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Finite Element Modeling Of A Pavement Piezoelectric Energy Harvester

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Abstract

One of the best methods to achieving renewable and clean energy is piezoelectric energy harvesters (PEHs), which convert mechanical and vibration energy into electrical energy. These generators appeared after the special and unique capabilities of piezoelectric and vibration to electrical energy can be directly converted. The use of these generators is seen in many fields including the use of roads and bridges to convert vibrations caused by the vehicles in to electrical energy and other thing. In this study a piezoelectric energy harvester with the feature of parallel piezoelectric connections was computer simulated using a finite element method. In a computer simulation unlike laboratory method that can only analyze one form of a system, different states and situations of factors can be simulated. In this study, to achieve an optimal state of power and output voltage of an existing PEH, the effects and behaviors of different parameters such as forces, frequencies, temperatures, housing dimensions, piezoelectric materials and the presence of isolators have been investigated. In addition, to obtain the significance of these factors, using the analysis of variance method, the importance and effectiveness of each of these parameters has been investigated. The results revealed that increasing the amount of force and frequency and decreasing the temperature increases the output voltage of this kind of PEH. Changing the dimensions of the housing if its area is constant, does not change the output result and the use of isolators reduces the output voltage. The effect of these parameters is compared to previous studies and the results are presented.

***Keywords*:** Piezoelectric energy harvester; Pavement vibration; Output voltage; Finite element method; Sensitivity analysis.

