Smart Structures and Systems, *Vol. 18, No. 2 (2016) 249-265*
DOI: http://dx.doi.org/10.12989/sss.2016.18.2.249

Bimorph piezoelectric energy harvester structurally integrated on a trapezoidal plate

Ahmet Levent Avşar and Melin Şahin*

Department of Aerospace Engineering, Middle East Technical University, Ankara, Turkey

(Received June 22, 2015, Revised March 5, 2016, Accepted April 26, 2016)

Abstract. A bimorph piezoelectric energy harvester is developed for harvesting energy under the vortex induced vibration and it is integrated to a host structure of a trapezoidal plate without changing its passive dynamic properties. It is aimed to select trapezoidal plate as similar to a vertical fin-like structure which could be a part of an air vehicle. The designed energy harvester consists of an aluminum beam and two identical multi fiber composite (MFC) piezoelectric patches. In order to understand the dynamic characteristic of the trapezoidal plate, finite element analysis is performed and it is validated through an experimental study. The bimorph piezoelectric energy harvester is then integrated to the trapezoidal plate at the most convenient location with minimal structural displacement. The finite element model is constructed for the new combined structure in ANSYS Workbench 14.0 and the analyses performed on this particular model are then validated via experimental techniques. Finally, the energy harvesting performance of the bimorph piezoelectric energy harvester attached to the trapezoidal plate is also investigated through wind tunnel tests under the air load and the obtained results indicate that the system is a viable one for harvesting reasonable amount of energy.

Keywords: piezoelectric energy harvesting; finite element; experimental modal analysis; wind tunnel test

1. Introduction

Energy harvesting from vibrations becomes more and more important due to decreased energy needs of small structures or sensors, in particular for a structural health monitoring system, and plays a critical role in the system they are integrated. It is stated (Erturk 2011) that the replacement cost and the chemical contamination of the batteries, due to lead, can also be eliminated by using vibration-based energy harvesting systems. The piezoelectric material can be lengthen or shorten if voltage difference is applied along the direction of polarization axis of piezoelectric material and this is called motor actions of piezoelectric material. This phenomenon can happen conversely due to nature of it, in other words if the mechanical force, compression or tension, is applied along the direction of the polarization axis of piezoelectric material, voltage generation can be observed from piezoelectric material. This is the generator action and because of it, piezoelectric materials are widely used in energy harvesting systems generally called as a piezoelectric energy harvester.

*Corresponding author, Associate Professor, E-mail: msahin@metu.edu.tr
[a] Ph.D., Email: aleventavsar@gmail.com

http://www.techno-press.org/?journal=sss&subpage=8 ISSN: 1738-1584 (Print), 1738-1991 (Online)

(APC International).

In order to harvest energy from vibration via piezoelectric materials, proper design methodology should be applied to maximize the harvested energy. Therefore, the analytical and/or finite element methods can be used at the first stage of the design to optimize the position, type and the application point of piezoelectric material and then, the vibration based energy harvester can be produced. Finally, performance of a vibration-based piezoelectric energy harvesting system should be investigated under the operational conditions. Wang *et al.* (2014) is modeled a special piezoelectric energy harvester, which is constructed with segmented electrode configuration, in order to increase the performance with respect to continues electrode configuration. During the modeling process; analytical, finite element and equivalent circuit model of piezoelectric energy harvesters are also compared. For example, Anton (2011) studied that the piezoelectric material is integrated into the wings of a small UAV in order to investigate the performance of an energy harvesting device. Within the mission profile of this small UAV, both voltage and acceleration can be collected as useful data. In this particular study, voltage generation of the piezoelectric material is also investigated via the acceleration history of the small UAV. In other study, the energy management of a critical component, an aero-servo-elastic system of an aircraft or sensors used in a structural health monitoring system can be performed through a vibration-based energy harvesting system. It is also presented (Erturk *et al*. 2010) that energy harvesting characteristic of piezoaeroelastic system is also analyzed by lumped parameter wing section model and in this particular research study, a piezoceramic patch is placed to plunge a stiffness member of the system. Due to the excitation coming from the air, energy is harvested via the piezoaeroelastic system. The energy need of critical sensors of a structural health monitoring system in an aircraft should also be considered carefully. It is usually not possible to use cables for the sensors especially in the rotary wing aircrafts on the rotating components. Therefore, wireless sensors should be used and energy need of these wireless sensors should be supplied by batteries. It is already known that if the battery is used, maintenance and replacement cost and reliability of the system should also be considered. In order to eliminate this battery usage, a vibration-based energy harvesting system can be integrated into the system. For example, a structural health monitoring system (Arms *et al*. 2008) is developed for collecting data of strain gauges and/or accelerometers. This system is also integrated into a rotating wing aircraft close to the main rotor, and therefore, sensors of the structural health monitoring system should also be wireless. In another study, a special energy harvester consisting of piezoelectric material is designed to operate a wireless sensor for a structural health monitoring system (Amoroso *et al.* 2015). During the design process of energy harvester, a numerical modeling is done by a commercial software and it is also verified through an experimental method.

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 widely studied in the literature. Abdelkefi (2016) presents different types of flow induced vibration energy harvesters. Bryant (2011) developed novel piezoelectric energy harvester which consists of simple pin connected flap and beam and it works under aeroelastic flutter vibration. Moreover, Bae (2013) studied nonlinear aeroelastic behavior of a piezoelectric energy harvester and it was modeled by a two dimensional typical section airfoil. Marqui Jr. (2012) also worked on dimensionless electroaeroelastic equations for predicting the power output at the flutter boundary and both electrical power output and flutter speed are investigated for piezeoelectric and electromagnetic energy harvesters. Furthermore, a cantilever plate-like wing with embedded piezoceramics performance evolution was investigated by considering aeroelastic vibrations (Marqui Jr. *et al*. 2011). In an another study, a performance of a piezoelectric energy harvester is analyzed by considering free play nonlinearity and the overall performance enhancement is investigated (Sousa *et al*. 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 *et al*. 2010). In this electromagnetic energy harvester example, a bluff body is positioned in front of the harvester. However, Gao (2011) showed that bluff body can also be directly attached to the energy harvester. 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 *et al*. 2013). In another study, piezoelectric micro cantilever sensor is used to harvest energy from wind (Liu *et al*. 2012). Hobeck (2012) developed a bio-inspired design for harvesting energy from low-velocity, 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 *et al*. 2015). 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 *et al*. 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, Dai *et al*. (2014) also worked on harvesting energy from piezoelectric material under both base and vortex induced vibration excitations. 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 *et al*. 2013). A numerical model is constructed for aeroelectromechanical performance of the piezoelectric energy harvester in the wake of the bluff body (Akaydın *et al*. 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 *et al*. 2015). Song *et al*. (2015) designed a special piezoelectric energy harvester by using two cylinders and two MF patches. In this particular design, both vortex and wake induced vibrations are used as a source of harvested energy.

