DESIGN OF A PIEZOELECTRIC ENERGY HARVESTER BY USING CYLINDER AS A BLUFF BODY

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ABSTRACT

In recent days, clean energy alternatives are searched and application of these alternatives are studied. One alternative method is used to smart material, such as piezoelectric material, to harvest energy. Energy can be harvested from vibrating structures by piezoelectric material due to its nature. By suitable design, piezoelectric material can generate electricity under vibratory loading. This electricity can also be used to operate part of the system. Especially, energy can be used to charge the batteries; therefore, battery free application can be possible by piezoelectric energy harvesting. This type of energy harvesting can be used in air vehicles to operate either one small system or a sensor used in structural health monitoring system. In this study, a piezoelectric vortex energy harvester is designed in order to obtain energy from flow induced vibration. For this reason, a piezoelectric bimorph harvester, which is a commercial off the shelf product, is used. In order to generate vorticities to give excitation around the first resonance frequency of piezoelectric bimorph harvester, a cylinder is selected as a bluff body. During the design stage of the harvester, the effect of the size and the position of the bluff body are also investigated via wind tunnel tests.

INTRODUCTION

ENERGY harvesting from vibration becomes more and more important due to decreased energy needs of small structures or small sensors, which may be used for structural health monitoring and play a critical role in the system [Ertürk, 2011]. By using vibration-based energy harvesting system, replacement cost and chemical contamination of the batteries, due to lead, can also be eliminated [Ertürk, 2011]. Therefore, piezoelectric material can be used to harvest energy from vibration due to its nature. As known, piezoelectric material is deformed mechanically, it can produce voltage difference. This phenomenon can happen conversely and so piezoelectric material can be used as a sensor in order to sense the motion of structures where they are bonded [PI Ceramic, 2011].

In order to harvest energy from vibration by piezoelectric material, proper design method should be applied to maximize the harvested energy. Therefore, the analytical or finite element methods can be used at the first design stage to optimize the position, type and application point of piezoelectric material, then the vibration based energy harvester can be

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produced. Finally, performance of a vibration-based piezoelectric energy harvesting system should be investigated under the operational condition. For example, the piezoelectric material is integrated to small UAVs wings in order investigate the performance of an energy harvesting device [Anton, 2011]. During the fly of this small UAV, voltage and acceleration can be collected as useful data.

Flutter and vortex induced vibration can be given as examples for flow induced vibration and the energy can also be harvested from the flow induced vibration via piezoelectric energy harvesters [Zhu, 2011]. Aeroelastic energy harvesting is also widely studied in the literature. Abdelkefi summarizes different types of flow induced vibration energy harvesters in his review study [Abdelkefi, 2016]. A novel piezoelectric energy harvester which consists of simple pin connected flap and beam is developed and it works under aeroelastic flutter vibration [Bryan, 2011]. Moreover, the nonlinear aeroelastic behavior of a piezoelectric energy harvester is studied and is modeled by a two-dimensional typical section airfoil [Bae, 2013]. The dimensionless electro-aeroelastic equations for predicting the power output at the flutter boundary are also studied and both electrical power output and flutter speed are investigated for piezoelectric and electromagnetic energy harvesters [Marqui, Jr., 2012]. Furthermore, a cantilever plate-like wing with embedded piezoceramics performance evolution was investigated by considering aeroelastic vibrations [Marqui, Jr., 2011]. In another study, a performance of a piezoelectric energy harvester is analyzed by considering free play nonlinearity and the overall performance enhancement is investigated [Sousa, 2011]. In the literature, there are different examples for vortex energy harvesters working under the vortex excitation. In one of the research studies, an electromagnetic energy harvester is designed to work under flow loading [Zhu, 2011]. In this electromagnetic energy harvester example, a bluff body is positioned in front of the harvester. However, it is showed that bluff body can also be directly attached to the energy harvester [Gao, 2011]. In this design, total system can resonate around its resonance frequency when the flow is passing around a bluff body. Numerical solution for energy harvesting from piezoelectric transducer attached to a cylinder is studied due to vortex-induced vibration [Mehmood, 2013]. In another study, piezoelectric micro cantilever sensor is used to harvest energy from wind [Liu, 2014]. A bio-inspired design for harvesting energy from low-velocity is developed [Hobeck, 2012] for highly turbulent fluid flow environments such as streams or ventilation systems. In this particular design, piezoelectric grass is used to as array of piezoelectric cantilevers for harvesting energy. A flexible piezo-film is also developed as a transducer for harvesting energy from water flow [Koyvanich, 201]. In this design, a bluff body is used in front of the transducer in order to generate vortices in water flow as an excitation. Theoretical model is also constructed for piezoelectric energy harvester attached to a cylinder [Dai, 2014]. In this model, a nonlinear distributed-parameter model for harvesting energy from vortex-induced vibrations is developed and it is validated by experimental techniques. Moreover, it is also worked on harvesting energy from piezoelectric material under both base and vortex induced vibration excitations [Dai, 2014]. In this study, the Euler–Lagrange principle and the Galerkin procedure are used to develop nonlinear model for this particular problem. Three different types of bluff bodies are attached to electromagnetic generator to observe the effect of it in the energy harvesting performance under the galloping oscillations of wind [Ali, 2013]. A numerical model is constructed for aeroelectromechanical performance of the piezoelectric energy harvester in the wake of the bluff body [Akaydın, 2013]. Fluid, structure and electrical model for the two different harvesters are coupled to obtain the performance for this comparative study. In literature, macro fiber composite (MFC) types of piezoelectric materials are used as energy harvesters. Piezoelectric energy harvester is designed by using MFC piezoelectric patch and energy is harvested by vortex generation in water flow due to cylinder [Shan, 2015]. A special piezoelectric energy harvester designed by using two cylinders and two MFC patches. In this particular design, both vortex and wake induced vibrations are used as a source of harvested energy [Song, 2015].

