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ENERGY HARVESTING STUDIES ON FIN LIKE STRUCTURE VIA PIEZOELECTRIC MATERIAL

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ABSTRACT

In recent days, alternative energy resources are discussed as an important topic for different applications, therefore an extensive study is conducted for the sustainable and renewable energy resources. One alternative method for energy harvesting is to use piezoelectric materials. Due to the nature of the piezoelectric materials, they can generate electricity under vibratory loading. In these types of applications, it is not possible to obtain huge energy but the batteries can be charged via these methods. 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, energy harvesting from fin like structure via piezoelectric material is presented. For this aim, finite element model is constructed in ANSYS Workbench 14.0 and this model is validated by experimental techniques. Under the air loading; energy harvesting performance of the piezoelectric materials attached to the fin like structure, is also investigated experimentally.

INTRODUCTION

Energy harvesting from different techniques, solar, wind or vibration, is a very hot topic in recent days. Environmental pollution and global warming is increasing rapidly due to increase in carbon pollution. In order to eliminate or reduce carbon emission, alternative energy sources should be found. Another reason is that the energy need of middle and/or small size structures are supplied by batteries. Using batteries is not effective regarding the maintenance cost and reliability of the system. Therefore batteries should be replaced by energy harvesting systems. Energy harvesting is defined as [1]:

“Energy harvesting: Energy recovery from freely available environmental resources. Primarily, the selection of the energy harvester as compared to other alternatives such as battery depends on two main factors: cost effectiveness and reliability. Another goal for energy harvesters has been to recharge the batteries in existing applications.”

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 [2]. By using vibration-based energy harvesting system, replacement cost and chemical contamination of the batteries, due to lead, can also be eliminated [2].

Alternatively, piezoelectric materials are also used in vibration-based energy harvesting systems. The reason is from the fact that when piezoelectric material is deformed mechanically, it can produce voltage difference because of the nature of it. This phenomenon can happen conversely and therefore piezoelectric material can be used as a sensor in order to sense the motion of structures where they are bonded [3].

The energy management of a critical component, such as an aero-servo elastic system of an aircraft or sensors for structural health monitoring system can be supplied by vibration-based energy harvesting system. For example, energy harvesting characteristics of piezoaeroelastic system are

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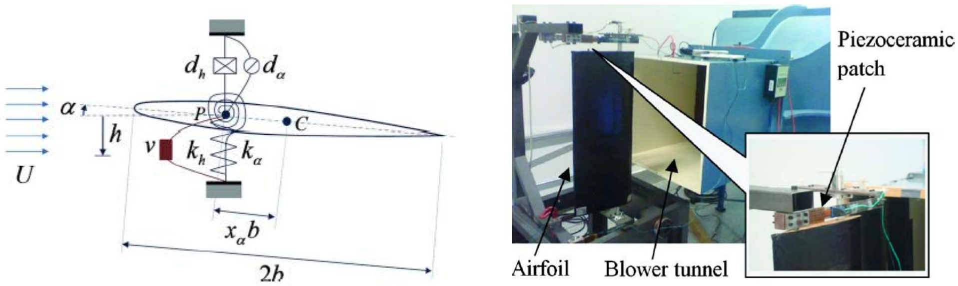
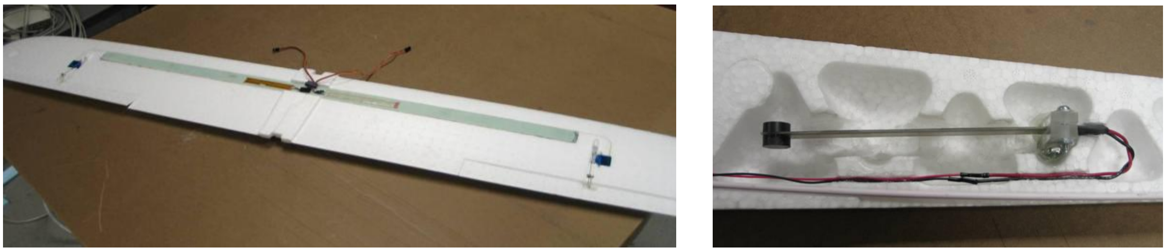
analyzed by lumped parameter wing section model [4]. In this particular study, piezoceramic patch is placed to plunge stiffness member of the system. Due to the air excitation, energy is harvested from the piezoaeroelastic system shown in Figure 1.



