Design, Simulation and Optimization of Bimorph Piezoelectric Energy Harvester

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Abstract: Piezoelectric energy conversion has received great attention for vibration-to-electric energy conversion over the last five years. A typical piezoelectric energy harvester is a unimorph or a bimorph cantilever located on a vibrating host structure, to generate electrical energy from base excitations. In this paper, we have optimized the dimensions of the proof mass and the bimorph piezoelectric layer to maximize the output voltage of the piezoelectric energy harvester. The results range from maximum to minimum using different combinations of the affecting parameters using Taguchi's orthogonal array for optimization of the parameters. The designed bimorph piezo energy harvesting system was modeled using COMSOL Multiphysics and the observed parameters are compared to the analytical results.

Keywords: MEMS, piezoelectricity, energy harvester, COMSOL Multiphysics

1. Introduction

Energy harvesting or scavenging are commonly used terms describing the process of converting energy available in the environment into electrical energy [1]. For about a decade, engineers have been challenged to design autonomous systems which fulfill their task and power themselves from available ambient energy. Such systems are known as autonomous or stand-alone systems. Piezoelectric energy harvesters are the main component of such systems. In recent advancements, energy harvesting have attracted considerable attention as an energy source for wireless sensor networks because batteries cause a series of inconveniences like limited operating life, size and contamination issues. Solar energy provides some solutions but it is limited in dark conditions. Piezoelectric devices are proved to be the potential source for power generation [2].

1.1 The Piezoelectric cantilever configuration

There are two types of piezoelectric materials, piezo-ceramics like Lead Zirconate Titanate(PZT) and piezo-polymers like Polyvinylidene Fluoride(PVDF). When piezoelectric materials are deformed or stressed, voltage appears across the material. The mechanical and electrical behavior can be modeled by two constitutive equations [4]:

$$S = \mathrm{s}^{E}T + \mathrm{d}_{t}E \qquad (1)$$

$$D = \mathrm{d}_{t}T + \epsilon^{T}E \qquad (2)$$

where S-mechanical strain, T-applied mechanical stress, E- Electric field, D-Electric displacement, sE - matrix of elasticity under conditions of constant electric field, d-piezoelectric coefficient matrix, εT = permittivity matrix at constant mechanical strain. A cantilever type vibration energy harvesting has very simple structure and can produce large deformation under deformation. The cantilever model can be used in two different modes,33 mode and 31 mode. The 33 mode (compressive mode) means the voltage is obtained in the 3 direction parallel to the direction of applied force. The 31 mode (Transverse mode) means the voltage is obtained in 1 direction perpendicular to the direction of applied force. The most useful mode in harvesting applications is 31 mode, because an immense proof mass would be needed for 33 configuration. The vibration spectrum shows that the acceleration decreases for higher modes of frequency compared to fundamental mode of frequency. Therefore, the design of the cantilever beam focusses on fundamental mode of frequency. [5]

2. Use of COMSOL Multiphysics® Software

Experimentation was performed by applying the parametric combinations following orthogonal array matrix to optimize the output power. We used COMSOL Version 5.2, MEMS MODULE to compute the values of the output power and the resonant frequency. The simulated result presents the range of frequency and output power for the design parameters. This study helps for optimization of the design parameters which can help increase the output power of the energy harvester.

5. Configuration

The power harvester consists of a piezoelectric bimorph clamped at one end with a proof mass mounted on the other end. The bimorph has a ground electrode embedded within it and two electrodes on the exterior surfaces of the cantilever beam. This configuration ensures that same voltage is induced on the exterior electrodes, even though the stress above and below the neutral layer is of opposite sign. Since the clamp is mounted to a piece of vibrating machinery the device is analyzed in a vibrating reference frame [6]. The model performs three analyses of the mechanical part of the energy harvester system. First, the power output is analyzed as a function of vibration frequency, with a fixed electrical load. Then the power output as a function of electrical load is explored. Finally, the DC voltage output, as a function of acceleration, is shown to be linear.

