Design and Simulation of Energy Harvesters for Automobile Vibration Energy

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Abstract—This paper presents design and simulation of a piezoelectric cantilever array of different substrate material for energy harvesting using automobile vibrations. The vibration energy used by the developed piezoelectric cantilever beam can be converted into electrical energy using piezoelectric effect as a piezoelectric energy harvester. The two piezoelectric layers were placed at the top and bottom faces of the substrate material. The simulation of the piezoelectric harvester was performed by COMSOL Multiphysics 5.3 where Finite Element Method (FEM) was used. The voltage and power output observed during the analysis. The analysis of different substrate material based harvester also observed. A maximum output power of 2.275mW and voltage of 5.506V was obtained from the Poly Methyle Methacrylate (PMMA) substrate based harvester at 12kΩ under the acceleration of 1 g (g = 9.81 m/s^2) at low resonant frequency of 23.1 Hz. The PMMA based array also analyzed.

Keywords —Energy harvesting, Cantilever beam, Vibration, Piezoelectric effect, Simulation, FEM, PMMA.

I. Introduction

With the boost of advance technology in electronic systems such as wireless sensors, researchers have focused on improvement of smaller volume and durable power sources. Batteries as a conventional power sources has some draw backs due to its higher volume and a limited lifetime [1, 2]. To mitigate the energy sources issue, energy harvesting is an attractive way to extracting energy from environmental renewable energy sources such as wind, solar, geothermal, and tidal [3]. Moreover, ambient mechanical vibration can be recycled to generate electrical energy for wireless sensor networks, chemical sensors [4] and health monitoring [5-7]. Vibration driven energy harvesters efficiently convert vibration energy into electrical energy using three electromechanical transduction processes: electrostatic, electromagnetic, and piezoelectric [1] [8-11]. Among those transduction methods, piezoelectric transducers have attained much attention due to the simplicity in configuration and higher conversion efficiency [12, 13]. In piezoelectric transduction, there are some piezoelectric materials namely Lead Zirconate Titanate (PZT), Polyvinylidene Fluoride (PVDF), [14] Aluminium nitride (AlN) [5]. When those piezoelectric materials have set under the condition of mechanical energy then electrical energy will be generated and vice versa [15].

Automobile vibration sources provide lower frequencies (2 to 25 Hz) as shown in Table I. In order to utilize vibration properly, resonant frequency of piezoelectric energy harvester should be less than the range. Moreover, maximum energy can be harvested efficiently when energy harvester driven at the resonant frequency [16, 17]. Due to flexibility, lower resonant frequency and high stress generation, cantilever beam structure is more preferred.

Table I: Automobile Vibration and their frequency range [18-21]

Vibration Source	**Phenomena Generated**	**Frequency Range**
Engine Torque Fluctuations	Surge Vibration	2-10Hz
Clutch Misalignment	Judder Vibration	2-10 Hz
Driveshaft Angle	Acceleration Vibration	10-20Hz
Unbalanced Rotation	Seclusive Noise	10-25Hz

II. Design Energy Harvester

In piezoelectric mechanism, if piezoelectric material is physically deformed by pressure, vibration or force then it will create induced electrical field. In contrast, if electrical energy is applied then mechanical deformation will induce [15]. The electrical charge density generated by the piezoelectric cantilever can be calculated by using the following piezoelectric constitutive equation.

$$S = s^E \cdot T + d_t \cdot E \qquad (1)$$

$$D = d_t \cdot T + e^T \cdot E \qquad (2)$$

Where S- Mechanical strain, T- Applied mechanical stress, D- Electric displacement, s^E-Matrix of elasticity under conditions of constant electric field.

The cantilever beam structure was consisted of two materials; substrate and PZT-5A as piezoelectric layers. The substrate material was in the middle position while PZT-5A was put top and bottom surface of the substrate. The properties of PZT-5A and different substrate materials have been shown in Table II. The dimension of piezoelectric layers and substrate material were 56 x 0.16 x14 mm (length × width × thickness in mm) as shown in figure 1 and figure 2.