1. Introduction

Piezoelectricity is the electric charge that accumulates in certain solid materials (such as crystals, certain ceramics, and biological matter such as bone, DNA and various proteins) in response to applied mechanical stress. The word piezoelectricity means electricity resulting from pressure and latent heat. It is derived from the Greek word piezein, which means to squeeze or press. French physicists Jacques and Pierre Curie discovered piezoelectricity in 1880. The piezoelectric effect results from the linear electromechanical interaction between the mechanical and electrical states in crystalline materials with no inversion symmetry. The piezoelectric effect is a reversible process; materials exhibiting the piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect, the internal generation of a mechanical strain resulting from an applied electrical field. For example, Lead-Zirconate-Titanate crystals will generate measurable piezoelectricity when their static structure is deformed by about 0.1% of the original dimension. Conversely, those same crystals will change about 0.1% of their static dimension when an external electric field is applied to the material. The inverse piezoelectric effect is used in the production of ultrasonic sound waves. Piezoelectricity is exploited in a number of useful applications, such as the production and detection of sound, piezoelectric inkjet printing, generation of high voltages, electronic frequency generation, microbalances, to drive an ultrasonic nozzle, and ultrafine focusing of optical assemblies. It forms the basis for a number of scientific instrumental techniques with atomic resolution, the scanning probe microscopies, such as STM, AFM, MTA, and SNOM. It also finds everyday uses such as acting as the ignition source for cigarette lighters, push-start propane barbecues, used as the time reference source in quartz watches, as well as in amplification pickups for some guitars and triggers in most modern electronic drums. Currently, industrial and manufacturing is the largest application market for piezoelectric devices, followed by the automotive industry. Strong demand also comes from medical instruments as well as information and telecommunications. Priya et al[1]have a study on piezoelectric energy harvester in micro scale PEHs and summarized key material such as power density and band width of reported structure at low frequency input. The previous studies [2, 3]have introduced PEHs as very useful and widely used device and believe that the source of this generators are very available and according to this point, they have reviewed all possible ways of achieving electric energy with the help of this device. Wong et al[4]designed a piezoelectric energy harvester system with a vibration source of rain droplets. Muthalif et al[5]compares the available tools for renewable energy extraction and on a low energy scale identified PEHs as a good and optimal method. Qian et al[6]designed, modeled and tested two-stage force amplification PEH and they showed that PEH could achieve to a good scale of electrical energy for a human walking application. Wuet al[7]built a PEH that floats in water sources like sea to convert its waves into electrical energy. Bhavanasi et al[8]reported that ferroelectric materials are attractive due to their application in energy harvesting owning to its piezoelectric nature. They are flexible and can sustain large strain compared to inorganic counterparts and with this reason they can help to improve output of PEH. The parameters of this material that was compared and analyzed are: young's modulus, residual tensile stress and etc. Sarker et al [9]studied one type of piezoelectric energy harvester and focused on all possible way for enhancing their performance. Zhang et al[10]modeled a piezoelectric energy harvester from pavements traffic loads. To achieve an optimum shape of energy, they characterized the main parameters including velocity and position of load and position of transducer and etc. The result is that the plate model is a better shape than previous studied model. Wang et al [11]designed a new optimal pavement piezoelectric energy harvester to achieve a good scale of energy for commonly usage. All parameters such as shape of system, piezoelectric connection and etc., were studied and results are presented. Zhang et al[12]compared the roadway energy harvester fields between one and four part piezoelectric energy harvester to make more optimized shape. Guan et al[13]designed a piezoelectric energy harvester from rotating movement like tires pressure monitoring to make a good value of energy from an unexpected way. Zhang et al[14]designed a new packaging method for pavement PEHs and by reducing the embedded depth of the piezoelectric chips enhanced the output powers and made guidelines for optimization of this system. To optimize the outputs, Kan et al[15]investigated the material of piezoelectric and introduced pbzrxTi(1-x)o3 which has better characteristics. Zhang et al[16]created a rotating piezoelectric energy harvested that its source is wind to provide electrical energy. Abdelkareem et al[17]has designed a piezoelectric energy harvester system to be placed next to shock absorbers systems such as mechanical dampers to convert their energy consumption into useful energy. Ali et al[18]designed a medical implant device to make all human movements such as muscle expansion to useful electrical energy. In order to increase the efficiency of energy harvester systems, Xie et al[19], has suggested parallel connections and wiring and in the study. The results revealed better outputs compared to similar cases. Izadgoshasb el al[20]designed a two degrees of freedom pendulum to use human maneuver's to provide the electrical energy needed for devices such as a heart battery. Khalili et al[21]has designed a road way PEHs system with its own special shape which has the feature of parallel connection. The previous studies [22-24]describe the increase in temperature as destructive factors in the PEHs and considered the good performance of these systems are atlow temperatures. He et al[25]designed a PEH floor structure to convert human walking vibration to electric energy. A double-layer squeezing structure was deployed in system. Sun et al[26]designed a flexible PEH based on polyimide composite by a cost effective two-step process. In addition of good output voltage the system can work at wide temperature ranges by using composites. Bendine et al[27]developed a finite element modeling of a PEH from a bridge subjected to time dependent moving loads to compare effects of different types of moving loads on outputs. Results showed that for a moving load frequency equal to natural frequency of bridge, lead to maximum output is. Kim et al[28]developed a propeller shape energy harvester to be used in running water like a river and they are looking to improve this method. For constant monitoring of a shaft, Micek et al [29]developed a wireless stress monitoring system based on a PEH and with help of a radio signal the produced energy of the shaft can be monitored. Wang et al[30]studied a 3D FEM model of a PEH system applying in airfield pavement under aircraft tire moving load and converts the vibration of multi-wheel aircraft load on taxiway and runway to electric energy. Refs.[31-33]have conducted experimental tests on effects of temperature on output voltage of PEHs and reported temperature as a destructive factor on this kind of systems. Song et al[34]designed a speed bump PEH for using in little scale services such as charging a cellphone. This device is located in a road and with passing of a medium sizedvehicle, the needing energy is produced. Brenes et al[35]developed a FEM model of a PEH system from vibration of railway bridge with employing Hamilton's vibrational principle and mechanical and electrical energy balance equation. The optimum harvester location, the optimum speed of train and the effect of resonance were discussed in term of output voltage. Chen et al[36]introduced a PEH device with a high density of harvested energy from highway traffic and in a laboratory .Studies[37, 38]developed and modeled and designed PEH for pavements application and tried to characterize and describe factors and ways to improve outputs. Esmaeeli et al [39]designed and optimized a rainbow shaped PEH system that mounted on the inner layer of a pneumatic tire for providing enough power for microelectronic devices required for monitoring intelligent tires. The outputs main factors such as tire velocity were studied and results are presented. In studies [40-43] it is resulted that parallel connection both in piezoelectric disk, chip or beam connection of piezoelectric stacks lead to better results.

