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Harmonic and Modal Finite Element Modeling of Piezo-Electric Micro Harvester

Fadi Al Faqs
Department of Mechanical Engineering Department, Balqa Applied University

ABSTRACT *: In recent years, vibration energy harvesters have drawn more attention in the world. Energy harvesting (also known as power harvesting or energy scavenging) is the process by which energy is derived from external sources (e.g. solar power, thermal energy, wind energy, salinity gradients, and kinetic energy), captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks. Energy harvesting devices converting ambient energy into electrical energy have attracted much interest in both the military and commercial sectors. Some systems convert motion, such as that of ocean waves, into electricity to be used by oceanographic monitoring sensors for autonomous operation. This work is concerned with, harmonic and modal modeling of piezoelectric micro harvester using finite element software (Ansys). The effect of Seismic mass on the voltage output of piezoelectric micro harvester is monitored. The developed finite element model is exposed to harmonic fluctuation on different masses to compare different cases. The results also show the dependency of the piezoelectric material on the operating frequency*.

Keywords: *Finite element, Harmonic, Micro harvester, Modal, Piezoelectric, Seismic mass*

I. Introduction

The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry [1]. The piezoelectric effect is a reversible process in that materials exhibiting the direct 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) [2]. Piezoelectric materials have a built-in polarization, and therefore respond differently to stresses depending on the direction. In order to predict the piezoelectric material response under different loading conditions, two well-known models such as the 3-1 mode and the 3-3 mode of electromechanical coupling for piezoelectric materials are usually used shown in Fig. (1) and Fig (2). In Fig (1), the electric field is produced on an axis orthogonal to the axis of applied strain, whereas in the 3-3 mode (Figure 2), the electric field produced is on the same axis as the applied strain [3].

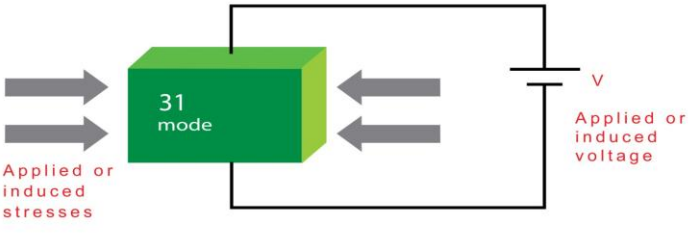

Figure (1): The electric field is produced on an axis orthogonal to the axis of applied strain

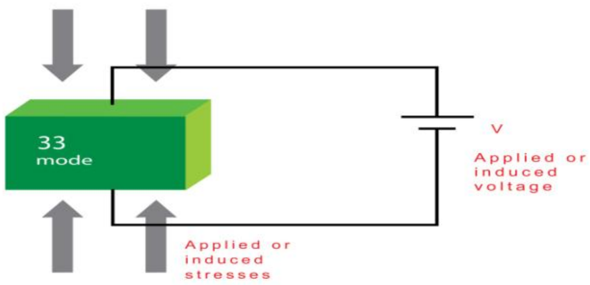

Figure (2): The electric field produced is on the same axis as the applied strain

The term energy harvesting refers to the generation of energy from sources such as ambient temperature, vibration or fluid flow. Converting the available energy from the environment allows a self-sufficient energy supply for small electric loads such as sensors or radio transmitters. Kinetic energy can be converted into electrical energy by means of the piezoelectric effect: Piezo elements convert the kinetic energy from vibrations or shocks into electrical energy [4].

Using suitable electronics, this effect can be used for creating a self-sufficient energy supply system. This is of particular interest whenever a power supply via cable is not possible and the use of batteries and the associated maintenance expenditure are not desired. While only modal and harmonic modeling of the micro harvester is discussed in this paper, the ultimate goal is to detect effect of seismic mass on the voltage output using different materials.