Table 1: Material Properties

Parameter	**PZT-5A**	**Silicon Substrate**	**Steel Substrate**	**Nickel Substrate**	**Zinc Oxide Substrate**	**Poly methyl methacrylate Substrate**
Density [kg/m^3]	7750	2329	7850	8900	5676	1190
Young Modulus (E) [Pa] (10^9)	72	170	200	219	210	$3x10^9$
Poisson Ratio	0.31	0.28	0.33	0.31	0.33	0.40
Electrical Conductivity Siemens per meter [S/m]	--	1000	4.032×10^6	13.8×10^6	0	$5X10^{-18}$

III. FEM Simulation

In solid mechanics physics, the boundary condition for the beam such as free end, fixed end, applied vibration and damping of the beam materials have been set up. During the boundary conditions of electrostatics physics, the top and bottom surface of the piezoelectric layers was used as ground and 12kΩ load resistance attached to inner surface of PZT-5A material as a terminal. The electrostatics physics was coupled with electrical circuit physics so that electrical response of the beam can be obtained.

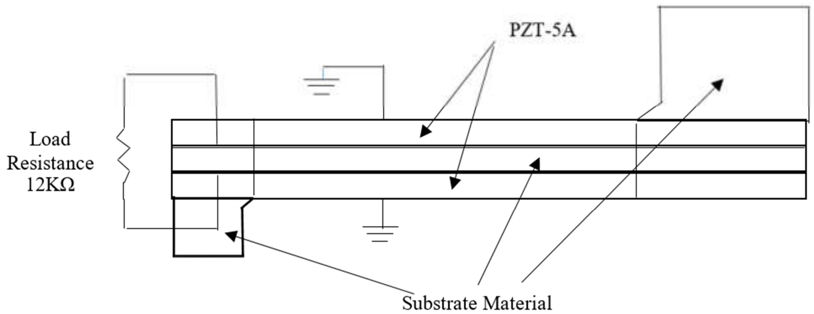

Figure 1: Piezoelectric Cantilever beam structure

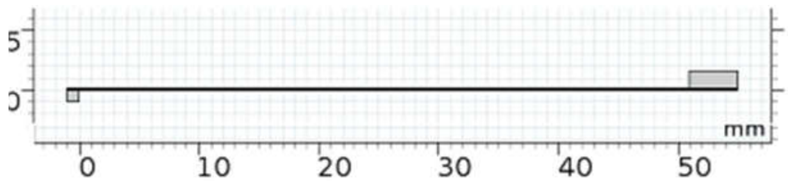

Figure 2: Piezoelectric Cantilever beam structure designed in COMSOL Multiphysics 5.3

IV. Simulation Results

(a) Voltage and Power generation :

A piezoelectric cantilever beam and array have been studied to obtain its electrical properties. Piezoelectric cantilever beam can be used as an energy harvester. The energy conversion from the mechanical energy to electrical energy will maximum when the piezoelectric cantilever beam will be driven at its resonant frequency. Electrical properties of the beam such as voltage output with respect to frequency range, voltage output with respect to applied acceleration and power output with respect to load resistance was analyzed. As the piezoelectric cantilever beam was driven under vibration force, a voltage output can be provided due to piezoelectric effect.

