Design and simulation of double planar spring based on polyimide for electrodynamic vibration energy harvesting

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Abstract. This paper deals with the simulation of planar spring as one of the components of the Electro dynamics Vibration Energy Harvesting (EVEH) devices. This EVEH device is composed of symmetric double spring planar, magnets and coils. Spring planar with four cantilever arms were made of polyimide material. The cantilever’s arm was designed with four type of planar spring. They have different dimension and number of magnet to be attach in the device. The dimension was 15x15 mm² and 25x25 mm² with one and two magnets, respectively. Planar spring was then simulated using Finite Element Analysis software (FEA) Comsol Multiphysics 4.3 for studying resonance frequency of the device. The resonance frequency was achieved 56 Hz with one magnet, and 40 Hz with two magnets at 25x25 mm² planar spring size, while for planar spring with dimension 15x15 mm² around 103 Hz with one magnet, and 74 Hz with two magnets. The results show, that design of 25x25 mm² was obtained the smaller resonance frequency than of 15x15 mm². The usage of one magnet shown higher resonance frequency than two magnets.

1. Introduction

Wireless Sensor Network (WSN) is a sensor that used to monitor physical or environmental conditions such as pressure and temperature [1]. WSN is used to monitor medical equipment, building construction and industrial machinery [2]. Batteries as a power source for WSN have a number of disadvantages, such as short life, a limited amount of chemical energy, and also difficult to maintenance [3]. The solution is to find a replacement battery as a power source for WSN.

As an alternative to battery replacement, some research has been done to find a replacement source of energy that can provide energy continuously. The source is known as energy harvesting devices. Energy harvesting is the converting the wasted energy sources in nature to be used as an electrical energy [4]. The sources are sound, light, heat, and vibration. Vibration energy is the one of wasted energy in the environment, such as ocean waves and human motion that provides mechanical energy that can be harvested for charging WSN electrically or generating electricity [5].

There are three methods that can converting mechanical vibration into electricity. The methods is electrostatic, electrodynamic, or piezoelectric transduction [6]. Electrodynamic methods have the advantage of producing larger amounts of energy than piezoelectric or electrostatic methods [4]. Energy
harvesting technology that used vibration energy to be converted into electrical energy by electrodynamic method known as Electrodynamic Vibration Energy Harvesting (EVEH).

An EVEH device generally consists of magnets, coils, springs and frames. EVEH converts the vibrational energy into electricity by moving the stationary magnetic coil. The working principle of EVEH uses the concept of magnetic induction and Faraday's Law. By the law of induction discovered by Faraday, it is possible to explain the conversion from mechanical energy to electricity and vice versa [7].

In 2017, the simulation used single symmetrical four cantilever planar spring FR4 with one magnet as a mechanical resonator was studied. With a load of 0.5 g given, it has a resonant frequency of 49 Hz [8]. Also in 2017, simulation used single asymmetrical two cantilever planar spring FR4 with one magnet as a mechanical resonator was studied. With a load of 0.5 g given, it has a resonant frequency of 39.93 Hz [9]. In 2015, the simulation using single asymmetrical square two cantilever planar spring extra-thin FR4 with one magnet as a mechanical resonator was studied. With a load of 0.1 g given, it has a resonant frequency of 60 Hz [10].

From the result above, the problem is about homogeneity of the vibration and also the material used. To solve the problem, we propose a new design with double planar spring with polyimide material. Hopefully, by using this the movement of the device become stable.

This paper is about simulation for harvesting of electrodynamic vibration energy with double planar spring made from polyimide. This device uses Neodymium Iron Boron (NdFeB) magnet and polyimide as planar spring material. Polyimide is taken from Pyralux material. Pyralux is a flexible PCB made of polyimide substrate which consists of two layers of copper and polyimide. Pyralux has several advantages compared to FR4, among others, can be integrated with PCB technology, but it also has a high homogeneity. This simulation uses Finite Element Analysis (FEA) software Comsol Multiphysics 4.3. The purpose of simulation is to know the value of resonant frequency on a device.

2. Theory
Figure 1 shows a vibration energy harvesting system consisting of magnets as inertia, spring and generator masses that can convert mechanical energy from vibration to electrical energy. The concept of energy harvesting is illustrated by a mass-spring-damper system with a moving mechanical resonator part due to the vibrational effects of the environment. This system is related to the framework of inertia (frame) with external sinusoidal vibrations in the form \( (t) = y \sin(\omega t) \). Sinusoidal vibrations cause mass transfer and frames called \( z(t) \), with mass of vibration sources greater than mass and the addition of external harmonic vibrations.

III.

![Figure 1. Electrodynamc vibration energy harvesting (EVEH) schematic.](image-url)
3. Design and Simulation

The important components of the energy harvester on the EVEH device is a mechanical resonator. The components of a mechanical resonator are planar springs and magnets. A mechanical resonator consists of a magnet and planar spring four cantilever. The mechanical resonator structure simulated in the FEA software Comsol Multiphysics 4.3 is shown in Figure 2.

![Figure 2](image)

**Figure 2.** Mechanical mechanical resonator structure (a) on the XYZ axis (b) on the YZ axis

The EVEH devices structure consist of mechanical resonators (planar springs and magnets), coils wrapped around bobbins, platform coils, planar spring and acrylic (spacer). Figure 3 shows the 2D structure of the EVEH devices.

