**Energy Equipment and Systems**

# Development of a laboratory system to investigate and store electrical energy from the vibrations of a piezoelectric beam

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ABSTRACT

*Energy harvesting from surrounding environment has been attractive for many researchers in recent years. Therefore, developing appropriate test apparatus to study energy harvesting mechanisms and their performance is of paramount importance. Due to their electromechanical characteristics, piezoelectric materials are used for harvesting energy from environmental vibrations. For optimum utilization of this system in harvesting and storing energy, the studies need to consider the environmental conditions. In this work, the electromechanical system is developed with the aim of conducting tests on piezoelectric materials. It is an integrated system which is developed and built after considering the limitations and sensitivity of piezoelectric material. In this research, the simple piezoelectric beam is also tested. Evaluation results via this system are analysed using Abaqus. The error value in receiving output voltage is 6% because an ideal open circuit state is considered by this software.*

## 1. Introduction

Piezoelectric materials can convert mechanical energy into electrical energy and vice versa [1]; therefore, they can convert wasted ambient vibrations into electrical energy. Based on the amount of electric power that these materials can generate, they can be considered for use in supplying energy to wireless systems. Energy harvesting from vibrations and motions has developed remarkably in recent years. Through the use of certain materials in shoes, e.g. lead zirconate titanate (PZT), Paradiso et al worked towards parasitic harvesting and simultaneous storage of energy from human walking motions [2]. Oh et al established an experimental investigation of a tree-shaped wind power system using piezoelectric materials [3]. Sonado et al developed a novel energy harvesting backpack that can generate electrical energy from the different forces between the wearer and backpack [4]. In order to obtain analytical expressions, several others [5–7] used the vibration mode shapes obtained from the Euler–Bernoulli beam theory along with the piezoelectric constitutive equation (that gives the electric- displacement) to relate the electrical outputs to the vibration mode shape. The important deficiencies in these mathematical modelling attempts and others were summarized in the literature [8], and they include the lack of consideration of the resonance phenomenon, ignorance of modal expansion, misrepresentation of the forcing due to base excitation, oversimplified modelling of piezoelectric coupling in the beam equation as viscous damping, and use of the static sensing / actuation equations in a

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fundamentally dynamic problem. Shu and Lien [9] represented the piezoelectric energy harvester by a lumped-parameter system. Some other researchers have focused on to the development of analytical and experimental methods on electric circuits to store the electricity generated by the harvester.

Guan and Liao proposed a quick test method to experimentally study the charge and discharge efficiencies of the energy storage devices by using super capacitors, which are suitable and more desirable than the rechargeable batteries [10]. A rectifier-free piezoelectric energy harvesting circuit has been suggested by Kiet el al [11]. The suggested circuit was simple and capable and could reach 71% of high conversion efficiency. In most studies, when different factors are examined in the piezoelectric materials coupled with electrical and mechanical equations, elements like nonlinearity, ambient factors, and type of connections are often ignored [12].

Considering the increasing use of piezoelectric materials in the harvesting and accumulating of ambient energy, it seems essential to examine their electrical and mechanical behaviour under different conditions. Since these materials are mostly used in a self-charging manner, they are often installed at long distances or under difficult ambient conditions. Therefore, it is of great importance to analyse their electro-mechanical behaviour and the amount of electric power generated by them. The purpose of this study is to set up an electro-mechanical laboratory system to analyse piezoelectric beams, harvest energy from them, and simultaneously store the energy. An

energy-harvesting system from ambient vibrations has four distinct stages: a) ambient vibration energy, b) Piezoelectric energy harvester, c) AC-DC converter and regulator circuit with a storage component, and d) Low power electrical device. All of the above mentioned stages were conducted empirically here, following which verification analysis and sample tests were performed by the developed system.