In this study, a PEH with the feature of parallel piezoelectric connections was simulated using finite element method. Unlike experimental methods that can only analyze one form of a system, in a computer simulation different states and situations of parameters can be simulated to achieve an optimal power and output voltage. The aim of this study is that for of an existing PEH, effects and behaviors of different parameters such as force, frequency, temperature, housing dimensions, piezoelectric material and the presence of isolators to be investigated. In addition, to obtain the significance of these parameters by analyzing of variance, the importance and effectiveness of each of these parameters has been investigated. To have a comprehensive understanding of these parameters, the main purpose is to identify the parameters affecting on the output voltage of the PEH system and to identify the importance and significance of each parameter. For example how the effects of one harmful parameter such as temperature, can be reduced by another effective parameter to achieve a more stable output.

2. Material and Method

2. 1. Finite Element Modeling

A piezoelectric energy harvester including four piezoelectric stacks that are in corners of housing system was simulated using finite element method. Each one of stacks consists of six piezoelectric disks whit a diameter of 25.1^{mm} and thickness of 6.8^{mm} and are connected in parallel as itis illustrated in Figure 1. In this study to achieve an optimal state of the existing piezoelectric energy harvester system, it is intended to examine all the parameters affecting the output of the system. For simulation sakes, ABAQUS was employed. The dielectric coefficient and another parameter according to Eqs (1) and (2) was adopted form[44]. In addition the housing of system assumed to be rigid metal type of material.

$$D_m = d_{mi}\sigma_j + \xi^{\sigma}_{ik}E_k \tag{1}$$
$$\varepsilon_i = S^{e}_{ij}\sigma_j + d_{mi}E_m \tag{2}$$

The first factor is the force applied on the entire surface of the housing. The values of applied force increases from 4.5^{KN} to 45^{KN} and is applied to the entire surface of the housing. Also, the frequency of applied forces is variable and it is considered to increase from lowest frequency (human walking frequency) that is 2^{HZ} to highest frequency (the travelling speed of vehicles) which is 75^{HZ}. An important parameter that has a significant effect is piezoelectric materials. A change in electromechanical properties of piezoelectric materials changes the output result. To understand the effects of different piezoelectric materials, six types of piezoelectric materials is considered including: navyI_840,navy VI_855,navyIII_880 and hybrid_841 from APC international[45] and PZT2 and PZT_5a[46]which are widely used. The simulation conditions are shown in Figure 1.

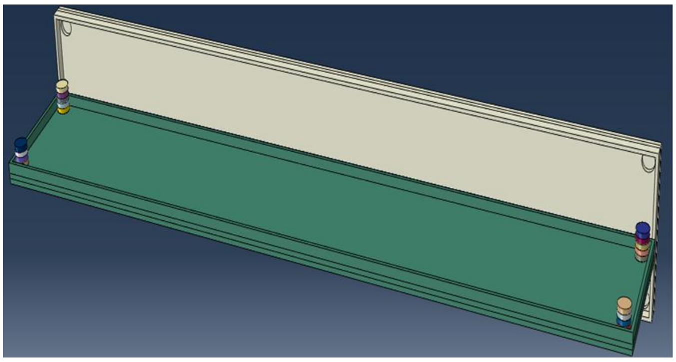

Fig. 1. Schematic illustration of the housing of PEH and the location of 4 piezoelectric stacks.