Having motivated by the research progressing in the field and the recent developments in the piezoelectric materials, in this particular study, a vortex energy harvester is designed in order to obtain energy from flow induced vibration. For this reason, a piezoelectric bimorph harvester, which is a commercial off the shell product, is used and the resonance frequency of it is also tuned to reach higher energy levels. During the design stage of the harvester, the effect of the diameter and the position of the bluff body are also investigated via wind tunnel tests.

DESIGN OF THE BIMORPH PIEZOELECTRIC BEAM USED AS A VORTEX ENERGY HARVESTER

The vortex energy harvester comprising piezoelectric material is designed to work under the flow induced vibration. In order to increase the voltage output, a solid cylinder is used as a bluff body in front of the harvester in order to generate vortices around the piezoelectric vortex energy harvester which can be seen in Figure 1.

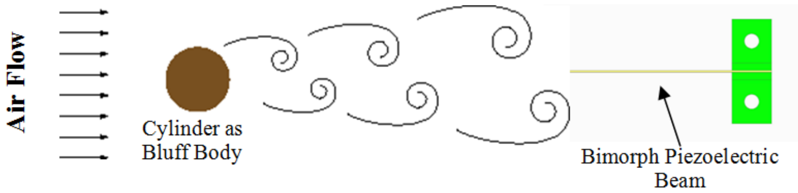

Figure 1: Vortex Energy Harvester with Cylinder and Plate as a Bluff Body

In this study, commercially available bimorph piezoelectric energy harvester, Mide Volture V25W [Mide, 2013], is used to construct the vortex energy harvester. A cylinder is also used as a bluff body in order to generate vortices. The 3-D model of the piezoelectric flow harvester can be seen in Figure 2. The vortices do not generally develop downstream of the cylinder; therefore, in order to generate a maximum excitation in the piezoelectric vortex energy harvester, the position of the cylinder with respect to the vortex energy harvester should be determined correctly. Therefore, there are slots opened in the base plate to adjust the position of the cylinder in X and Y coordinates in order to find the correct position for the maximum excitation of the vortex energy harvester around its fundamental resonance frequency.