## 2.Developing a Vibration-Generating System As a Motion Source

Most ambient vibrations and motions have a low frequency manner (less than 50 Hz). Examples include motions in sea waves, aircraft wings, and human activities. Laboratory systems that examine the optimal harvesting energy from ambient vibrations must generate vibrations within given displacements throughout this frequency range. In this study, a laboratory system is designed and built for the study of piezoelectric beams. The developed system is shown in Fig.1. The vibration-generating system is made up of an electro-motor, a power transmission shaft, rotational unbalance mass, a chassis, and an inverter. In this system, the applied frequency range can be changed from 0 to 40 Hz. The inverter can be used to change the input frequency of the system, by varying the input voltage of the system. Here, the percentage of inverter error is about 0.02%. The output shaft of the electro-motor is connected, by means of a mechanical coupling, to a support that has a double-row ball bearing. Since the ball bearing is of the 'rigid' type, the unbalance



**Fig.1.** Laboratory system for study of piezoelectric beams 1.Electromotor 2.Shaft 3 Support 4.Disk 5.Mis-alaighnement mass 6.Chassis 7.Inverter 8. Electrical circuit 9. Piezoelectric beam

force will not cause run-out during rotation. An aluminium disk is connected to the end of the shaft. Due its easy and more-homogeneous machining capability as compared to other metals available in market, aluminium is selected for constructing the disc. To provide more options in generating unbalance loads, 12 row containing 4 holes each were drilled on the aluminium disc. The rows are placed within 30 degrees circumferential pitch. When unbalance copper masses are added to the disk, some loads are transferred to the system. Table 1 show the materials used in the components and their dimensions.

The vibration-generating system is mounted on a rigid chassis; consequently, the unbalance force does not have a noticeable effect (deformation) along the x-axis. We used an accelerometer to measure the base displacement amplitude of the piezoelectric beam. By using displacement amplitude and frequency as input variables, the base excitation for the beam in the form of displacement can be written as Eq.(1).

$$Y=Y_0 \sin(\omega t) \tag{1}$$

where, $Y_0$, $\omega$, and t demonstrate Amplitude at y direction, frequency, and time respectively. This system can be a real example of one where we can examine the harvesting of energy from the wing motions of an unmanned aerial vehicle (UAV). In this case, the electro-motor is representative of the UAV engine.

# 3. Development of a Data Logger System to Evaluate Generated Electric Power

Major problems appeared in the analysis of the data from piezoelectric including noise and lack of full power capture, as well as the voltage produced by the piezoelectric. Thus, the design and implementation of an electrical circuit for obtaining and storing data from piezoelectric, particularly one that is able to provide reliable analysis, is of great importance. In recent years, the use of microprocessors in capturing and analysing data has seen remarkable advancement. Due to their low power consumption, easy programming capability and acceptable buffer at low volume systems, 'ARM'[1] microprocessors are generating serious interest. Figure 2 illustrates the circuit designed to capture and store data from piezoelectric excitation. Section B shows the piezoelectric signal-conditioning unit of receiving voltage. It consists of two sub-levels, namely B-1 and B-2. It also completes the piezoelectric output monitoring and is responsible for delivering it to the microprocessor. Capacitors and inductors are used in order to accurately receive the output voltage of piezoelectric. A piezoelectric has an inherent capacitance which is modelled electrically in the simulation of the piezoelectric [8]. This results in the appearance of an unexpected DC voltage due to gradual charge/discharge of the voltage in cases when the piezoelectric experiences a

Table 1.Mechanical information of vibration-generator

|  | **Material** | **Size** |
|---|---|---|
| Chassis | Steel, SAE1075 | 500*300*5 (l*w*h)[2]mm |
| Support | ALUMINIUM | 40*90*90 (l*w*h) mm |
| electromotor | - | 220*140 (d*h)[3] |
| Bolts | IRON METAL | M8.8 |
| Unbalance mass | COPPER | 10*27 (d*h) |
| Shaft | Steel, SAE1045 | 10*100 (d*h) |
| Disk | ALUMINUIM | 100*4 (d*h) |

[3]Diameter*Height (D*Z)