2. 2.Temperatures

Temperature is another parameter that has been studied to determine effects of increasing or decreasing it on the output voltage of the PEH under study. Piezoelectric material properties changes with changing temperature and output voltage of system change too. Hence, the temperature-dependent properties of piezoelectric materials are considered.

2. 3. Isolators

The effects of using isolators between piezoelectric on outputs is also investigated. Metal-rubber and SMA-MR with determined young's module and loss factor have been used as an isolator with different thicknesses and layer by layer between the piezoelectric disks .Figure 2 depicts the structure of one piezoelectric stack with isolator layers.

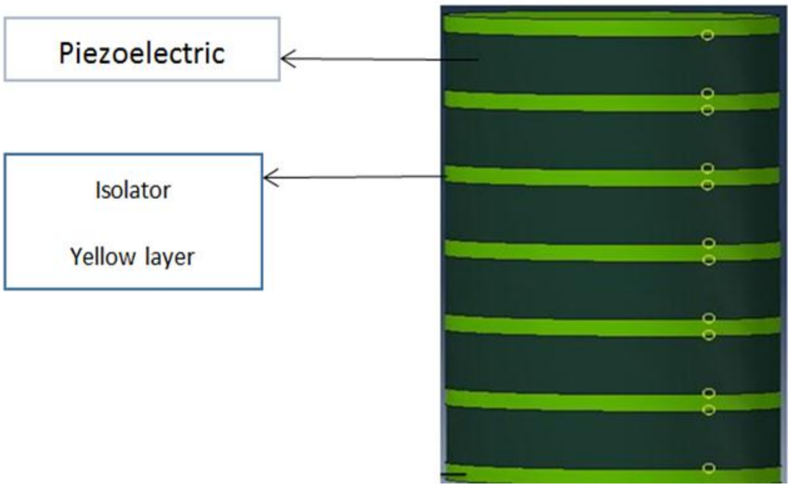

Fig. 2. Schematic structure of one piezoelectric stack with isolators

2. 4. Analysis of variance

Analysis of variance (ANOVA)is a collection of statistical models and their associated estimation procedures used to analyze the differences among group mean in one sample. Finally the value and importance of parameters including force, frequency and piezoelectric material and the temperature with the help of ANOVA procedure in SPSS software is investigated.

The method of global sensitivity indices developed by Sobol is based on ANOVA decomposition. Based on this method, the voltage variance V can be expressed as[47]:

$$V=\int_0^1 f_i^2\,(\alpha)\mathrm{d}\alpha - f_0^2\ ,\ f_0 = \int_0^1 f(\alpha)\mathrm{d}\alpha \tag{3}$$

Where f(α) stands for the objective function. The design vector α has been scaled between zero and one. The contribution of a design variable α_i to the voltage variance without accounting for any of its interactions with other variables is denoted as:

$$V_i = \int_0^1 f_i^2(\alpha_i)d\alpha_i\ , 1 \ll i \ll 4 \tag{4}$$

Each partial variance gives a measure of the contribution of set of variables to the total variance, and provides an indication of the irrelative importance. Therefore the sensitivity index for design variable α_i without considering its interactions with other variables to an objective variability is given as:

$$S_i=\frac{V_i}{V} \tag{5}$$

The total sensitivity index for design variable αi is then defined as:

$$S_{Ti} = \sum S_{(i)} \tag{6}$$

Where S(i) is each sensitivity index containing αi .

3. Results Discussion

3. 1. Verification Studies

As mentioned before, this study is a FEM simulation model of an experimental model of PEH system in Ref. [21]. Hence, for verification studies Ref. [21] is adopted as the verification reference. As shown in Figure 3 and tabulated in Table 1,the error of this research compared to the verification reference is only 3%.

