Design, Development and Testing of a Vibration Based Piezoelectric and Electromagnetic Dual Mode Energy Harvester

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Abstract: *This paper presents the design of vibration based piezoelectric and electromagnetic dual mode energy harvester. The energy harvester consists of a cantilever beam with the Neodymium Iron Boron (NdFeB)magnets at some distance from free end and piezoelectric disc at the fixed end. Using this system, the mechanical vibration of different frequencies at different amplitudes is given to the beam. The piezoelectric disc at fixed end, while the electromagnetic induction principle at the free end is used to convert the mechanical vibrations into electricity. The expressions for piezoelectric and electromagnetic harvesting power with the physical characteristics of the beam are derived for electrical power and validated experimentally. The energy under the first resonant natural frequency of 28 Hz is harvested. The maximum voltage and the power at the first resonant frequency for 2mm exciting vibration are 0.164 V and 4.8 mW. This amount of power is sufficient to provide power for typical wireless sensors such as accelerometers and strain gauges.*

Keywords: Piezoelectric, electromagnetic induction, dual mode energy harvester, cantilever beam.

I.Introduction

With the recent advances in wireless and microelectromechanical systems technology, the demand for portable electronics and wireless sensors is growing rapidly. Because these devices are portable, it becomes necessary that they carry their own power supply. In most cases, this power supply is the conventional battery however, problems can occur because the electronics could die at any time and replacement of the battery can become a tedious task. In case of wireless sensors, these devices can be placed in vary remote locations such as structural sensors on a bridge or global positioning system (GPS) tracking devices on animals in the wild.

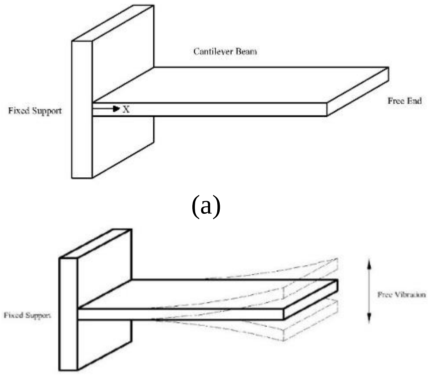
When the battery is extinguished of all its power, the sensor must be retrieved and the battery replaced. Because of the remote placement of these devices, obtaining the sensor simply to replace the battery can become a very expensive task or even impossible. If ambient energy in the surrounding medium could be obtained, then it could be used to replace or charge the battery.

The output from piezoelectric discs alone are very low and hence can be increased by using electromagnetism. Since the output from piezoelectric disc alone is efficient at low frequencies while the output from electromagnet alone at high frequencies, so by using piezoelectric and electromagnetic dual mode energy harvester wide range of ambient vibrations can be harvested.

II. Analysis of cantilever beam

2.1 Analytical analysis of cantilever beam for natural frequency

Consider a cantilever beam of length L, width B and thickness T as shown in figure below



(a)

(b)

Fig. 2.1 (a) Cantilever beam, (b) Cantilever beam subjected to free vibration

Let us consider the Euler- Bernoulli beam equation that describes the vibration behavior of cantilever beam as follows:
Euler-Bernoulli method is used to model the cantilever beam. The governing equation for the cantilever beam is given as

$$\frac{\delta^2}{\delta t^2}w(x,t)+\left(\frac{EI}{\rho AL^4}\right)\frac{\delta^4}{\delta x^4}w(x,t)=\ F(t) \qquad ...(1)$$

Assuming general solution for above equation as

$$w(x,t)=\ Y(x)\ \times\ W(t) \qquad ...(2)$$

By putting general solution (2) in equation (1) it becomes

$$\frac{EI}{\rho AL^4}\frac{d^4}{dx^4}Y(x) = {w_n}^2 \times Y(x)$$

$$i.e\ \frac{d^4}{dx^4}Y(x) - \beta^4 \times Y(x) = 0 \qquad \text{...(3)}$$

Where,

$$\beta^4 = {w_n}^2 \times \frac{\rho AL^4}{EI} \qquad \text{...(4)}$$

By putting boundary condition (2) we get,

$$\cos(\beta_i L) \times \cosh(\beta_i L) = -1 \qquad \text{...(5)}$$

Where i= number of mode shapes = 1, 2,3...n

By solving solution (5) for different values of mode numbers we get,

$$\beta = 1.875, 4.694, 7.885, \dots etc$$

For first natural frequency

$$\beta_1 = 1.875$$

and put in equation (5) we get for cantilever beam

$$\mathrm{w}_{\boldsymbol{n}} = 1.875^2 \times \sqrt{\frac{EI}{\rho AL^4}} \qquad \text{...(6)}$$