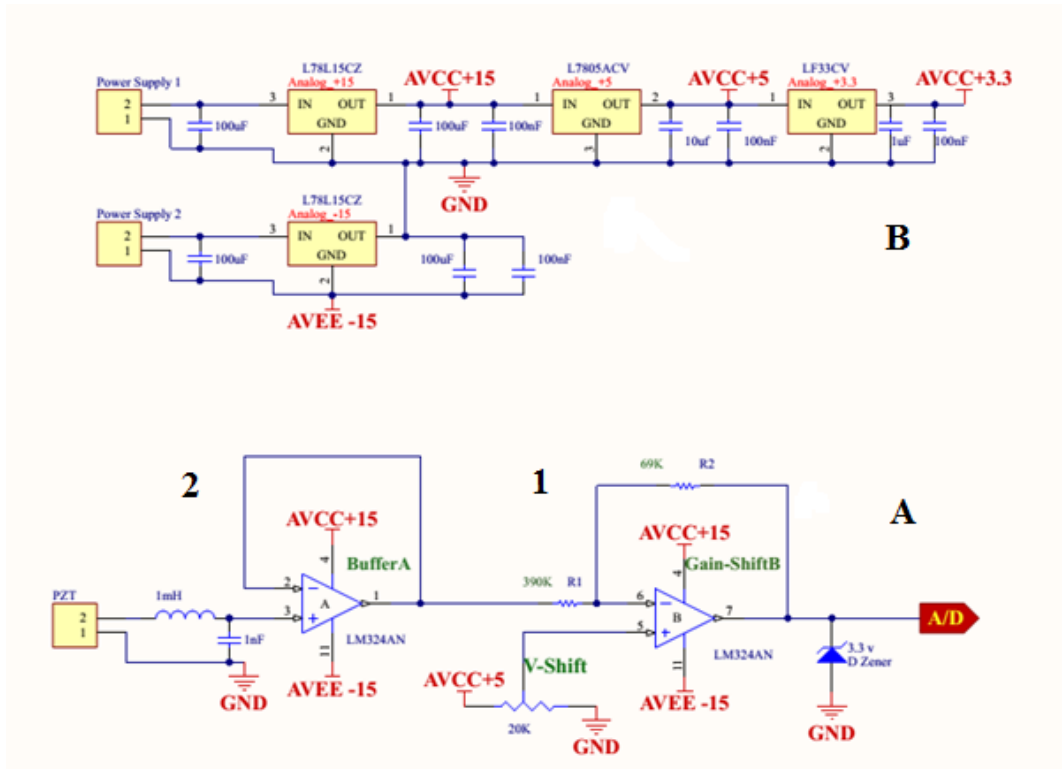[1]Advanced RISC Machine
[2]Length*Width*Height(Z*X*Y)

**Fig.2.** Designed circuit for capture and transmit data from piezoelectric to microprocessor
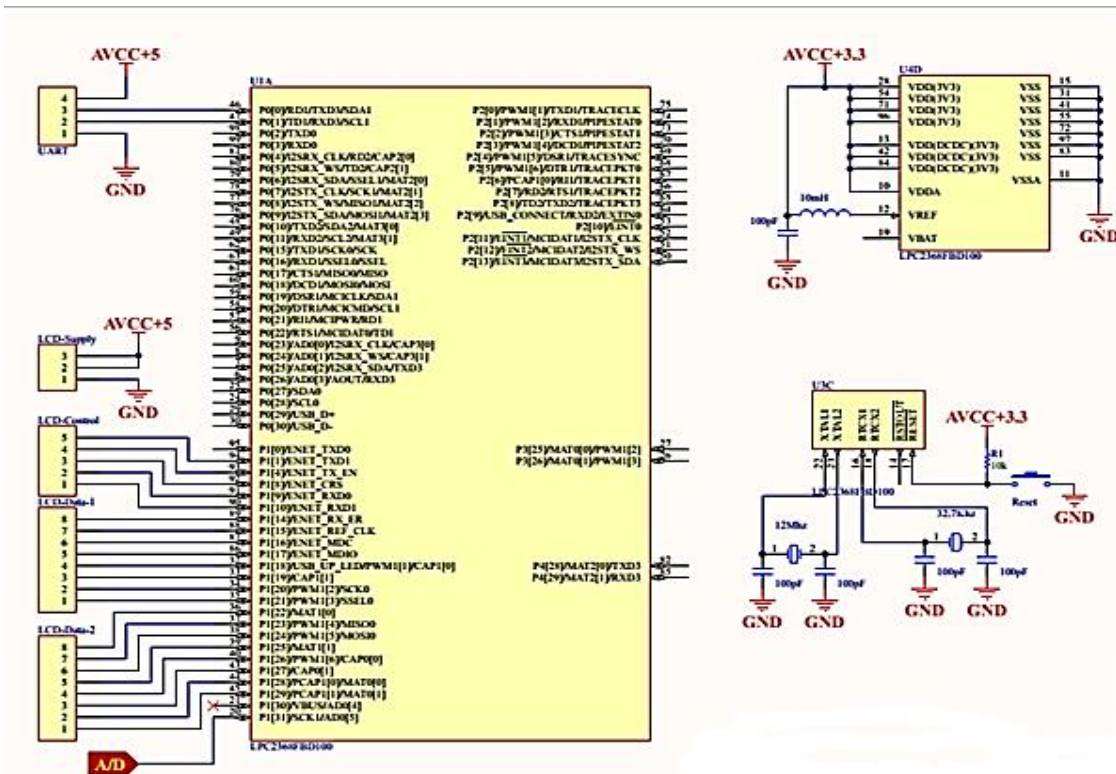


