Modeling of a Novel Magneto-electro-elastic Energy Harvesting System Subjected to Applied Electric Voltage with Simultaneous Use as an Electrical Actuator System

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ABSTRACT

This paper introduces a novel harvester to store the electrical power, which comes from the power of external applied electrical voltage. In the last decade, most of the energy harvesters have been designed and analyzed in the form of cantilever beams. In the present article, the harvesters are analyzed as a cantilever beam with the Euler-Bernoulli beam assumptions. The beam of energy harvester consists of an active Magneto-electro-elastic (MEE) layer attached to the piezoelectric layer. Assuming that the connection of these layers is perfect, the uni-morph configuration is investigated. The magneto-electro-elastic governing coupled equations of the MEE energy harvester are derived for a harmonic external applied electrical voltage in the transversal direction based on Euler-Bernoulli theory, Gaussian law, and Faraday law. These equations are solved analytically to find out the amount of harvested power and voltage. The obtained results state that by adjusting the electromechanical parameters, up to 66% of the input power and 27% of the applied voltage can be harvested. Choosing the right geometric parameters can increase the harvested power and voltages connected to the electrodes and external coil by 120.31%, 49.05% and 60.98%, respectively. Finally, the results prove the usefulness and efficiency of the dual-usage (actuator-harvester) of the new energy harvester.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>η</td>
<td>Normalized natural frequency</td>
<td>rad/s</td>
</tr>
<tr>
<td>μij</td>
<td>Magnetic permeability constants</td>
<td>N/A2</td>
</tr>
<tr>
<td>ω EM</td>
<td>Mechanical to magnetic modal coupling term</td>
<td>V.s/A</td>
</tr>
<tr>
<td>σij</td>
<td>Components of stress</td>
<td>N/m²</td>
</tr>
<tr>
<td>θ EM</td>
<td>Magneto-mechanical coupled term</td>
<td>N.m/V</td>
</tr>
<tr>
<td>Λ EM</td>
<td>Ratio of harvested to the input power</td>
<td>W/W</td>
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</table>

INTRODUCTION

Electrical energy is a valuable type of energy because of its ease of use and efficiency. Today, fossil fuels are the primary energy sources to produce electrical energy. Therefore, the optimal use of these resources is a desirable task because they are a non-recyclable source of energy and have a role in the pollution of the...
environment [1]. Recently, use of wasted energy has become an option to produce electrical energy [2, 3]. This was led to energy harvesting technology. The electrical power produced by this promising technology is usually recyclable and contributes to the sustainability of the system’s infrastructure. It is usable in cooling and heating, electricity generation, and health monitoring structures.

One of the most common energy sources for energy harvesting systems is ambient vibrations, which have high energy capacity and are suitable for small-scale devices. The kinetic energy is converted into electricity in three different ways: active materials (such as piezoelectric [4]), electromechanical coupling mechanisms (such as electrostatic [5], and electromagnetism [6]), and the use of special instruments and materials that combine the above [7].

The basis of the work of electrostatic generators is capacitors with variable capacitance. Unfortunately, these generators require an initial polarization voltage or charge. Therefore, they need a battery at the start [5]. A permanent magnet and a coil are used as a converter in electromagnetic generators and work better on the macro-scale [6]. The advantage of these generators is their relatively high output current. The piezoelectric effect is a characteristic of some materials (like material which is called PZT, PVDF, and MFC) that in response to mechanical stresses, the electrical potential created and vice versa. Using each of these three methods to convert the vibration oscillations into electrical power has been separately investigated. The energy harvesting system used one of these methods is called a vibrational energy harvester (VEH).

Using composite and functionally graded, and smart materials attract many researchers due to their special vibrational behaviours [8]. Among them, some smart materials known as MEE composites have received significant interest in material science recently. These materials have both piezoelectric and piezo magnetic properties, and they can convert electrical, magnetic, and mechanical energy into each other. Thus, using MEE composites in energy harvesting systems are recommended [9].

To the best of the author’s knowledge, no one was used the energy harvester system under both the electrical excitation and the ambient vibration. One can import an electrical excitation to the energy harvester to amplify the system’s vibration and harvest more energy. The results prove that there is an opportunity to save the remaining output voltage in addition to the ambient vibration source of energy.