Here, material used for cantilever beam is Aluminium alloy 6061-T6 having following properties

Table 2.1 Properties of beam

Physical Properties:	
1. Young's modulus, E (Pa)	6.89 $*10^{10}$
2. Density, ρ (Kg/m^3)	2700
Dimensions of beam:	
1. Length, L (m)	210 $*10^{-3}$
2. Width, B (m)	30 $* 10^{-3}$
3. Thickness, T(m)	2.9 $* 10^{-3}$
4. Moment of Inertia, $I = \frac{BT^3}{12}$ (m^4)	60.97 $* 10^{-12}$
5. Cross section area, $A = B * T$ (m^2)	8.7$* 10^{-5}$

By putting all above values in equation (6), we get natural frequency of first mode as

w_n= 337.12 rad/s

$\therefore f_n = 427.53 / (2*\pi) = 53.65$ Hz

2.2 Modal analysis of cantilever beam in workbench 18.0

In ANSYS Workbench 18.0, modal analysis of cantilever beam is done to find out the natural frequency.

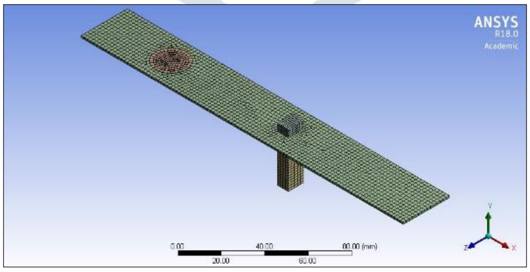
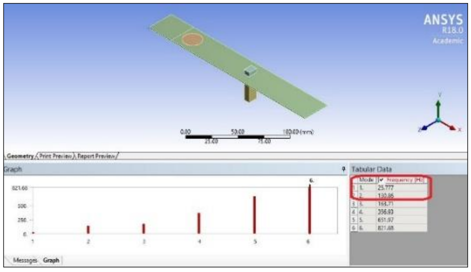


Fig. 2.2 Meshing of cantilever beam with magnets and piezoelectric disc



	Mode	Frequency [Hz]
1	1.	25.777
2	2.	130.86
3	3.	168.71
4	4.	356.93
5	5.	651.97
6	6.	821.68

Fig. 2.3 Modal analysis of cantilever beam

In figure 2.2 the beam with magnets and piezoelectric disc is meshed with the Hexahedron elements with 17917 nodes and 3406 elements. The Hex Dominant Method is used for meshing.

In figure 2.3 the modal analysis results of the beam is shown and the natural frequency of the system is found to be 25.77 Hz. The difference between the analytical and ANSYS modal analysis natural frequency is due to considerations of magnets and the piezoelectric disc.

2.3 Harmonic analysis of beam for piezoelectric voltage

Harmonic analysis of beam is carried out in ANSYS Workbench 18.0 for the velocity of magnets and the stress near the fixed end. The results are shown in figure 2.4.