Studying the micro harvesters that contain a fixed cantilever attracted many researchers. It was investigated by Andoscaa *etal.* [5] And Saadon and Sidek [6]. Many other researchers studied the piezo electric micro harvester with cantilever beams [7–13]. On the other hand the vibration of energy harvester was observed and studied by many researchers [14–21]. The previous investigations have mainly concentrated on the output voltage of the piezoelectric micro harvester. However, they did not concentrate on the effect of the seismic mass material on the output voltage of the piezoelectric micro harvester. It is found that material density of the seismic mass play a major role on the output voltage of the piezo electric micro harvester.

Material Properties:

The structure under consideration consists of a fixed piezoelectric cantilever connected to structural isotropic seismic mass at the top. The piezoelectric material is made of AlN while the seismic mass is made of a structural materials which are gold, copper, and iron.

The density of the piezoelectric material (AlN) is 3260 Kg/m^3 while its modulus of elasticity is 3440 GPa at room temperature [22]. Whereas for the density and modulus of elasticity for gold are 19320 Kg/m^3 and 79 GPa respectively. Also, the density for copper is 8960 Kg/m^3 and its modulus of elasticity is 120 GPa. Finally for iron, the density and modulus of elasticity are 7880 Kg/m^3 and 210 GPa respectively.

Finite Element Modeling

The micro harvester is composed of a fixed micro cantilever beam attached to a square plate with a seismic mass at the free ends of the beam. The beam is made of piezoelectric layer which is Aluminum Nitride (AlN). The micro harvester under consideration is shown in fig (3).

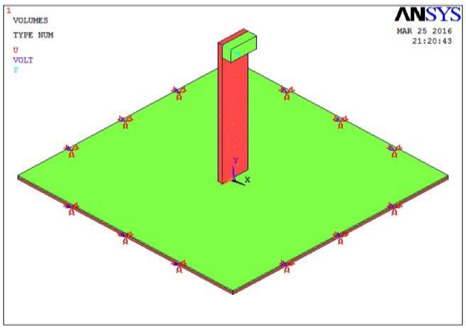

Figure (3): piezo electric micro harvester finite element model

Modeling and analysis are carried out using the student version of the finite element software package ANSYS14. In this work, Micro energy harvester is modeled using the solid226 and solid186 elements in the finite element type tool ANSYS. The piezoelectric material is modeled using the solid226 elements which has thermoelectric capabilities which include Seebeck, Peltier, and Thomson effects, as well as Joule heating. In addition to thermal expansion, structural-thermal capabilities include the piezo electric effect in dynamic analyses. On the other hand the seismic mass is modeled using solid186 elements which has structural properties. Each of the two elements has 20 nodes. The layers are fully bonded by merging the nodes on the common boarders. Modal and harmonic finite element analyses of the structures are performed. The finite element meshes were first refined till stable solutions of the natural frequencies are obtained. We set our own criterion for a stable solution where subsequent values of natural frequencies differ by less than 0.5%. Example of mesh refinement is shown in Table (1). The mesh was performed using an overall 7000 elements as shown in fig. (4) With 556 elements meshing the seismic mass. A harmonic force of 100 N is applied on the seismic mass which have a frequency range from 0 to 1000 Hz.

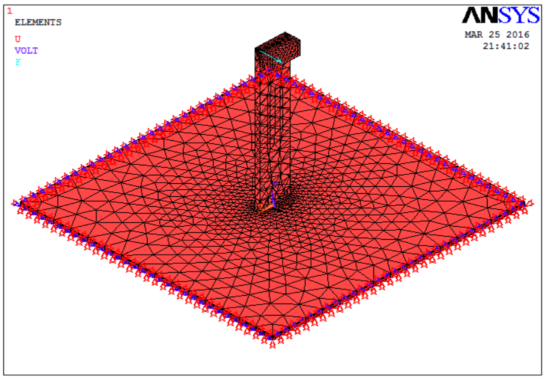

Figure (4): Meshing of piezo electric micro harvester finite element model

II. Results

Modal analysis was performed prior to the harmonic analysis to verify the model mode shapes and natural frequencies within a frequency range from 0 to 1000 Hz. In this analysis the seismic mass is made of Gold.