As it can be seen from the literature, the most of the studies are stand alone application of the piezoelectric energy harvesters. The main objective of this particular research study, on the other hand, is to integrate a piezoelectric energy harvester to a flexible host structure and to harvest considerable energy under the vortex induced vibration. Having considered this issue and investigated the research on vibration-based energy harvesting techniques and methods, a two dimensional trapezoidal plate is chosen as a host structure to harvest energy from the ambient vibratory motion. The trapezoidal plate used as a host structure in this particular application is a commonly used shape in aeronautical engineering (i.e., fin-like structure) which can generally be used as a control surface of various aerial vehicles. Although choosing any other places on the aerial vehicle to locate the harvester is a possibility, the control surfaces are generally having a better quality air flow and in this way, a better control on the frequency content of the flow would be achieved. Another reason to select this particular trapezoidal plate for the experimental studies is from the fact that the dynamic characteristics of the plate of interest have been well studied previously in (Kahraman 2011). First, the finite element models are constructed for trapezoidal plate and then validated via various experimental studies. Both finite element and experimental modal analyses are performed for better understanding of the passive dynamic characteristics of the trapezoidal plate and eventually to reduce the possibility of interfering the resonance frequencies of it and that of the bimorph piezoelectric energy harvester. Following this, the finite element analysis for the trapezoidal plate hosting bimorph piezoelectric energy harvester is performed in order to investigate their dynamic behaviors which are also verified via experimental modal analysis. Finally, wind tunnel tests are performed so as to observe the energy harvesting performance of the bimorph piezoelectric energy harvester".

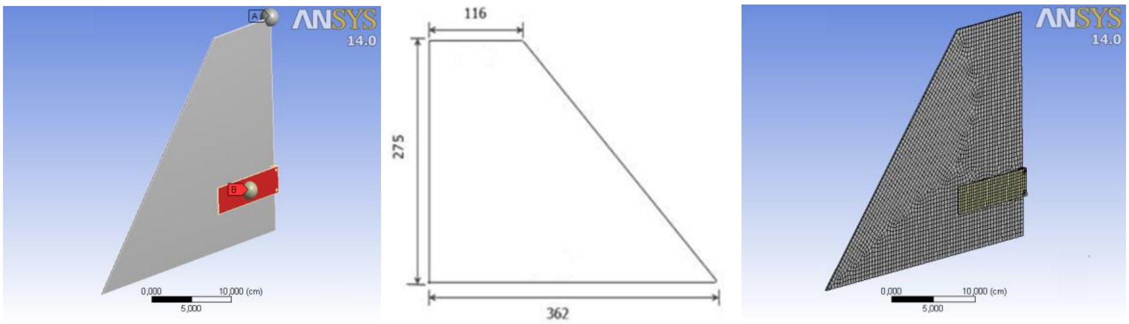
2. Dynamic model of the trapezoidal plate

In general, before attaching any external structure to any host structure, dynamic characteristic of the host structure should be investigated before and after the integration in order to investigate the effect of the external structure on the dynamic characteristics of the host one. Sometimes, it is impossible to avoid the change in dynamic characteristics of the host structure and therefore special precautions should be taken in order not to degrade the performance of the host structure. However, the main aim is to integrate the external structure without creating any adverse effect on the passive dynamic characteristics of the host structure. Therefore, dynamic characteristic of the host structure should be investigated very well in advance and for this reason, analytical and/or finite element methods can generally be used. If the structure is complex, it is very hard to use analytical methods and thus finite element methods turn out to be the only way to obtain the dynamic characteristic of the host structure. In this research study, the passive dynamic characteristic of the trapezoidal plate is investigated by creating a finite element model. By also performing a modal analysis through a finite element method, the natural frequencies and the corresponding displacement mode shapes are determined. Following these analyses, the location for the beam harvester is determined by observing the displacement mode shapes of the host structure. This particular finite element analysis is then validated via experimental techniques.

2.1 Finite element model of the trapezoidal plate

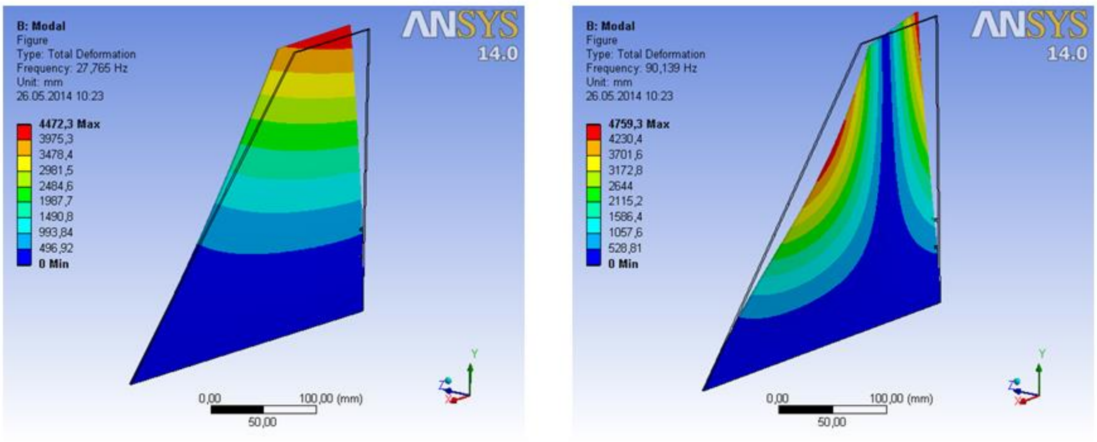
In order to understand the dynamic behavior of the trapezoidal plate (Fig. 1(a)), material of which is an Aluminum 6061-T6, a finite element model is constructed by ANSYS Workbench ver. 14.0 (ANSYS 14.0 Help Manuel, 2011). Geometrical properties of the 2 mm thick trapezoidal plate are given in Fig. 1(b). The mesh generated on the structure consists of 25000 three-dimensional eight-node SOLID 186 type of elements having three displacement degrees of freedom in each node and the generated finite element model has 2000 nodes in total. Normal mode dynamic analysis is then performed in order to find the first two natural frequencies of trapezoidal plate. In this particular analysis, fixed boundary condition is given to 362 mm edge of the trapezoidal plate shown in Fig. 1(b).

After performing the modal analysis, the first two natural frequencies of the plate (tabulated in Table 1) with the corresponding displacement mode shapes are given in Fig. 2.