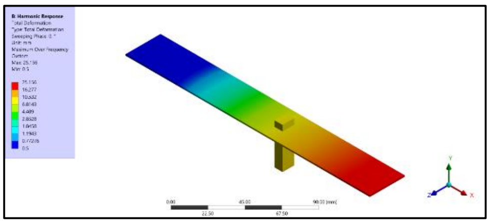


Fig. 2.4 Harmonic Analysis-Maximum deflection

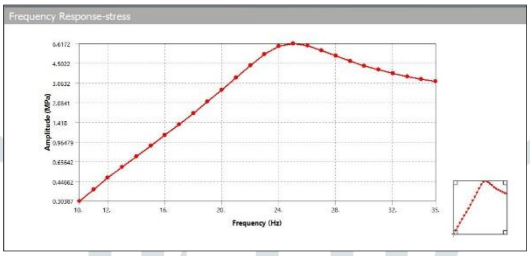


Fig. 2.5 Harmonic Analysis-Stress near the fixed end

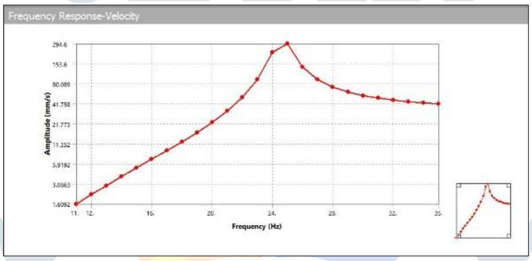


Fig. 2.6 Harmonic Analysis-Velocity of magnets

In above figures 5.2-5.4 the harmonic analysis results are shown. The maximum deflection is 25.156 mm at the free end at 25.15 Hz. Also the maximum stress near free and maximum velocity of magnets are occurred at the 25 Hz.

III.Experimentation and results

3.1 Piezoelectric Energy Harvester

The harvester with the dimensions given table 2.1 is developed and experimented. An electrodynamic exciter machine was used to vibrate the beam at different frequencies and amplitudes. The output voltage and power from the piezoelectric discs are measured using multimeter.

Piezoelectric Disc:
Diameter: 2.7 cm (27mm)
Thickness: 0.1 cm (1mm)

An unimorph and bimorph piezoelectric bonded cantilever beam was developed and the voltages across 5 ohms were measured for increasing frequencies and amplitude of vibration.