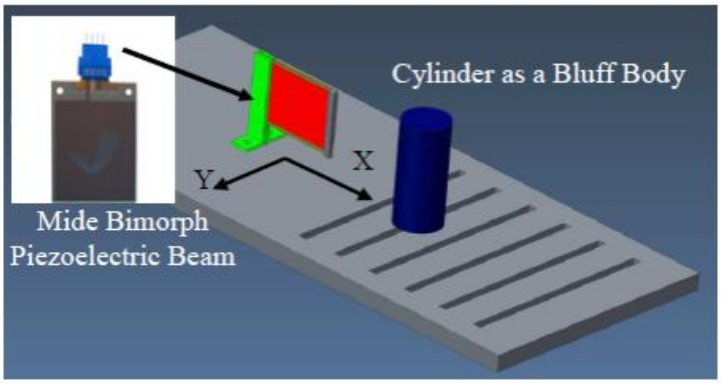

Figure 2: 3D Model Vortex Energy Harvester

The fundamental resonance frequency of the Volture V25W vortex energy harvester is tuned by adding an 8.2 gram tip mass which is a necessity regarding the working range of the wind tunnel. Then, so as to find the exact fundamental resonance frequency of the piezoelectric flow harvester, a modal test via shaker is performed through the base excitation. In this test, white noise input is generated and given to the modal shaker by Pulse Data Acquisition System [B&K, 2016] and is controlled by a single axis accelerometer (Bruel&Kjaer 4507 [B&K, 2016]). The voltage output of the piezoelectric energy harvester is collected via NI Data Acquisition System (Figure 3a). This collected voltage output is then processed in MATLAB [MATLAB, 2016] to obtain the power spectrum of it and as is shown in the Figure 3b that the fundamental resonance frequency of the flow harvester is obtained as at around 56.64 Hz.

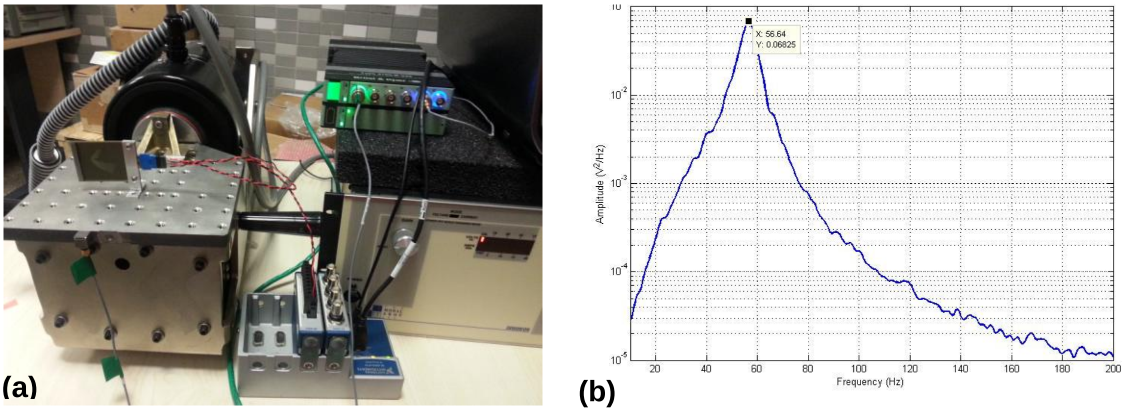

Figure 3: (a) Experimental Setup, (b) First Resonance Frequency of the Bimorph Piezoelectric Energy Harvester

WIND TUNNEL TEST OF THE PIEZOELECTRIC VORTEX ENERGY HARVESTER

In order to understand the effect of the diameter and the position of the cylinder in the performance of the vortex energy harvester, the model given in Figure 2 is manufactured and shown in Figure 4. In this model, four different diameters of cylinders; 20, 30, 40 and 50 mm, are used during the wind tunnel test to investigate the effect of the size of the bluff body. Flow speeds can be re-calculated by using these cylinder diameters and the fundamental resonance frequency of the vortex energy harvester through Equation (1) for the generation of vortices. The corresponding obtained flow speeds are presented in Table 1. In the calculations, the Strouhal Number (St) can be taken as 0.2 as an assumption for Reynolds Number (Re) $<10^5$ for subcritical flow [Techet, 2000]. After finding the flow speeds, maximum Re is re-calculated as around 42000 and the Strouhal Number assumption is validated for the subcritical flow before the planned wing tunnel tests.

