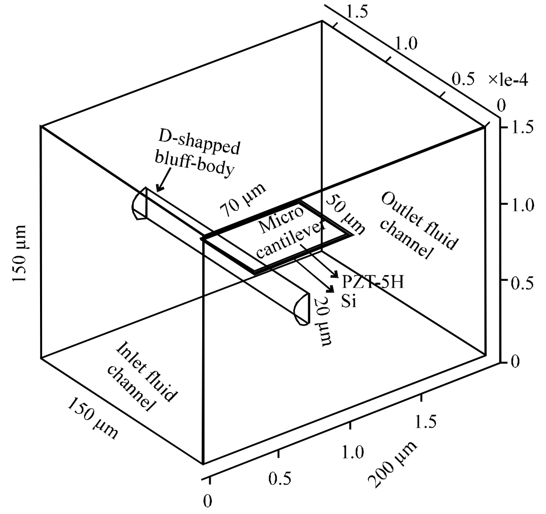

Fig. 1: Schematic of the micro energy harvester consisting of a piezoelectric cantilever with a D-shaped bluff body attached in a cross-flow (not to scale)

Table 1: Micro energy harvester and micro fluid channel geometric properties in COMSOL

Modeled segment	Properties	Values (µm)
Fluid channel	Length	200
	Width	150
	Height	150
Solid cantilever	Length	58
	Width	50
	Thickness	3
PZT-5A	Length	58
	Width	50
	Thickness	3
D-shaped bluff-body	Diameter	40

the wake are clearly depicted. Such a configuration can self-start and sustain the necessary oscillations under uniform and steady flow conditions. In addition to this advantage such as an energy harvester will potentially operate at a lower flow speed and will have higher aero elastic efficiency.

Model description of the micro energy harvester: The modeling of the micro energy harvester is based on bi-layer cantilever structure in the wake of a D-shaped bluff-body. The piezoelectric energy harvester is considered packaged inside a micro fluid channel to harvest fluid flow oscillation by the micro cantilever. The micro cantilever relies on lift and drag force of the fluid flow which causes vibration. The flexible cantilever layer and the supporting D-shaped bluff-body are made from silicon while Lead Zirconate Titanate (PZT)-5A is used for piezoelectric layer which is positioned on the top of the supporting layer and is poled along the thickness direction resulting in transverse (d31) operation mode. The COMSOL-multiphysics drawing tools are used to create the flow channel and three-dimensional composite solid objects using boolean operations like union, intersection and difference of the bluff-bodies. Table 1 summarizes the geometric properties range and value of the flow channel and the solid composite objects. According to Table 1, the micro fluid channel has a volume of 4.5e-12 m^3 with the surface area measured is 1.65e-7 m^2. The solid cantilever and the PZT-5A layer have the same volume and surface area which are measured 5.79e-15 m^3 and 6.23 m^2, respectively.

Operation principle of the micro energy harvester: When a bluff obstacle is placed in a fluid flow channel whose direction is perpendicular to the axis of the bluff obstacle, i.e., in a cross-flow as shown in Fig. 2, turbulence generated by the flow around and in the wake of the bluff obstacle (Carli *et al.*, 2010). The turbulence represents the random fluctuations of the flow and 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 pattern of periodic, alternating vortex shedding that occurs in the flow behind the body is referred as von Karman's vortex street (Akaydin *et al.*, 2012). 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 obstacle in the direction perpendicular to the flow. Thus, the bluff obstacle is set to vibrate due to the alternate shedding of vortices. The fluidic pressure impulse on the piezoelectric cantilever results in short-term lift force. Since, the vortices, shedding in a periodic manner, the resulting lift forces on the cantilever also vary periodically with time. The cantilever deflection causes mechanical stress within the PZT-5A layer that results in the generation of electrical energy based on piezoelectric effect.

