ENERGY HARVESTING USING PIEZOELECTRIC AND ELECTROMAGNETIC TRANSDUCERS

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Abstract: Nowadays, a major concern is the need to develop new energy sources. In this context, a sector that has attracted much interest is one in which devices that are able convert other types of energy into electrical energy. This technique is known as Energy Harvesting and consists of energy capture and storage from ambient sources. This paper works with piezoelectric and electromagnetic transducers, which are able to convert mechanical vibrations into electrical energy. However, when an electrical circuit is coupled to the transducer the mechanical system is strongly influenced by it. This paper presents a model that considers the coupling influence between these systems. The structure modeled as a free sliding beam with one electrical load. A program was developed to analyze the behavior of this system, as well as the optimal conditions for power harvested.

Keywords: Energy Harvesting, Transduction Matrix Piezoelectric Transducer, Electromagnetic Transducer.

1. INTRODUCTION

Energy Harvesting, Power Harvesting or Energy Scavenging is about the act of converting ambient energy in electrical energy (electrical power). In every cases this energy was been wasted or lost before. Normally, the electrical energy converted is stored in a kind of battery to be used later but that don’t prevent the energy be used in the same time that is converted too.

In this form, the Energy Harvesting may be a solution for source energy in many cases, mainly in remote, inaccessible or hostile environments applications where the connection with the electrical energy network is difficult. Frequently, these devices are small, wireless autonomous, like those used in wearable electronics and wireless sensor networks.

The external source can be solar, wind, thermal, salinity gradients and kinetic. In this paper the source is kinetic; specifically, vibration sources that can be anything that have periodic motion. For example the small vibrations of a machine, the motion of walking, even the motion of blood circulation. However, for this conversion to be possible the transducer should transform mechanical energy in electrical energy. The transducers mostly used for this are electromagnetic, electrostatic and piezoelectric. In this work, the harvesting of energy is through piezoelectric and magnetic transducers.

Piezoelectric transducers are constituted by piezoelectric materials. This material has the ability to directly convert material fixed in the mass in motion and a conductive coil fixed on housing of transducer. The motion of a magnetic field relative to a conductive coil causes current to flow in the coil (Amirtharajah and Chandrakasan, 1998) (El-ham et al, 2001).

Piezoelectric transducers are been applied in many types of applications among then we can quote; military sector, implantable devices; shoe inserts, Eels (to get energy from wave energy) and others.

In this context, many studies had been conducted they: Sodano et al. (2002) performed a study to investigate the amount of power generated through the vibration of a piezoelectric plate, as well as methods of power storage; Lesieutre et al. (2002) investigated the damping added to a structure due to the removal of electrical energy from the system during power harvesting; Lejeune et al. (2005) constructed an electromechanical structure, trying to optimize the power flow of vibration-based piezoelectric energy-harvesters.

The biggest problem when a electric circuit is connected in the transducer is that occurs a interaction between the electrical and mechanical systems. This paper works with a model proposed by Nakano et al (2007) for describes this interaction. This model is based a two-port network model of a transducer. The methodology is applied for both electromagnetic and piezoelectric transducers connected a
resistive load and the behaviour of these systems is studied. The optimum load for maximum power harvested of the system is also was investigated.

2. TWO-PORT NETWORK MODEL

To model the harvesting system a two-port network model of a transducer is used connected to the Thevenin equivalent for the vibrating structure and an electric load. This model was proposed by Nakano et al (2007) and can be seen in figure (1).

In figure (1) $f_b$ is the blocked force, $Z_{me}$ is the Mechanical Impedance of the system, $u$ is the velocity, $f$ is the force on transducer, $Z_{mt}$ is the Mechanical Impedance of the transducer, $Z_{st}$ is the Electrical Impedance of the transducer, $Z_{el}$ is the Impedance of the external load, $i$ is the current, $v$ is the voltage on load, $T_{em}$ and $T_{me}$ are the transduction coefficients. $T_{me}$ describes the force produced per unit electric current and similarly $T_{em}$ represents the voltage generated per unit velocity.