(a) (b)

Figure 1: (a) Piezoaeroelastic Model of Wing System (b) Wind Tunnel Test Experiment for Piezoaeroelastic System [4]

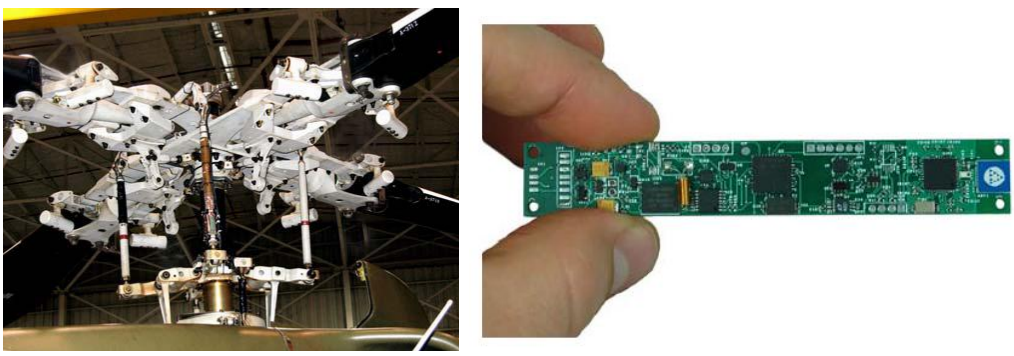
Different types of piezoelectric patches are used in unmanned air vehicles (UAV) to investigate their voltage output characteristics [5]. In this particular research study, macro fiber composite patch (MFC), piezoelectric fiber composite (PFC) patch and PFC cantilevered with polycarbonate base and tip mass are integrated to UAV for harvesting energy and shown in Figure 2.



(a) (b)

Figure 2: (a) MFC and PFC Patches (b) PFC Cantilevered with Polycarbonate Base with Tip Mass [5]

The energy need of critical sensors for structural health monitoring system in the aircraft should also be considered carefully. It is practically impossible to use cables for the sensors located especially in the rotating wing aircrafts near the rotating components. Therefore, wireless sensors should be used and energy need for the wireless sensors should be supplied by batteries. It is already known that if the battery is used, the maintenance and replacement cost and reliability of the system should also be considered carefully. In order to eliminate battery usage, vibration-based energy harvesting system can be integrated into the system. For instance, structural health monitoring system, which is integrated into rotating wing aircraft near the main rotor, is developed for measuring data of strain and/or acceleration etc. [6]. Due to the location of the sensor, this process should be wireless and therefore piezoelectric energy harvesting system can be used to operate a wireless sensor.

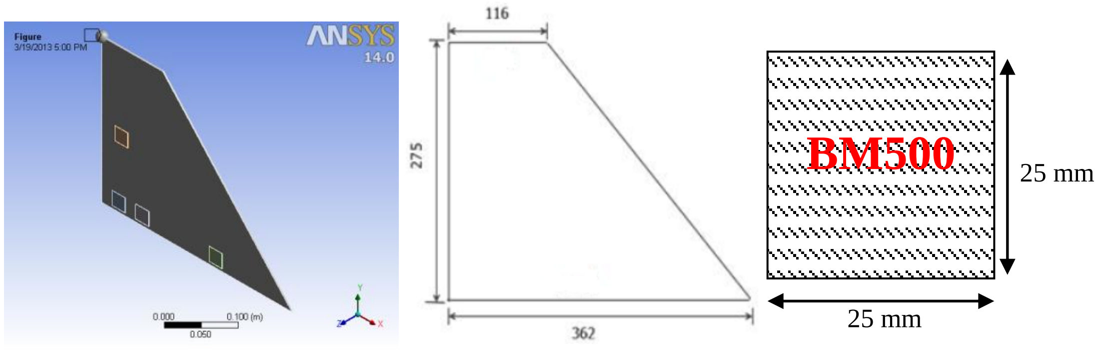


(a) (b)

Figure 3: (a) Helicopter Main Rotor System (b) Wireless Sensor with Energy Harvesting System [6]

FINITE ELEMENT MODEL OF SMART FIN

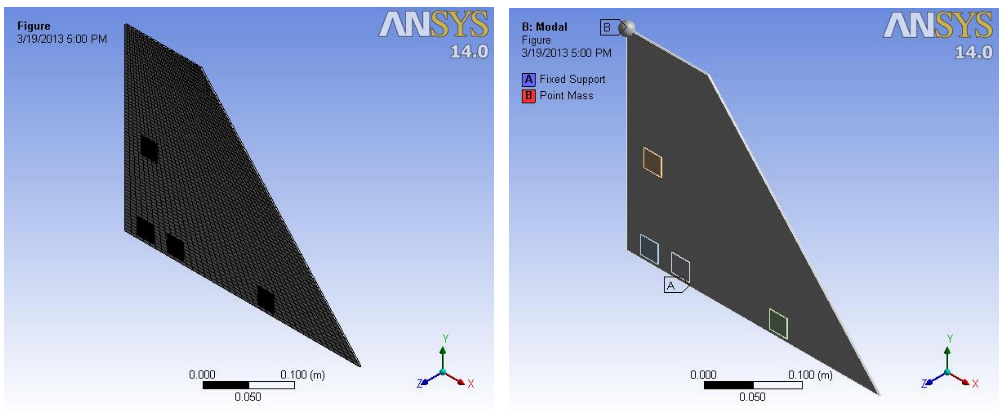
First of all, solid model of smart fin is constructed in CAD software and it is directly used in finite element program, which is ANSYS Workbench 14.0 [7]. Smart fin, aluminum type 6061-T6, consists of 4 piezoelectric patches. These patches are made up of BM 500 [8] piezoelectric material. The geometry of both smart fin and the piezoelectric patches are given in Figure 4.