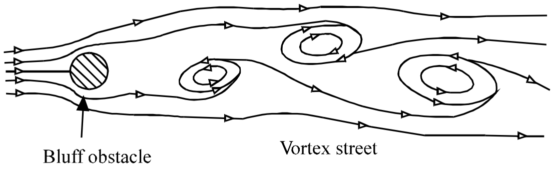

Fig. 2: Streamline diagram of the vortex-shedding phenomenon (Weinstein *et al.*, 2012)

APPLICATION MODES IN COMSOL FOR THE ENERGY HARVESTER MODEL

FEA Model of the micro energy harvester is realized within COMSOL Myltiphysics by employing solid stress-strain with fluid interaction application mode and Piezo Solid application mode from MEMS Module Model Library. The solid stress-strain with fluid interaction application mode includes Moving Mesh Arbitrary Lagrangian-Eulerian (ALE) and Incompressible Navier-Stokes application modes by default (COMSOL, 2008).

Fluid motion: Fluid part of the model is solved with Navier-Stokes equations in spatial (deformed) coordinate system within the flow channel. The fluid is incompressible and fluid motion is governed by the following Navier-Stokes equations, solving for the velocity field, u = (u, v) and the pressure, p: in the spatial (deformed) moving coordinate system (COMSOL, 2008):

$$\rho\frac{\partial u}{\partial t}-\nabla.\left[-pI+\eta\left(\nabla u+(\nabla u)^{T}\right)\right]+\rho(u.\nabla)u+\nabla_{p}=F \tag{1}$$

$$-\nabla.u=0 \tag{2}$$

Where:

I = The unit diagonal matrix

F = The volume force affecting the fluid

The model neglects gravitation and other volume forces affecting the fluid, so F = 0. η is the dynamic viscosity, ρ is the density.

Structural mechanics: The structural deformations are solved using elastic formulation and nonlinear geometry formulation to allow large deformation which uses the reference frame and is only active in the beam. The bluff-body is fixed in the fluid channel so that it cannot move in any direction. All other boundaries experience a load from the fluid given by:

$$F_T = -n.\left(-pI+\eta\nabla\left(u+(\nabla u)^T\right)\right) \tag{3}$$

where, n is the normal vector to the boundary. This load represents a sum of pressure and viscous forces. In addition, the predefined fluid load takes the area effect between the reference frame for the solid and the moving ALE frame in the fluid into account (COMSOL, 2008).

Moving mesh: The motion of deformed mesh is modeled using Winslow smoothing. The moving mesh application which defines the relation between the spatial frame and the reference frame, solves mesh smoothing equations in the fluid domain using the solid displacements to define the coordinate transformations inside the beam. This mode confirms fluid domain deforming along with the bluff structure (COMSOL, 2008).

Subdomais physics: The Micro Energy Harvester Model has total three subdomains; the channel through fluid flows is the fluid domain, D-shape bluff body and PZT-5A layer are another two solid subdomains. PZT-5A used is a transversely isotropic material which is a special class of orthotropic materials has same properties in one plane (isotropic behavior) and different properties in the direction normal to this plane. The stress-charge form is selected for the constitutive equation. For the polarization in the z-direction in a 3D cartesian coordinate system, respective data are used in elasticity-matrix elements in the 'CE' matrix, the piezoelectric coupling-matrix in the 'e' matrix and the relative permittivities in the 'εrS' matrix. Material properties parameters of the fluid, D-shaped bluff body and piezoelectric material are provided in Table 2.

Table 2: Micro energy harvester material used for the FEA analysis

Subdomain	Properties	Values
Fluid	Density	1000 kg/m^3
	Dynamic viscosity	0.001 Pa.sec
D-shaped bluff body (solid)	Young's module	8e6 Pa
	Poisson's ratio	0.33
	Density	7850 kg/m^3
PZT-5A	Density	7500 kg/m^3

Boundary physics: In structural mechanics application mode, boundary, D-shaped bluff body are constrained as "fixed". In contrast, the cantilever, protruding out of the trailing edge of the D-shaped bluff body is "free" which experience a load during fluid flows. This load represents a sum of pressure and viscous forces. In moving mesh application mode, boundary conditions control displacement of moving mesh with respect to initial geometry. Motion of deformed mesh is modeled using Winslow smoothing. At boundaries of the bluff body, this displacement is the same as the structural mechanics deformation. At exterior boundaries of flow domain, it is set to zero in all directions. The Navier-Stokes equations are solved in the spatial (deformed) coordinate system. In the Piezo Solid Application mode, zero charge/symmetry is selected for all the boundaries except the upper and lower surface of the PZT-5A which is grounded. At the inlet, the model uses a fully developed laminar flow. Zero pressure is applied at the outlet. At all other boundaries, no-slip conditions are applied.