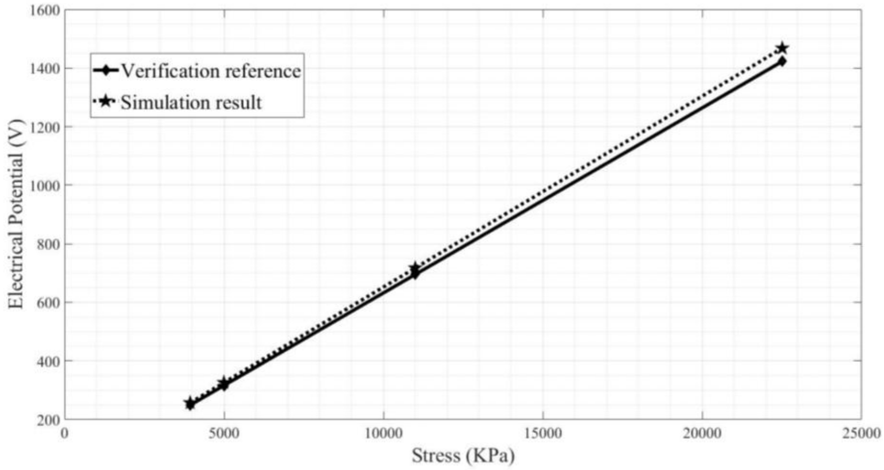

Fig. 3. Verification of results for relationship between stress and output voltage. Ref. [21] is the verification reference.

Table1. Compared data for verification

Result of [21]	Result of this study	Error
Y=0/0632X	Y=0/0652X	3%

According to Figure 4, another important point is the symmetry in the output results of four stacks in this energy harvester because of the symmetry in the stacks position in the housing.

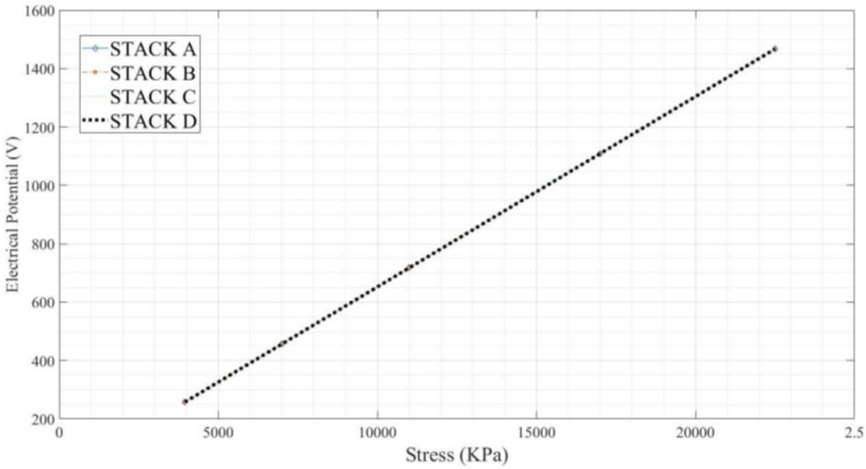

Fig. 4. Symmetric results for output voltage of four stacks.

3. 2. Effects of force and frequency whit different material

According to the Figure 5 increasing the force increases the stress and consequently increases the output voltage. Increasing the frequency also increases the output voltage by increasing the slope of stress–voltage line. This simulation is performed for all the mentioned martial in section 2-1 and the results are shown in Figure 5. Results are also tabulated in Table 2.

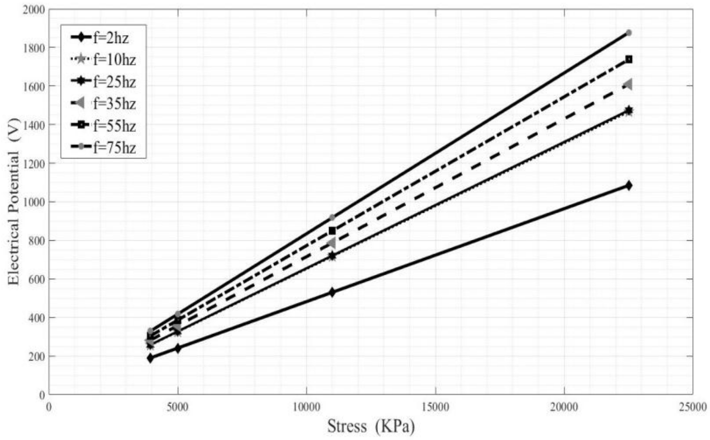

Fig. 5. Effect of force and frequency on output voltage

Table 2. Effect of force and frequency on the Slope of voltage-stress line for different materials