MODELLING OF AN MEE ENERGY HARVESTER UNDER ELECTRICAL EXCITATION

An electrically excited MEE energy harvester is shown in Figure 1. In this figure, \( V_m \), \( V_e \), and \( V_M \) represent input voltage, generated voltages on the electrodes attached to the MEE layer and the voltage induced in the \( N \)-turn coil, respectively.

A Cartesian coordinate system \((x,y,z) = (x_1, x_2, x_3)\) is used to derive the governing constitutive equations. The coupled constitutive equations for an anisotropic and three-dimensional linear MEE energy harvester beam may be expressed as follows [10]:

\[
\sigma_i^M = C_{ik}^M \varepsilon_k^M - e_{ik}^M P_k^M - f_{ik}^M H_k^M \\
D_i^M = e_{ik}^M P_k^M + h_{ik}^M E_k^M - g_{ik}^M M_k^M \\
B_i^M = f_{ik}^M H_k^M + g_{ik}^M M_k^M + \mu_{ik}^M B_k^M
\]

where \( \sigma_i, D_i, B_i \) are the stress, electric displacement, and magnetic induction (i.e., magnetic flux); \( \varepsilon_i, E_i \) and \( H_i \) are the strain, electric and magnetic fields; \( C_{ij}, h_{ij}, \) and \( \mu_{ij} \) are the elastic, dielectric, and magnetic permeability coefficients; \( e_{ij}, f_{ij} \) and \( g_{ij} \) are the piezoelectric, piezomagnetic and magnetoelectric coefficients, respectively. The standard contraction indices have been used for the elastic variables (i.e., \( \varepsilon_{ii} = e_{22}, \) etc.).

Because the thickness of the beam is significantly less than its radius of curvature under different loads, the in-plane electric and magnetic fields can be ignored (i.e., \( E_1 = E_2 = 0 \) and \( H_1 = H_2 = 0 \)). So, the coupled constitutive Equations (1) reduced into Equations (2). and the analytical equations are derived using Euler-Bernoulli beam theory [10].

\[
\sigma_1^M = C_{1111}^M \varepsilon_1^M - e_{111}^M P_1^M - f_{111}^M H_1^M \\
D_2^M = e_{111}^M P_1^M + h_{111}^M E_1^M - g_{111}^M M_1^M \\
B_3^M = f_{111}^M H_1^M + g_{111}^M M_1^M + \mu_{111}^M B_1^M
\]

The constitutive equation of the piezoelectric layer is as follows [10]:

\[
\sigma_1^P = C_{1111}^P \varepsilon_1^P - e_{111}^P P_1^P
\]

Assuming the electric field is uniform throughout the constant piezoelectric layer thickness \( h_0 \), then the electric field \( E_1^P \), exist in terms of the input voltage \( V_m \)(connected to the resistive loads \( R_{in} \)) across the thickness of the

![Figure 1](image-url)
piezoelectric layer. Also, the electrical field of the MEE layer $E_{w}$, in terms of the voltage $V_{e}$ can be expressed as follows [8]:

$$E_{w}^{P}(t) = - \frac{V_{e}(t)}{\rho_{p}} \quad (4a)$$

$$E_{w}^{M}(t) = - \frac{V_{e}(t)}{\rho_{m}} \quad (4b)$$

With the help of Faraday’s law, the magnetic field $H_{3}(t)$ can be obtained in terms of the current $i_{m}(t)$ and the number of turns of the coil $N$ as expressed in the following relation [11].

$$H_{3}(t) = \frac{N i_{m}(t)}{\rho_{m}} \quad (5)$$

The basic equations listed will be used to derive the coupled magneto-electro-elastic equations from investigating the performance of a MEE energy harvester.

The relative deflection of the neutral axis, $w(x,t)$, is caused by electrical excitation, $V_{in}$. The following equation is the governing equation of vibration of the beam under base excitation [12]:

$$M_{xx} + c_{w} l w_{,xxx} + c_{m} w + m \ddot{w} = 0 \quad (6)$$

where $l$ is the moment of the cross section of the beam, $c_{w}$ viscous air damping coefficient, $c_{m}$ equivalent composite structural damping coefficient, and $m$ is the mass per unit length of the beam. Also, $M(x,t)$ is the internal bending moment of the beam which is calculated for Uni-morph configuration of the MEE energy harvester by Equation (7).

$$M(x,t) = - b \left( \int_{h_{b}}^{h_{a}} \alpha_{M}^{2} z dz + \int_{h_{a}}^{h_{b}} \alpha_{M}^{2} z dz \right) \quad (7a)$$

where $b$ is the width of the beam, $h_{a}$, $h_{b}$, $h_{c}$, and $h_{m}$, are defined in Figure 2, and $\bar{z}$ is the location of the neutral axis.