SIMULATION RESULTS IN COMSOL

The fluid flow driven micro energy harvester has been modeled and analyzed using COMSOL different application mode simulations. Key interest in the simulation was a three-way coupling between the fluid dynamics phenomena, the energy harvester's micro cantilever associated electrical field and its mechanical structural response provides with electrical outputs, velocity profile, deformed shapes as well as various mechanical outputs. Cantilever tip displacement and induced potential at different fluid-flow velocities are recorded. Analysis is performed to find the magnitudes and locations of maximum stress and electrical potential on the cantilever beam for five different fluid-flow velocities ranging from 1-5 m sec^{-1} acting on the energy harvester micro cantilever.

The aero-electromechanical model description of the micro energy harvester and its behavior while immersed in a fluid flow is shown in Fig. 3. Fluid behavior effect is clearly visible on the cantilever and fluid flow domain itself. The flow channel which expressing velocity field as a directional vector, changes in the fluid-flow due to the

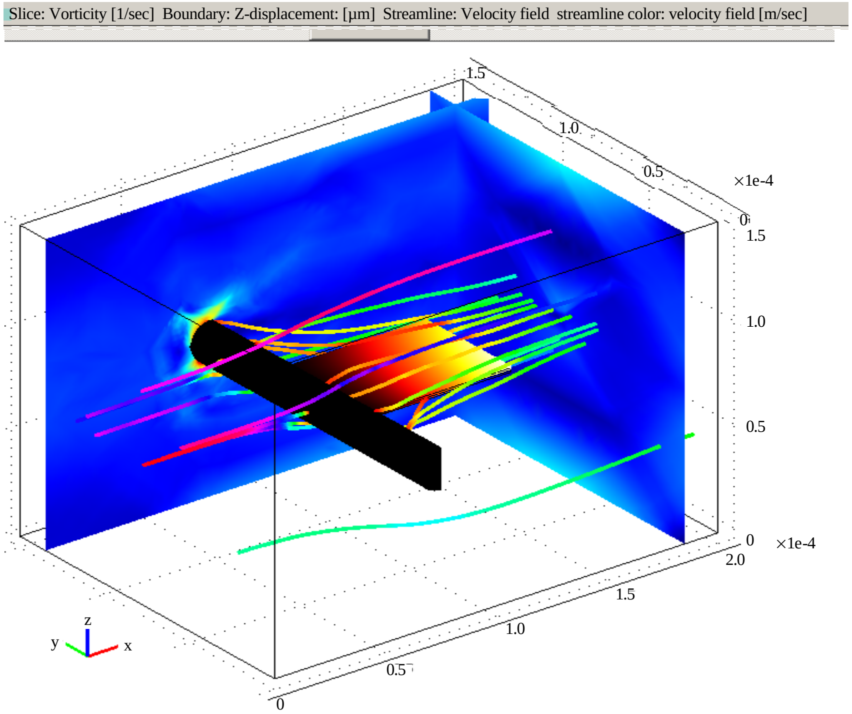

Fig. 3: An aero-electromechanical simulation (two cross sections) shows the velocity field and the flow lines at flow velocity of 1.5 m sec^{-1} around bluff body