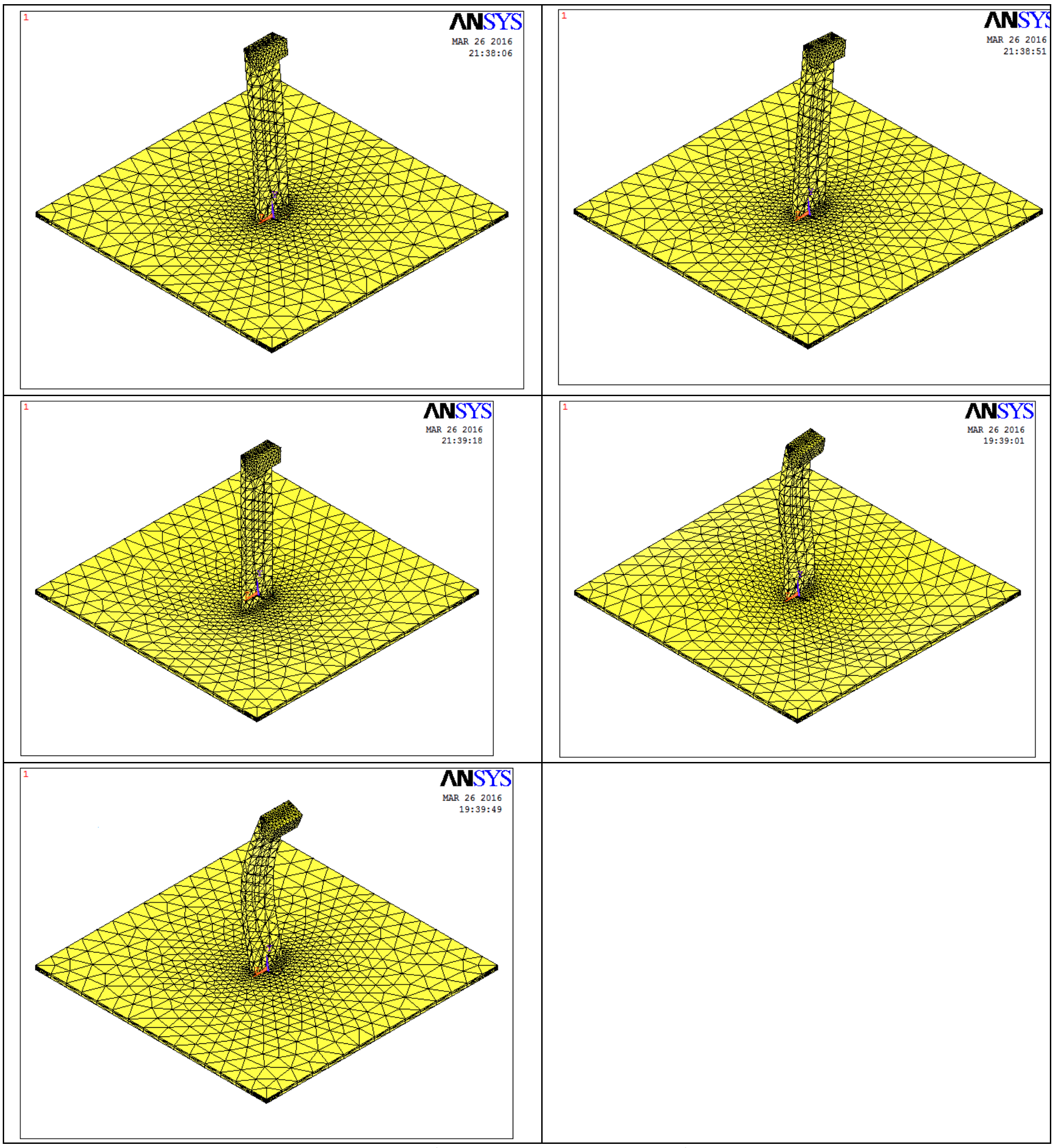

Figure (5): Modal analysis of piezo electric micro harvester finite element model