**Fig.3.** Designed circuit of ARM-LPC1768 microcontroller

mechanical impact. In a detailed evaluation with specific inputs, this makes the analysis inaccurate. For this reason, a capacitor of 1 NF is inserted in the series with piezoelectric output, while for reference voltage A/D on the ARM microprocessor board, a 3.3 volt regulator is used. Thus, voltage range of (0, 3.3 volts) should be used for the channel input A/D of the microprocessor. OP-AMP (B-2) is placed for voltage regulation and voltage production in the range of 0.3.3 volts. For detailed sampling of actual voltage output from the piezoelectric, an almost-infinite resistor should be placed on the path, in order for it to be considered an open circuit. Accordingly, a sub-level buffer is used at the beginning of the OP-AMP (B-1). In fact, the output of OP-AMP (B-1) which is closed with a buffer follows the input identically. Figure 3 depicts the circuit design of ARM-LPC1768 microcontroller. Data processed in the micro controller through an USB port on the PC is entered into MATLAB.

## 4.Energy storage system

The piezoelectric output voltage is an AC voltage. For storage purposes, this voltage should be converted into a DC voltage. Thus, a rectifier is used. Figure 4 depicts the schematic diagram of this circuit. Part (a) in this figure shows the piezoelectric internal circuit. In general, this circuit has a RLC. Part (b) also shows the bridge diode circuit. R-bleed shown in this figure is a high value resistor in order to avoid any voltage from the intrinsic capacitor, when no excitation is exerted on the piezoelectric material. The existence of voltage in the system compensates for the strain in the beginning and then harvests energy when the system is excited. In addition, by putting an electric resistor in front of piezoelectric output voltage, the maximum harvested piezoelectric power can be calculated. According to Fig. 5, it can be seen that by increasing the electric resistor in the current path, electric power will also increase, and then, decrease.

In addition, as given in Table 2, an electric resistor in which the electrical energy reaches the maximum value is 80kΩ. This resistor is important for two reasons. First, when piezoelectric material is used, this resistor should be employed in the consumer. Second, this resistor may be used to calculate internal impedance of the piezoelectric material. It should be noted that the numbers of Table 2 are obtained in the first natural frequency of the piezoelectric beam.