(a) (b) (c)

Figure 4: (a) General View of Smart Fin, (b) Geometry of Smart Fin and (c) Piezoelectric Patch

By using these geometries, mesh of the smart fin is generated in ANSYS Workbench 14.0 and shown in Figure 5(a). This mesh has 33000 nodes and 5000 elements. SOLID 226 element type is used for piezoelectric material and the fin is meshed by SOLID 186 element type. Following the mesh forming, modal analysis of this smart fin is performed to investigate the dynamic characteristic of the structure. In the modal analysis, fixed boundary condition is given to long edge of the smart fin which can be seen in Figure 5(b). In this analysis, mass of the accelerometer which is used in experimental validation of finite element modal is also added to structure.



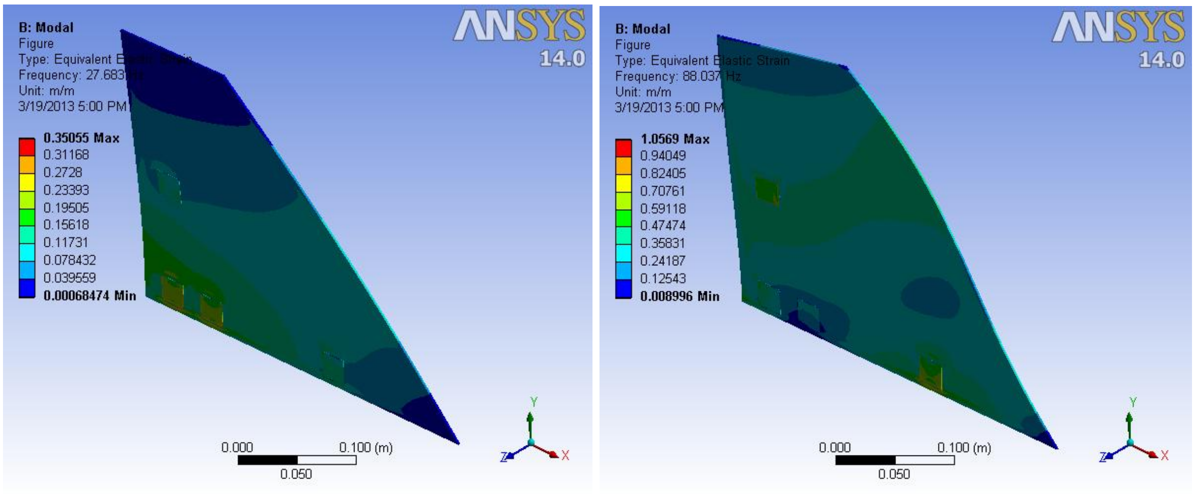
(a) (b)

Figure 5: (a) The Mesh of the Smart Fin (b) The Boundary Condition of the Smart Fin

After performing modal analysis, the first two natural frequencies of the smart fin are found and tabulated in Table 1. The strain mode shapes corresponding to each natural frequency are also given in Figure 6.

Table 1: The First Two Natural Frequencies of the Smart Fin

Mode Number	Finite Element (Hz)
1st Out-of-plane Bending	27.68
2nd Out-of-plane Bending	88.04



(a) (b)

Figure 6: The Strain Mode Shapes of Smart Fin

(a) The first out-of-plane bending (b) The second out-of-plane bending

EXPERIMENTAL VALIDATION OF THE FINITE ELEMENT MODEL OF THE SMART FIN

In order to validate the finite element analysis, four BM 500 piezoelectric patches are attached to the AL-6061-T6 fin like structure. Then, experimental modal analysis is conducted under modal shaker excitation (Figure 7) in order to obtain the resonance frequencies of the structure. The frequency response function (FRF) of the smart fin is obtained by under random vibration input via PULSE software [9] and they are presented in Figure 8. The results of the finite element and experimental study are then compared and summarized in Table 2.