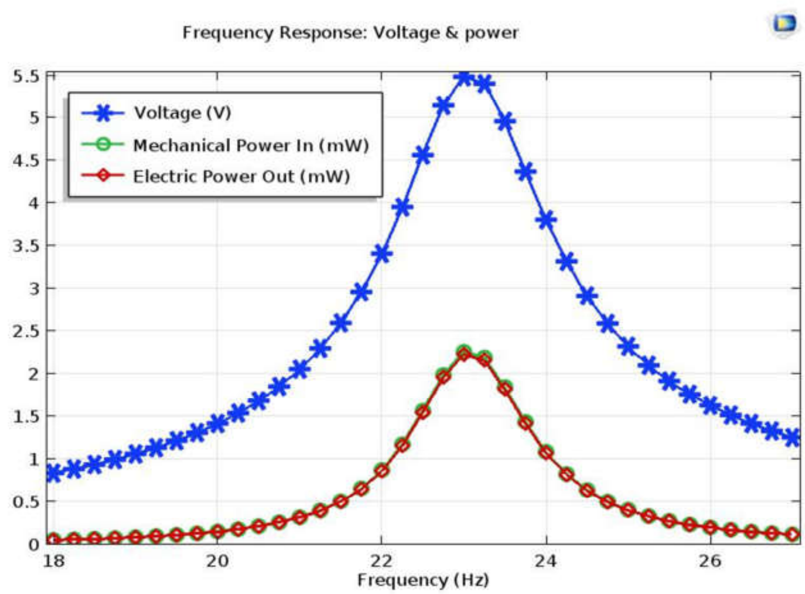

Figure 3: Generated Voltage and Power output V/s Frequency of PMMA substrate based Harvester

The generation of voltage output was analyzed in the frequency domain analysis of 18-27 Hz at vibration acceleration of 1 g as shown in Figure. 3. The voltage generation was obtained around 5.506V at 23.1Hz at 12kΩ. A maximum power output of 2.24mW was achieved with a load resistance of 12kΩ at resonant frequency of 23.1 Hz.

(b) Effect of Substrate Material:

Silicon, Nickel, Poly methyl methacrylate (PMMA), Zinc Oxide (ZnO) and Lead (Pb) are used as substrate materials in two independent cases by keeping PZT-5A as a piezoelectric material. It is conventionally used piezoelectric material with excellent piezoelectric properties. The material properties of substrate materials are summarized in Table1. The five cases considered in this section has different as substrate material and independent piezoelectric material i.e. PZT-5A. The resonance frequency of the energy harvester depends upon material as well as geometric properties of substrate and piezoelectric material. For this case the dimension for all purpose cantilevers was same.

The table 2 and table 3 shows the power outputs of cantilever based on different substrate materials. The silicon, Zinc Oxide (ZnO), Nickel, Poly Methyl Methacrylate and structural steel have their resonance frequency 20.2Hz, 20.2Hz, 13.1Hz, 23.1Hz and 13.6 Hz respectively. It is clear that the power output is more in PMMA based cantilever and resonance frequency of all substrate material lies in desired automobile vibration frequency (2 to 25Hz).

Table 2: Output Voltage For different substrate layer of bimorph cantilever beam

Silicon (Si)				Zinc Oxide (ZnO)				Nickel (Ni)			
Fre. (Hz)	Volt. (V)	Mech. Input Power (mW)	Elect. Output Power (mW)	Fre. (Hz)	Volt. (V)	Mech. Input Power (mW)	Elect. Output Power (mW)	Fre. (Hz)	Volt. (V)	Mech. Input Power (mW)	Elect. Output Power (mW)
15	0.5178	0.0182	0.01787	18	1.295	0.1421	0.1399	10	0.3642	0.0085	0.0082
19	2.1638	0.3169	0.31216	18.5	1.660	0.2334	0.2298	11	0.5928	0.0224	0.0219
20	4.241	1.2168	1.19938	19	2.164	0.3962	0.3903	12	1.2527	0.1001	0.0980
20.1	4.3693	1.2911	1.27275	19.5	3.085	0.8053	0.7935	12.5	2.3124	0.3410	0.3342
20.2	4.4135	1.3173	1.29862	20	4.241	1.5210	1.4992	13	3.6615	0.8545	0.8379
20.3	4.3671	1.2897	1.27144	20.1	4.369	1.6139	1.5908	13.1	3.4818	0.7726	0.7576
20.4	4.2390	1.2151	1.19798	20.2	4.413	1.6466	1.6232	13.2	3.1000	0.6123	0.6006
20.5	4.0505	1.1093	1.09380	20.3	4.367	1.6121	1.5893	13.3	2.6780	0.4569	0.4482
21	3.1774	0.6824	0.67306	21	3.177	0.8532	0.8414	14	1.2175	0.0943	0.0926
22	1.7702	0.2117	0.20891	22	1.770	0.2647	0.2611	14.5	0.9328	0.0609	0.0598
23	1.2024	0.0976	0.09639	23	1.202	0.1220	0.1204	15	0.6589	0.0276	0.0271