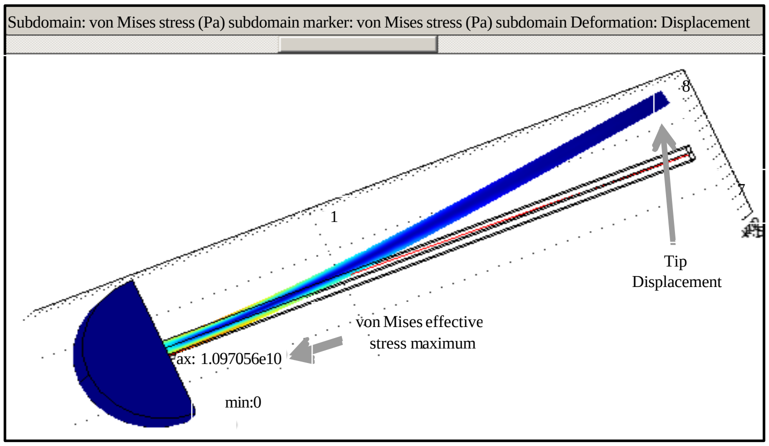

Fig. 4: The von Mises effective maximum stress on cantilever

D-shaped bluff body. Top and bottom surfaces of the cantilever experience increased viscous and pressure forces that case cantilever deformation.

Figure 4 shows the maximum von Mises effective stress 10.97 GPA on the micro cantilever that resulted from a static analysis. While fluid-flow causes the flexible cantilever to deform, starting out from an un-deformed state as expected the maximum von Mises stress determined at the left side of the beam, i.e., in the vicinity of the fixed side of the D-shaped bluff-body and the minimum value at the right side of the beam. A transient analysis was conducted to solve the transient solution of the displacements and velocities as functions of time. Rayleigh damping parameters were specified proportional to the mass (αdM) and stiffness (βdK). The analysis of was carried out at excitation frequency of 500 Hz. The purpose of this analysis was to find the transient response from a harmonic load during the first five periods (10 msec) considering the memory limitation at the workstation. Figure 5 shows the displacement plot of the micro cantilever tip, at ambient pressure at x-displacement (dashed line), y-displacement (dashed-dotted line) and z-displacement (solid line). This displacement impact on the magnitudes and locations of the maximum strain, stress and electrical potential of the micro cantilever. The quantitative view of the time evolution of z-displacement, shows a cantilever tip around 60 µm as shown in Fig. 6.

The frequency response analysis of the micro energy harvester with the same Rayleigh damping setting for the transient analysis was carried out to find the transient response with an excitation frequency in the range 100-600 Hz considering specific application requirements. From the plot it is evedent that the energy harvester micro cantilever produce the maximum tip displacement at 100 Hz. Addition of a tip mass with the micro cantilever could be helpful to increase the frequency bandwidth of the energy harvester that is planed for a future simulation. Figure 7 shows the maximum stress is just above 11 MPa appears at 100 Hz.