Material / Frequency	NAVY I 840	Hybrid 841	NAVYIII 880	NAVY VI 855	PZT-5A	PZT2
2HZ	0.0482	0.0443	0.0438	0.0305	0.0490	0.0631
10HZ	0.0652	0.0621	0.0593	0.0452	0.0580	0.0910
25HZ	0.0663	0.0644	0.0620	0.0481	0.0610	0.0961
55HZ	0.0772	0.0720	0.0718	0.0611	0.0685	0.1075
75HZ	0.0834	0.0801	0.0776	0.0662	0.0748	0.1176

3. 3. Effect of Temperature

As showed in Figure 6 for the PZT-5a piezoelectric material the temperature voltage curve is depicted for different frequencies. Increasing the temperature reduces the output voltage of an energy harvester to the point that called the core temperature of the material. The core temperature is the temperature where the output voltage of piezoelectric material reaches to zero. With increasing temperature, as the frequency of the applied force increases, the intensity of voltage drop also increases.

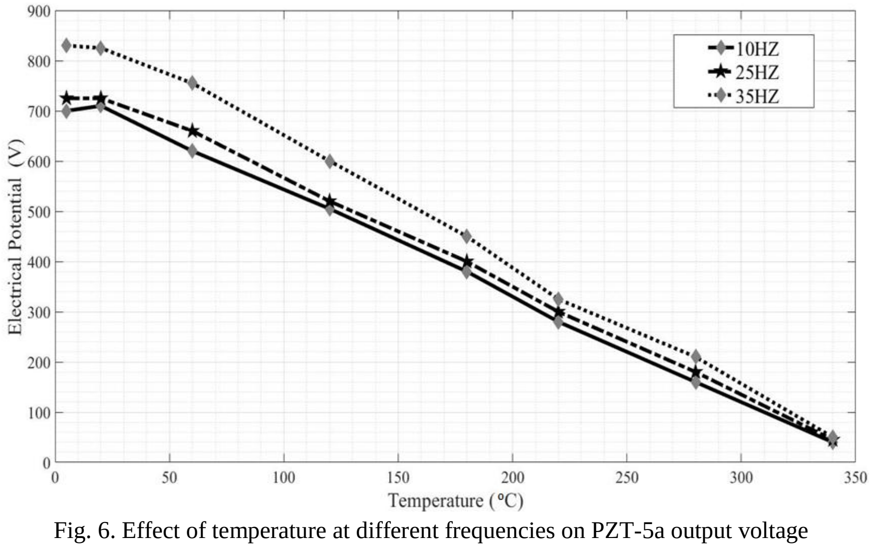

Fig. 6. Effect of temperature at different frequencies on PZT-5a output voltage

3. 4. Effect of isolators

According toFigure7 the presence of one isolator layer between two piezoelectric disks, reduces the effect of the forces. A sharp drop in output voltages is obvious because the isolators neutralize the frequency of the applied forces with its damping properties. With increasing in thickness of isolators the output voltage drops more as showed in Figure 8.