The research reveals that for voltage sources such as piezoelectric, which has high impedance in output and low current rate, silicon diodes are the best choice for making the bridge diode.
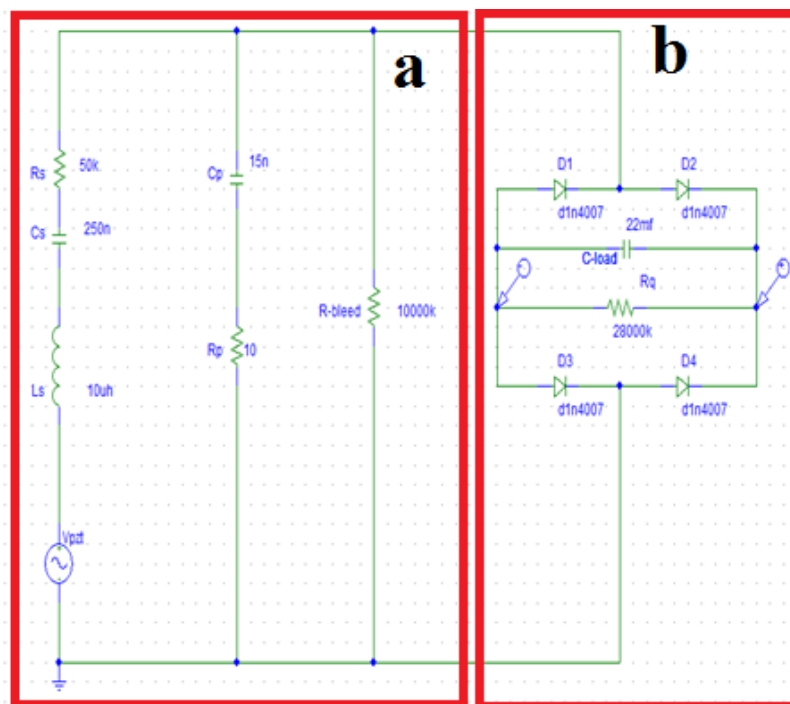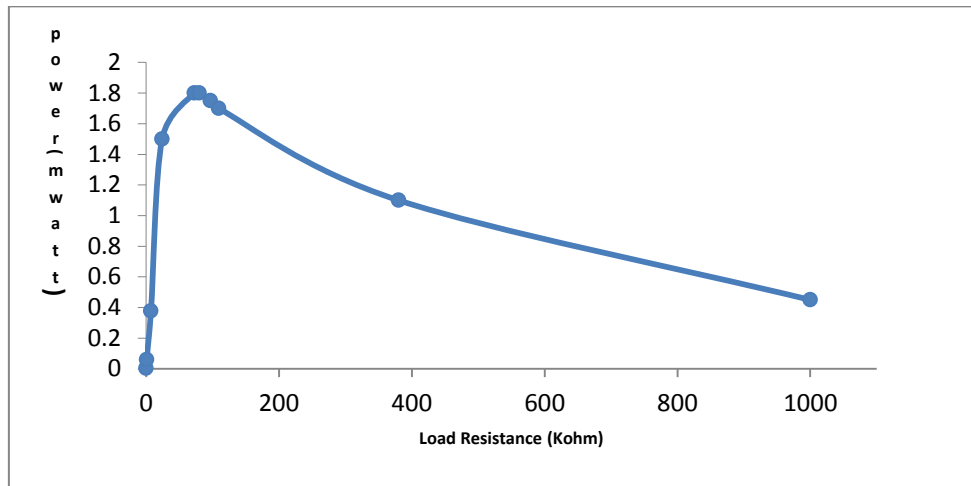


**Fig.4.** Energy storing circuit

**Fig.5.** Electrical power –external load resistance

**Table2.**Internal circuit properties of piezoelectric

|  | Max power at 80kohm | resistance | inductor |
|---|---|---|---|
| **Piezoelectric circuit** | 1.8mw | 50kohm | 10μF |

## 5.Using the Developed System to Examine the Performance of the Piezoelectric Beam

The most popular among engineering piezoceramics, PZT (lead zirconate titanate), was developed at the Tokyo Institute of Technology in the 1950s. Various versions of it (particularly PZT-5A and PZT-5H) are among the most commonly used engineering piezoceramics today. As far as energy-harvesting research is concerned, PZT-5A and PZT-5H are the most widely implemented piezoceramics according to the literature [14].To validate the laboratory system, a piezoelectric beam obtained from Piezo System Co.[3] was used. The Piezoelectric beam is shown in Fig.6. The electro- mechanical properties of the piezoelectric beam are shown in Table 3.



**Fig.6.** Used piezoelectric for energy harvesting

As shown in Fig.2, the beam is connected to the system as a cantilever beam under base excitation.

Moreover, we used Abaqus FEA to validate the output voltage with a given mechanical input. Figure 7 shows the beam as modelled in the software.
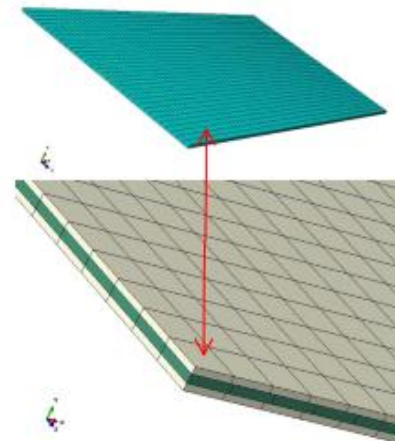


**Fig.7.** FEM model for piezoelectric beam

The results are presented in Fig.8, which shows that the laboratory results and the finite element results are in good agreement. The error value in receiving output voltage is 6% because an ideal open circuit state is considered by this software. Furthermore, to validate the electrical circuit, the impulse test