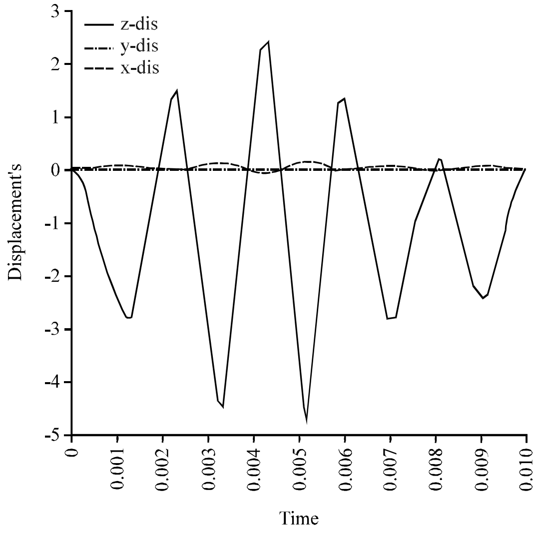

Fig. 5: Cantilever tip displacement in transient analysis with rayleigh damping

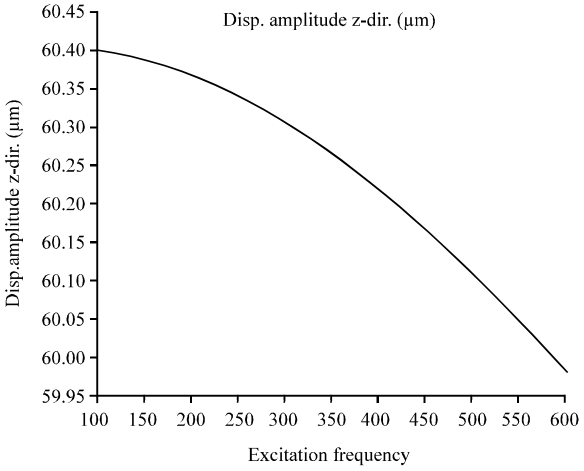

Fig. 6: Displacement amplitude at excitation frequency range of 100-600 Hz

The heat generation within the micro energy harvester subjected to high frequency vibration was performed in the frequency domain. This study computed a fully coupled thermoelastic response for a vibrating beam structure by combining the stress-strain analysis with the linearized heat-transport equation. Figure 8 displays the temperature distribution at the end of the simulated 2 sec process. As the figure shows, the maximum temperature rise in the beam is 4.899e-9°C.

Figure 9 shows the pressure distribution on the surface of the micro cantilever after 4 msec of simulation. The ambient pressure, pA, in this case is 300 Pa and the acceleration switches on at the beginning of the simulation. Fluid-flow driven pressure distribution across the 50 µm width elastic cantilever beam is analyzed. This result shows that the fluid-flow induced pressure level is low near the clamed end but reaches a maximum level of 3 kPa near the edge of the free end of the micro cantilever. The narrow gap formed by the micro cantilever (two solid horizontal surfaces) restricts the displacement of the fluid flow perpendicular to the micro cantilever surfaces. When the energy harvester cantilever squeezes the gap, the fluid flows out from its edges. The narrow pathway restricts the fluid flow which causes fluid pressure to increase which decelerates the cantilever vibration.

The D-shaped bluff-body was used for conversion of fluid-flow into periodic vortex shedding and the