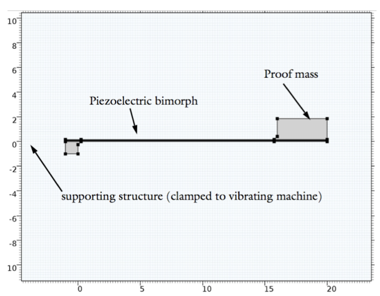


Figure 1 – Configuration of bimorph piezoelectric harvester in COMSOL

Table 1 – Initial values of the parameters

Load resistance	12 kΩ
Width of piezo plate	14 mm
Length of piezo plate	21 mm
Proof mass dimensions	4 mm x 1.7 mm

3. Equations and Analytical Calculations

The model in COMSOL is analyzed by making variations in load resistance, width and length of piezoelectric plate. The power generated depends on the resonant frequency and the load resistance by the expression:

$$P = V_{rect}\left(\frac{2\alpha}{\frac{\pi}{2}+RC_p\omega_p} + \frac{\frac{\pi}{2}+RC_p\omega_r}{\alpha R}\right) \tag{3}$$

which gives us:

$$P = \frac{V_{rect}}{R} \tag{4}$$

The power harvester consists of a piezoelectric bimorph clamped at one end with a proof mass mounted on the other end. The bimorph has a grounded electrode embedded within it and two electrodes on the exterior surfaces of the cantilever beam. [7,8,9]

4. Results

The parameters varied are Load resistance, width of piezo plate, length of piezo plate and all other values are kept constant. Table 2, table 3 and table 4 shows the effect of the variation of these parameters on the resonant frequency and the electrical power output.

Table 2: Variation of Output parameters with load resistance

Exp Run	Load Resistance (kΩ)	Voltage (V)	Resonant frequency (Hz)	Mechanical power (mW)	Electrical power (mW)
1	6	4.85	74.5	1.955	1.995
2	8	4.975	75	1.55	1.57
3	10	5.15	75	1.34	1.36
4	12	5.395	75.5	1.3	1.3
5	14	5.639	76	1.2	1.2
6	16	6	76.5	1.089	1.1
7	18	6.2	77	1.09	1.09
8	20	6.6	77.5	1.05	1.07

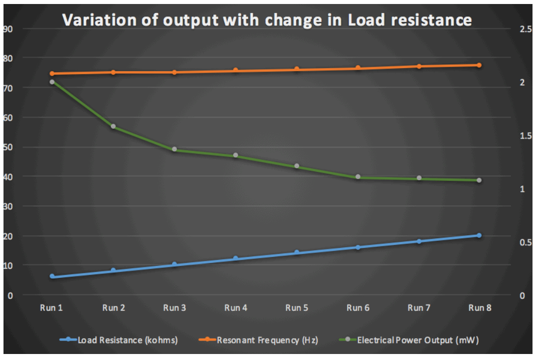


Figure 2 - Graph showing variation of Output parameters with load resistance

Table 2 shows that resonant frequency is directly proportional to the load resistance and we have the lowest value of power output with the highest load resistance which verifies the relation in equation 2 above. The green line in the graph shows the inverse relation between the load resistance and the output power. This can be an important parameter that can be used during fabrication. Figure 4 shows the simulated results output for experiment run 1 of table 2.

Table 3: Variation of Output parameters with change in width of piezo plate

Exp Run	Width of piezo-plate (mm)	Voltage (V)	Resonant frequency (Hz)	Mechanical power (mW)	Electrical power (mW)
1	10	5.045	75	1.06	1.076
2	11	5.13	75	1.09	1.112
3	12	5.199	75	1.125	1.4
4	13	5.3	75.5	1.165	1.185
5	14	5.395	75.5	1.215	1.228
6	16	5.662	76	1.309	1.34
7	18	5.82	76.5	1.41	1.425
8	20	6.062	76.5	1.532	1.548
9	22	6.33	77	1.67	1.688