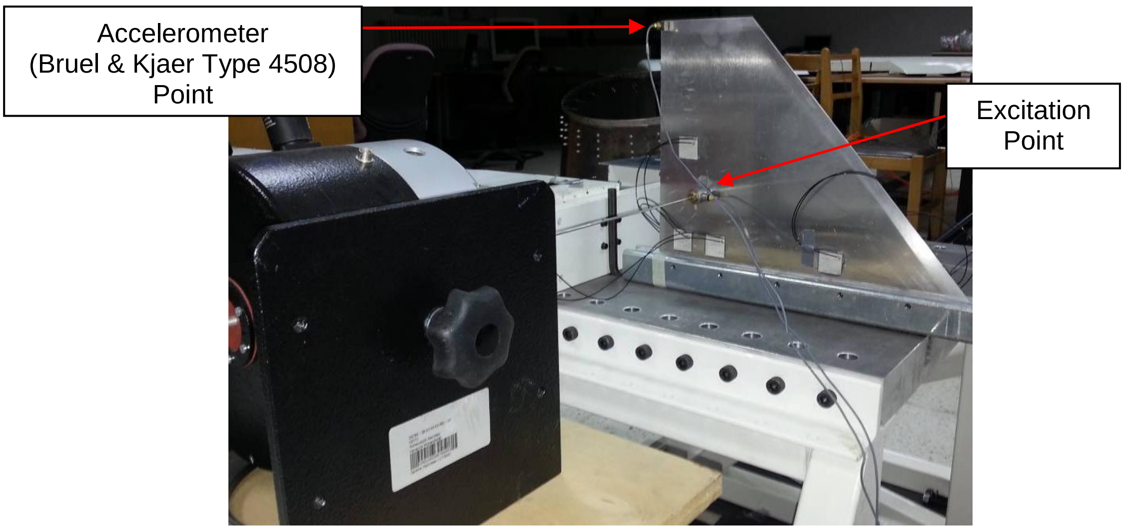


Figure 7: Experimental Setup of Smart Fin

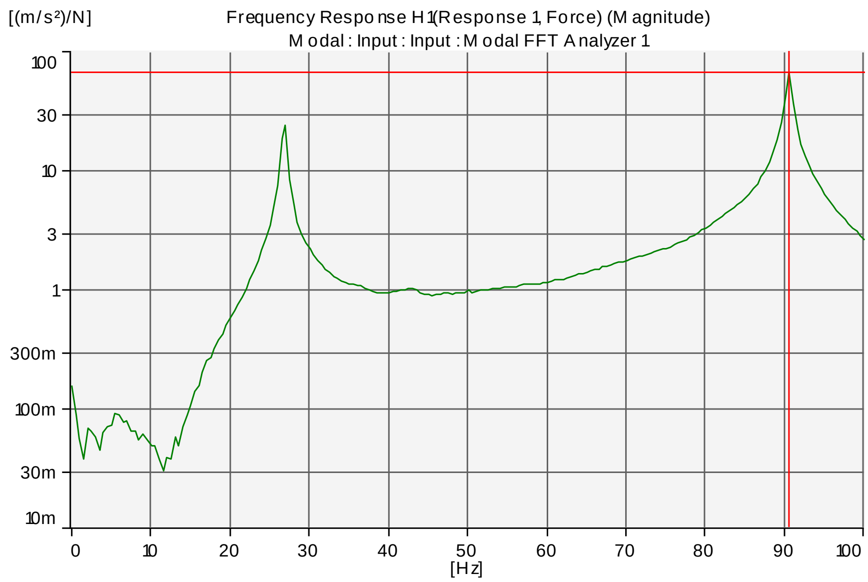


Figure 8: FRF of the Smart Fin

Table 2: Natural Frequencies of the Smart Fin

Mode Number	Finite Element (Hz)	Experimental (Hz)	Deviation (%)
1st Out-of-plane Bending	27.68	26.50	4.45
2nd Out-of-plane Bending	88.04	91.65	3.94

EXPERIMENTAL STUDIES ON ENERGY HARVESTING FROM SMART FIN UNDER AIR LOADING

In order to investigate the energy harvesting performance of the piezoelectric patches in real life conditions, a wind tunnel test is conducted. The setup for this test is shown in Figure 9. During the test, individual voltage generation of the patches is obtained by NI Data Acquisition System. The position and the name of each piezoelectric patches are given in Figure 10.