For the transducer the relationship between the mechanical and electrical variables is expressed by:

$$\begin{bmatrix} f \\ v \end{bmatrix} = \begin{bmatrix} Z_{mt} & T_{me} \\ T_{em} & Z_{st} \end{bmatrix} \begin{bmatrix} u \\ i \end{bmatrix}$$  

(1)

where $|T_{me}| = |T_{em}|$  

(2)

The voltage across the external load is given by:

$$v = -Z_{el}i$$  

(3)

Substituting equation (3) into the equation for voltage for the transducer given in equation (1) gives the current as function of velocity:

$$i = -\frac{T_{em}}{Z_{st} + Z_{el}} u$$  

(4)

Substituting equation (4) into the equation for the force in equation (1) gives the force as a function of velocity:

$$f = (Z_{mt} - \frac{T_{em}Z_{st}}{Z_{st} + Z_{el}}) u$$  

(5)

The force in the transducer can be expressed as:

$$f = f_b - Z_{mt}u$$  

(6)

Now, substituting equation (6) in (5) gives the expression for the velocity:

$$u = \frac{f_b}{Z_{st} - \frac{T_{em}Z_{el}}{Z_{el} + Z_{st}}}$$  

(7)

where $Z_m = Z_{mt} + Z_{ms}$  

(8)

Power harvested is considered as the power dissipated in the electric load. Under the harmonic excitation this power is:

$$P_h = \frac{1}{2} \text{Re}[-iv']$$  

(9)

where $(\cdots)^*$ means the complex conjugated

From equation (3) and (4):

$$P_h = \frac{1}{2} \text{Re}[Z_{el}] |\frac{-T_{em}}{Z_{st} + Z_{el}} u|^2$$  

(10)

3. TRANSDUCERS

The piezoelectric and electromagnetic transducers models showed in this work were based is previous study of Preumont (2006) and Nakano et al (2007). These models are used to find the mechanical and electrical impedances and transduction coefficients for this transducer

3.1. Piezoelectric transducer

Figure (2) shows the piezoelectric transducer used in this work. In this picture $E$ is Electric Field, $T$ is Stress, $l$, $b$, and $t$ are length, width and thickness of transducer.

$$A = l \cdot b \cdot t$$

From equation (3) and (4):

$$P_h = \frac{1}{2} \text{Re}[Z_{el}] |\frac{-T_{em}}{Z_{st} + Z_{el}} u|^2$$  

(10)

This transducer can be modelled as a uniaxial and element the constitutive equations can be written as:

$$\begin{bmatrix} Q \\ S \end{bmatrix} = \begin{bmatrix} e^T & d_{31} \\ d_{31} & s_E \end{bmatrix} \begin{bmatrix} E_f \\ T \end{bmatrix}$$  

(23)

where $Q$ is Electric displacement, $S$ is Strain, $s_E$ is compliance of material under constant electric field, $d_{31}$, is piezoelectric constant, $e^T$ is permittivity when the stress is constant.

Assuming a harmonic force the constitutive equation can be transformed to:

$$\begin{bmatrix} f \\ q \end{bmatrix} = \begin{bmatrix} \frac{1}{c_{mt}} & -D_{31} \\ -D_{31} & \frac{1}{c_{et}} \end{bmatrix} \begin{bmatrix} q_{mt} \\ q_{et} \end{bmatrix}$$  

(24)
where $f$ is force, $v$ is voltage, $q_{mt}$ is mechanical deflection and $q_{et}$ is electrical charge, $D_{31}$ is the piezoelectric transducer constant, $C_{mt}$ is mechanical compliance with open electrodes ($q_{et} = 0$) and $C_{et}$ is electric capacitance of the transducer for a fixed geometry ($q_{mt} = 0$). Defining a coupling coefficient, $\kappa$, by:

$$\kappa = \frac{|d_{31}|}{\sqrt{|\varepsilon_{33}|}}$$  \hspace{1cm} (25)

