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# Fabrication and Characterization of Planar Spring Based on FR4-PCB for Electrodynamics Vibration Energy Harvesting Application

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**Abstract.** Planar spring as a mechanical resonator is very important in designing an electrodynamic vibration energy harvesting application (EVEH) to generate output power with high efficiency. Generally, component of the mechanical resonator is a cantilever beam that is designed using one cantilever with an inertial mass placed cantilever tip. In this study, a planar spring which has four arms cantilever beam was designed and fabricated using an extra-thin FR4-PCB material with a total thickness of 130 µm. There are four types of planar spring that were designed and fabricated in this research to produce resonant frequencies at about 30, 40, 50 and 60 Hz with 1 mm width cantilever arm and various length of 13.5, 11.2, 9.8 and 8.7 mm, respectively. FR4 resonator is fabricated using technology LASER-cutting in order to obtain results precisely. The resonant frequency generated by the mechanical resonator is characterized using vibrator system with certain acceleration. The resonant frequency of the planar spring was obtained at a frequency where the maximum induced voltage occurs. The resonant frequency generated by each type of planar spring was obtained at 24.81, 34.24, 40.2, and 46.8 Hz with three conditions of acceleration of 0.02, 0.06, and 0,1g (g=9.8 m/s$^2$).

## 1. Introduction

Advances in technology microfabrication of integrated circuits (ICs) and sensor micro electro-mechanical system (MEMS sensor) has led to the springing up of wireless sensor node (Wireless Sensor Node, WSN) that has a small size, low cost and low power consumption. Most WSN is equipped with one or more sensors, a microcontroller, a wireless transceiver and resources. At present, the battery is still a major resource to maintain the operation of many wireless sensor nodes. However, batteries have limited energy, limited life and the need for the regular replacement when it runs out of energy, so this will increase the cost of maintenance [1]. To resolve this problem, energy harvesting (energy harvesting) that derived from the surrounding environment has become a source of alternative energy for the battery.

Vibrating kinetic energy sources is one of the many sources of energy is converted into electrical energy to provide electrical energy for WSN, among the sources of energy that vibrate includes a step or human motion, vibration of industrial machinery, bridges, vehicles, and so forth. Some literature has reported research on harvesting the kinetic energy into electrical energy using the method of harvesting, which is piezoelectric, electrostatic and electromagnetic or electrodynamics [2-5]. The third of the kinetic energy harvesting techniques, the method of electrodynamics energy harvesting is a technique that is very interesting and even become the focus of this study. Converting the energy produced by the electrodynamics energy conversion is greater than piezoelectric or electrostatic method. The working principle of harvesting mechanical energy into electrical energy is using the concept of magnetic induction, Faraday's law.

There are many considerations have to be fulfilled in designing the energy harvesting module, that derived from the mechanical energy source. One of the most significant issue concerning the frequency of vibration of the energy sources is, for example, in many industrial applications of industrial machines having a frequency of a vibration in the range of tens to 100 Hz, while the frequency of vibration is raised by motion or step of the human being in the range below 10 Hz. This paper will discuss the fabrication and characterization of a miniaturized energy harvester's module using mechanical resonator. When the resonator has the same resonant frequency with the vibration source, the energy that will be generated will be maximum. Mechanical resonators used in this study was designed to have a resonant frequency of 30, 40, 50 and 60 Hz using extra thin PCB-FR4 material.

## 2. Principle of Electrodynamic Vibration Energy Harvesters

The Electrodynamic Vibration Energy Harvesters (EVEH) converts kinetic energy into electrical energy by electromagnetic transduction mechanism. A general spring-mass model was built to describe the harvester system by C.B. Williams and R.B. Yates [6], as shown in Figure 1. This system can be modeled analytically as a mass-spring-damper consisting of a total damping coefficient, *ct*, spring constant, *k*, and the seismic mass, m.