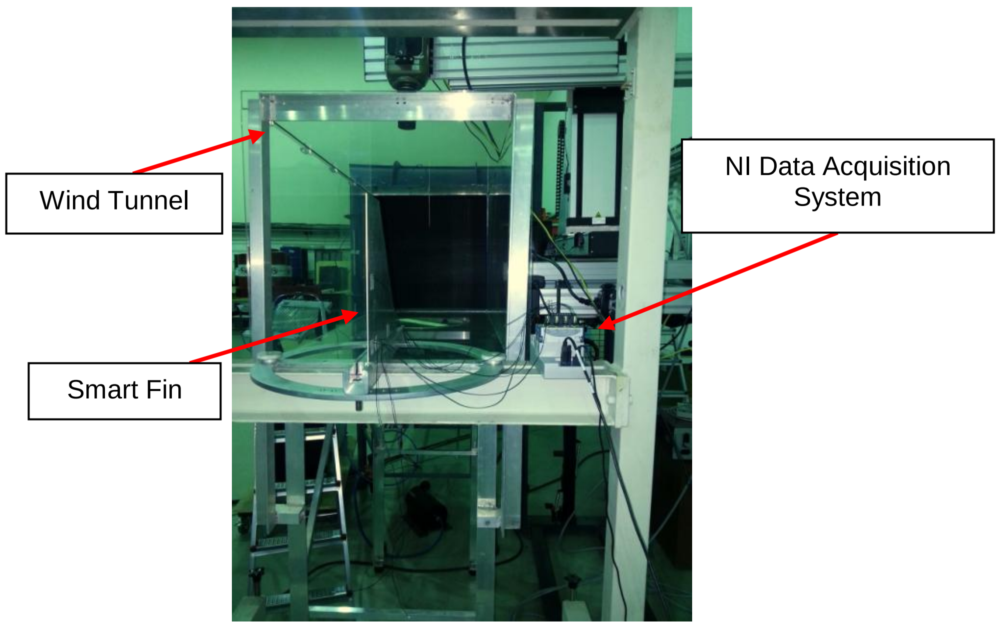


Figure 9: Wind Tunnel Experimental Setup

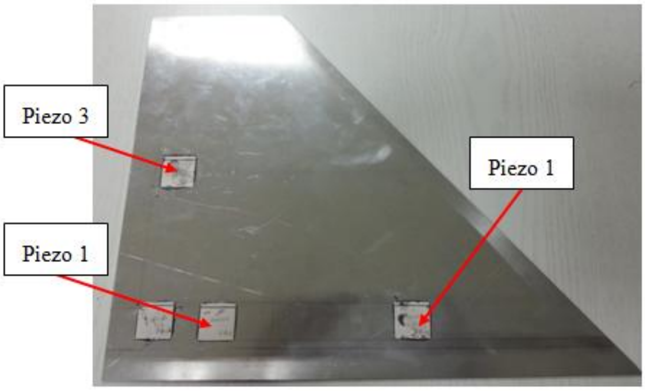


Figure 10: Position and Name of Each Piezoelectric Patches

Wind tunnel tests are performed under two different conditions. For the first test condition, in order to excite the smart fin at its first natural frequency, a vortex generator is used. For the second one, the vortex generator is not used and only the air speed is varied. At lower air speeds, the voltage generation is observed at very small levels. However, the voltage generation of each BM 500 is considerably high and can be used and converted as energy at higher air speed levels. The voltage generations of each BM 500 are given in Figure 11, 12 and 13 for the 15 m/s air speed.