(a) (b) (c)

Fig. 1 (a) General View of the Plate, (b) Geometry of the Plate and (c) Finite Element Mesh of the Plate
Units are in mm



(a) **(b)**

Fig. 2 Displacement Mode Shapes (a) 1st Out-of-plane Bending (b) 1st Torsion

Table 1 The First Two Natural Frequencies of the Trapezoidal Plate

Mode Type	Finite Element Analysis (Hz)
1st Out-of-plane Bending	27.76
1st Torsion	90.14

2.2 Experimental validation of the finite element model of the trapezoidal plate

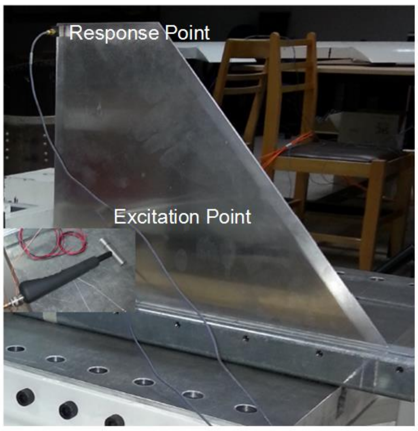
In order to validate the finite element model of the trapezoidal plate, an experimental modal analysis is performed. In this analysis, an impact hammer (Brüel&Kjaer 8206) and a miniature accelerometer (Brüel&Kjaer 4517-002) are used as an excitation source and a response measuring device, respectively. The location of the accelerometer is selected by observing the mode shapes of the structure and then, it is placed to a maximum displacement location for better observation of the resonance peaks in each mode. The location of the accelerometer and excitation location of the impact hammer is shown in Fig. 3(a). The response of the structure is then obtained within the frequency range of 10 to 100 Hz. The frequency response (i.e. the accelerance graphs) is obtained via Brüel&Kjaer PULSE software (Brüel&Kjaer PULSE Software Help Manuel, 2014) (Fig. 3(b)) and the resonance frequencies of the trapezoidal plate are extracted from this particular response. The results of the finite element and the experimental modal analyses are finally compared and summarized in Table 2. As it can be seen from that table, the results are in close agreement with less than 2% difference.

3. Dynamic model of the trapezoidal plate with bimorph piezoelectric energy harvester

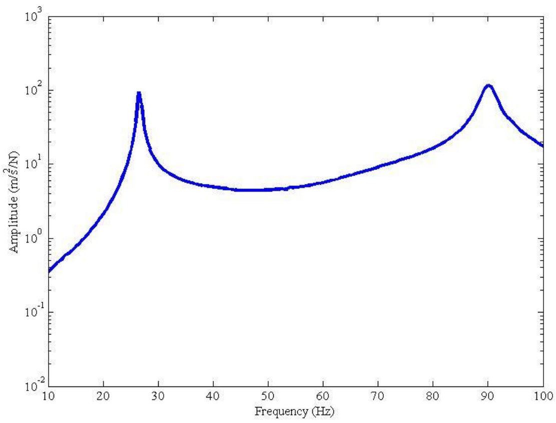
In order to harvest energy from the trapezoidal plate, bimorph piezoelectric energy harvester is attached on its surface. Bimorph piezoelectric energy harvester is formed by Macro Fiber Composite (MFC) type of piezoelectric material (Smart Material Corp, 2012). This is a special material due to its flexibility and energy harvesting capacity. Two identical MFCs are placed and glued to either side of the Aluminum 6061-T6 beam (Fig. 4). After this process, bimorph piezoelectric energy harvester is ready for integration to the trapezoidal plate.

Table 2 Natural Frequencies of the Trapezoidal Plate

Mode Type	Finite Element Analysis (Hz)	Experimental Modal Analysis (Hz)	Deviation (%)
1^{st} Out-of-plane Bending	27.76	27.50	0.95
1^{st} Torsion	90.14	91.65	-1.65

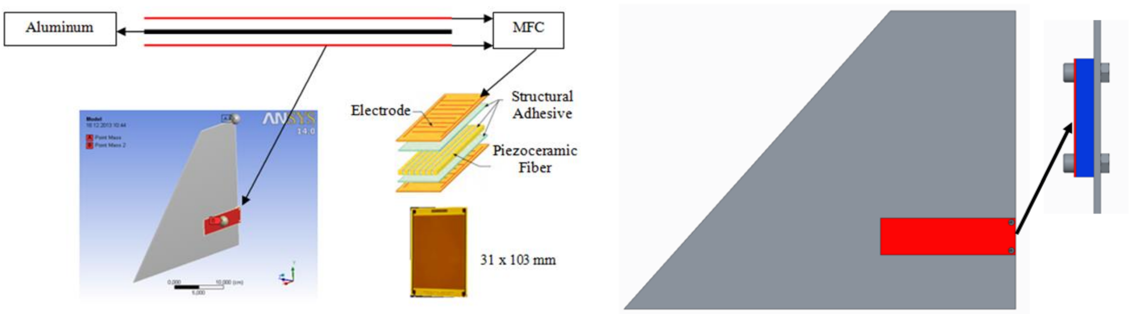


(a)



(b)

Fig. 3 (a) Modal Test Setup and (b) Frequency Response of the Trapezoidal Plate



(a) (b)

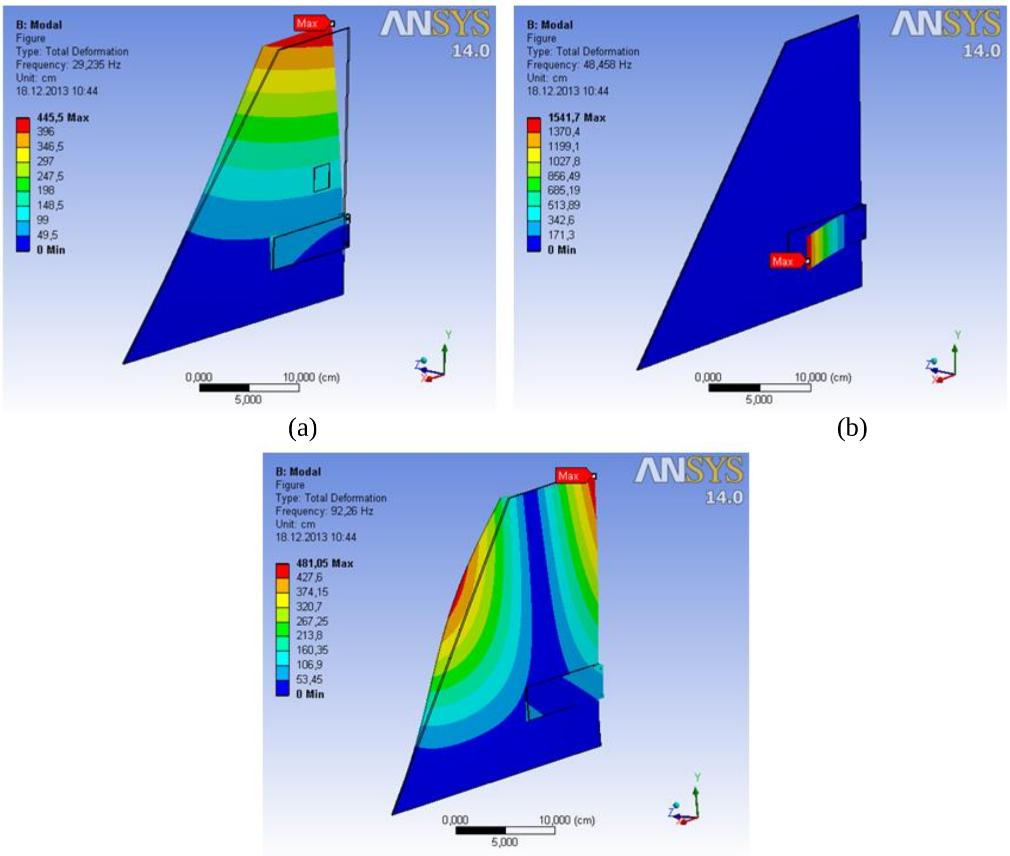
Fig. 4 (a) Bimorph Piezoelectric Energy Harvester and the Host Trapezoidal Plate and (b) Mount Detail of the Bimorph Piezoelectric Energy Harvester