$$St = \frac{f_s D}{U} \tag{1}$$

Figure 4: Manufactured Vortex Energy Harvester and Bluff Bodies

Table 1. Diameter of Cylinder vs Different Flow Speed

Frequency of Vortex Harvester (Hz)	**Diameter of Cylinder (m)**	**Flow Speed (m/s)**
56.64	0.02	5.70
56.64	0.03	8.55
56.64	0.04	11.40
56.64	0.05	14.25

In order to investigate the energy harvesting performance of the vortex energy harvester in real life conditions, wind tunnel test is conducted. Schematic view of the wind tunnel used in the test is given in Figure 5 [Mercan, 2010]. During the wind tunnel test, the vortex energy harvester is positioned in the test section of the wind tunnel and shown in Figure 6.

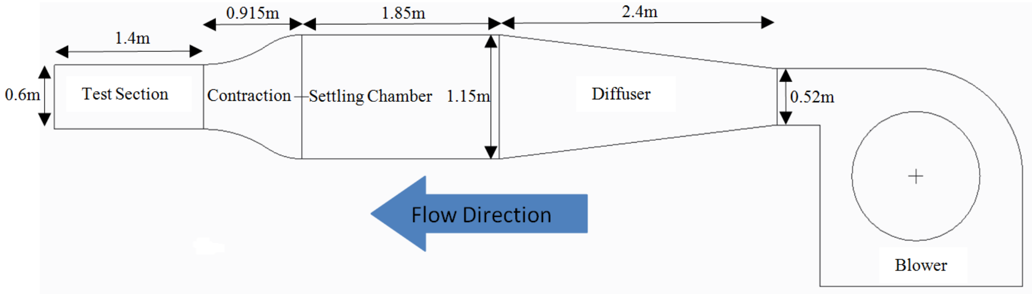

Figure 5: Schematic View of the Wind Tunnel

The main of aim of the study is to analyze the effect of the diameter and the position of the cylinder on the energy harvesting performance. In order to find the best position for each cylinder, 6 slots (Figure 7) are used in order to arrange the position in X direction. Moreover, each cylinder is also positioned in Y direction with respect Y/D=0 (i.e. cylinder position in Y direction for Y/D=0 is called as P1 which stands for the Position 1), Y/D=0.5 (cylinder position in Y direction for Y/D=0.5 is called as P2 which stands for the Position 2) and Y/D=1 (cylinder position in Y direction for Y/D=1 is called as P3 which stands for the Position 3), as it is mentioned in the study [Sarıoğlu, 2000] that the effect of vortices is diminished after Y/D=1.5.