Substituting Equations (2) and (3) into Equations (7), the internal bending moment for each configuration is obtained as follows [12]:

$$M(x,t) = C_{I} \frac{\partial w(x,t)}{\partial x^2} + \frac{\rho_{M} w}{\rho_{m}} \left[ \frac{\partial \phi_{M}(x)}{\partial x} \right] (H(x) - H(x - L)) + \frac{\rho_{M} w}{\rho_{m}} \left[ \frac{\partial \phi_{MM}(x)}{\partial x} \right] [H(x) - H(x - L)] \quad (8)$$

where $\phi_{in}$, $\phi_{EM}$ and $\phi_{MM}$ are the electro- and magneto-mechanical coupled terms and defined as follows:

$$\phi_{in} = \frac{b_{in}^{p}}{2 \rho_{p}} \left[ (h_{b})^{3} - (h_{a})^{3} \right] \quad (9a)$$

$$\phi_{EM} = \frac{b_{EM}^{p}}{2 \rho_{m}} [ (h_{c})^{2} - (h_{a})^{2} ] \quad (9b)$$

$$\phi_{MM} = \frac{b_{MM}^{p} N_{M}}{2 \rho_{m}} [ (h_{c})^{2} - (h_{b})^{2} ] \quad (9c)$$

Using the separation of variables method, one can write the relative deflection as follows [13]:

$$w(x,t) = \sum_{r=0}^{\infty} W_{r}(x) T_{r}(t) \quad (12)$$

where $T_{r}(t)$ and $W_{r}(x)$ are the time response and the $r$-th normal mode shape of the cantilever beam, respectively. Then, the motion equation in modal space can be written as Equation (12).

$$\frac{d^{2} T_{r}(t)}{d t^{2}} + 2 \lambda_{r} \omega_{r} \frac{d T_{r}(t)}{d t} + \omega_{r}^{2} T_{r}(t) + a_{EM} W_{r}(x) + a_{MM} V_{in}(t) = F V_{in}(t) \quad (13)$$

where $F V_{in}(t)$ is the electrical excitation induced force and expressed as follows:

$$F V_{in}(t) = - a_{in} \dot{V}_{in}(t) \quad (14a)$$

where:

$$a_{in} = \frac{b_{in}^{p}}{2 \rho_{p}} \left[ (h_{b})^{3} - (h_{a})^{3} \right] \frac{d W_{r}(x)}{d x} \bigg|_{x=L} \quad (14b)$$

$$a_{EM} = \frac{b_{EM}^{p} N_{M}}{2 \rho_{m}} [ (h_{c})^{2} - (h_{a})^{2} ] \frac{d W_{r}(x)}{d x} \bigg|_{x=L} \quad (14b)$$

$$a_{MM} = - \frac{b_{MM}^{p} N_{M}}{2 \rho_{m}} [ (h_{c})^{2} - (h_{b})^{2} ] \frac{d W_{r}(x)}{d x} \bigg|_{x=L} \quad (14b)$$

Now, the differential equation of the electrical circuit of the two ends of the electrodes used around the MEE
layers is extracted. Initially, the two ends of the electrodes and external coils were connected to external electrical resistors $R_E$ and $R_M$ to use the voltages generated by $V_E$ and $V_M$

Using Equation (4), the second constitutive Equation (2b), is reduced to Equation (15) for the MEE energy harvester.

$$D_M(x, t) = -e_{31} h_{MC} \frac{\partial^2 W}{\partial x^2} \left( x, t \right) - \frac{\partial}{\partial y} V_E(t) + \frac{\partial}{\partial z} V_M(t)$$

where $h_{MC}$ is the distance between the neutral and mid axes of the active MEE and $\text{sgn}(z)$ is the sign function.