During the integration process, the main objective is not to change the passive dynamic properties of the trapezoidal plate drastically, in other words, the natural frequencies of the trapezoidal plate should not be affected much from the existence of the bimorph piezoelectric energy harvester. For this reason, it is aimed to put bimorph piezoelectric beam to the minimum displacement location and the minimum displacement location of the trapezoidal plate is located at the cantilever-end. However, getting closer to the cantilever-end comprising a fixture with bolts and nuts may adversely affect the quality of the flow in the wind tunnel tests. So, during the experiments, the bimorph piezoelectric energy harvester has been structurally integrated to the most convenient location with minimal structural displacement. The most convenient position of the bimorph piezoelectric beam is found by considering the displacement mode shapes comprising the first out-of-plane plane bending and the torsional one of the plate-like structure (Fig. 2). After finding the proper position of the bimorph piezoelectric beam, experimental analysis is performed to validate the finite element analysis results.

3.1 Finite element model of the trapezoidal plate with bimorph piezoelectric energy harvester

MFC type piezoelectric material is used to construct bimorph piezoelectric energy harvester. The dimension of the Aluminum 6061-T6 beam is 103 x 31 x 2 mm (Length x Width x Thickness). Schematic representation of the beam, its position on the host structure and the geometric properties of MFC is shown in Fig. 4(a). The bimorph piezoelectric energy harvester is integrated to the trapezoidal plate by a separator and this beam is fixed by two M3 screw and nuts. This type of connection is preferred instead of using glue that the bimorph piezoelectric energy harvester can easily be detached after experimental studies. Mechanical details of the integration can be seen in Fig. 4(b). Finite element model for the trapezoidal plate with bimorph piezoelectric energy harvester is constructed in ANSYS Workbench to find the first two natural frequencies of the host trapezoidal plate and the bimorph piezoelectric energy harvester. Finite element mesh of this model has 32000 elements and 4500 nodes in total. In this particular model, the aluminum beam comprising MFC piezoelectric patch has been structurally modeled by considering both the geometrical and the material properties of aluminum beam and by adding the mass property of the MFC patches on each surface of the beam regarding MFC's flexibility and thickness. Therefore, the beam used as a bimorph piezoelectric energy harvester is not modeled in detail by considering the voltage-structural coupling issues in finite element environment. The fixed boundary condition is given to the long horizontal edge of the plate. After performing modal analysis in finite element environment, the first three natural frequencies of the structure are extracted and compared with finite element results of trapezoidal plate without bimorph piezoelectric energy harvester in Table 3 in order to investigate the effect of it on the dynamic characteristics of the passive trapezoidal plate. The corresponding mode shapes are also shown in Fig. 5.

As it can be seen from the analysis results, after the integration of the bimorph piezoelectric energy harvester, the natural frequencies of the trapezoidal plate are slightly changed and the fundamental natural frequency of the piezoelectric beam is observed to be well separated from the rest of the frequencies. By looking the newly obtained mode shapes of the trapezoidal plate with the harvester, it is realized that they are similar to that of the trapezoidal plate without the bimorph piezoelectric energy harvester and it can be said that the dynamic behavior of the trapezoidal plate is not drastically affected from existence of the bimorph piezoelectric energy harvester.



(a) (b) (c)

Fig. 5 Displacement Mode Shapes (a) 1st Out-of-plane bending mode of the trapezoidal plate, (b) 1st Out-of-plane bending mode of the bimorph piezoelectric energy harvester and (c) 1st Torsional mode of the trapezoidal plate

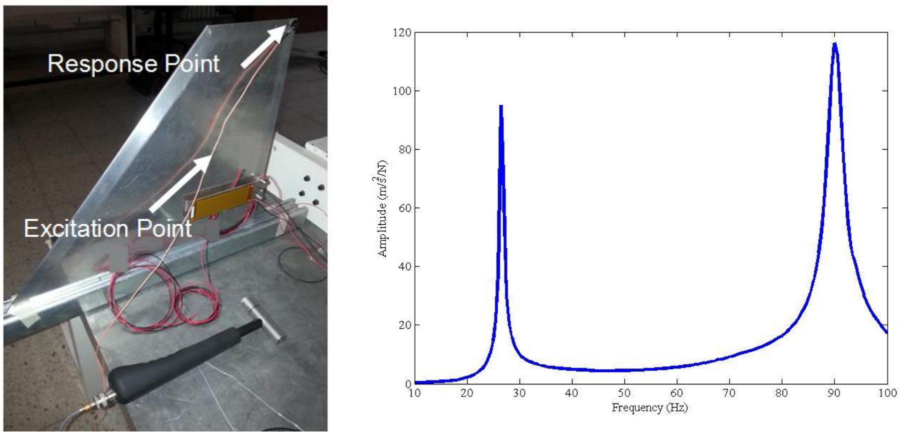
Table 3 Natural Frequencies of the Trapezoidal plate with Bimorph Piezoelectric Energy Harvester

Mode Number and Type	**Finite Element Analysis for Trapezoidal Plate with Bimorph Piezoelectric Energy Harvester (Hz)**	**Difference from Table 1 [%]**
1st Out-of-plane Bending	29.24	5.33
1st Out-of-plane Bending of Bimorph Piezoelectric Energy Harvester	48.46	-
1st Torsion	92.26	2.35

Finally, the main aim of this study is to harvest energy from bimorph piezoelectric harvester under vortex induced vibration and as a general vibration engineering practice, the frequency content of the vortex flow is considered as the main source in order to maximize the vibration on the bimorph piezoelectric energy harvester rather than on the sub-structure which is not desired. For this reason, the bimorph piezoelectric energy harvester has been chosen in such a way that its fundamental resonance frequency is somehow different - possibly away - from one of the resonance frequencies of the trapezoidal plate.