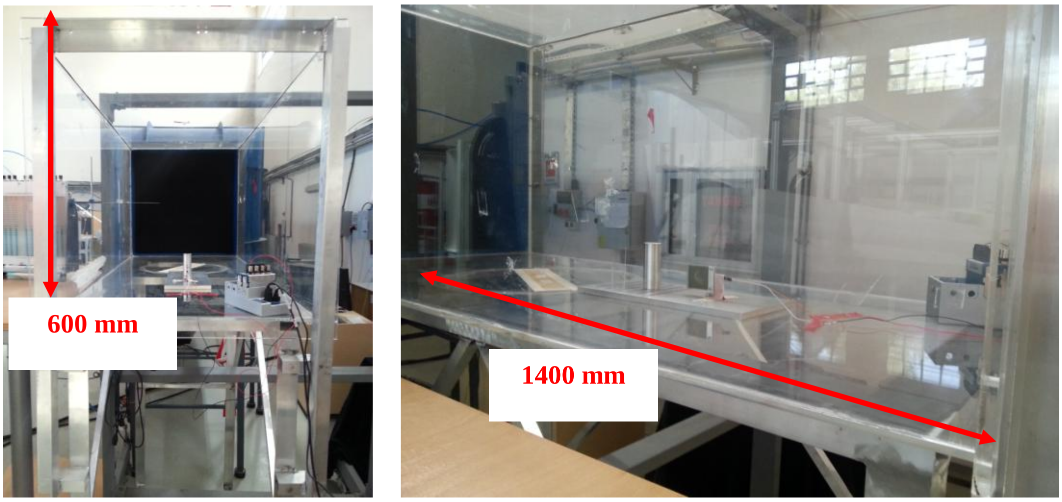

Figure 6: Wind Tunnel Test Setup for the Vortex Energy Harvester

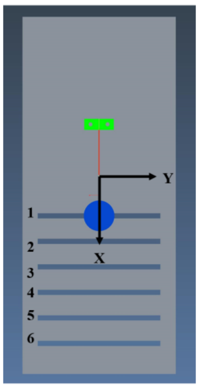

Figure 7: X and Y Coordinates and the Slot Numbers

During the wind tunnel test, voltage generation of the vortex energy harvester is collected by NI Compact DAQ and read by NI Signal Express Software [NI, 2016]. In various test cases, Y/D ratio is fixed and X direction position is changed by using the slots. There are, in total, 4 different diameters are used and 18 different positions are selected for the wind tunnel test. Therefore, in order to compare the results of the each test case, the power spectral density (PSD) of the time record of the voltage output is obtained through MATLAB and a selected example of the results, which belongs to the P1 of 50 mm diameter of the cylinder, is presented in Figure 8. As seen from this figure that the maximum voltage output is obtained around the resonance frequency of the vortex energy harvester. Moreover results for 20 mm and 30 mm diameters and for 40 mm and 50 mm diameters are tabulated in Table 2 and Table 3, respectively, in terms of the maximum voltage output around the resonance frequency. In these tables, the maximum voltage output is given with respect to diameter and the position of cylinder used. Moreover, the maximum voltage generation and optimum position obtained for four different diameters are presented in Figure 9 in order to visualize the test results. Time history for the maximum voltage generation four different diameters is also given in Figure 10.

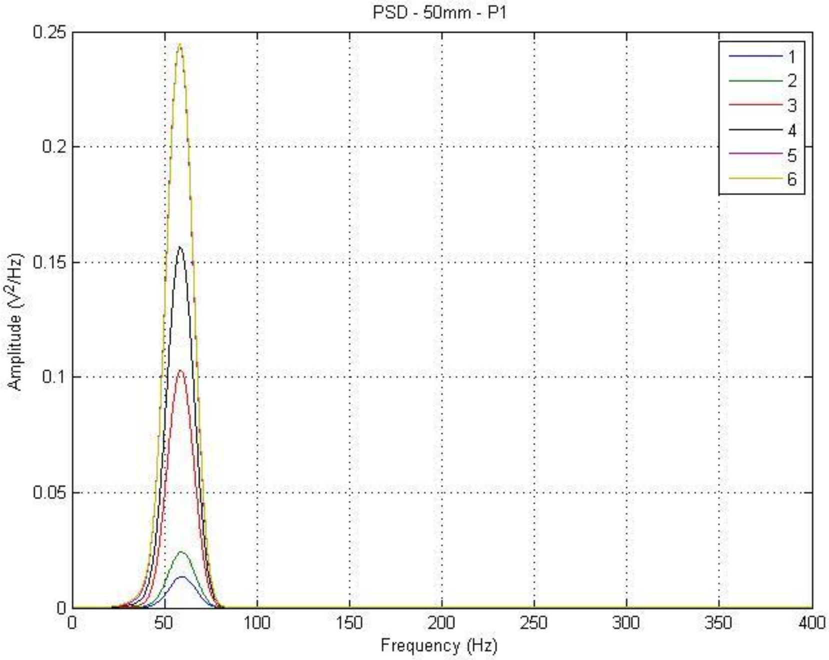

Figure 8: X and Y Coordinates and the Slot Numbers

Table 2: Wind Tunnel Test for the Maximum Voltage output for Diameter 20 and 30 mm

	Diameter					
	20mm			**30mm**		
Position	**P1 Slot 4**	**P2 Slot 3**	**P3 Slot 3**	**P1 Slot 4**	**P2 Slot 3**	**P3 Slot 3**
Voltage Output (V^2/Hz)	0.0045	0.0043	0.0048	0.0260	0.0320	0.0310