The first five natural frequencies are found with the values: 131.075 Hz, 330.103 Hz, 644.884 Hz, 1178.493 Hz, and 1744.024 Hz. It is clearly seen that the first three mode shapes has a straight deformed shape with just a lateral deflection. The more deflection it has the more output voltage will be induced in the piezoelectric material. It is widely known that the fundamental natural frequencies will be significant during the harvester's operation. On the other hand the fourth mode shape has a full sine wave whereas the fifth mode shape has a half sine wave. Table (1) shows the first five natural frequencies of the piezoelectric micro harvester for different element meshing.

Table (1): Mesh refinement results for the micro harvester

Number of Elements	First Natural Frequency (Hz)	Second Natural Frequency (Hz)	Third Natural Frequency (Hz)	Fourth Natural Frequency (Hz)	Fifth Natural Frequency (Hz)
1000	132.051	328.651	643.516	1180.124	1745.536
2000	131.738	328.951	643.894	1179.676	1745.161
3000	131.428	329.258	644.206	1179.287	1744.821
4000	131.285	329.546	644.421	1178.956	1744.637
5000	131.150	329.785	644.611	1178.759	1744.428
6000	131.105	329.923	644.703	1178.574	1744.211
7000	131.075	330.103	644.884	1178.493	1744.024

Then, a harmonic force is applied to the micro harvester. The force, with a magnitude of 100 N and a frequency range from 0 to 1000 Hz, is applied at top of the seismic mass. The harmonic deflection response of the finite element model of the seismic mass of the piezo electric micro harvester in the axial and transverse directions are shown in fig (6) and fig (7) respectively.

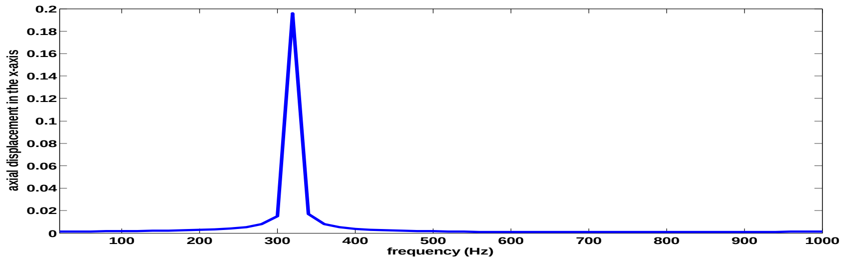

Figure (6): harmonic axial deflection response of a golden seismic mass of the micro harvester model

As seen from figure (6) that the axial deflection of seismic mass is frequency dependent. The maximum axial deflection is at the forcing frequency 330.103 Hz which is a fundamental natural frequency. It is well known that the piezo electric material output voltage is proportional to induced cantilever deflection when applying a force. Hence it is expected that the maximum voltage is at the same frequency.

Fig (7) shows the transverse deflection response of seismic mass in the piezo electric micro harvester. The transverse deflection behavior is similar to the axial deflection since it is also frequency dependent and the maximum transverse deflection is at the forcing frequency 330.103 Hz.

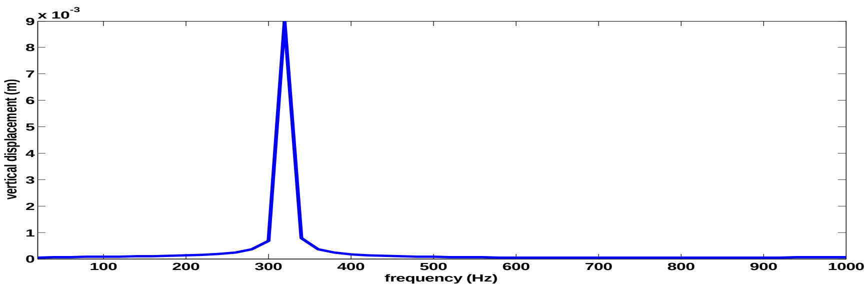

Figure (7): harmonic transverse deflection response of the micro harvester model with a golden seismic mass