3.2 Experimental validation of finite element model of the trapezoidal plate with bimorph piezoelectric energy harvester

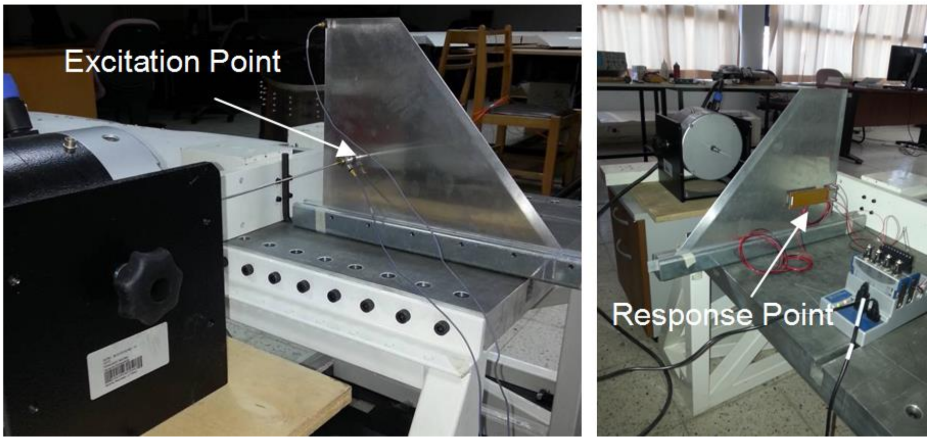
So as to investigate the real dynamic behavior of the trapezoidal plate with bimorph piezoelectric energy harvester, an experimental study is performed via an impact hammer. During the modal test, an impact hammer (Brüel&Kjaer 8206) and a miniature accelerometer (Brüel&Kjaer 4517-002) are used (Fig. 6), and the location of the accelerometer and the excitation point by the impact hammer is given in Fig. 6(a). The frequency response of the whole structure is obtained by PULSE software (Fig. 6(b)) in the frequency range of 10-100 Hz and the first two resonance frequencies are found as 27.50 and 93.00 Hz, respectively.



(a) (b)

Fig. 6 (a) Modal Test Setup and (b) Frequency Response of the Trapezoidal Plate with Bimorph Piezoelectric Energy Harvester

In this test, the first out-of-plane bending mode of the bimorph piezoelectric energy harvester is investigated as it is observed from the finite element results that the first natural frequency of the piezoelectric bimorph beam is well separated from that of the trapezoidal plate. Therefore, another test setup is constructed to obtain that particular one with modal shaker (Fig. 7) providing a sine sweep excitation between 40-60 Hz to the system. During the modal test, the whole structure is excited through the modal shaker (Fig. 7(a)) and the voltage output of MFC is collected by NI CompactDAQ (NI CompactDAQ Help Manuel, 2014) (Fig. 7(b)). For the each sweep frequency, the voltage output of the MFC is collected through NI Signal Express Software (NI Signal Express Help Manuel, 2014) and then the voltage-frequency graph is drawn and presented in Fig. 8(a). As it can be seen from the voltage response of the bimorph piezoelectric energy harvester, the resonance frequency of the beam is found as 49.00 Hz. Moreover, in order to monitor the voltage output of the bimorph piezoelectric energy harvester, a ground vibration test is conducted. In this test, excitation at the resonance frequency of the bimorph piezoelectric energy harvester is given to the structure and the tip acceleration, which is tuned to 1 g, is controlled by a miniature accelerometer (Brüel&Kjaer 4517-002). During the test, NI CompactDAQ is used to obtain the voltage output (i.e., response) of the bimorph piezoelectric energy harvester (Fig. 8(b)) at its resonance frequency. As it can be seen from Fig. 8b, the bimorph piezoelectric energy harvester generates considerable voltage output at its resonance frequency for the controlled 1 g vibration.

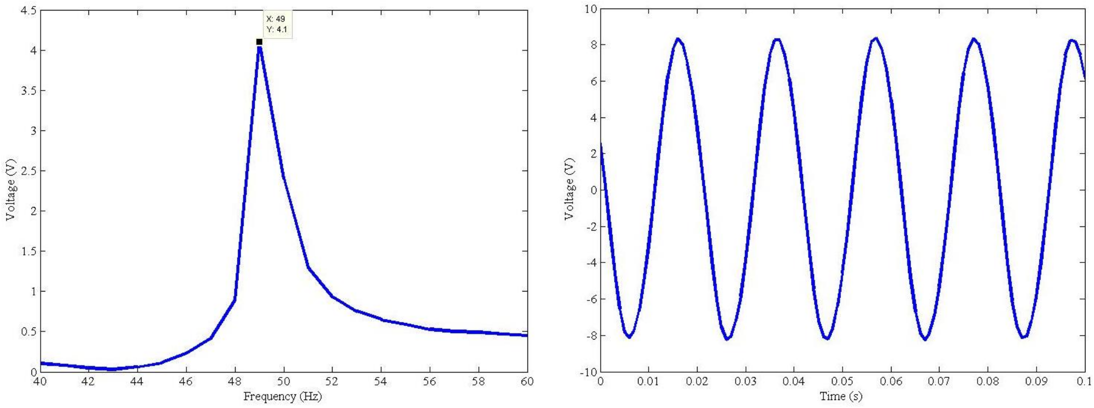


(a) (b)

Fig. 7 Shaker Test Setup (a) Excitation Point and (b) Response Point

Table 4 Natural and Resonance Frequencies of the Trapezoidal Plate with Bimorph Piezoelectric Energy Harvester

Mode Number and Type	Finite Element Analysis (Hz)	Experimental Modal Analysis (Hz)	Deviation (%)
1st Out-of-plane Bending	29.24	27.50	6.33
1st Out-of-plane Bending of Bimorph Piezoelectric Energy Harvester	48.46	49.00	1.10
1st Torsion	92.26	93.00	0.79



(a) (b)

Fig. 8 Frequency (a) and Voltage (b) Response of the Bimorph Piezoelectric Energy Harvester

Finally, Table 4 is constructed in order to summarize and compare the results of the trapezoidal plate without bimorph piezoelectric energy harvester. Considering the results tabulated in Table 4, it can be said that the finite element model is validated via experimental technique. Moreover, it is also proven experimentally that dynamic characteristic of the trapezoidal plate is not affected by the integration of the bimorph piezoelectric energy harvester.

4. Wind tunnel test

In order to investigate the energy harvesting performance of the bimorph piezoelectric energy harvester in real life conditions, wind tunnel tests are conducted. Schematic view of the wind tunnel, which is used for the tests, is given in Fig. 9(a) (Mercan *et al*. 2010). During the wind tunnel tests, trapezoidal plate with the bimorph piezoelectric energy harvester is positioned in front of the test section of the wind tunnel as shown in Figs. 9(b) and 9(c).

If the flow goes only around the trapezoidal plate hosting the bimorph piezoelectric energy harvester, the harvester may not be excited by the flow and the expected voltage generation of the bimorph piezoelectric energy harvester might be comparably low. Therefore, a vortex generator is used to excite the bimorph piezoelectric energy harvester around its first natural frequency so as to increase the voltage generation of MFC by making the vortex shedding frequency close to the first resonance frequencies of the beam harvester.

In order to generate a vortex shed by the flow, a bluff body should be used in front of the excited structure through in coming flow and a cylinder is selected for this purpose in this study. Eq. (1) describes the Strouhal Number (St) and it is a dimensionless number defining the oscillation characteristics of the flow (Techet 2010).