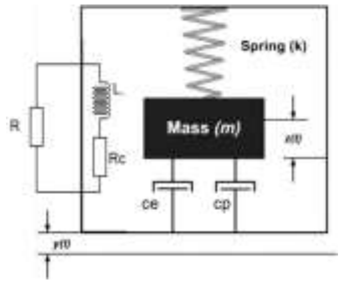


**Figure 1.** The schematic electrodynamic vibration energy harvesting (EVEH).

Voltage generated in the wire coil, that is supported by a spring mechanism is caused by the presence of magnetic induction that moves along the z -axis. When the module system is vibrated by the displacement, *y(t)*; mass transfer, *z(t)*, produced by the relative mass which is attached to a spring. Energy losses in the system (consisting of the parasitic losses, *cp*, and the reduction of electrical energy generated by the mechanical transduction, *ce*), are represented by the total attenuation coefficient, *ct*. From these analytic modeling, the equations of motion can be derived as follows:

$$m\frac{d^2z}{dt^2} + c_t\frac{dz}{dt} + kz(t) + F_{mn}[z(t)] = F_d(t) \qquad (1)$$

where $F_{mn}$ is the magnetic force acting on the coil and $F_{d,}$ is the external driving force due to harmonic vibrations. The maximum energy that can be harvested by this system occurs when the external frequency is equal to that of the resonant frequency of the system, $\omega_n^2$ = k/m. Williams and Yates showed that the power dissipated in the damper (i.e, extracted by both transduction mechanisms and parasitic damping mechanism) is given by:

$$P_{av} = \frac{m\xi_t Y^2\left(\frac{\omega}{\omega_n}\right)^3\omega}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2+\left[2\xi_t\left(\frac{\omega}{\omega_n}\right)\right]^2} \qquad (2)$$

where m is the mass of moving parts, $Y$ and $\omega$ are the amplitude and angular frequency of the motion harmonic, respectively, $\omega_n$ is the resonant angular frequency of the mass-spring oscillator, $\xi_t = c_t / 2m\omega_n$ is total damping ratio, and *ct* is the total damping factor. Equation (1) assumes that the generator is driven by a harmonic movement, hence in steady state; $P_{av}$ is equal to the kinetic energy supplied per second of from the existing vibrations. The maximum power dissipation occurs at resonance, which is given as

$$P_{av} = \frac{mY^2{\omega_n}^3}{4\xi_t} \qquad (3)$$

Mechanical resonator is a very important component of the EVEH as previously described. Mechanical resonators are used to increase the amplitude of mechanical vibrations that are transferred from the surrounding environment. They are designed to match the frequency characteristics of the application environment. A mechanical resonator is characterized by the resonant frequency.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{n \cdot E \cdot w \cdot t^3}{4 \cdot L^3 \cdot m}} \qquad (4)$$

## 3. Design and Fabrication of Device

Figure 2 shows the 3D structure of the Electrodynamic Vibration Energy Harvesting (EVEH) and a shape type of PCB planar spring or mechanical resonator. Generally, EVEH structure (Figure 2a) consists of a planar spring, coil and the permanent magnet and supporting components for the assembly of the system. Copper coils are placed at the bottom of the frame, and extra thin-FR4 PCB planar spring having four cantilever beam and a platform for attachment NdFeB permanent magnets is in the center of the platform. PCB planar spring and a permanent magnet is used as part of the move, meaning the coil frame is mounted and used as the static part of the generator. In the work principle of harvesting energy, the electrical energy is produced subjected to external vibration; the mass of evidence is that a permanent magnet mounted induction is responds to deflection. According to Faraday's law of electromagnetic induction, the degree of deflection induces a change in the terminal voltage of the coil output.

Figure 2b shows the design layout of the mechanical resonator that has four cantilevered arms while the platform in the center of the planar spring is where the inertial mass is placed. In this experiment, the structure of planar spring is designed and fabricated with four type of various length and fixed width of cantilever arm. Each type of planar spring is designed for resonant frequency within 30, 40, 50 and 60 Hz with various cantilever arms of 13.5, 11.2, 9.8 and 8.7 mm length respectively with a 1 mm of fixed width. Planar spring is fabricated using double-sided cooper layer of extra thin FR4-PCB (1 oz.) with a size of 2.5 x 2.5 $mm^2$ and a total thickness PCB about 0.13 mm.