Next, integrating the electric displacement in Equation (14) over the surface of the electrodes, using Gauss’s law, the electrical charge $Q_e(t)$ appearing on the electrode attached to the MEE layer can be expressed as follows [12]:

$$Q_e(t) = \int A_e \partial D_M(x, t) dA_e =$$

By imposing Equation (15) into Equation (16), for each configuration, and calculating the integral, an expression for the charge is obtained as a function of time.

$$C_M \frac{dQ_e(t)}{dt} + \frac{1}{R_E} V_E(t) = \sum_{r=1}^{q} \theta_{ME} \frac{dT_r(t)}{dt} + \chi_{ME} \frac{dV_M(t)}{dt}$$

$C_M$ denotes the internal capacitance of the MEE layer, and $\theta_{ME}$ and $\chi_{ME}$ are the coefficients of modal and magnetic to electric coupling terms in the circuit connected to the electrodes, respectively. That are obtained in the following forms:

$$C_M = \frac{\mu_0 M^2 b_t}{h_m}$$

$$\theta_{ME} = -e_{31} h_{MC} \frac{\partial W}{\partial x} \bigg|_{x=L}$$

$$\chi_{ME} = \frac{\mu_0 M^2 b_t}{\rho_M}$$

One can rewrite Equations (17) into general form as Equation (19).

$$C_M \frac{dQ_e(t)}{dt} + \frac{1}{R_E} V_E(t) = \sum_{r=1}^{q} \theta_{ME} \frac{dT_r(t)}{dt} + \chi_{ME} \frac{dV_M(t)}{dt}$$

Faraday’s law states that the voltage $V$ is induced proportional to the time derivative of magnetic flux linkage, $\phi$, [14]. As a result, the voltage induced in the $N$-turn coil $V_M$ may be calculated as follows:

$$V_M(t) = -N \frac{d\phi}{dt}$$

Generally, $\phi$, is calculated as follows:

$$\phi = \sum_{n=1}^{N} f_n B \cdot dA$$

According to substitution of Equation (5) into Equation (2c) and using Table 2, the magnetic field flux density, $B_M$, is obtained as:

$$B_M(x, t) = -\frac{h_{MC}}{\mu_0} \frac{\partial W}{\partial x} \left( x, t \right) - \frac{\partial}{\partial z} V_E(t) + \frac{\partial}{\partial y} V_M(t)$$

Using Equations (20), (21), and (22), the below differential equations are obtained as follows:

$$L_c \frac{dV_E(t)}{dt} + R_M V_M(t) = \sum_{r=1}^{q} \theta_{MMr} \frac{dT_r(t)}{dt} + \chi_{EM} \frac{dV_M(t)}{dt}$$

Here, $L_c$, $\theta_{MMr}$, and $\chi_{EM}$ represent self-inductance of the coil, the coefficient of modal and electric to magnetic coupling terms, respectively. That are obtained in the following forms:

$$L_c = \mu_0 M^2 b_t$$

$$\theta_{MMr} = -\frac{h_{MC}}{\mu_0} \frac{\partial W}{\partial x} \bigg|_{x=L}$$

$$\chi_{EM} = \frac{\mu_0 M^2 b_t}{\rho_M}$$

One can reduce Equations (24) into general form as follows:

$$L_c \frac{dV_E(t)}{dt} + R_M V_M(t) = \sum_{r=1}^{q} \theta_{MMr} \frac{dT_r(t)}{dt} + \chi_{EM} \frac{dV_M(t)}{dt}$$

Finally, the governing differential equations of the electrically excited MEE energy harvester are classified as follows:

$$\frac{d^2 T_r(t)}{dt^2} + 2 \zeta_r \omega_r \frac{dT_r(t)}{dt} + \omega_r^2 T_r(t) + \alpha_{MMr} V_E(t) + \alpha_{MMr} V_M(t) = F(t)$$

Next, in order to derive analytical expressions for the dynamic response of the MEE energy harvester, it is assumed that the applied voltage, $V_{in}(t)$, is defined as $V_{in}(t) = V_{Am} \cos(\omega t)$ (where $V_{Am}$ is the amplitude of the applied voltage). Similarly, the time response expression of the beam in modal space (Equation (12)), $T_r(t)$, and the generated voltages, $V_E(t)$ and $V_M(t)$, can be expressed as follows:

$$V_E(t) = V_{AE} \cos(\omega t)$$

$$V_M(t) = V_{AM} \cos(\omega t)$$

$$T_r(t) = T_{Ar} \cos(\omega t)$$

where $T_{Ar}$, $V_{AE}$ and $V_{AM}$ are the temporal response and generated voltage amplitudes, respectively. Thus, one
can rewrite the electrical excitation induced force (Equation (14)) as follows:

\[ F_{V_{in}}(t) = F_{V_{Ar}}e^{j\omega t} \]