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

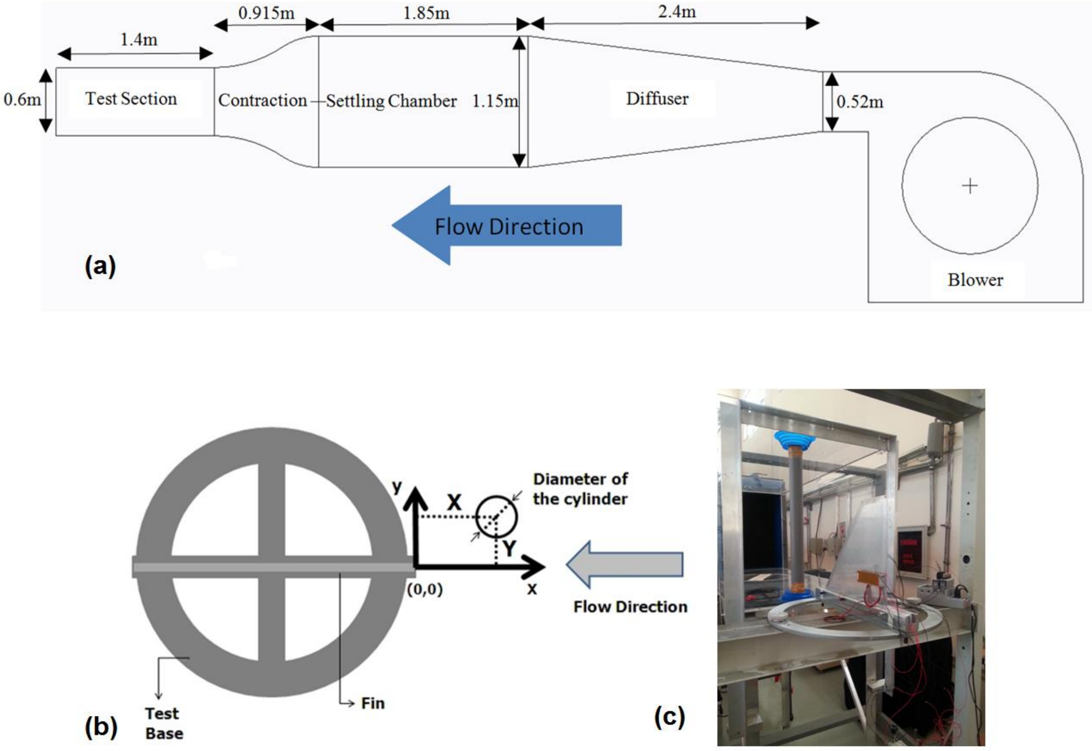


Fig. 9 (a) Schematic View of Wind Tunnel, (b) Position of Vortex Harvester and (c) Wind Tunnel Test Setup

where; St is Strouhal Number, D is diameter of cylinder, f_s is the vortex shedding frequency and U is the flow speed.

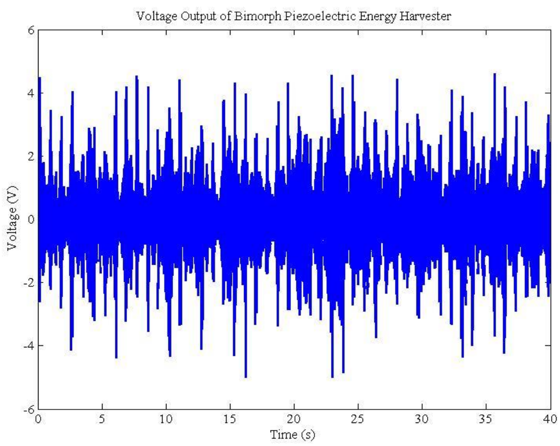
In this study, 0.05 m diameter cylinder is used in the wind tunnel and St can be taken as 0.2 for Reynolds Number (Re) which is below 10^5 for subcritical flow (Techet 2010). For the energy harvesting test conditions, the flow is assumed to be subcritical and the St is also taken as 0.2. The vortex shedding frequency should be at around 49 Hz which is the first out-of-plane bending frequency of the beam. By using the parameters mentioned and Eq. (1), the flow speed of wind tunnel is calculated as 12.25 m/s. By using this velocity and Eq. (2), Re is calculated as approximately 42000 and Strouhal Number assumption is validated for the subcritical flow.

$$\mathrm{Re} = \frac{UD}{\upsilon} \tag{2}$$

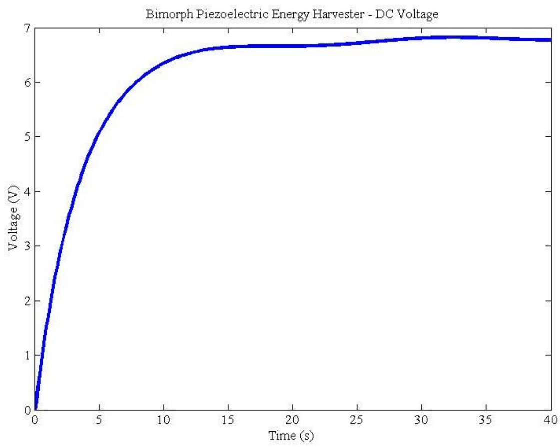
where; Re is Reynolds Number, D is diameter of cylinder, υ is the kinematic viscosity and U is the flow speed.

The position of the cylinder is also important from the excitation point of view of the bimorph piezoelectric energy harvester. For this reason, various different positions of the cylinder is previously investigated (Kahraman 2011 and Sarıoğlu 2000). Finally, test setup for the vortex generator, given in Fig. 14, is constructed. X is taken as 0.2 m and Y is chosen as 0.025 m in the test to increase the vortex excitation density (Kahraman 2011).

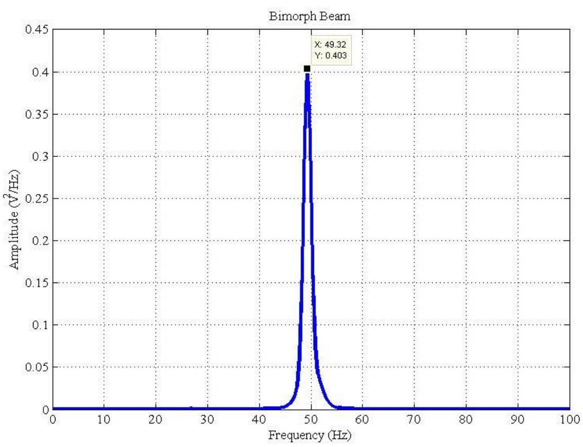
During the test, the flow speed of the wind tunnel is set to 12.25 m/s. After flow goes around the cylinder, the bimorph piezoelectric energy harvester vibrates around its first resonance frequency. Then, the voltage output of MFC is obtained by NI CompactDAQ and recorded by NI Signal Express Software. In the first test, the AC voltage generation performance of the bimorph piezoelectric energy harvester is investigated and the obtained result is given in Fig. 10. The peak to peak voltage generated by the beam harvester is observed at around 4 Volts with some variations.