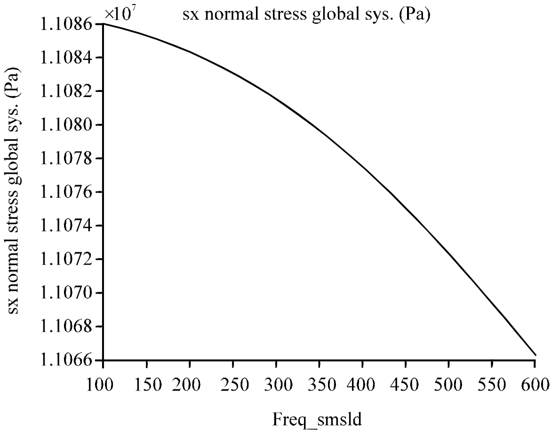

Fig. 7: Maximum stress appears at 100 Hz

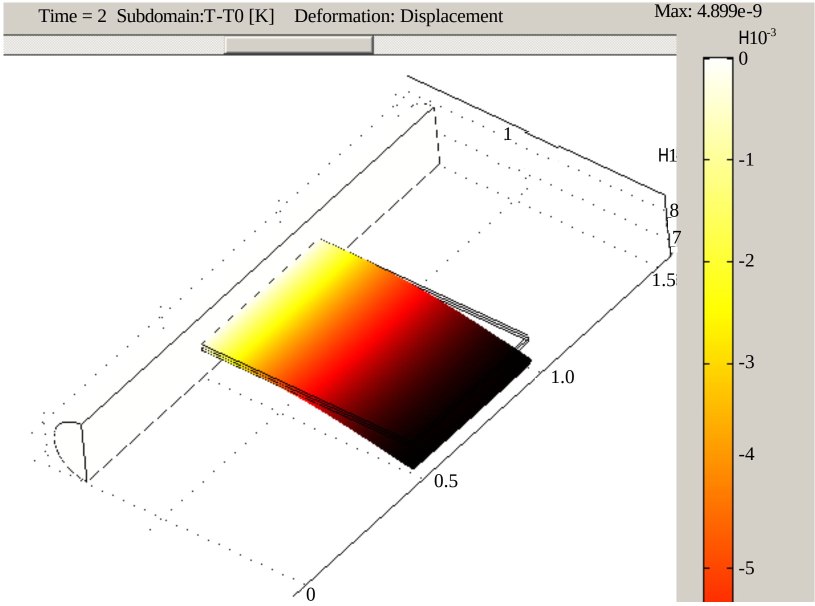

Fig. 8: Temperature increase in the beam after 2 sec of forced vibrations

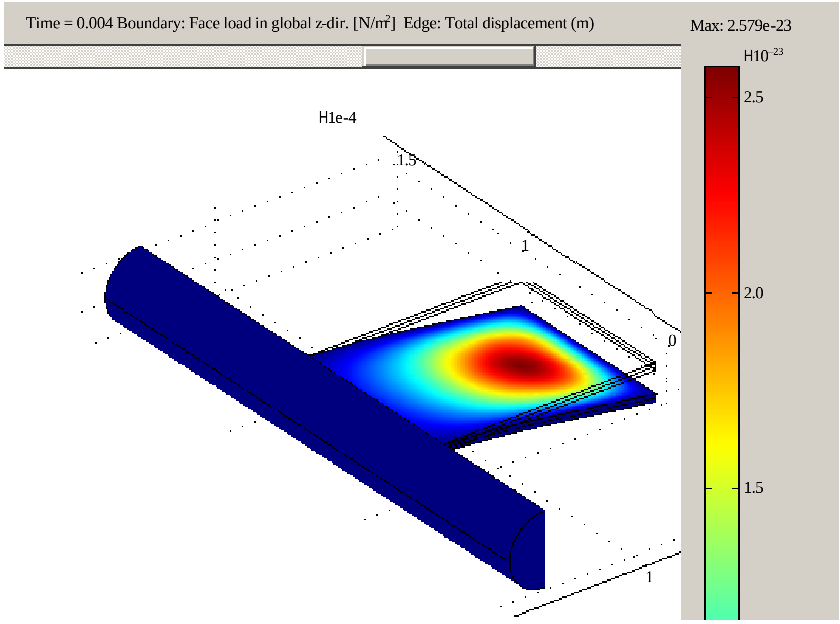

Fig. 9: Fluid-flow driven pressure distribution across the 50 μm width elastic cantilever beam

magnitude of stress, acting on the attached cantilever was greatly magnified. As expected, the deflection increased strongly with the flow velocity. A stress of 3088 Pa exerted on the cantilever at 5 m sec^{-1}. While the strategy of this study is similar to what was pursued by Pobering and Schwesinger (2008) that resulted in 0.83 V at 35 m sec^{-1}. In comparison, this study achieved 2.9 mV at 5 m sec^{-1} fluid-flow velocity as shown in the plot of Fig. 10. Moreover, simulation was limited to two-dimension analysis. Benefits of this kind of micro energy harvester device can be seen as a micro power source for sensors monitoring temperature and humidity usually operating on a low duty cycle with as little as 1-20 μW (Howey *et al*., 2011). Other application areas such as liquid or gaseous water pipes and natural gas lines also exhibit similar fluid flow characteristics. This model

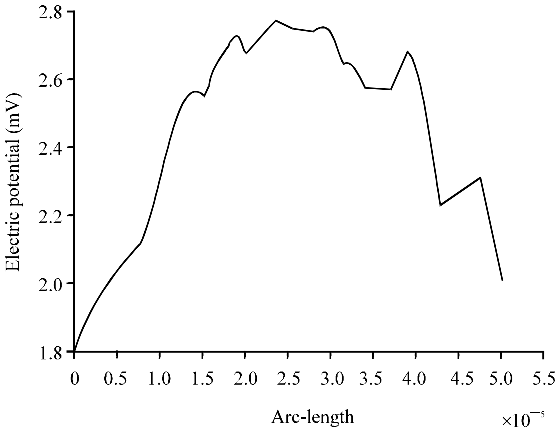

Fig. 10: Induced electric potential of maximum 2.9 mV across the cross-cut line in the piezoelectric domain at 5 m sec^{-1} fluid-flow velocity

provides relatively high performance at low fluid-flow velocity and will ideally provide the necessary performance over a wider range of fluid-flow velocities.