Fig. 3.1 Photographs of the harvesting beam connected to exciter

The results from Unimorph piezoelectric bonded beam is shown in following figure

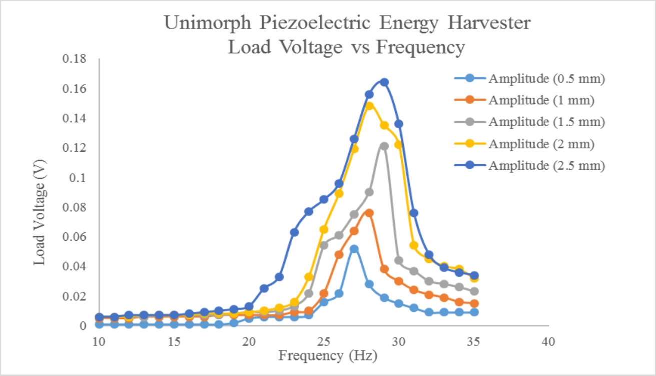


Fig. 3.2 Load Voltage vs Frequency for Unimorph piezoelectric bonded beam

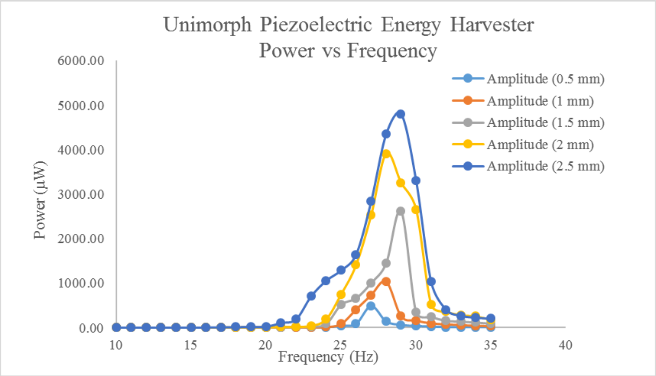


Fig. 3.3 Power vs Frequency for Unimorph piezoelectric bonded beam

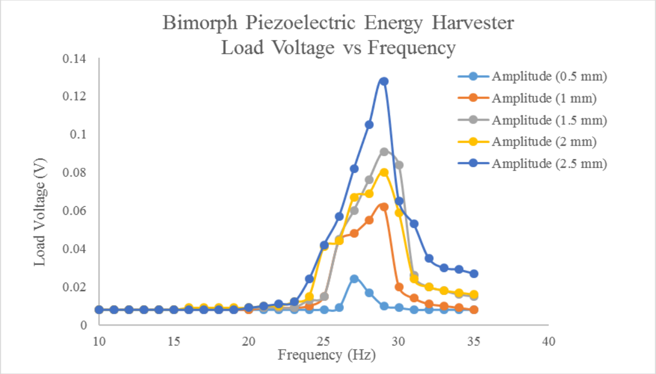


Fig. 3.4 Load Voltage vs Frequency for Bimorph Piezoelectric bonded beam

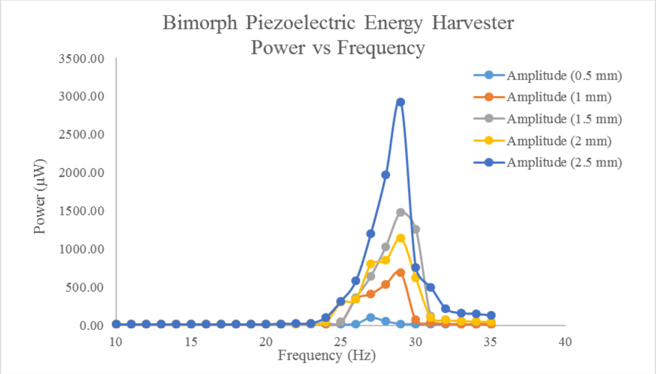


Fig. 3.5 Power vs Frequency for Bimorph piezoelectric bonded beam

3.2 Electromagnetic energy Harvester

The harvester with the dimensions given in table 3.1 is developed and experimented. An electrodynamic exciter machine was used to vibrate the beam at different frequencies and amplitudes and the output voltage and power from the electromagnetic coil are measured using multimeter.

Magnets:
Material: Neodymium Iron Boron Coated
Magnetic Field: 1.170 T
Cross sectional area: 7 *10^{-5} m^2
Number of magnets used: 7

Conducting Wire:
Material: Copper wire (27 AWG)
(AWG: American Wire Gauge, 27AWG = 0.36mm diameter)
Specific Resistivity: $1.68 * 10^{-8}$ Ω-m

Magnets are placed at the distance of 7.5 cm from the free end and by varying the frequency the experimental results are shown in figures 3.6 and 3.7.

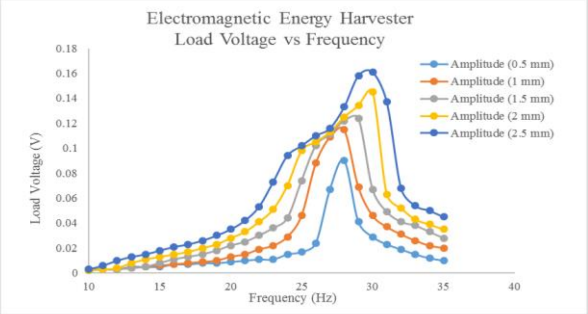


Fig. 3.6 Electromagnetic load voltage vs Frequency

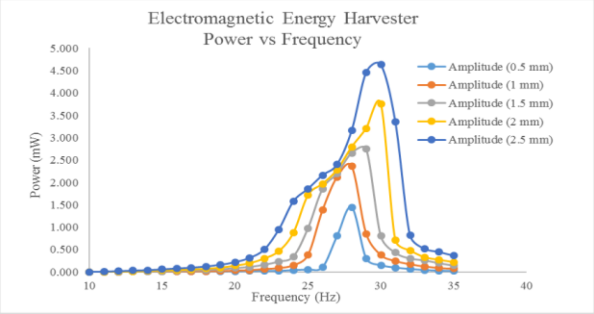


Fig. 3.7 Electromagnetic Power vs Frequency

In figure 3.2 to figure 3.7 It is seen that the voltage and power increases as the amplitude of vibration increases. Also the voltage and power is maximum when the system is vibrating at its natural frequency.

IV. Conclusion

Modal and harmonic analysis of beam is carried out in ANSYS workbench 18.0 and the natural frequency is found out to be 25 Hz which is nearly equal to the experimental natural frequency of 28 Hz. That difference is due to the damping and fixity of the beam. The maximum voltages of 0.164 V and 0.128 V with corresponding powers of 4.8 mW and 2.9 mW for Unimorph and Bimorph piezoelectric bonded cantilever beam is obtained at the frequency of 29 Hz and 2 mm amplitude of vibrations. The maximum Electromagnetic voltage of 0.161 V and corresponding power of 4.63 mW is obtained at 30 Hz for 2 mm amplitude of vibrations. By using Electromagnetic mechanism there is minimum 200% increment in harvesting energy.

Since the harvested energy is in miliwatts This dual mode energy harvested can be used in the Micro Electro Mechanical System (MEMS) areas.

By using proper boost up circuits, above energy can be used to power the typical wireless sensors such as accelerometers, etc.

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