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Original scientific paper

DESIGN OF AN ENERGY HARVESTING SYSTEM USING PIEZOELECTRIC MATERIALS

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A b s t r a c t: Energy harvesting by using piezoelectric materials is one of the most widely used techniques for conversion of waste energy into useful. Using this technique, generated vibration energy from machines can be converted into useful electrical energy. In this paper, an energy harvesting system that supplies power for low-power consumption devices has been designed. The experimental model consists of a rotating machine that generates mechanical vibrations that actuate a cantilever beam and a piezoelectric transducer as a sensor for energy harvesting. The aim is to generate greater power as an output, which could be achieved by obtaining maximal strain for the given frequency range of the vibration source. The frequency range of the vibration machine is variable and multiple frequencies have been used. Using the Euler-Bernoulli method, the beam dimensions have been calculated so that its natural frequency matches the operating machine frequency. By reaching the resonant point of the cantilever beam, the maximal power from the designed energy harvesting system can be generated.

Key words: energy harvesting; piezoelectric transducers; vibrations of rotating machine; cantilever beam

ДИЗАЈН НА СИСТЕМ ЗА СОБИРАЊЕ ЕНЕРГИЈА СО КОРИСТЕЊЕ ПИЕЗОЕЛЕКТРИЧНИ МАТЕРИЈАЛИ

А п с т р а к т: Собирањето енергија со примена на пиезоелектрични материјали е една од најкористените техники за конверзија на генерираната неискористена енергија во корисна. Користејќи ја оваа техника, генерираната енергија од вибрациите на машините може да се претвори во корисна електрична енергија. Во овој труд е дизајниран систем за собирање енергија кој може да обезбеди енергија за уреди со мала потрошувачка на енергија. Експерименталниот модел се состои од ротирачка машина која генерира механички вибрации кои активираат конзолен носач и пиезоелектричен материјал како сензор за собирање енергија. Целта е да се генерира поголема излезна моќност, што може да се постигне со добивање максимално напрегање за дадениот опсег на фреквенција на изворот на вибрации. Опсегот на фреквенции на машината за вибрации е променлив и се користат повеќе фреквенции. Користејќи го методот на Ојлер-Бернули, пресметани се димензиите на конзолниот носач така неговата природна фреквенција да се совпаѓа со фреквенцијата на работната машина. Со достигнување на резонантната точка на конзолата се постигнува генерирање на максимална моќност од дизајнираниот систем за собирање енергија.

Клучни зборови: собирање енергија; пиезоелектрични материјали; вибрации на ротирачка машина; конзола

1. INTRODUCTION

Over the last decades, green manufacturing has attracted a great deal of attention worldwide. The use of different types of renewable energy is studied in order to replace traditional fossil fuels, which harm both the environment and public health [1, 2]. Clean energy can be achieved by using the waste energy from the ambient environment such as solar, acoustic, wind, and vibrational energy. In the following Table 1, a comparison of power density generated from different ambient sources has been shown. All values are normalized by volume and are reported as μW/cm^3 its high energy conversion ability from mechanical vibration. This technique uses the properties of piezoelectric materials to generate voltage under the influence of a mechanical force. The experiments done by [3, 4] show vibrations as a good source for energy harvesting, secondly only to solar energy in ideal conditions.

Table 1

The power density of different energy sources [3, 4]

Energy source	Power density (μW/cm^3)
Solar (outdoors)	15 000–direct sun/150–cloudy day
Solar (indoors)	6 – office desk
Vibrations (piezoelectric conversion)	250
Vibrations (electrostatic conversion)	50
Acoustic noise	0.003 at 75 dB, 0.96 at 100 dB
Temperature gradient	15 at 10 ºC gradient

Energy harvesting on a global macroscale is studied with the goal of replacing fossil fuels with clean energy, while on a microscale with the goal differs. With the recent advances in wireless and micro-electromechanical systems (MEMS) technology, the demand for portable electronics and wireless sensors grows rapidly. These sensors are portable and because of that, they require their own power supply which is usually secured by a conventional battery. However, due to their finite lifespan, problems can occur. For portable electronics or electronics within systems that are hard to physically reach, replacing the battery is problematic and extremely time-consuming activity since the electronics could fail at any time. For such systems, harvesting mechanical vibrations using piezoelectric materials are one of the best alternative sources of energy due to their implementation in various environments.