The others parameters of equation (24) are given by:

$$\frac{1}{C_{mt}} = \frac{K_a}{1-\kappa^2}$$  \hspace{1cm} (26)

$$\frac{1}{C_{et}} = \frac{1}{\varepsilon (1-\kappa^2)}$$  \hspace{1cm} (27)

$$D_{31} = \frac{d_{31} K_a}{\varepsilon (1-\kappa^2)}$$  \hspace{1cm} (28)

where $C = \frac{\varepsilon A}{l}$  \hspace{1cm} (39)

and $K_a = \frac{A}{s^2 l}$  \hspace{1cm} (30)

In these equations $C$ is the capacitance of the transducer with no external load ($f_e = 0$), $K_a$ is the stiffness of the transducer with short-circuited electrodes ($v_e = 0$) and $A$ is the cross section area.

Finally, the mechanical and electrical impedances and the transduction coefficients are given, respectively, by:

$$Z_{mt} = \frac{1}{j \omega C_{mt}} (1 + j \eta_{mt})$$  \hspace{1cm} (31)

$$Z_{et} = \frac{1}{j \omega C_{et}} (1 + j \eta_{et})$$  \hspace{1cm} (32)

$$T_{me} = T_{em} = \frac{D_{31}}{j \omega}$$  \hspace{1cm} (33)

where $\eta_{mt}$ and $\eta_{et}$ are the loss factors in the mechanical and electrical compliances.

3.2. Electromagnetic transducer

Figure (3) shows the electromagnetic transducer used in this work. In this picture $L_{mt}$ is reaction mass, $C_{mt}$ is the transducer compliance and $R_{mt}$ is the damping coefficient.

The transduction coefficients are defined as:

$$|T_{me}| = |T_{em}| = Bl$$  \hspace{1cm} (34)

where $B$ is the magnetic flux density and $l$ is the effective length of the coil.

$$Z_{et} = R_{et} + sL_{et}$$  \hspace{1cm} (36)

4. MODEL OF FINITE BEAM

Two systems were investigated in this work using a Euler-Bernoulli beam. One with a piezoelectric patch bonded on a surface of beam and other with an electromagnetic transducer connected on free extremity of beam.

The mechanical Impedance of the beam depends of the boundary conditions and was determined using the methodology shown by Gardonio and Brennan (2004). The transfer impedance due a force excitation at $x_i$ and a velocity response at $x_j$ is given by the inverse of the mobility:

$$Z_{ij} = \frac{1}{Y_{ij}}$$  \hspace{1cm} (37)

and

$$Y_{ij} = j \omega \sum_{n=1}^{\infty} \frac{\psi_n(x_i) \psi_n(x_j)}{\delta^2 (\omega_n^2(1+\eta_n) - \omega^2)}$$  \hspace{1cm} (38)

where $\psi_n(x)$ is the $n$th natural mode, $\omega_n$ is the natural frequency for the $n$th natural mode, $l$ is the length of the finite beam and $\eta$ is the loss factor for the material of beam. The natural modes $\psi_n(x)$ can be obtained in many textbooks. Here we work with the approach developed by Gonçalves et al (2007).

For a finite beam with a piezoelectric element bounded is necessary to find the uniform equivalent beam for applying this theory. Figure (4) shows the finite beam element and the cross-section before and after determines the equivalent beam.
Considering the electromagnetic transducer coupled in the beam structure to finding the equivalent impedance of the system is necessary to consider the impedance of the transducer in connection impedance of the beam using this matrix equation:

\[ [Z] = [(I - Y_b Z_0)^{-1} Y_b]^{-1} \]  

(39)

where \( Y_b \) is the mobility of the beam, \( Z_0 \) the impedance of the transducer coupled in the beam structure and \( Z \) is the impedance of the system.