(28)

where:

\[ F_{V_{Ar}} = -\alpha EMV_{in} \]

Substituting Equations (27) and (28) into Equation (26):

\[ [(\omega_0^2 - \omega^2) + j(2\zeta \omega_0 - \omega)]T_{Ar} + \alpha EMV_{AE} + a_{MM\omega}V_{AM} = F_{V_{Ar}} \left( \frac{1}{R_E} + j\omega C_M \right) + j\omega \left( \sum_{r=1}^{\infty} \delta_{M\omega} T_{Ar} + \chi_{MM\omega}V_{AM} \right) \]

(29)

By solving the Equation (29) and substituting the results in Equation (27):

\[ V_E(t) = \sum_{r=1}^{\infty} \left( \frac{j\omega M_{ME} F_{V_{Ar}}}{\rho_g R_E + \sum_{r=1}^{\infty} \delta_{M\omega} (r_z \omega + j\omega C_M)} + \chi_{ME}\right) e^{j\omega t} \]

(30a)

\[ V_M(t) = \sum_{r=1}^{\infty} \left( \frac{j\omega M_{ME} F_{V_{Ar}}}{\rho_g R_E + \sum_{r=1}^{\infty} \delta_{M\omega} (r_z \omega + j\omega C_M)} + \chi_{ME}\right) e^{j\omega t} \]

(30b)

\[ T_r(t) = 1 - \sum_{r=1}^{\infty} \left( \frac{j\omega M_{ME} F_{V_{Ar}}}{\rho_g R_E + \sum_{r=1}^{\infty} \delta_{M\omega} (r_z \omega + j\omega C_M)} + \chi_{ME}\right) e^{j\omega t} \]

(31)

where electromagnetic voltage ratio, \( V_{ME} \), is obtained as follows:

\[ \frac{1}{n_{ME}} = \frac{V_M}{V_E} = \frac{\sum_{r=1}^{\infty} \left( \frac{j\omega M_{ME} F_{V_{Ar}}}{\rho_g R_E + \sum_{r=1}^{\infty} \delta_{M\omega} (r_z \omega + j\omega C_M)} + \chi_{ME}\right) e^{j\omega t}}{\sum_{r=1}^{\infty} \left( \frac{j\omega M_{ME} F_{V_{Ar}}}{\rho_g R_E + \sum_{r=1}^{\infty} \delta_{M\omega} (r_z \omega + j\omega C_M)} + \chi_{ME}\right) e^{j\omega t}} \]

(32)

Substituting Equation (31) into Equation (12), the displacement of each point on the MEE energy harvester under electrical excitation is obtained. The electrical current frequency response functions are obtained by dividing the resulting voltages by the load resistance of the electrical circuits.

In order to compute the MEE energy harvester efficiency under electrical excitations, the input and output power must be compared. Thus, using Ohm’s law \( (V = IR) \), and \( P = 0.5VI \), the total power made by energy harvester, \( P_{total}(t) \), are expressed as follows:

\[ P_E(t) = \frac{1}{2} V_E^2 \]

(33a)

\[ P_M(t) = \frac{1}{2} V_M(t)^2 \]

(33a)

\[ P_{total}(t) = P_E(t) + P_M(t) \]

(33b)

The MEE energy harvester efficiencies under electric excitation, \( \Lambda_E, \Lambda_M \) and \( \Lambda_{ME} \), are introduced as the ratio of harvested to the input parameters and expressed as follows:

\[ \Lambda_E = \frac{V_E(t)}{V_{in}(t)} \]

(34a)

\[ \Lambda_M = \frac{V_M(t)}{V_{in}(t)} \]

(34b)

\[ \Lambda_{ME} = \frac{P_{total}(t)}{P_{in}(t)} \]

(34c)

RESULTS AND DISCUSSION

In this section, the results obtained from the analytical solutions in the previous section are presented. Numerical results will be carried out for \( BaTiO_3-CoFe_2O_4 \) composite as the MEE layer with a volume fraction \( c = 0.5 \). The geometry and material properties used in the following case studies are listed in Table 1.