Many researchers have studied the vibration problems of piezoelectric structures, and some achievements have been made. Liu *et al*. [5] studied the dynamic analytical solution of a piezoelectric stack utilized in an actuator and a generator based on the linear piezo-elasticity theory. Parashar *et al*. [6] studied the nonlinear shear-induced flexural vibrations of piezoceramic actuators. Mukherjee and Chaudhuri [7] demonstrated the effect of large deformations on piezoelectric materials and structures under time-varying loads. Chen *et al*. [8] studied the natural vibration and transient response of a functionally graded piezoelectric material (FGPM) curved beam with a numerical method. Dong *et al*. [9] discussed the influence that piezoelectric materials exert on the vibration behavior of a stepped cantilever beam with surface bonded or embedded piezoelectric materials. Kim and Tadesse [10] stated that the generated power density of the piezoelectric transduction is more than three times greater than the power density of electrostatic and electromagnetic transducers. Jeon *et al*. [11] found that the highest power density from piezoelectric material subjected to the external vibrational source was 37 μW/mm^3. For the electromagnetic effect, Saha *et al*. [12] showed that a value of 4.375 μW/mm^3 could be generated from the electromagnetic-based generator subjected to the vibrating beam. Despesse *et al*. [13] built a system to convert the surrounding mechanical vibrations into electrical energy using the electrostatic transducer. The research within this field shows piezoelectric energy harvesting as an energy source alternative for conventional batteries.

In this paper, an experimental model is presented, where a piezoelectric transducer is used to harvest energy of mechanical vibration from a rotatory machine. The piezoelectric material is placed on a cantilever beam and coupled together with an energy harvesting module.

2. MATHEMATICAL MODELING

a) *Vibration of a cantilever beam*

Mechanical systems which have a continuously distributed mass are referred to as continuous systems. These systems theoretically have infinite degrees of freedom. An analytical solution to the dynamics of these systems is possible only for simple cases with an approximation of homogeneous material as well as constant width along the length of the system. Using these approximations, partial differential equations can be employed with constant coefficients to solve the problem. The solutions to these PDEs represent the frequency of the system and the modes of oscillation of the elastic structure. One of the most used methods for modeling continuous systems and the one which will be used in this paper is the Euler-Bernoulli method.

The Euler-Bernoulli method takes into account the bending energy of the structure and the kinetic energy of the transversal movement of the beam. The differential equation of motion of a continuous beam according to the Euler-Bernoulli method is the following mathematical dependency:

$$EIy\frac{\partial^4 y(x,t)}{\partial x^4} = f(x,t) - \rho A\frac{\partial^2 y(x,t)}{\partial t^2}, \quad (2.1)$$

where $\rho A\frac{\partial^2 y(x,t)}{\partial t^2}$ is the kinetic energy, $EIy\frac{\partial^4 y(x,t)}{\partial x^4}$ the potential energy, and $f(x,t)$ is the actuation of the system.

A full description of the modeling of a cantilever beam has been developed in greater detail by Mineto [14] and Šiškovski [15].

b) *Piezoelectric modeling*

The piezoelectric effect exists in two domains: the first is the direct piezoelectric effect that describes the material's ability to transform mechanical strain into electrical charge; the second form is the converse effect, which is the ability to convert an applied electrical potential into mechanical strain energy. The direct piezoelectric effect is responsible for the material's ability to function as a sensor which is used in this paper. The mechanical and electrical behavior of a piezoelectric material can be modeled by two linearized constitutive equations. These equations contain two mechanical and two electrical variables. The direct effect and the converse effect may be modeled by the following matrix equations:

– direct piezoelectric effect:

$$\{D\} = [e]^{\mathrm{T}}\{\mathrm{S}\} + [\alpha^s]\{\mathrm{E}\}$$

– converse piezoelectric effect:

$$\{\mathrm{T}\} = [c^E]\{\mathrm{S}\} - [e]\{\mathrm{E}\}$$

where {D} is the electric displacement vector, {T} is the stress vector, $[e]$ is the dielectric permittivity matrix, $[c^E]$ is the matrix of elastic coefficients at constant electric field strength, {S} is the strain vector, $[\alpha^S]$ is the dielectric matrix at constant mechanical strain, and {E} is the electric field vector. The matrix form of the equations for the direct and converse piezoelectric effect for a piezoceramic material which is polarized on the 3rd axis are given in the equations (2.2 and 2.3).