Table 3: Wind Tunnel Test for the Maximum Voltage output for Diameter 40 and 50 mm

	Diameter					
	40mm			50mm		
Position	**P1 Slot 5**	**P2 Slot 5**	**P3 Slot 4**	**P1 Slot 6**	**P2 Slot 5**	**P3 Slot 6**
Voltage Output (V^2/Hz)	0.1410	0.1400	0.1280	0.2450	0.2080	0.1650

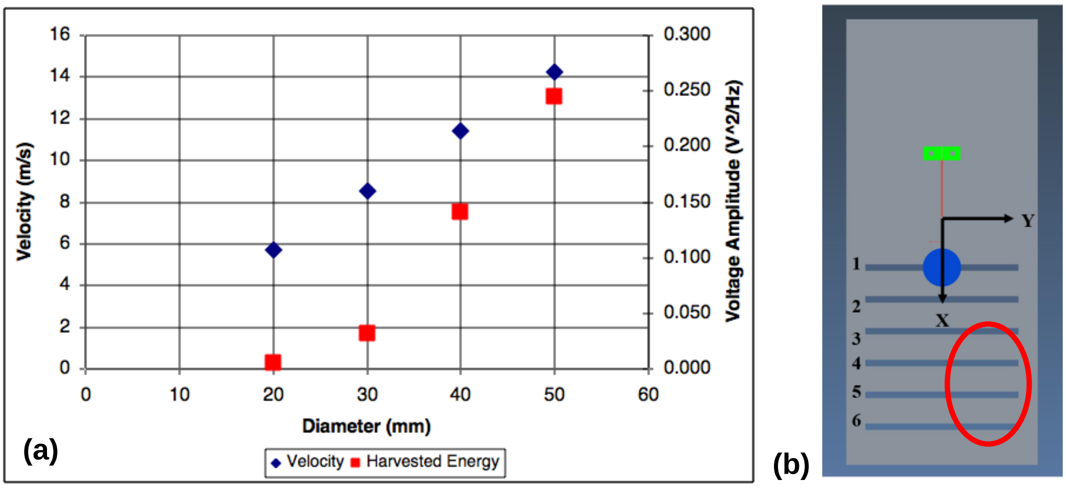

Figure 9: (a) Maximum PSD of the Voltage Generation for Different Flow Speed and Diameter of the Cylinder at the Resonance Frequency, (b) General Locations for the Cylinder for Maximum PSD Output