Figure (7) shows clearly that the axial deflection of the seismic mass of the piezo electric micro harvester is much higher than the transverse one (as can be seen at frequency 330.103 Hz) since it is along the force direction. Figure (8) shows the harmonic response of the output voltage of finite element model of the micro harvester when gold is the seismic material. The magnitude of the harmonic force is 100 N and the tested operating frequency is up to 1000 Hz.

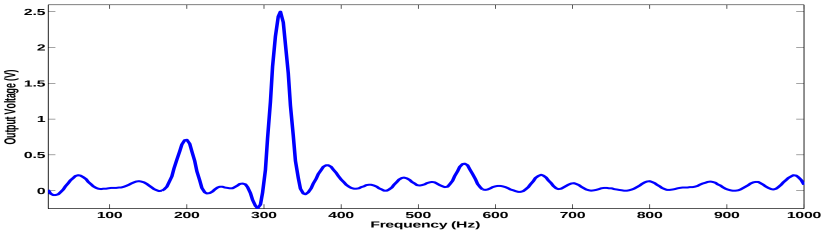

Figure (8): harmonic voltage response of the model of micro harvester having a gold seismic mass

It is clearly seen that the output voltage of finite element model of the micro harvester depends on frequency. The maximum induced voltage is produced at 330.103 Hz as expected previously which is a fundamental natural frequency of the micro harvester.

The effect of seismic mass material on the output voltage of the piezoelectric micro harvester is investigated using finite element modeling using three different materials ordered respectively as per density; gold, copper, and iron . The results are shown in figure (9).

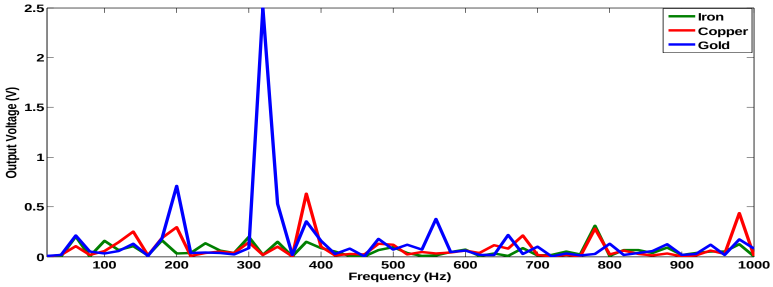

Figure (9): harmonic voltage response of piezo electric micro harvester comparing Seismic mass different materials

Figure (9) shows clearly that the output voltage is highly dependent on the material density of the seismic mass in the piezoelectric micro harvester. It compares the harmonic voltage response of the finite element model of the piezo electric micro harvester for different seismic mass materials. Since each material has a specific density, variations are observed in the behavior of deflections as the forcing frequency is changed. As seen from the figure, denser materials produce more deflections and hence more output voltage. The effect of natural frequency seen clearly at the natural 330.103 Hz.

III. Conclusion

The dynamic behavior of piezo electric micro harvester is investigated using finite element analysis. Mode shapes and natural frequencies are extracted using finite element analysis. The effect of seismic mass material in the piezo electric micro harvester is investigated. It is found that when the material density increases the voltage output of the piezo electric micro harvester increases. The results also show the dependency of the voltage on frequency, hence, the effect of the material density appears significantly under harmonic loading. In the present work, it is found that gold produces the highest voltage output when used as the material of the seismic mass. Another advantage for gold that it has a high electrical conductivity which is essential when voltage output is stored in the next stage after energy scavenging. Finally it is recommended to verify the present findings, which are based on finite element results, by analytical and experimental investigations.

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