A full description of the piezoelectric effect and its modeling is beyond the scope of this paper. However, a significant number of published papers have developed these equations in greater detail such as Mineto [14].

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0\\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0\\ S_{31} & S_{32} & S_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & S_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & S_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & 2(S_{22}-S_{12})\end{bmatrix}\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_{23}\\ \tau_{31}\\ \tau_{12}\end{bmatrix} + \begin{bmatrix}0 & 0 & d_{31}\\ 0 & 0 & d_{32}\\ 0 & 0 & d_{33}\\ 0 & d_{24} & 0\\ d_{15} & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}E_1\\ E_2\\ E_3\end{bmatrix} \quad (2.2)$$

$$\begin{bmatrix}D_1\\ D_2\\ D_3\end{bmatrix} = \begin{bmatrix}0 & 0 & 0 & 0 & d_{15} & 0\\ 0 & 0 & 0 & d_{24} & 0 & 0\\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{bmatrix} + \begin{bmatrix}e_{11}^{\sigma} & 0 & 0\\ 0 & e_{22}^{\sigma} & 0\\ 0 & 0 & e_{33}^{\sigma}\end{bmatrix}\begin{bmatrix}E_1\\ E_2\\ E_3\end{bmatrix} \quad (2.3)$$

3. EXPERIMENTAL SETUP

a) *Model description*

The experimental setup shown in Figure 2 consists of a rotational shaft whose frequency can be controlled using a frequency regulator. Coupled to the base of the machine is a cantilever beam with an attached piezoelectric transducer (PI-876-A12). The piezoelectric transducer is placed as close as possible to the clamped end, as seen in Figures 1 and 2, in order to achieve maximum deformation. The experimental setup is the following: the cantilever beam is designed at a length of 240 mm, width of 40 mm, and height of 1.5 mm. The excitation frequency of the machine is varied in order to achieve resonant conditions of the cantilever beam. In this setup, a different mass is added to the free end of the cantilever beam and the change in frequency, as well as the voltage output of the harvester, are measured. All the elements used for this experiment are shown in the Figure 2.

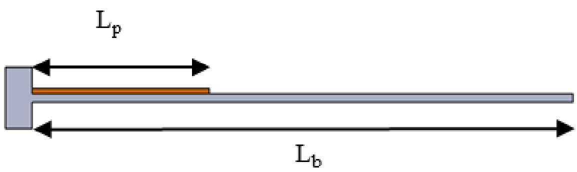


Fig. 1. Cantilever beam with attached PZT sensor

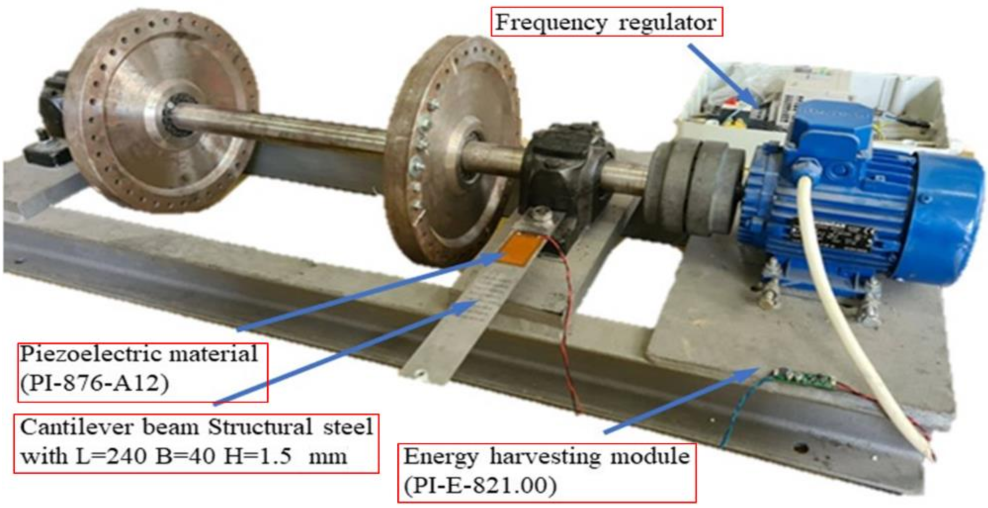
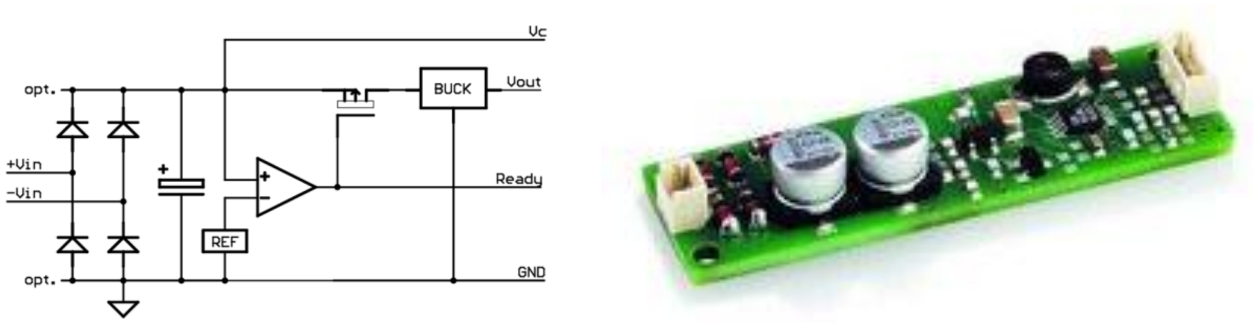