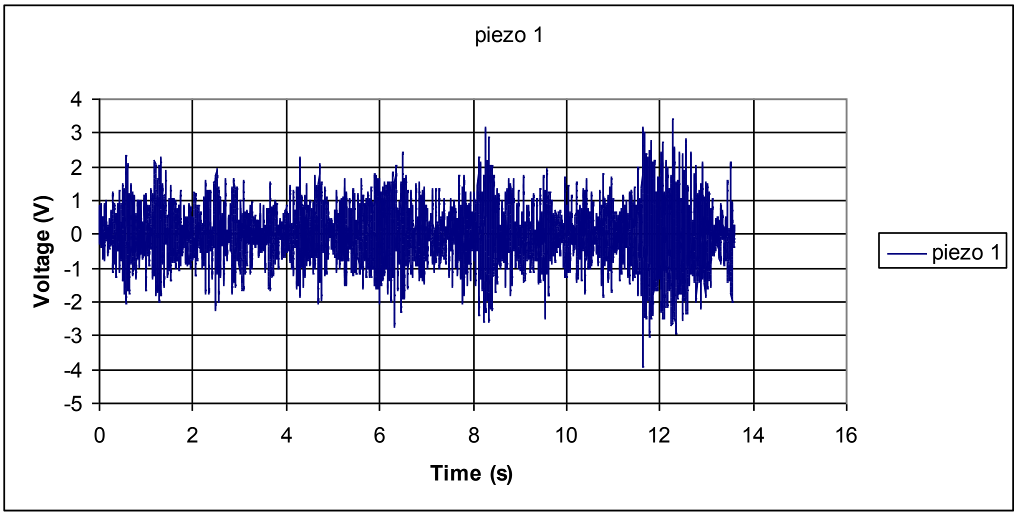


Figure 11: Voltage Generation of Piezo 1 under Air Flow

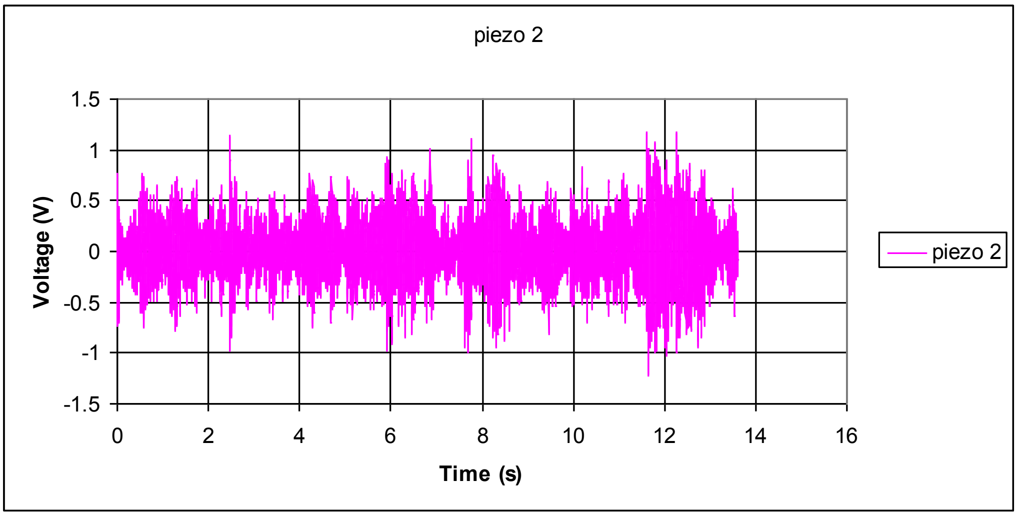


Figure 12: Voltage Generation of Piezo 2 under Air Flow

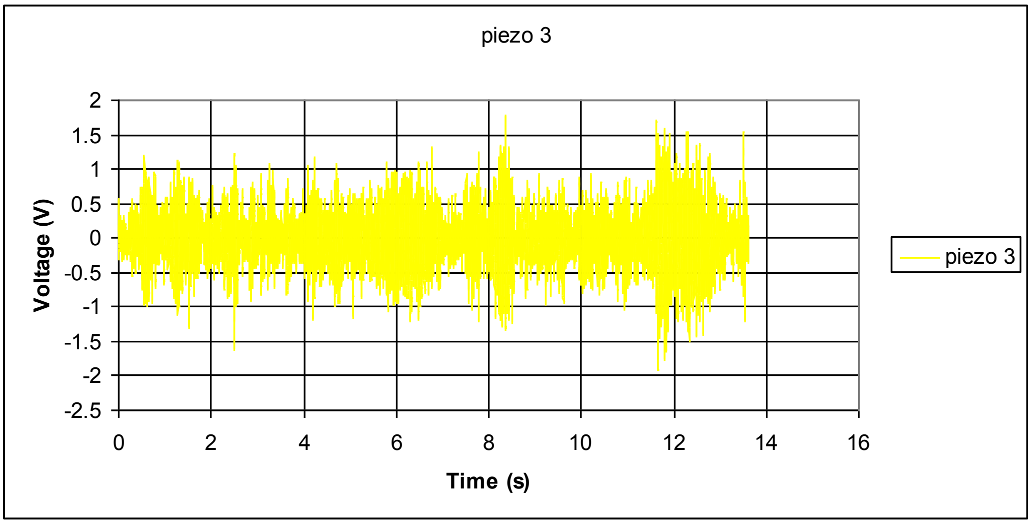


Figure 13: Voltage Generation of Piezo 3 under Air Flow

As explained before, vortex generator is used to excite the smart fin around its first natural frequency. If the vortex shedding frequency is close to the first resonance frequency of the smart fin, it is possible to excite the smart fin and the voltage generation of the piezo will be high. For this reason, 0.05 m diameter cylinder is used in the wind tunnel. Strouhal Number (St) can be taken as 0.2 for Reynolds Number (Re) < 10^5 for subcritical flow [10]. For the test condition, the flow is assumed to be subcritical and the St is also taken as 0.2. The vortex shedding frequency should be at around 26.50 Hz which is the first out-of-plane bending frequency of the smart fin. By using these parameters and the formula below, flow speed is calculated as 6.63 m/s. Finally, test setup for the vortex generator (Figure 14) can be constructed [11]. X is taken as 0.2 m and Y is chosen as 0.025 m during the tests.

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

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

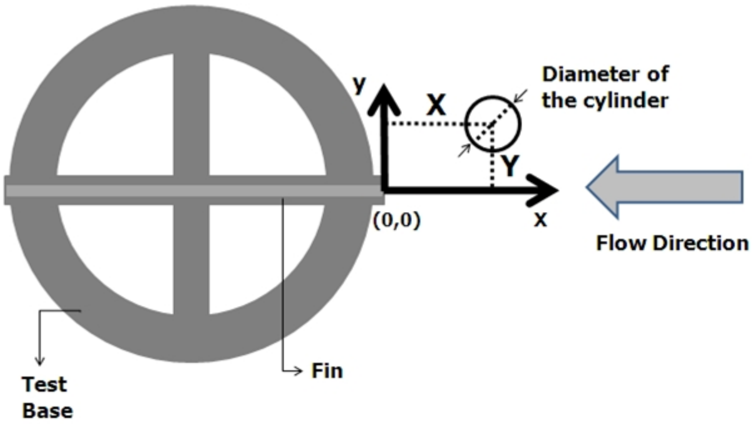


Figure 14: Vortex Generator Test Setup [11]

During the tests, time series of each piezo voltage output is collected by NI Data Acquisition System. The results obtained for the vortex generator usage are presented in Figure 15, 16 and 17.