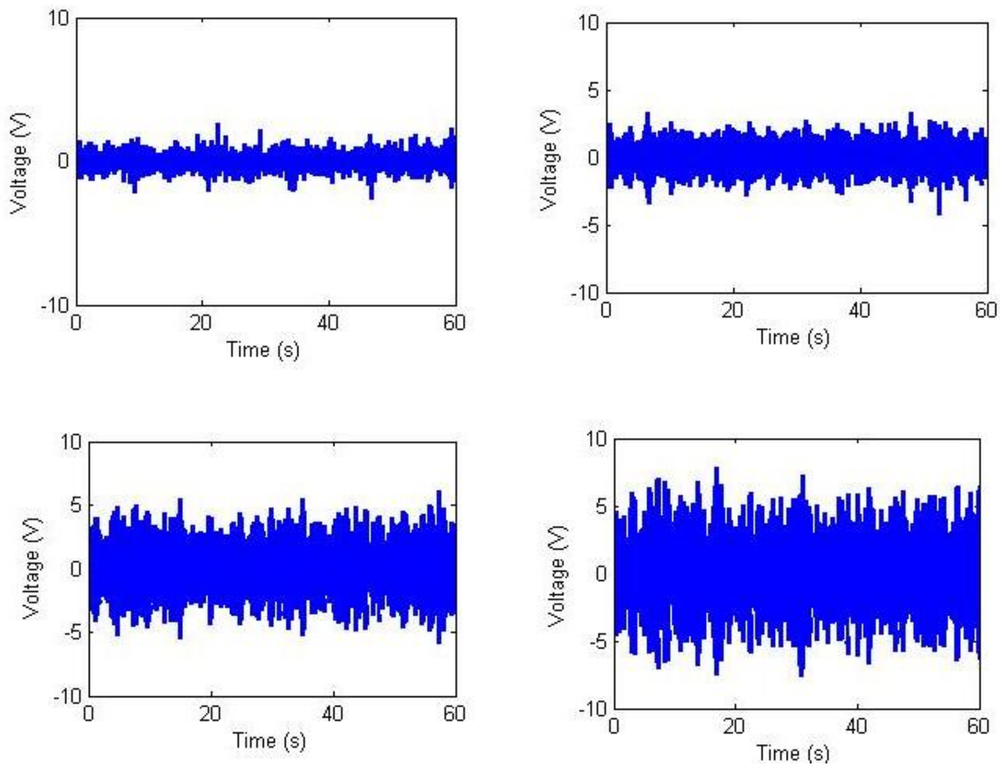

Figure 10: Maximum Voltage Generation for Different Diameter of the Cylinder(a) 20 mm Diameter (b) 30 mm Diameter (c) 40 mm Diameter (d) 50 mm Diameter

The fundamental resonance frequency of the vortex energy harvester is also calculated under the real operating condition. For this purposes, the PSD of the voltage output of the vortex energy harvester can be taken by MATLAB by using the time history data obtained from the wind tunnel test. The PSD of the voltage output of the vortex energy harvester is given in Figure 11 and it can be seen from the figure that the fundamental resonance frequency is around 58.00 Hz. This result is very close to the one obtained from the modal shaker test (i.e. 56.64 Hz) and therefore the experimental study is verified.

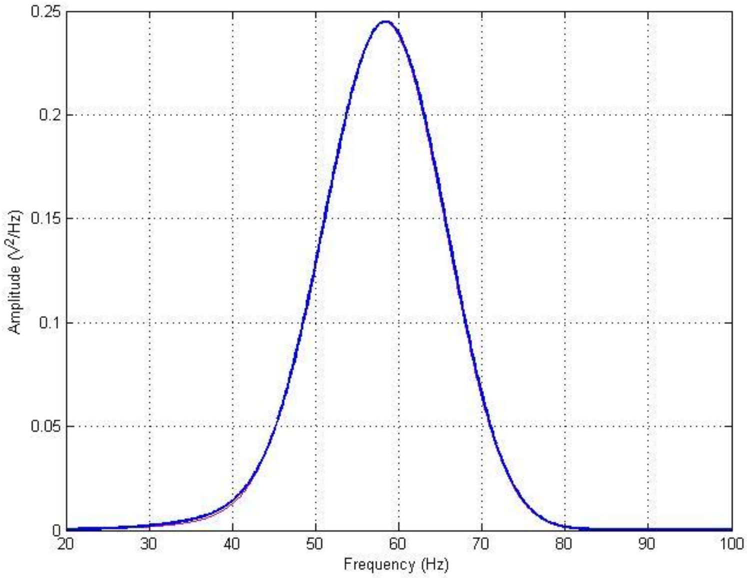

Figure 11: Frequency Response of the Voltage Data for 50 mm Diameter Cylinder in the Determination of the Fundamental Resonance Frequency of the Vortex Energy Harvester

After these tests, it can be seen from the Figure 12a that the voltage output of the vortex harvester increases due to the increase in the flow speed as there is an increase in the turbulence content of the flow as well. Moreover, the voltage output can be maximized for each diameter of the cylinder if the cylinder is positioned roughly in the red circular region as indicated in Figure 12b. This study showed that if the flow is turbulent and it generates vortices, the vortex energy harvester performance can be increased around the fundamental resonance frequency region. Moreover, the correct position of the cylinder should be determined through the wind tunnel test in order to increase the harvested energy. Following these numerical and experimental studies, the vortex energy harvester can be used more efficiently by selecting the diameter and position of the cylinder. It is practically not very feasible to use this type of voltage output to operate a particular system or to charge a battery. In order to make this voltage usable for the aforementioned purposes, rectifier circuit should be used. Therefore, a rectifier circuit [Smart Material Corp, 2012] converting AC voltage to DC one with is 2 nF capacitance used during the wind tunnel tests. For a cylinder of diameter 50 mm and at P1/Slot 5 position, DC voltage generation of the vortex energy harvester is given as an example in Figure 12a. By using this DC voltage generation of the vortex energy harvester and the capacitance value of rectifier circuit, the average power generation can be obtained by using Equation (2) where C is the capacitance of the rectifier circuit, V is the voltage and Δt is the time difference. Average power is also presented in Figure 12b.