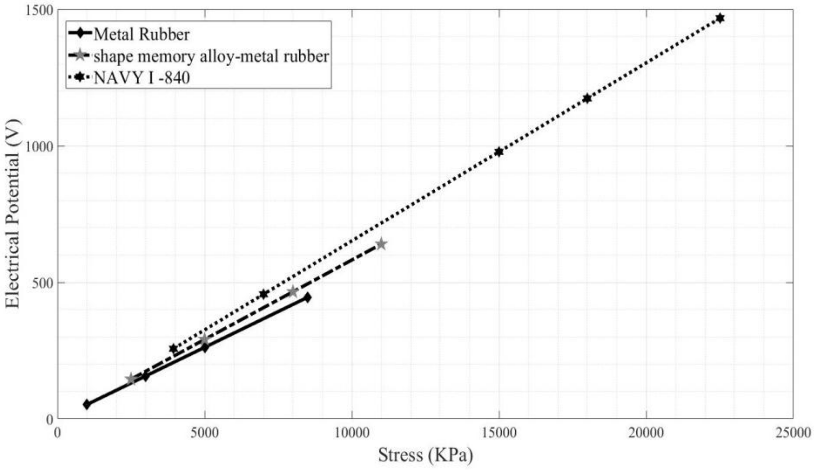

Fig. 7. Effect of isolators on NAVY I -840 output voltage

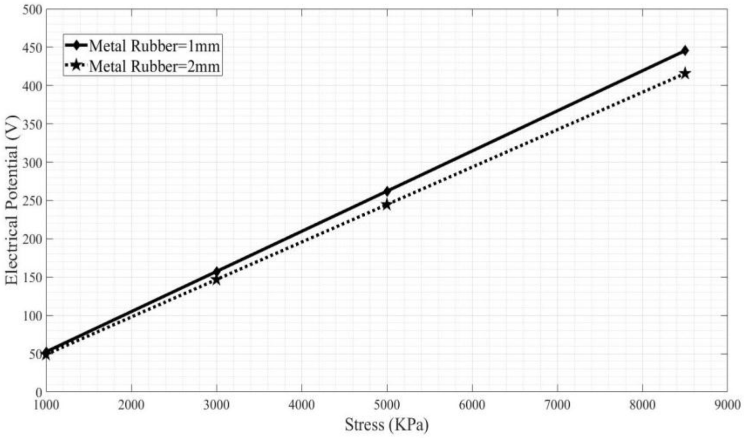

Fig. 8. Effect of MR isolators with different thickness on NAVY I -840 output voltage

3. 6. Analysis of variance (ANOVA)

As discussed in section 2-4, in an ANOVA procedure, the significance of different parameters on the output voltage of the PEH under study is studied. These parameters are: applied force and its frequency, piezoelectric voltage coefficient and young’s modulus in X direction. The results are reported in Table 3.

Also, because of temperature dependent nature of piezoelectric properties, the significance of temperature is investigated in separate analysis and reported in Table 4. The temperature range is considered to be from 0^{oC} to 100^{oC}.

Table 3. Total variance explained of factors

Parameters	Total	% of Variance	Cumulative %
Force	2.720	54.395	54.395
Frequency	1.000	20.000	74.395
Piezoelectric voltage coefficient	1.000	20.000	94.395
Young’smodulus in X direction	0.280	5.605	100.000

Table 4. ANOVA table for temperature

Parameters	F	Sig.
Temperature	1.292	0.283

According to Tables 3 and 4, while considering the output voltage of PEH, temperature is not an important parameter and it can be ignored and in contrary, the value of applied forces is a very significant parameter.

4. Conclusions

In this study a piezoelectric energy harvester including four piezoelectric stacks in the corners of housings' system was computer simulated using finite element method. Each stack consists of six piezoelectric disks whit a diameter of 25.1mm and thickness of 6.8mm and are connected in parallel. The results of this study in general can be expressed as:
1) Increasing applied force causes increasing the stress in housing accompanied by increasing stress in piezoelectric stacks which causes increasing output voltage. Also it should be mentioned that increasing frequency of applied force increases the output voltage that was shown in Figure 4.
2) Increasing the temperature of the system caused a decrease in output voltage because of special properties of piezoelectric materials.
3) Using layer by layer isolators between piezoelectric disks caused reduction in applied frequency of forces and consequently decreasing in output voltage.
4) According to ANOVA, the importance of different parameters was measured and it is determined that the main parameters for output voltage are: applied force, frequency of force, and piezoelectric voltage coefficient respectively.

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