Modeling of electromagnetic energy harvesting from vehicle damper in shock absorber of motorcycle

S Susilo[1*], S Abdullah[1], D Satria[1], M R Ghifari[1], and B A Hermawan[1]
[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Sultan Ageng Tirtayasa, Jl. Jenderal Sudirman Km 03 Cilegon, Banten 42435, Indonesia

[*]sidik@untirta.ac.id

Abstract. Modeling of electromagnetic energy harvesting on the vehicle suspension system is presented in this paper. This study uses the up and down movement oscillation of the shock absorber to vibrate the SDOF module which is consist coil and a permanent magnet. The mathematical model is developed by using Faraday law to estimate the electrical response of the energy harvester. The effect of resistance load is admitted in the mathematical model its effect on the performance of the energy harvester. The effect is investigated for different values of frequency and resistance load. This method proposed regenerative absorber is effective and practical for renewable energy applications.

1. Introduction

Nowadays, harvesting ambient energy has been growing research topic area. One of the most trend in electronic devices todays is small, wearable, and wirelessly. In other words its become portable and can be integrated in any object. All those electronic devices need external power supply, during last decades the size of the energy needed has been decreased caused by the size of the devices. Therefore, harvesting energy from ambient in low power is needed. Many methods to scavenging ambient energy sources such as force, pressure, light source, temperature gradient, and mechanical vibration to pursue alternative power supply for electronic devices [1]. In particular mechanical vibration energy harvesting has attract much attention of research in the interest area of ambient energy harvesting. Vibration energy harvesting is made from three main method of transduction mechanical to electrical converting processes: electrostatic, electromagnetic, and piezoelectric materials. Interest in the application of electromagnetic energy harvesters to converting mechanical energy into electrical energy has been developed by different research facilities [2]. A conventional electromagnetic energy harvester is a system which is related to the particular design of the electromagnetic coupling. Numerous studies have been published regarding the mathematical modelling and the experimental tests of the electrical energy which can be harvested from this system [3]. There have been relatively few reported studies on the modelling of electromagnetic power generators for microelectromechanical systems (MEMS) applications. Many vibration sources can be used as an excitation for the vibration energy harvester devices [4]. The electromagnetic harvester usually is positioned into a vibrating host, when a harmonic base motion applied to the structure as well as the output voltage is generated. Electromagnetic energy harvesters have a high output voltage but low current level, and they have a simple structure, which is mean making them compatible with MEMS. This study uses the up and down movement oscillation of the shock absorber to vibrate the SDOF module which is consist coil and a permanent magnet as shown in Figure 1. In this paper, we focus in

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

deriving the mathematical model for a single degree of freedom (SDOF) electromagnetic energy harvesting system. The modeling of vibration energy harvesting by electromagnetic in SDOF system is presented, and the voltage and power output is calculated and presented.

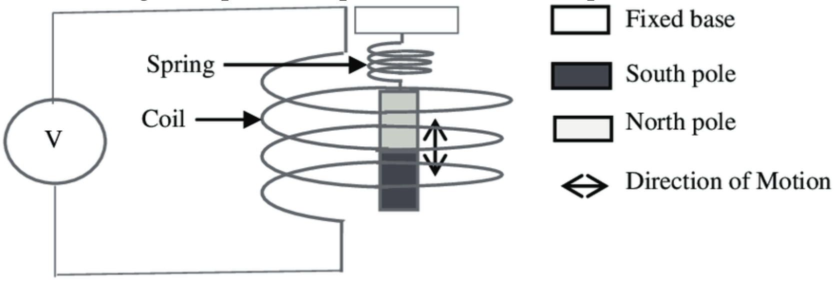

Figure 1. Schematic generate electricity of the electromagnetic concept.