The performance of the MEE energy harvesting system under external electrical excitation is considered. The effect of the parameters extracted from the previous section, \( R_M, R_E, R_M, 1\rho \) and \( h_M \) on the MEE energy harvester efficiencies, \( \Lambda_E, \Lambda_M \) and \( \Lambda_{ME} \) has been investigated.

The effects of the non-dimensional electrical excitation frequency, \( \eta \), on the power efficiency, \( \Lambda_{ME} \), for four different values of the electrical load resistances connected to the applied circuit voltage \( (R_{in} = 10^5 \Omega) \)

**Table 1. Material properties and geometric dimensions of the layers of the harvester**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{11}^p ) (N m(^{-2}))</td>
<td>Piezoelectric Young’s modulus</td>
</tr>
<tr>
<td>( C_{11}^m ) (N m(^{-2}))</td>
<td>MEE material Young’s modulus</td>
</tr>
<tr>
<td>( e_{31}^p ) (C m(^{-2}))</td>
<td>Piezoelectric coefficient of the Piezoelectric layer</td>
</tr>
<tr>
<td>( e_{31}^m ) (C m(^{-2}))</td>
<td>Piezoelectric coefficient of the MEE layer</td>
</tr>
<tr>
<td>( f_y ) (N A(^{-1}))</td>
<td>Piezomagnetic coefficient</td>
</tr>
<tr>
<td>( h_y ) (C N m(^{-2}))</td>
<td>Dielectric coefficient</td>
</tr>
<tr>
<td>( g_y ) (N s V(^{-1}) C(^{-1}))</td>
<td>Magnetoelastic coefficient</td>
</tr>
<tr>
<td>( \mu_y ) (N s ( V^2 ) C(^{-1}))</td>
<td>Magnetic permeability</td>
</tr>
<tr>
<td>( \rho_E ) (kg m(^{-3}))</td>
<td>Piezoelectric density</td>
</tr>
<tr>
<td>( \rho_M ) (kg m(^{-3}))</td>
<td>MEE material density</td>
</tr>
<tr>
<td>( l ) (mm)</td>
<td>Length of the beam</td>
</tr>
<tr>
<td>( b ) (mm)</td>
<td>Width of the beam</td>
</tr>
<tr>
<td>( h_{b} ) (mm)</td>
<td>Thickness of the piezoelectric layer</td>
</tr>
<tr>
<td>( h_{m} ) (mm)</td>
<td>Thickness of the MEE layer</td>
</tr>
</tbody>
</table>
$10^5 \Omega$, $10^6 \Omega$, and $10^4 \Omega$) are plotted in Figure 3. It is evident that an increase in $\eta$ and $R_m$, leads to an increase in the $\Lambda_{ME}$. Figure 3 shows that the maximum value of $\Lambda_{ME}$ is calculated for $R_m = 10^6 \Omega$ ($\Lambda_{ME} = 0.4758$ W/W). In other words, 47.58% of the input power can be stored. While this ratio is only equal to 0.51% for the amount of $R_m = 10^4 \Omega$. Due to the fact that electrical load resistance $R_m$, has no effect on the values of voltage efficiency, only its effect on the power efficiency has been investigated.

In Figures 4 to 6 the effects of the $\eta$ and $R_E$, on the $\Lambda_{ME}$, $\Lambda_E$ and $\Lambda_M$ for four different values of the electrical load resistances connected to the electrical circuit of the electrodes ($R_E = 10^6 \Omega$, $10^5 \frac{\Omega}{\Omega}$, $10^4 \Omega$, and $10^2 \Omega$) are plotted. The plotted results show the different effect of each value of electrical resistance $R_E$ in increasing or decreasing efficiencies. From the drawn results, it can be concluded that in order to harvest the maximum power, the range $10^5 \Omega \leq R_E \leq 10^5.5 \Omega$ should have a higher priority in the choice of $R_E$. It is obvious from Figure 5 that for $R_E = 10^5 \Omega$, 26.87% of the applied voltage can be stored in the circuit connected to the electrodes, which is a significant amount to reduce the consumption of electronic circuits. In order to store higher voltage values, the range $10^5.5 \Omega \leq R_E \leq 10^6 \Omega$ must be selected. Also, the maximum efficiency $\Lambda_M$ occur in $R_E = 10^5 \Omega$ to the numerical value of $\Lambda_M = 0.0014$ V/V that is insignificant compared to the $\Lambda_E$.