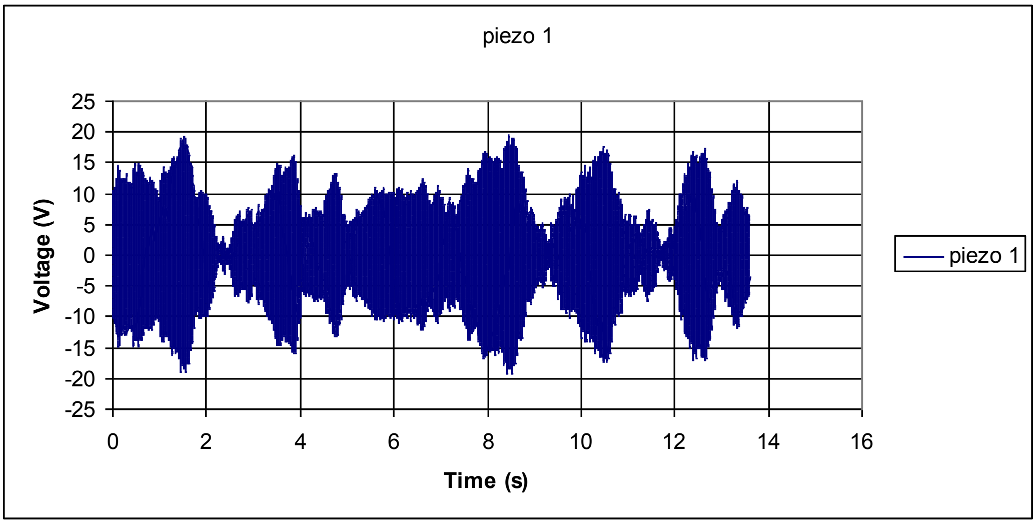


Figure 15: Voltage Generation of Piezo 1 with Vortex Generator

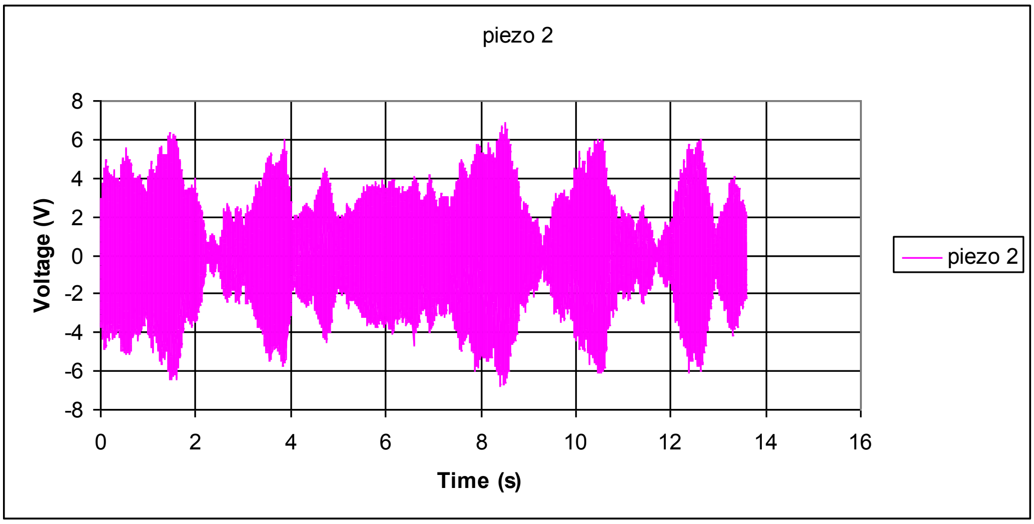


Figure 16: Voltage Generation of Piezo 2 with Vortex Generator

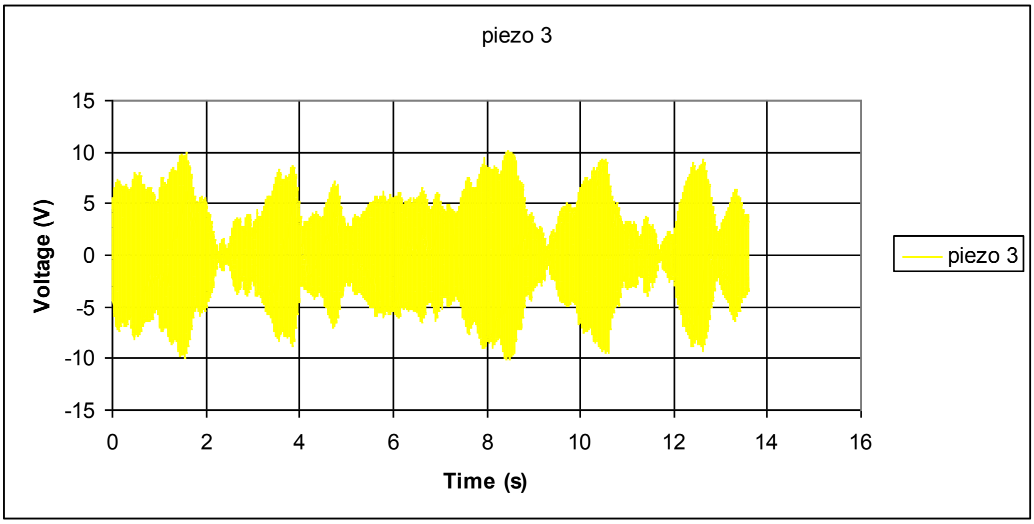


Figure 17: Voltage Generation of Piezo 3 with Vortex Generator

By taking the FFT of time series of piezo 1, response of the smart fin is found in the frequency domain and given in Figure 18. The first two natural frequencies of the smart fin obtained from this figure are found to be very close to results of both finite element and experimental modal analysis.