2. Methodology

Dynamic model of a electromagnetic energy harvester at the mass of a SDOF system as shown in Figure 2 excited by, $w_b(t)$ is base input displacement. A SDOF energy harvesting system is consisting of a moving mass, m connected to the base with a spring, k and damping element, c. Since vibration based energy harvesters are excited due to the motion of their base, the lumped parameter representation of base excitation. A SDOF lumped spring mass system is utilized to study the dynamic characteristics of a vibrating body associated with piezoelectric energy harvesting. This mathematical model approach, requires a description of the dynamics of the point of interest the governing equation of motion based on due to the vibrating base [5].

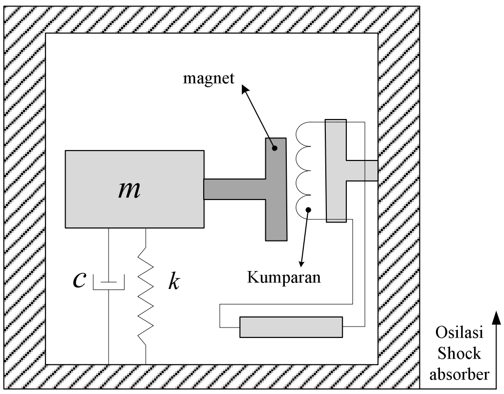

Figure 2. Schematic electromagnetic based on shock-absorber energy harvesting.

The vector of the degree of freedom based on the base excitation problem it is assumed that the base move harmonically as can be seen in Figure 3, can represented as the complex exponential

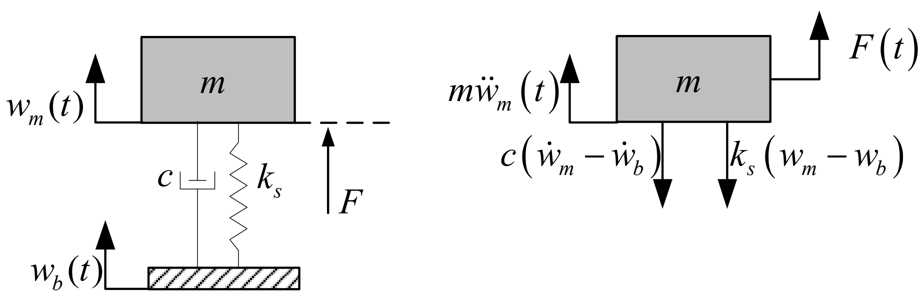

Figure 3. Single degree-of-freedom (SDOF) spring-mass-damper model of energy harvester.

$$m\ddot{w}_m + c\left(\dot{w}_m - \dot{w}_b\right) + k_s\left(w_m - w_b\right) = 0 \tag{1}$$

where, w_b denotes the amplitude of the base motion, ω represent the frequency of the base excitation and j, is the imaginary unit. As well as left side of the beam is a loaded with mass, considering a harmonic forcing function applied to the SDOF and caused wave propagation. This is the inertial force of the mass, thus the boundary conditions for shear and moment are given as:

$$F\left(x,t\right) = EI\frac{\partial^3 w\left(x,t\right)}{\partial x^3} = m\frac{\partial^2 w\left(x,t\right)}{\partial x^2} \tag{2}$$

$$M\left(x,t\right) = EI\frac{\partial^2 w\left(x,t\right)}{\partial x^2} = 0 \tag{3}$$

Using the general solution to the beam same as in Eq. (2), for general matrix of force can be written as:

$$\begin{bmatrix} F_1 \\ M_1 \\ 0 \\ 0 \end{bmatrix} = YI\begin{bmatrix} -mjk^2 & mjk^2 & mk^2 & -mk^2 \\ -k^2 & -k^2 & k^2 & k^2 \\ -jk^3e^{-jkL} & jk^3e^{-jkL} & k^3e^{-kL} & -k^3e^{kL} \\ -k^{2-jkL} & -k^2e^{jkL} & k^2e^{-kL} & k^2e^{kL} \end{bmatrix}\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} \tag{4}$$

and the dynamic stiffness is defined by:

$$\boldsymbol{Kw} = \boldsymbol{F} \tag{5}$$

These equations can be written in matrix form as from Eq. (7), (10) and (11), the dynamic stiffness matrix is equal to

$$\boldsymbol{K} = YI\left[\boldsymbol{F}\right]\left[\boldsymbol{w}\right]^{-1} \tag{6}$$

After the definition of the beam dynamics element it is possible to develop a simple order to explain how the stiffness matrix can be estimating displacement of any point in order to find the governing electrical circuit equation of the SDOF-electromagnetic energy harvesting.