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[3]www.piezo.com

**Table3.**Mechanical properties

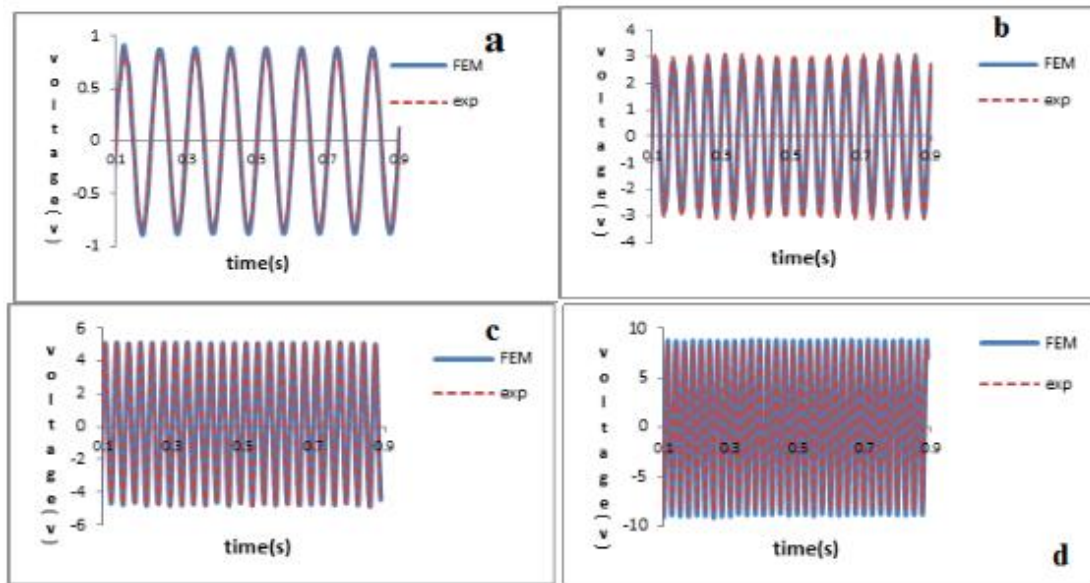| Name | PIEZOELECTRIC "d" coefficient(m/V) | | Density (kg/m³) | Elasticity Modulus (pa) | | Poisson's ratio | |
|---|---|---|---|---|---|---|---|
| | $d_{33}$ | $d_{31}$ | | $E_{11}$ | $E_{33}$ | $\vartheta_{12}$ | $\vartheta_{32}$ |
| | | | 7800 | | | | |
| PSI-5A4E | $390*10^{-12}$ | $-190*10^{-12}$ | | $5.2*10^{10}$ | $6.6*10^{10}$ | 0.3 | 0.4 |
| Copper | -- | | 9000 | $97*10^{9}$ | | 0.31 | |



**Fig.8.** Experimental and FEM method results of harmonic excitation a.10hz b.20hz c.30hz d.40hz

is performed. The obtained natural frequencyfrom this test is compared with its FEM counterpart in Table 4. The voltage-time diagram for the impulse test is presented in Fig.9. Considering Table 4, Fig.9 it can be concluded that the developed laboratory system has enough accuracy for conducting relevant studies on PZT benders.
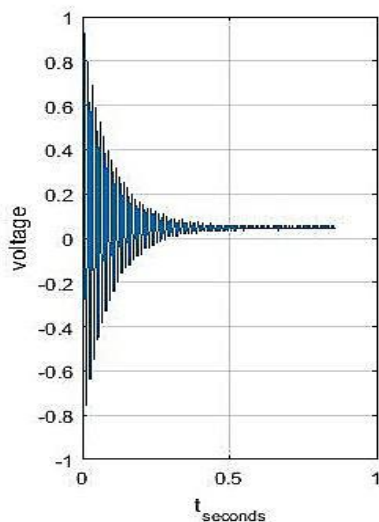


**Fig.9.**Experimental output voltage by impact excitation

## 6.Conclusion

The harvesting and storing of energy from ambient vibrations by means of piezoelectric materials can provide a good power supply for wireless systems. Therefore, it is important to study the behaviour of piezoelectric materials under different electrical and mechanical conditions. For this reason, a laboratory system was developed in this study for research on energy harvesting and storage through piezoelectric materials. Validation of the developed system was done by means of Abaqus FEA, and a good level of validity was observed for the system.

Using this laboratory system, one can examine various aspects of piezoelectric materials, including the type of connections, ambient conditions, and the effect of electrical resistances.

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**Table 4.** Natural frequencies of FEM and laboratory system analysis

| First natural frequency(Hz) | FEM | Laboratory system | Error% |
|---|---|---|---|
| | 67.5 | 68.2 | 1% |

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