CONCLUSION

This study reports ongoing work in development of a finite element modeling of a micro energy harvester without any rotating part that couples mechanical, piezoelectric and fluid domains to convert fluid-flow driven kinetic energy into electricity is presented. COMSOL finite element analysis results will be helpful in selecting the material and certain criteria for polymers to be used in prototype design as well as in setting design parameters for fabrication. The micro cross-sectional area exposed to fluid-flow and relative simple geometry with fewer peripheral components makes it an ideal device for MEMS applications, especially for remote systems. The finite element model includes various analyses, the structural analysis evaluated stress and deflection of the cantilever when exposed to a laminar fluid flow. Heat produced while the micro energy harvester subjected to high frequency vibration was measured. Simulation result showed approximately 3 mV could be achieved from the device piezoelectric domain with a volume of $58\times50\times2$ μm^3. Because the D-shape bluff-body with the cantilever not optimized yet, therefore the output voltage and consequently output power can be increase after optimization. The goal of this study is to introduce a new flow micro energy harvester, predict its power through electromechanical modeling. The future thrust of this research is to optimize the D-shaped bluff body and the micro cantilever dimensions such that the excitation frequency matches with the natural frequency of the micro cantilever, further increasing cantilever deflection and associated energy.

REFERENCES

Akaydin, H.D., N. Elvin and Y. Andreopoulos, 2010. Energy harvesting from highly unsteady fluid flows using piezoelectric materials. J. Intell. Mater. Syst. Struct., 21: 1263-1278.

Akaydin, H.D., N. Elvin and Y. Andreopoulos, 2012. The performance of a self-excited fluidic energy harvester. Smart Mater. Struct., Vol. 21. 10.1088/0964-1726/21/2/025007.

COMSOL, 2008. COMSOL Multiphysics® Modeling Guide: Version 3.5a. COMSOL AB, Stockholm, Sweden, Pages: 518.

Carli, D., D. Brunelli, D. Bertozzi and L. Benini, 2010. A high-efficiency wind-flow energy harvester using micro turbine. Proceedings of the International Symposium on Power Electronics Electrical Drives Automation and Motion, June 14-16, 2010, Pisa, Italy, pp: 778-783.

Erturk, A. and D.J. Inman, 2011. Piezoelectric Energy Harvesting. John Wiley and Sons, Chichester, UK., ISBN-13: 9781119991359, Pages: 416.

Howey, D.A., A. Bansal and A.S. Holmes, 2011. Design and performance of a centimetre-scale shrouded wind turbine for energy harvesting. Smart Mater. Struct., Vol. 20. 10.1088/0964-1726/20/8/085021.

Liu, H., C.J. Tay, C. Quan, T. Kobayashi and C. Lee, 2011. Piezoelectric MEMS energy harvester for low-frequency vibrations with wideband operation range and steadily increased output power. J. Microelectromech. Syst., 20: 1131-1142.

Mitcheson, P.D., E.M. Yeatman, G.K. Rao, A.S. Holmes and T.C. Green, 2008. Energy harvesting from human and machine motion for wireless electronic devices. Proc. IEEE, 96 1457 1486.

Pobering, S. and N. Schwesinger, 2008. Power supply for wireless sensor systems. Proceedings of the IEEE Sensors, October 26-29, 2008, Lecce, Italy, pp: 685-688.

Rancourt, D., A. Tabesh and L.G. Frechette, 2007. Evaluation of centimeter-scale micro wind mills: Aerodynamics and electromagnetic power generation. Proceedings of the 7th International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications, November 28-29, 2007, Freiburg, Germany, pp: 93-96.

Weinstein, L.A., M.R. Cacan, P.M. So and P.K. Wright, 2012. Vortex shedding induced energy harvesting from piezoelectric materials in heating, ventilation and air conditioning flows. Smart Mater. Struct., Vol. 21. 10.1088/0964-1726/21/4/045003.

Xu, F.J., F.G. Yuan, J.Z. Hu and Y.P. Qiu, 2010. Design of a miniature wind turbine for powering wireless sensors. Proceedings of the Sensors and Smart Structures Technologies for Civil, Mechanical and Aerospace Systems, March 8-11, 2010, San Diego, CA., USA.

Zhu, D., S. Beeby, J. Tudor, N. White and N. Harris, 2010. A novel miniature wind generator for wireless sensing applications. Proceedings of the IEEE Sensors, November 1-4, 2010, Kona, HI., USA., pp: 1415-1418.