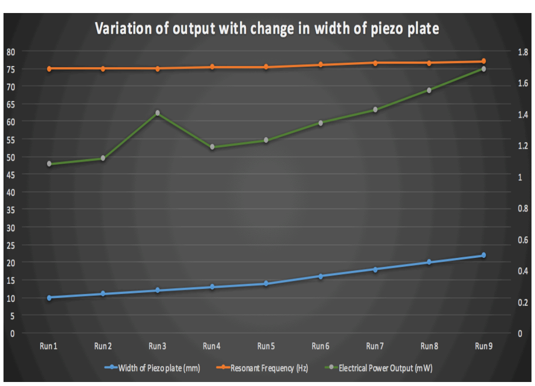
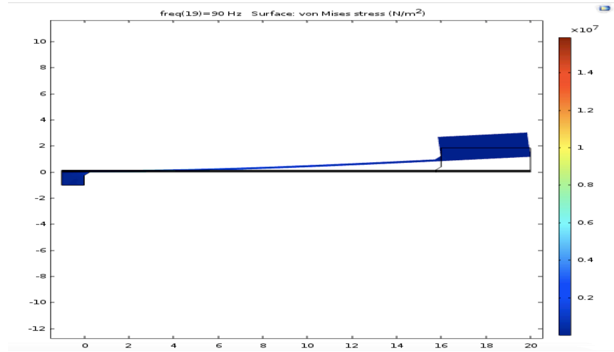
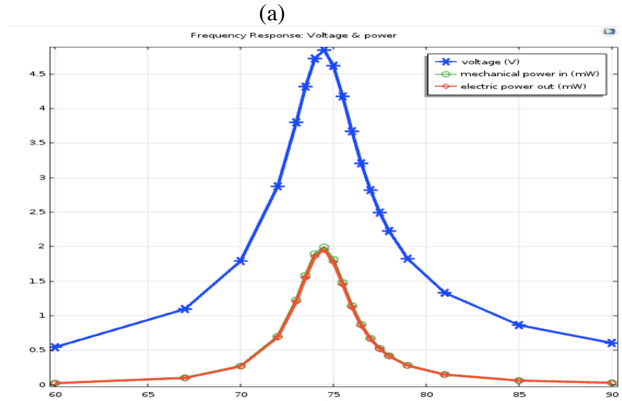


Figure 3 – Graph showing variation of output parameters with width of piezo plate



(a)



(b)

Figure 4 a & b – Simulation results for experiment run 1 for load resistance variation

Table 3 it is observed that higher the width of the piezo plate, lesser is the damping and hence a higher resonant frequency is obtained and higher power output is obtained. Taguchi orthogonal array is used to obtain the optimum values of the output parameters with the optimum combinations of input parameters as shown in table 4 and figure 5.

Table 4 – Taguchi Orthogonal array showing the variation of output parameters with optimum combination of input parameters.

Exp. Run	Load Resistance (kΩ)	Width of piezo plate (mm)	Length of piezo plate (mm)	L/W ratio	Voltage (V)	Resonant Frequency (Hz)	Mechanical Power (mW)	Electrical Power (mW)
1	6	13	19	1.4615	3.915	90	1.279	1.305
2	7	13	19	1.4615	4.14	90	1.225	1.249
3	8	12	23	1.9167	2.494	60	0.389	0.397
4	9	16	23	1.4375	3.255	67	0.595	0.602
5	10	17	20	1.1765	4.655	81	1.081	1.096
6	11	17	18	1.0588	4.68	100	0.985	1.01
7	12	16	20	1.2500	4.663	81	0.909	0.915
8	13	15	21	1.4000	5.63	76	1.22	1.23
9	14	15	22	1.4667	6.06	70	1.31	1.326
10	15	14	22	1.5714	6.05	70	1.22	1.24
11	16	14	21	1.5000	5.91	76.5	1.09	1.1
12	17	12	18	1.5000	4.745	100	0.663	0.67

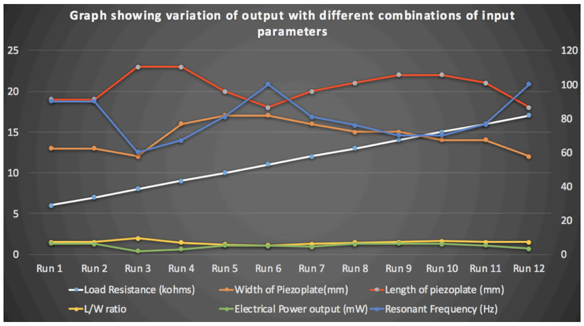


Figure 5 – Graph showing variation of output parameters with optimum combinations of the input parameters

From the readings of table 4 it can be observed that the electrical power output is maximum value of 1.326 mW (marked yellow) when the voltage is maximum and load resistance is towards the higher scale at a low scale resonant frequency.

8. Conclusions

Above comparison provides the optimized parameters for best harvester design. With the proof mass being constant, load resistance variation, yields that the output power is inversely proportional to load resistance and resonant frequency is directly proportional. When the width of the piezo plate is increased, the damping factor reduces which causes a higher resonant frequency and an increase in power output. Increase in length of the piezo plate increases the damping factor and hence causes a drop in the resonant frequency and the output power. In all the cases the proof mass dimension is kept a constant and varying the proof mass dimensions along with the length and width of the piezoelectric plate might give a different output which is included in future study. Thus COMSOL simulative study emerges as the effective tool to provide confidence to designers to design time and cost effective designs.

9. References

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