$$P_{avg} = \frac{\frac{1}{2} CV^2}{\Delta t} \tag{2}$$

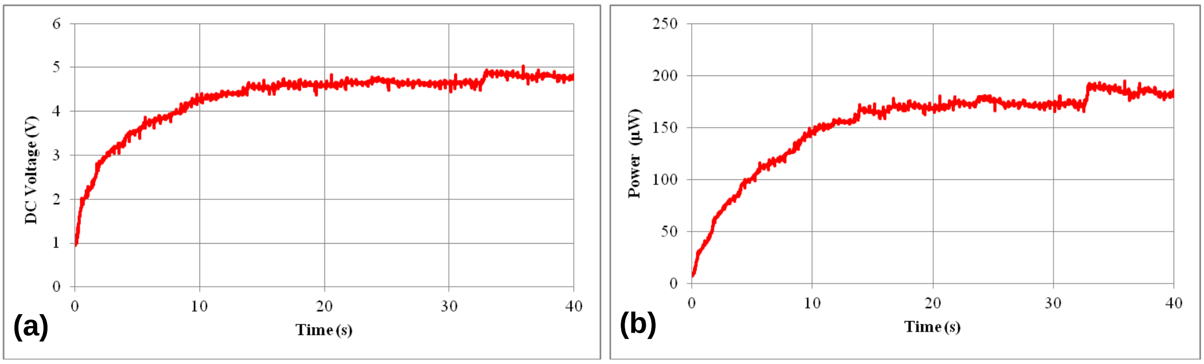

Figure 12: (a) DC Voltage and (b) Power Generation of the Vortex Energy Harvester

CONCLUSION

In this research study, energy harvesting performance of the bimorph piezoelectric beam is investigated under the vortex flow excitation. For this aim, a commercial bimorph piezoelectric beam, Mide Volture V25W, is selected and a vortex energy harvester is constructed to investigate the effect of the diameter and the position of a bluff body (i.e. a cylinder). First of all, the fundamental resonance frequency of the bimorph piezoelectric beam is tuned roughly to 57.00 Hz and then validated via experimental modal analysis. Following this, the energy generation capability of the vortex energy harvester is examined under real conditions in a wind tunnel through various tests. The main objective is to arrange a flow speed and choose the diameter of a bluff body in such a way that the fundamental resonance frequency of the vortex energy harvester is excited. As it can be observed from the test and analysis results that when the flow speed increases, a higher voltage generation levels can be achieved in comparison to low speed applications through the designed vortex energy harvester. Additionally, the PSD of the time series of vortex energy harvester is taken to obtain the fundamental resonance frequency of the vortex energy harvester and the results indicated that the resonance frequency obtained under operational condition is very close to that of experimentally obtained one. This study also shows that the harvested energy depends on both size and the position of the cylinder located in front of the vortex energy harvester. Having seen the importance of the position and the size of the cylinder in the energy harvesting performance, a conceptual design is then proposed for the tuned vortex energy harvester having the capability of adapting itself to different flow velocities to increase the desired harvested energy. A control system including a servo actuator should also be developed and installed to accurately actuate the proposed mechanism. Finally, this type of harvester can be integrated to any structure which is expected to work against the air flow. Before the integration of the vortex energy harvester, the flow characteristics should also be investigated and well understood beforehand. By using the information and the knowledge gathered through both the numerical and the experimental work, the fundamental resonance frequency of the vortex energy harvester can be tuned via positioning the bluff body in order to maximize the amount of harvested energy.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support provided by the Middle East Technical University under grant number BAP-03-13-2012-001 for the project titled "Vibration-based Energy Harvesting from an Aerial Vehicle via Piezoelectric Material".

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