Table 3: Output Voltage For different substrate layer of bimorph cantilever beam

Poly Methyl Methacrylate (PMMA)				Structural Steel			
Fre. (Hz)	Volt. (V)	Mech. Input Power (mW)	Elect. Output Power (mW)	Fre. (Hz)	Volt. (V)	Mech. Input Power (mW)	Elect. Output Power (mW)
20	1.416662	0.150847	0.148662	10	0.442466	0.010223	0.009970
21	2.056509	0.317706	0.313276	11	0.644651	0.021655	0.021163
22	3.411509	0.873859	0.862103	12	1.088822	0.061667	0.060374
22.5	4.567486	1.566038	1.545328	13	2.747551	0.392080	0.384441
23	5.486532	2.259164	2.22978	13.5	4.694087	1.143676	1.122124
23.1	5.506888	2.275863	2.246357	13.6	5.012206	1.303777	1.279372
23.2	5.455176	2.233226	2.204366	13.7	4.962572	1.277920	1.254159
24	3.806615	1.087057	1.073357	13.8	4.586025	1.091211	1.071055
24.5	2.917205	0.638301	0.630377	13.9	4.059239	0.854814	0.839128
25	2.322326	0.404444	0.399496	14	3.547407	0.652757	0.640857
26	1.629583	0.199075	0.196707	15	1.377031	0.098250	0.096566

(c) PMMA based Cantilever Array

The more power generated from the PMMA based cantilever beam array as shown in figure 12. This array consist only two cantilever beam with same dimensions with proof of mass but the placement of proof mass is different location. The lower cut-off frequency is 22.1Hz and upper cut-off frequency is 25.4 Hz. The bandwidth of this PMMA based cantilever beam array is 3.3H.

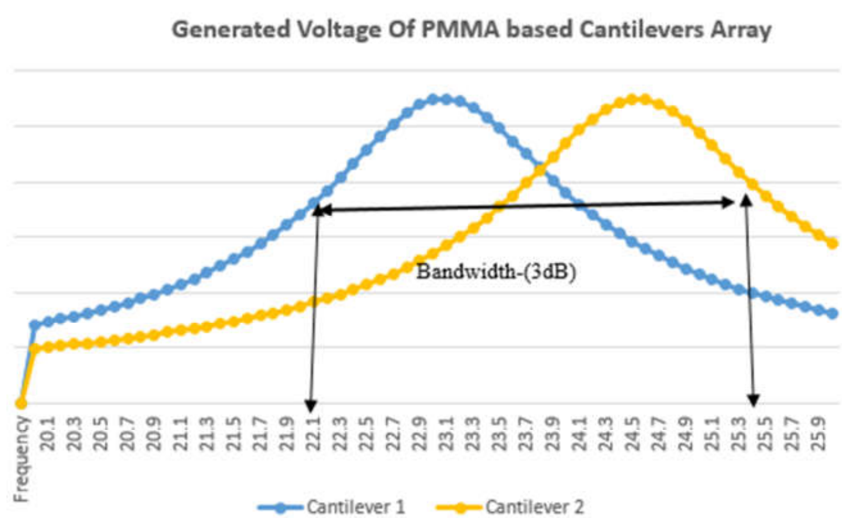

Figure 4: Voltage Output of Piezoelectric cantilever Array

V. Conclusion

In this paper, the electrical properties of a piezoelectric cantilever beam was investigated under the condition of automobile vibration. When the vibration acceleration sources of 1 g was applied to the beam. The piezoelectric beam was set up such a way that it provided automobile vibration energy into electrical energy as an energy harvester. The PMMA substrate based piezoelectric harvester, maximum voltage of 5.506V power output of 2.24mW was achieved at 12kΩ under the acceleration of 1 g at resonant frequency of 23.1Hz. The effect of substrate material also observed that the power and voltage output were different with their resonance frequency. The piezoelectric PMMA substrate based cantilever array also analyzed. The lower cutoff frequency was 21.1Hz and upper cutoff frequency was 25.4Hz. The bandwidth of this array was observed 4.3Hz.

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