(a)



(b)



(c)

Fig. 10 AC Voltage Response of Bimorph Piezoelectric Energy Harvester in Time Domain

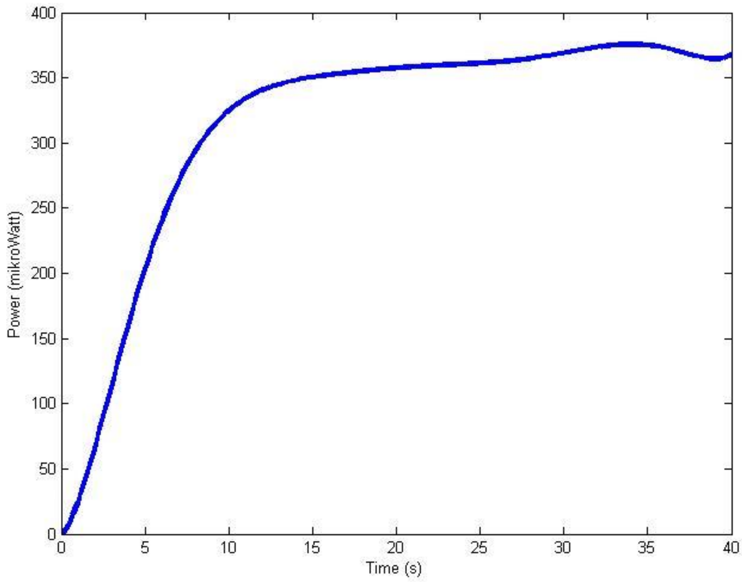


Fig. 11 MFC Bimorph Piezoelectric Energy Harvester Watt Generation

In order to operate an electrical system or to charge a battery, the DC voltage should be achieved and supplied. Therefore, a Rectifier Circuit (Smart Material Corp. 2012) or specially designed circuit for energy harvesting (Hofmann 2011) should be used to convert an AC voltage into a DC one in order to operate a particular system. In this study, a rectifier circuit is used to investigate the DC voltage generation performance of the bimorph piezoelectric energy harvester. During the wind tunnel test, a rectifier circuit is connected to the bimorph piezoelectric energy harvester and the DC voltage output of the beam is obtained by NI CompactDAQ which is also shown in Fig. 10. As it can be seen from the voltage response results, the harvester is capable of generating approximately 7 Volt-DC under the air flow loading. Then, the power spectral density (PSD) of the obtained time history of MFC is obtained and presented in Fig. 10(c). The peak frequency of PSD is found at around 49.32 Hz and it is very close to that of obtained both from finite element analysis and the modal test results. This also concludes that the bimorph piezoelectric energy harvester is excited near its resonance frequency via vortex shed in the flow field generated.

By using this DC voltage generation of the vortex energy harvester and the capacitance value of rectifier circuit (2 nF), the average power generation can be obtained by using Eq. (3) where C is the capacitance of the rectifier circuit, V is the voltage and Δt is the time difference. Δt is taken as the sampling time of data and it is 0.0001. Average power is also presented in Fig. 11. This, of course, guarantees the maximum level of possible energy to be harvested from the aforementioned vibrating system.

$$P_{avg} = \frac{\frac{1}{2}CV^2}{\Delta t} \tag{3}$$

5. Conclusions

In this study, energy harvesting from trapezoidal plate by bimorph piezoelectric energy harvester is investigated by also proving a particular design approach for the integration of it on a trapezoidal plate. Knowing the fact that integration of any external device on a host structure might easily alter the passive dynamic characteristics of the host structure, various analyses are performed in order to avoid this undesirable outcome and to have similar dynamic characteristics after the integration. First, the finite element analyses are performed for the trapezoidal plate aiming its dynamic characteristics before the integration of the bimorph piezoelectric energy harvester. Then, these analyses results are also validated through experimental modal analyses. The suitable location for the integration of the bimorph piezoelectric energy harvester is decided by investigating both the first and the second out-of-plane bending displacement mode shapes of the trapezoidal plate. The harvester is finally located to most convenient location with minimal structural displacement in order to maintain the same passive dynamic characteristics of the host structure. Following this, a finite element analysis is conducted for the trapezoidal plate hosting the bimorph piezoelectric energy harvester. It is observed from this finite element analysis and the experimental verification results that the resonance frequencies of the trapezoidal plate are slightly altered and the resonance frequency of the bimorph piezoelectric energy harvester is decoupled. After verifying the proposed design approach, a ground vibration and wind tunnel tests are performed to investigate the energy harvesting capability of the bimorph piezoelectric energy harvester. In these vibration tests, voltage output of the bimorph piezoelectric energy harvester around its first resonance frequency is investigated through a shaker excitation. Furthermore, the energy generated by the bimorph piezoelectric energy harvester is also examined via wind tunnel tests. It can be concluded from the analyses results that, in order to get higher voltage levels, the flow harvester should be excited around its fundamental natural frequency as the maximum strain level is achieved.

During the wind tunnel test, both AC and DC voltage generation of the flow harvester are investigated. As a known fact that the piezoelectric materials generate AC voltage under the vibration excitation, a rectifier type of a circuit is used to transform it to DC one. As it can be seen from the obtained analyses results, a considerable amount of DC voltage is generated by the bimorph piezoelectric energy harvester and it can be concluded that a low energy level system could be operated or batteries could be charged through the harvester via the rectified voltage.

As a conclusion, in this research paper, a design methodology of a piezoelectric energy harvester for a trapezoidal plate is provided and various test scenarios are also explained in details. The finite element models are constructed for both host structure and the harvester and these models are then validated by experimental studies. Moreover, the wind tunnel tests are also performed in order to investigate the real life performance of the harvester. Although further detail analyses regarding aerodynamic, aeroelastic, flutter or such can also be performed in order to investigate the performance of an air vehicle with the new integrated structure, it is observed from this particular research study that the proposed design is a realizable one as the piezoelectric beam energy harvester integrated on a trapezoidal plate.

Acknowledgments

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”.