2.1. Energy Harvesting Model

In order to derive the equations of electrical circuit of the piezoelectric material in beam form configuration, one should first examine the electroelastic dynamics of the piezoelectric beam under bending vibrations. The deflections are to highlight the space- and time-dependent radius of curvature φ, at an arbitrary point x, on the neutral axis at time t. The electric charge output Q, can be obtained from the integral form of Gauss's law [16] as

$$\frac{d}{dt}\left(\int_A D_i dA\right) = Q \tag{7}$$

where D, is the electric displacement vector of components in the piezoelectric material beam layer, i is the unit outward normal and the integration is performed over area of the electrode A. The electrical displacement in the piezoelectric layer is expressed as a function of strain and the electric field in the cross-sectional area of the piezoelectric layer.

$$Q = b\int_0^L \left(e_{31}S + \varepsilon E\right)dx \tag{8}$$

where b, is the width of the piezoelectric beam (assumed to be constant throughout the whole range), L is length of the piezoelectric beam, e_{31} is the piezoelectric constant in the 31-mode, ε is permittivity constant of piezoelectric material and E is the electric field within cross-sectional area of the piezoelectric layer. Because there is an electrode covered on the surface of the piezoelectric beam upper and bottom layer. Assuming the potential difference voltage is the same between upper and bottom and denoted as V_p, the electric field can be expressed as

$$E = -\frac{\partial v}{\partial z} = -\frac{V_p}{t_p} \tag{95}$$

where t_p is the thickness of the piezoelectric beam.

The strain S, on surface of piezoelectric beam along x -direction at a distance from the neutral axis can be obtained by taking the second partial derivative of transverse displacement $w\_\{p\}(x,t)$ [17],

$$S_x = -z\frac{\partial^2 w(x,t)}{\partial x^2} \tag{10}$$

Where z is the neutral axis of the piezoelectric beam. It is assumed that the thickness is the same the whole surface beam area. Substituting Eq. (15) and (16) into (14).

$$Q = -b\int_0^L e_{31}\frac{t_p}{2}\frac{\partial^2 w}{\partial x^2}dx + b\int_0^L \varepsilon\left(-\frac{V_p}{t_p}\right)dx \tag{11}$$

Eq. (17) can be also expressed as

$$Q = \frac{be_{31}t_p}{2}\left[\varphi(L_0) - \varphi(L)\right] - bL\varepsilon\frac{V_p}{t_p} \tag{12}$$

where $\varphi(x,t) = \frac{\partial w(x,t)}{\partial x}$ is the displacement of the piezoelectric beam, $\varphi(L_0)$ and $\varphi(L)$ are the corresponding values at the beginning and at the end of the piezoelectric beam layer.

The current, charge, and voltage are all in time functions. The frequency of these period functions depends on the mechanical vibration. Because of the differential piezoelectric charge on the surfaces is the current flow to the external resistance load.

$$I = \omega Q \tag{13}$$

where ω is frequency of the piezoelectric vibrating beam, the relationship between current and voltage for electrical circuits with pure resistance load R_L is

$$I = \frac{V}{R_L} \tag{14}$$

Combining Eq. (19) and Eq. (20) to Eq. (18), the output current from piezoelectric beam can be obtained as

$$I = \frac{\omega be_{31}t_p\left[\varphi(L_0) - \varphi(L)\right]}{2\left(1 + \omega bL\varepsilon\frac{R_L}{t_p}\right)} \tag{15}$$