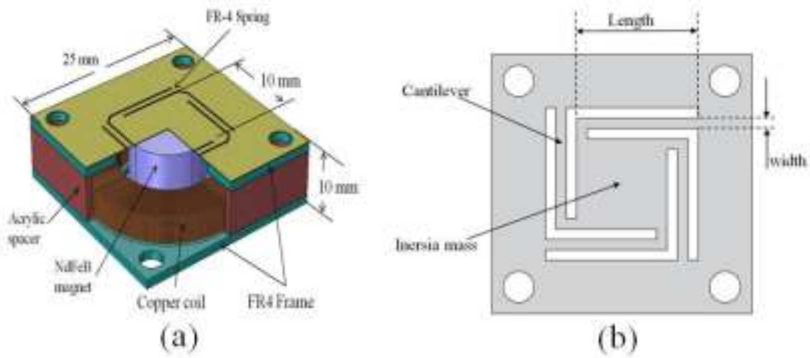


**Figure 2.** (a) Schematic structure of electrodynamics vibration energy harvesting and (b) a shape type of PCB planar spring or mechanical resonator.

A simple fabrication process for the mechanical resonator components and assembling components into one system energy harvester is shown in Figure 3. The process steps include design layout of the planar spring (Fig. 3a), followed by the FR4 PCB substrate cleaning process and cutting with a laser cutter in accordance to the design layout (Fig. 3b). The etching of copper layers (Fig. 3c) on both sides of the PCB is the next process before finally cleans off the FR4 substrate. After the mechanical resonator fabrication, the next step is to characterize the resonant frequency of the resonator components. The components are assembled into a vibration energy harvesting system as shown in figure 3d.

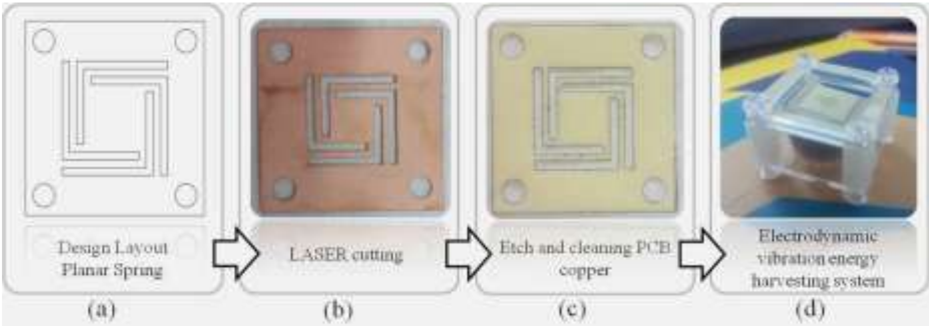


**Figure 3.** (a-c) Step fabrication of planar spring and (d) assembling into EVEH system.

## 4. Experiment Results and Discussion

Figure 4 shows the custom vibration system equipment diagram of experiment setup for the characterization of mechanical resonant frequency of PCB planar spring. The subwoofer loudspeaker with good performance capabilities is well suited for low frequency vibration input source [7]. The input signal from the tone generator software is delivered to audio amplifier for subwoofer vibration. The EVEH generator system as shown in Fig 3d is attached on the jig of the vibrator. A digital multimeter is then connected to the coil of generator to measure the open-circuit voltage of the generator. When the frequency of the input vibration is equal to the natural frequency of the mechanical resonator structure, the spring-mass system operates at resonance; at that point, the permanent magnet has the maximum of the amplitude, and the coil produces the maximum voltage.

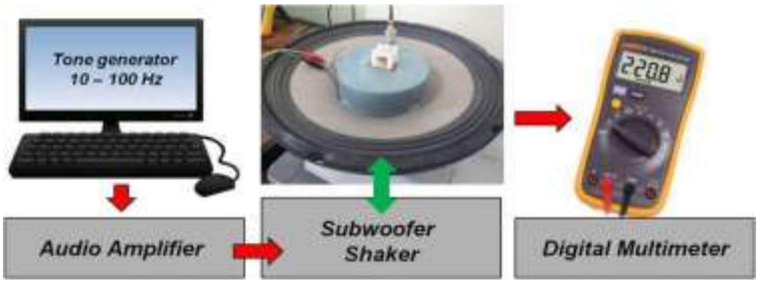


**Figure 4.** The experiment test setup.

Figure 5 shows the output voltage response of the EVEH with changes in the input frequency. The relationship of the results obtained from measurements of the peak output voltage to frequency changes show the response of the resonant frequency of the planar spring. From the measurement results for the fourth resonant frequency planar type of spring with the vibration sources of 0.02g, 0.06g and 0.1g brackish obtained for each of these conditions are type-1: 23.61, 25 and 24.81 Hz (Fig. 5a), and for type-2: 30.42, 33.12 and 34.24 Hz (Fig. 5b), whereas for type-3: 35.51, 38.91 and 40.2 Hz (Fig. 5c), and the latter type-4 as shown in Figure 5d responded to the resonant frequency at 41.05, 44.4 and 46.8 Hz.