References

Abdelkefi, A. (2016), “Aeroelastic energy harvesting: A review”, *Int. J. Eng. Sci*., **100**, 112-135.
Advanced Linear Technology (2007), “EH300/EH301 EPAD® ENERGY HARVESTING Modules for low power applications”, USA.
Akaydin, H.D., Elvin, N. and Andreopoulos, Y. (2013), “Chapter 10, flow induced vibrations for piezoelectric energy harvesting”, (Eds., Niell Elvin and Alper Erturk), Advances in Energy Harvesting Methods, pp 241-267, Springer Science and Business Media, Newyork, USA.
Ali, M., Arafa, M. and Elaraby, M. (2013), “Harvesting energy from galloping oscillations”, *Proceedings of the World Congress on Engineering 2013 Vol III*, WCE 2013, July 3 - 5, 2013, London, U.K.
Amoroso, F., Pecora, R., Ciminello, M. and Concilio, A. (2015), “An original device for train bogie energy harvesting: a real application scenario”, *Smart Struct. Syst.*, **16**(3), 383-399.
ANSYS Workbench 14.0 Help Manual (2011).
Anton, S.R. (2011), “Multifunctional Piezoelectric Energy Harvesting Concepts”, PhD Dissertation, University of Virginia Tech, USA.
APC International (2011), *Piezoelectric Ceramics: Principles and Application (Paperback)*, Mackeyville, PA USA.
Arms, S.W., Townsend, C.P., Churchill, D.L., Galbreath, J.H., Corneau, B., Ketcham, R.P. and Phan, N. (2008), “Energy harvesting, wireless, structural health monitoring and reporting system”, P*roceedings of the 2nd Asia Pacific Workshop on SHM*, Melbourne.
Available at: www.bksv.com/Products/transducers/vibration/accelerometers/accelerometers/4517.aspx (accessed in July 2015)
Available at: www.bksv.com/Products/transducers/vibration/impact-hammers/8206.aspx (accessed in July 2015).
Bae, J.S. and Inman, D.J. (2013), “Aeroelastic characteristics of linear and nonlinear piezo-aeroelastic energy harvester”, *J. Intel. Mat. Syst. Str*., 1-16.
Brüel&Kjaer PULSE Software Help Manual (2014).
Bryant, M. and Garcia, E. (2011), “Modeling and testing of a novel aeroelastic flutter energy harvester”, *J. Vib. Acoust*., **133**, 011010 (11pp).
Dai, H L., Abdelkefi, A. and Wang, L. (2014), “Theoretical modeling and nonlinear analysis of piezoelectric energy harvesting from vortex-induced vibrations”, *J. Intel. Mat. Syst. Str*., 1-14, doi: 10.1177/1045389X14538329.
Dai, H.L., Abdelkefi, A. and Wang, L. (2014), “Piezoelectric energy harvesting from concurrent vortex-induced vibrations and base excitations”, *Nonlinear Dynam*., **77**, 967-981.
Erturk, A. (2011), *Piezoelectric Energy Harvesting*, John Wiley and Sons, West Sussex, United Kingdom
Erturk, A., Vieira, W.G.R., De Marqui, Jr., C. and Inman, D.J. (2010), “On the energy harvesting potential of piezoaeroelastic system”, *Appl. Phys. Lett*., **96**, 184103-1-184103-3.
Gao, X. (2011), “Vibration and Flow Energy Harvesting using Piezoelectric”, PhD Dissertation, Drexel University, USA.
Hobeck, J.D. and Inman, D.J. (2012), “Artificial piezoelectric grass for energy harvesting from

turbulence-induced vibration", *Smart Mater. Struct.*, **21**, 105024 (10pp).
Hofmann, H. (2011), Power Electronic Circuits for Vibration-Based Energy Harvesting using Piezoelectric Devices. Available at: http://www.psma.com/sites/default/files/uploads/tech-forums-energy-harvesting/presentations/2011-apec-sp-111-power-electronic-circuits-vibration-based-energy-harvesting-using-piezoelectric-dev.pdf (accessed in July 2015)
Kahraman, E. (2011) "Investigation of the Dynamic Properties of Trapezoidal Plates", MSc. Dissertation, METU, Turkey.
Koyvanich, K., Smithmaitrie, P. and Muensit, N. (2015), "Perspective microscale piezoelectric harvester for converting flow energy in water way", *Adv. Mater. Lett.*, **6**(6), 538-543.
Liu, H., Zhang, S., Kathiresan, R., Kobayashi, T. and Lee, C. (2012), "Development of piezoelectric microcantilever flow sensor with wind-driven energy harvesting capability", *Appl. Phys. Lett.*, **100**, 223905; doi: 10.1063/1.4723846
Marqui Jr., C.D. and Erturk, A. (2012), "Electroaeroelastic analysis of airfoil-based wind energy harvesting using piezoelectric transduction and electromagnetic induction", *J. Intel. Mat. Syst. Str.*, **24**(7), 846-854.
Marqui Jr., C.D., Vieira, W.G.R., Erturk, A. and Inman, D.J. (2011), "Modeling and analysis of piezoelectric energy harvesting from aeroelastic vibrations using the doublet-lattice method", *J. Vib. Acoust.*, **133**, 011003-1 (9pp).
Mehmood, A., Abdelkefi, A., Hajj, M.R., Nayfeh, A.H., Akhtar, I. and Nuhait, A.O. (2013), "Piezoelectric energy harvesting from vortex-induced vibrations of circular cylinder", *J. Sound Vib.*, **332**, 4656-4667.
Mercan, B., Ostovan, Y., Dogan, E. and Uzol. O. (2010), "Effect of chordwise modulated waveform tip injection on the characteristics of the tip vortex", *Proceedings of the 40th Fluid Dynamics Conference and Exhibit*, Chicago, Illinois, USA
National Instrument Data Acquisition System Help Manual (2014).
National Instrument Signal Express Software Help Manual (2014).
Sarıoğlu, M. and Yavuz, T. (2000), "Vortex shedding from circular and rectangular cylinders place horizontally in a turbulent flow", *Turk J. Engin. Environ. Sci.*, **24**, 217-28.
Shan, X., Song, R., Liu, B. and Xie, T. (2015), "Novel energy harvesting: A macro fiber composite piezoelectric energy harvester in the water vortex", *Ceramics Int.*, **41**, 763-767.
Smart Material Corp (2012), Macro Fiber Composite – MFC.
Smart Material Corp. (2012), "Energy Harvester Development Kit", Germany.
Song, R., Shan, X., Lv, F., Li, J. and Xie, T. (2015), "A novel piezoelectric energy harvester using the macro fiber composite cantilever with a bicylinder in water", *Appl. Sci.*, **5**, 1942-1954.
Sousa, V.C., Anicezio, M.D.M., Marqui Jr., C.D. and Erturk, A. (2011), "Enhanced aeroelastic energy harvesting by exploiting combined nonlinearities: theory and experiment", *Smart Mater. Struct.*, **20**, 094007 (8pp).
Techet, A.H. (2010), "Vortex Induced Vibration- Lecture Notes", Massachusetts Institute of Technology, USA.
Wang, H., Tang, L., Shan, X., Xie, T. and Yang, Y. (2014), "Modeling and performance evaluation of a Piezoelectric Energy Harvester with segmented electrodes", *Smart Struct. Syst.*, **14**(2), 247-266.
Zhu, D. (2011), "Chapter 2: Vibration Energy Harvesting: Machinery Vibration, Human Movement and Flow Induced Vibration", www.intechopen.com.
Zhu, D., Beeby, S., Tudor, J., White, N. and Harris, N. (2010), "A novel miniature wind generator for wireless sensing applications", *Proceedings of the IEEE Sensors 2010*, ISBN 978-1-4244-8170-5, Waikoloa, Hawaii, USA.

CC