![Figure 3](image)

**Figure 3.** Structure of EVEH 2D devices

Mechanical resonator is the component of the EVEH that consist of magnet and planar spring. Mechanical transducer studying the resonant frequency. To get the resonant frequency value we use equation (1)

\[ f = \frac{1}{2\pi} \sqrt{\frac{nEw h^3}{4l^2(m_m + 0.24 m_c)}} \]  

where \( n \) is the number of cantilever, Modulus Young \( E \), cantilever width \( w \), planar spring thickness \( h \), cantilever length \( l \) and \( m_m, m_c \) are the magnetic mass and cantilever mass.

The component that simulated in software FEA Comsol is (1) planar spring and (2) magnet. For planar spring, the energy harvesters in this simulation are made of very thin planar springs. The magnet is placed in the center of pyralux planar spring. Frame as the platform of the device, spacer (separator) and two frames as a planar spring holder. Planar spring is simulated using a planar spring type that has four cantilever arms.
Cantilever is a structure with one side pinched and the other free from the frame. Cantilever has several types and each type of cantilever has different length and width. The type of planar spring with four cantilever is shown in the Figure 4.

Planar spring with four cantilever in Figure 4 has a cantilever length of 4,114 mm and a width of 6,909 mm. Planar spring with a fixed magnet in the center is used as a mechanical resonator for the EVEH device. The design of planar spring is simulated using Comsol 4.3. Some parameters such as width, length and thick are described previously, selected to generate resonant frequency.

The planar spring material used in the simulation is Polyimide. Polyimide is taken from pyralux material. Pyralux is a flexible PCB made from Polyimide substrate. Pyralux consists of Cu and Polyimide layers. The mechanical properties possessed by Polyimide is obtain in Table 1.

![Figure 4. Planar spring 4 cantileve](image)

**Table 1. Mechanical properties of polyimide**

| Parameter          | Value  | Unit  |
|--------------------|--------|-------|
| Thick              | 0.075  | [mm]  |
| Young Modulus      | 2.5x10^9 | [Pa]  |
| Density            | 1300   | [kg/m^3] |
| Poisson ratio      | 0.34   |       |

For the magnet that used in this simulation is the NdFeb magnet (Neodymium Ferit Boron), which has a diameter of 6 mm and a thickness of 2 mm. Magnet is used as a flux generator that is located on the planar spring. Parameters of Fe is obtaining in Table 2.

This simulation uses planar spring with size 15x15 mm^2 and 25x25 mm^2, with variation of number of magnet that is amount of one magnet and two magnets that shown in Figure 5. The simulation uses software FEA Comsol Multiphysics 4.3 to studying the resonant frequency. The resonant frequency is the natural frequency that obtain by the simulation. Besides that, the simulation is used to studying the displacement graph. The displacement graph shows the displacement obtain by the mechanical resonator with the load given.
4. Results and Discussion

Figure 5 shows the 3D structure of EVEH Device in simulation using software FEA Comsol. The results along with the resonant frequency obtained by the four types of planar spring. Type 1 is using one magnet with 25x25 mm² dimension, type 2 used two magnets with 25x25 mm² dimension, type 3 used one magnet with 15x15mm² dimension and type 4 used two magnets with 15x15mm² dimension. The resonant frequency obtained when the frequency reaches the maximum voltage, it occurs when induced magnet. The color difference indicates the difference displacement on each side of planar spring. The blue color indicates that the planar spring is stiff and do not make any displacement. Meanwhile, the red color indicates that the planar spring moves and makes any displacement.

Table 2. Magnetics parameter

| Parameter          | Value  | Units  |
|--------------------|--------|--------|
| Thick              | 2      | [mm]   |
| Young Modulus      | 152x10⁹| [Pa]   |
| Density            | 7170   | [kg/m³]|
| Poisson ratio      | 0.27   |        |
Figure 6. Resonant frequency in mechanical resonator (a) type 1, (b) type 2, (c) type 3, (d) type 4

Figure 7. Domain frequency responses of planar spring with a given load 0.5 g (a) type 1, (b) type 2, (c) type 3, (d) type 4.
Beside the resonant frequency, another result that obtained by the simulation using software FEA Comsol 4.3 is the domain frequency. The domain frequency is shown by the displacement graph of each type planar spring. It shows in Figure 7 that the simulation in software FEA Comsol 4.3 also obtain the domain frequency response that represented the displacement graph of the EVEH Device.

We can establish when magnetic mass increases, the resonant frequency of the planar spring is lower as seen in the resonant frequency formula. In addition, the planar spring dimension also influences the magnitude of the resonant frequency. When the width of cantilever increase then the resonant frequency of the planar spring be lower too. Besides that, the domain frequency value obtained by planar spring with one magnet is larger than with two magnets. This is because the domain frequency value is inversely proportional to the magnetic mass.

5. Conclusion
The simulation of planar spring 25x25 mm$^2$ with one magnet, 25x25 mm$^2$ with one magnet, 25x25 mm$^2$ with one magnet, and 25x25 mm$^2$ with one magnet has done. The result show 3D structure with resonant frequency and domain frequency response that represent the displacement graph of EVEH Device. The simulation result shows that the planar spring obtain a displacement graph of 6.3 mm at 56 Hz, 4.5 mm at 40 Hz, 4.8 mm at 103 Hz, and 3.6 mm at 74 Hz, respectively.

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