Based on the result of design and obtained measurements, a significant difference can be found in the value where the differences in the resonant frequency that occurs in the range of 5 Hz to 10 Hz. From the measurement results shown, the relationship of the resonance frequency of a planar spring is clearly affected by the acceleration of its vibration source. We can establish the relationship as when the speed is high, the response of the resonant frequency of the spring is higher too. Meanwhile, the longer arm of the cantilever planar spring resonance frequency becomes lower.

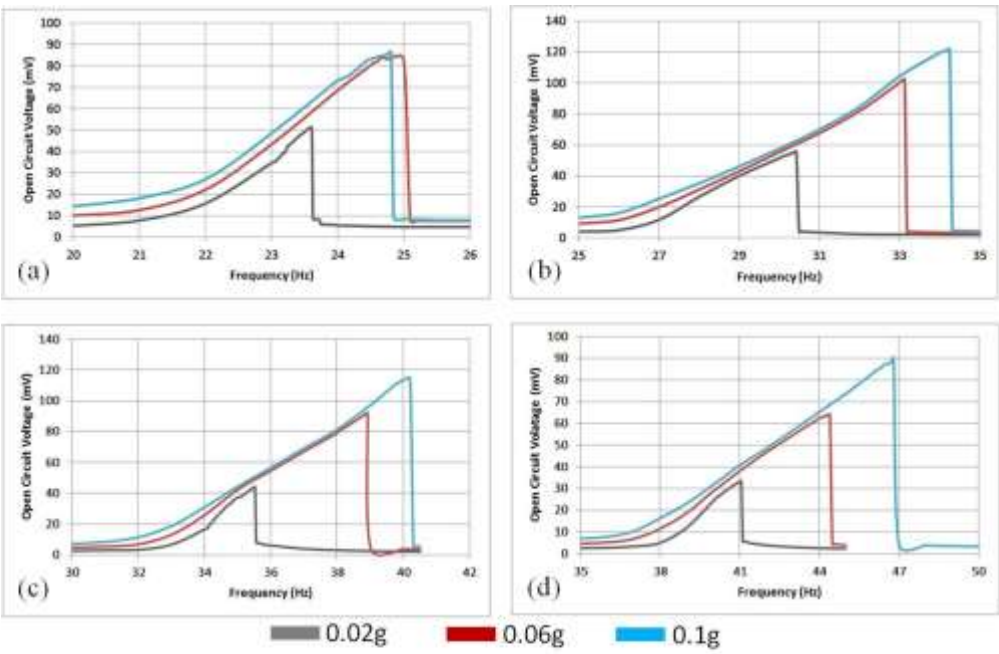


**Figure 5.** The output voltage response of the EVEH versus input frequency. Resonant frequency of PCB FR4 planar spring for (a) type-1, (b) type-2, (c) type-3 and (d) type-4 with vibration source acceleration in 0.02g (gray color), 0.06g (red color) and 0.1g (blue color) respectively.

The generator demonstrated nonlinear response which produced a different of resonance frequency when acceleration vibration source changed. And also the induced output voltage depends on the vibration frequency source. The maximum output voltage is generated in the resonant frequency, and drops significantly out of the frequency range.

## 5. Conclusions

This paper presents the design, fabrication and characterization of the planar springs as the mechanical resonator that made from FR4-PCB for electrodynamics vibration energy harvesting (EVEH) applications. The use of a very thin material PCB-FR4 can be integrated with electronic drive components on a one chip PCB for the energy harvesting systems. Based on the results of measurements, the FR4 used as the planar spring material is very suitable for the sources of energy vibrating. It has a very low acceleration, just below 0.1 g with vibration frequencies below 100 Hz. In this study, we have designed a mechanical resonator with variations of resonant frequencies of planar springs at 30, 40, 50 and 60 Hz. The measurement results showed the differences of the resonant frequencies, in the range of 5 to 10 Hz with a vibration source acceleration condition at 0.02, 0.06 and 0.1g.

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