Figures 7 to 9 illustrate the effects of the $\eta$ and $R_M$, on the $\Lambda_{ME}$, $\Lambda_E$ and $\Lambda_M$ for four different values of the electrical load resistances connected to the electrical circuit of the external coil ($R_M = 10^6 \Omega$, $10^4 \Omega$, $10^2 \Omega$, and $10^1 \Omega$). The results show the better performance of the MEE harvester in the range of $10^1 \Omega \leq R_M \leq 10^2 \Omega$ for
harvesting electric power. The maximum value of $\Lambda_{ME}$ is calculated for $R_M = 10^1 \Omega$ ($\Lambda_{ME} = 0.6596$ W/W) that this value is 36.78% better than the value obtained from the results of Figure 4. As a result, the load resistance $R_M$ connected to the external coil can have a decisive role on the power efficiency $\Lambda_{ME}$. It can be seen that electrical resistance $R_M$ has little effect on changes in electrical voltage efficiencies. The changes of $R_M$ improve the values of $\Lambda_E$ and $\Lambda_M$ by 15.98% and 6.21%, respectively.

Finally by considering that the thickness of harvesters is the limiting parameter of the design, harvester efficiencies $\Lambda_{ME}$, $\Lambda_E$ and $\Lambda_M$ were checked for different thickness ratios in Figures 10 to 12, respectively. The obtained results show that the equal thickness of the piezoelectric and MEE layers has a better effect on the power and voltage efficiencies of the discussed harvester.
CONCLUSION

In this paper the performance of the energy harvesters made of active MEE layers and under electrical excitation was analyzed. The MEE beam consisted of the piezoelectric material as the substrate layer and MEE composite as the active layer. The unimorph and bimorph configurations of the MEE layers (including serial, parallel, and single-layer connections) were studied, assuming that the connections between these layers are perfect. The coupled magneto-electro-elastic governing equations were obtained using Euler-Bernoulli theory, Faraday laws and Gauss, and then, these equations were solved analytically to obtain the generated electrical power and voltage. The effects of $R_M$, $R_E$, and $R_m$, on the MEE energy harvester efficiencies, have been investigated. The results show that a significant amount of electrical excitation voltage can be stored from the circuits connected to the electrodes. Also, the load resistance $R_M$ connected to the external coil can have a decisive role on the power efficiency. For energy harvesting purposes, one can use the electrical excitation as the second source added to the ambient vibration.

REFERENCES

چکیده

در این مقاله، یک برداشت کننده جدید به منظور ذخیره توان الکتریکی که از توان ولتاژ الکتریکی اعمال شده خارج نشان می‌گیرد، معرفی می‌گردد. برداشت کننده اثری به شکل تیر و مشکل از یک لایه با خواص فعلی مگنتو-الکترو-الستیک متصول به یک لایه پیوند الکتریکی است. بررسی برداشت کننده با فرض اعمال کامل بین لاپیه و بکریندیت تک لایه فعلی صوت هزینه است. معادلات دیرانسیل کویل شده مغناطیسی-الکتریکی-سیستمی حاکم بر سیستم برداشت کننده انرژی مگنتو-الکترو-الستیک در جهت عرضی و تحت تأثیر یک ولتاژ الکتریکی هارمونیک اعمالی بر اساس نظرهای نیویلر-برنولی، قانون گاویس و قانون فارادی بدست آمده‌اند. این معادلات بهصورت تحلیلی حل شده، نتایج بدست‌آمده به‌مدت بیان می‌کند که با تنظیم برخی محدودیت‌های لازم و انتخاب پارامتر‌های مناسب، براورد توان و ولتاژ بیشتری در برداشت‌کننده دوگانه (محرک - برداشت کننده) به‌دست می‌آید. به‌عنوان نتیجه‌گیری نهایی، می‌توان به اثبات وجود استفاده دوگانه (محرک - برداشت کننده) از برداشت کننده انرژی پیشنهادی اشاره کرد.