Fig. 2. Experimental model setup

b) *Energy harvesting circuit*

The piezoelectric strip generates electricity while being deformed, but if this power is not being used or stored, it will be dissipated with no utilization. Having a piezoelectric energy harvester requires a rectifier circuit in order to convert the AC wave from the harvester to the DC voltage, which is suitable for energy storage.

The used energy harvesting module is PI-E-821.00, and its electronic circuit is shown on Figure 3. Figure 3 shows a full-wave rectifier with a diode bridge. On one side the piezoelectric material is connected and on the other the output towards the battery or sensor. The harvester has two capacitors each of 100 µF and an output voltage of 3.3 V or 5 V.



a) b)

Fig. 3. a) Electronic circuit of PI-E-821.00. **b)** Energy harvester PI-E-821.00

4. RESULTS AND DISCUSSION

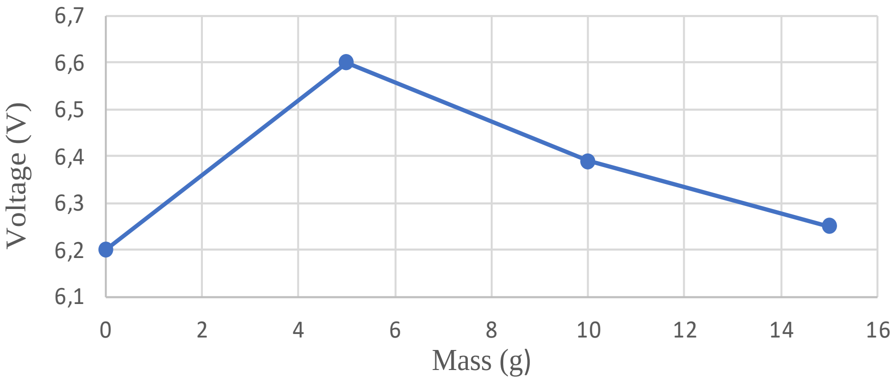
In the experimental setup the dimensions of the beam are length (L = 240 mm) width (W = 40 mm) and height (H = 1.5 mm) and the angular frequency of the machine is varied. A mass is added to the end of the cantilever and the changes in the frequency and output voltage as well as the amplitude of the vibrations are measured. On the Table 2 the results of the measurements are shown.