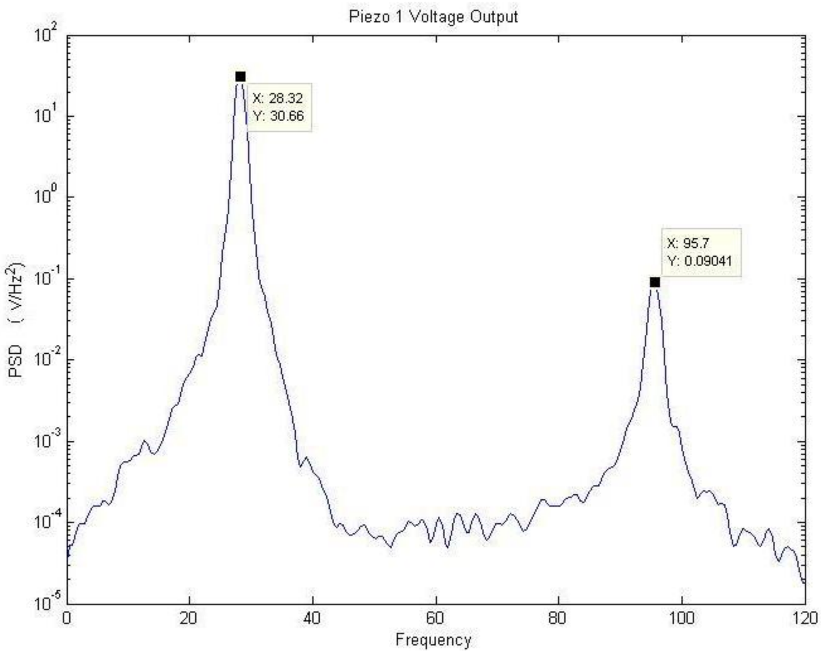
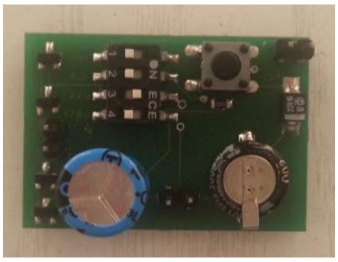
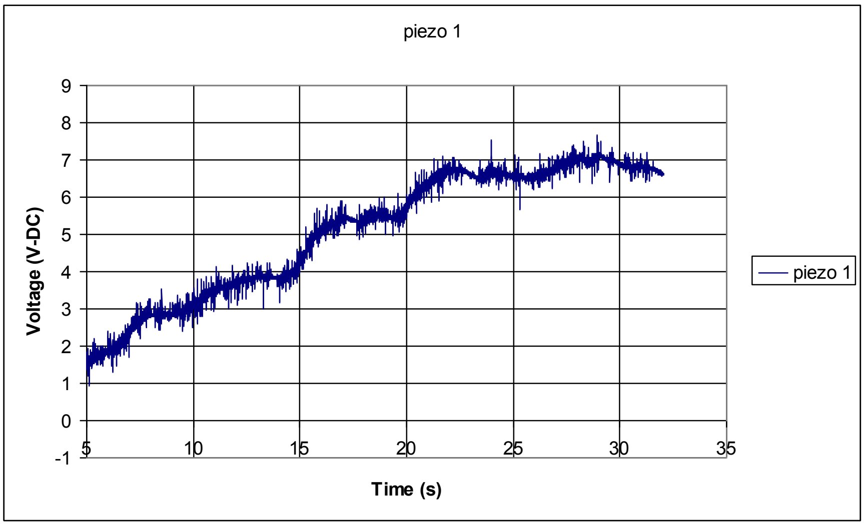


Figure 18: FFT of Time Series of Piezo 1 with Vortex Generator

As observed from the wind tunnel tests, piezoelectric materials generate AC voltage during the excitation of the smart fin. It is not possible to use this type of voltage to operate a system or charge a battery. In order to make this voltage useable, rectifier circuit should be used. The rectifier circuit [12] (Figure 19(a)) converting AC voltage to DC one is used during the wind tunnel tests. Piezo 1 is connected to this circuit and AC voltage generation of this piezoelectric material is rectified to the DC one and the result for this test is given in Figure 19(b).



(a)



(b)

Figure 19: (a) Rectifier Circuit and (b) AC to DC Voltage Conversion of Piezo 1

CONCLUSION

In this study, energy harvesting from the fin like aircraft structure is investigated. For this reason, finite element model is constructed and the dynamic properties of the harvesting system are obtained. Then, this finite element model is validated via experimental studies. As it can be seen from Table 2, both finite element and experimental results are very close to each other.

The energy generation of the piezoelectric patches on thin fin like structure is also examined under real conditions in the wind tunnel tests. The results indicated that, in order to get higher voltage levels, the smart fin should be excited around its natural frequencies as maximum strain levels are reached at around the resonances of the structure. Moreover, the dynamic characteristics of the smart fin are also obtained under the operational conditions (i.e. wind tunnel tests with vortex generator) by simply taking the FFT of the time series of piezo 1 regarding the first two natural frequencies.

Additionally, in order to operate a system or charge a battery, the rectifier type of circuit should be used to convert AC voltage of piezoelectric patches to DC one by making the voltage generation of piezoelectric patches useable for the energy harvesting systems.

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