5. NUMERICAL SIMULATION

Figure (5) shows the beam of interest and the table (1) the properties of the system and the piezoelectric material. The input of the system was represented in the figure above too and it was acceleration with unitary amplitude. The load connected was just a resistance representing a battery for both cases.

The inputs for the transducers are different than inputs of the system. For the piezoelectric material the input is a force and was found by this equation:

\[ f_t = \frac{N I E}{\alpha x T q} \]  

(40)

where \( q \) is the distance between the neutral axis and the upper surface of PZT and \( N = E/E_t \).


descriptions Symbols Values
| Length of the beam and piezoelectric transducer | \( I \) | 0.1 [m] |
| Width of the beam and piezoelectric transducer | \( b \) | 0.02 [m] |
| Thickness of the piezoelectric transducer | \( t_p \) | 0.000266 [m] |
| Thickness of the beam | \( t \) | 0.002 |
| Piezoelectric constant of material | \( d_{33} \) | -320 \times 10^{-12} [C/N] |
| Young’s modulus of the piezoelectric transducer | \( E \) | 62 [GPa] |
| Dielectric constant of the piezoelectric transducer | \( e_f \) | 3.36452 \times 10^{-8} [F/m] |
| Electrical loss factor of the piezoelectric transducer | \( \eta_{pl} \) | 0.003 |
| Mechanical loss factor of the piezoelectric transducer | \( \eta_{me} \) | 0.000056 |
| Density of the piezoelectric transducer | \( \rho_0 \) | 7600 [m/Ag] |
| Density of the beam | \( \rho \) | 2700 [m/Ag] |
| Young’s modulus of the beam | \( E \) | 70 [GPa] |
| Mechanical loss factor of the beam | \( \eta \) | 0.003 |
| Mass of electromagnetic transducer | \( M_{em} \) | 0.02 [kg] |
| Damping of the electromagnetic transducer | \( R_{em} \) | 3.5 [Ns/m] |
| Compliance of the electromagnetic transducer | \( C_{em} \) | 0.0026 [m/N] |
| Constant of the electromagnetic transducer | \( B \) | 2.6 [N/A] |
| Inductance of the electromagnetic transducer | \( L_{em} \) | 1 [mH] |
| Resistance of the electromagnetic transducer | \( R_{em} \) | 1.8 [Ω] |

However, for the electromagnetic transducer the input is a velocity given by:

\[ u = \frac{\left(\frac{1}{\rho_{em} + \frac{1}{\eta_{em}}} + \frac{1}{Z_{em} + \frac{1}{\eta_{em}}}ight)}{\left(\frac{1}{\rho_{em} + \frac{1}{\eta_{em}}} + \frac{1}{Z_{em} + \frac{1}{\eta_{em}}}ight)} \]  

(41)

where \( u \) is the velocity for a reactive mass and \( u \) will be the velocity of beam where the transducer are connected.

Figure (6) shows the first fourth modes of vibration for the beam. The impedance of the beam was determined used the 100th first modes.

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For the electromagnetic transducer the voltage and power for different resistances values can be seen in figures (9) and (10), respectively.

Observing figures (8) and (10) we can note the optimum regions for the power from both transducers as a function of the resistance and frequency. Also can be noted that the bandwidth is bigger for the piezoelectric transducer than for the electromagnetic. It represents a good advantage for piezoelectric transducers.

3. CONCLUSION

This paper has described an electro-mechanical model for an energy harvesting device for piezoelectric and electromagnetic transducers.

A study has been undertaken to determine the optimum load conditions in both cases. When the load increase an open circuit rescuer the power becomes very small. For the opposite, when the load tends to zero, simulating a short circuit, the voltage and the power is smallest, tends to zero.
too. The optimization of the load for the system is extremity important to ensure efficiency of the harvesting system.

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REFERENCES