Table 2

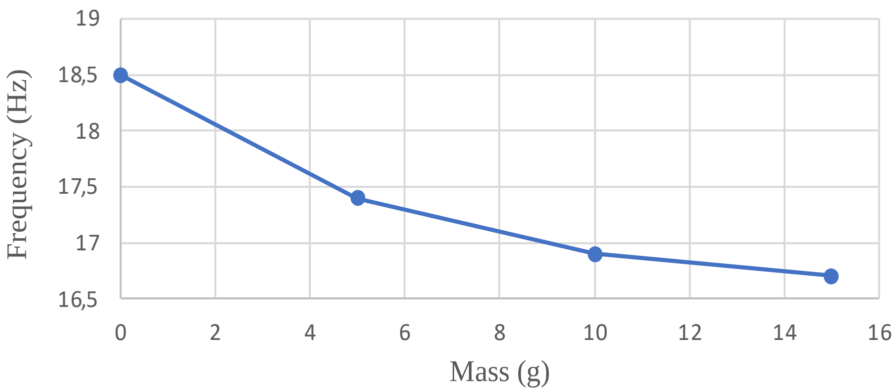
Experimental variables

Mass (g)	Frequency of resonance (Hz)	Output voltage (V)	Amplitude of vibrations (mm/s)
0	18.5	6.2	3.62
5	17.4	6.6	3.4
10	17.9	6.39	3.1
15	16.7	6.25	2.8

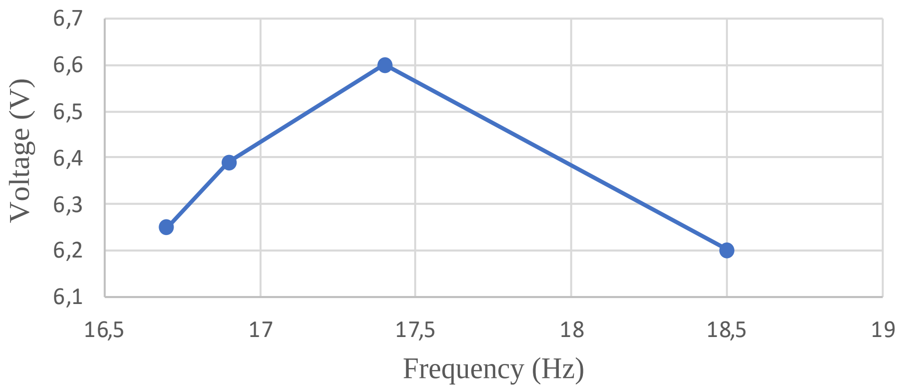
Looking at the information of the Table 2. As the point mass increases the natural frequency of the beam decreases, as well as the amplitude of vibrations that can be seen. On the other hand, the output voltage behaves in a different manner. These results are presented on the Figure 4.



a) Voltage vs Mass



b) Frequency vs Mass



c) Frequency vs Voltage

Fig. 4. Experimental results

Looking at Figure 4a, it can be seen that having a point mass on the end of the cantilever beam increases the energy output of the piezoelectric material compared to an empty cantilever beam. This behavior is noted up until a mass of 5 grams, further increase of the mass lowers the output energy. As expected, the addition of a mass to the end of the cantilever beam lowers the natural frequency of the cantilever beam which can be seen on Figure 4b. Having the natural frequency of the cantilever beam lowered means that in order to have a resonant condition, the frequency rotation of the machine also needs to be lowered. Having the frequency lowered affected the output voltage of the energy harvesting as can be seen on Figure 4c. Lowering the frequency of rotation of the machine correlates to lower amplitudes of vibration. These lower vibrations correspond to lower deformations of the cantilever and lower energy output of the piezoelectric material. It can be concluded that an optimal variation would be to have a point mass on the end of the cantilever beam which is in the range of 3–5 grams. Further analysis of this behavior is necessary to declare whether the point mass added is correlated to the overall mass of the beam, its length, or its width.

4. CONCLUSION

Within this paper, a proof of concept has been designed for the possibility of harvesting vibrational waste energy and converting it into useful electrical energy. Within the experiment, the system has been modeled as a unimorph cantilever harvester meaning, only a single piezoelectric transducer has been used, while the use of a bimorph harvester will yield doubled output power. The generated power can then be used to provide continuous and uninterrupted electrical power to low-power devices. It was seen that the introduction of a point mass to the system increases the deformations achieved in resonance, hence increasing the energy output of the piezoelectric material. The experiments were made in the frequency range of 16–19 Hz. It has been measured that the amplitudes of the vibrations increase as the frequency of rotation of the machine increases showing that for machines operating at higher frequencies more power can be obtained.

One of the major limitations of research within this field is the fact that the power generated by piezoelectric materials is too small to power most electronics which is the reason that in these circumstances only low-power sensors are used. Knowing this, the research focuses on new and innovative methods of accumulating the harvested energy as well as methods of further increasing the amount of energy the PZT material can harvest. Furthermore, the efficiency of the power harvesting circuit must be maximized in order to allow the full amount of energy generated to be transferred to the storage medium.

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