As well as for the output voltage

$$V = \left(\frac{\omega be_{31}t_p\left[\varphi(L_0) - \varphi(L_1)\right]}{2\left(1 + \omega bL\varepsilon\frac{R_L}{t_p}\right)}\right)R_L \tag{16}$$

The output power from piezoelectric beam can be written as

$$P = \left(\frac{\omega b e_{31} t_p \left[\varphi(L_0) - \varphi(L) \right]}{2\left(1 + \omega b L \varepsilon \dfrac{R_L}{t_p}\right)} \right)^2 R_L \tag{17}$$

3. Results and discussion

In this study, the piezoelectric material beam, lead zirconium titanate (PZT) is used as energy harvester from the vibration energy. A 0.69 mm piezo-ceramics layer is covered by 0.03 mm insulation film (APC600/200/0.75SA) from APC International, Ltd. It is assumed that the width and length of the substructure layer and PZT layer are the same.

Table 1. Material properties of the SDOF energy harvesting system

Properties	Value
Length, L	0.06 m
Width, b	0.02 m
Thickness, t_p	0.69×10^{-3} m
Young's Modulus, Y	3.5×10^{9} N/m^2
Mass density	7600 kg/m^3
PZT permittivity constant, ε	8.854×10^{-12} F/m
Piezoelectric constant, e_{31}	2.74×10^{-10} C/N
Capacitance of piezoelectric	190,000 pF
Spring stiffness, k_s	600 N/m
Proof mass, m	100 gram

A current possibility that can influence of the main parameters of the energy harvesting structure system that affect to the performance of the energy harvesting devices could be filled with the development of numerical and analytical in order to understand the influence of the main parameters of the energy harvesting devices.

3.1. Mathematical model results

The mathematical models based on Eq. (21) were developing with MATLAB®. The material properties of the PZT beam and SDOF system investigated in this case study are given in Table (1). As well, combining Eq. (21) and dynamic stiffness matrix for SDOF-piezoelectric beam system in Eq. (12) the current output from SDOF energy harvesting system can be obtained as well as the output voltage and power. Fig. 3, 4, and 5 show the relation between the input excitation frequencies and output currents, voltages and powers in a various range of resistance load. The analysis given in this study considers the resistance load, R_L 100 $\rightarrow$ 10 Mohm.

Considering Fig. (3) and Fig. (4), it can be observed that both the voltages and the currents are identical at these optimum values of load resistance for optimum excitations in several specific frequencies points. The set of the resistance load regarded here from 100 to 10 Mohm. Therefore, the low resistance load (100 ohm) used here is close to short circuit condition and the top values of the resistance load (10 Mohm) is close to open circuit electrical conditions [17].

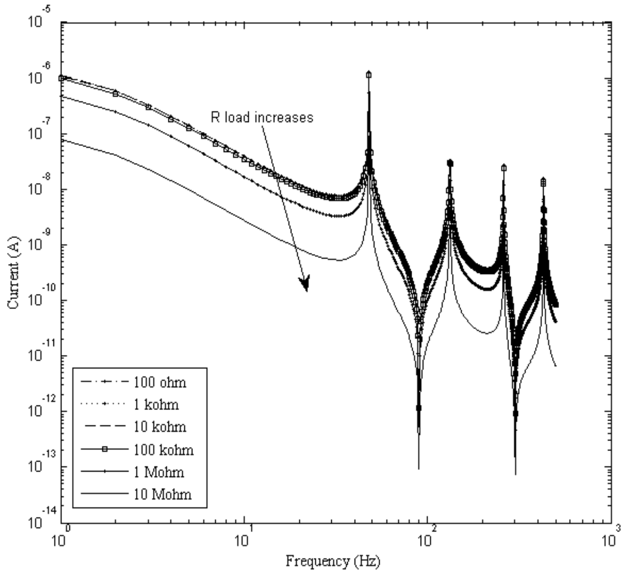

Figure 4. Output current of the SDOF vibration energy harvesting system for a broad range of load resistance

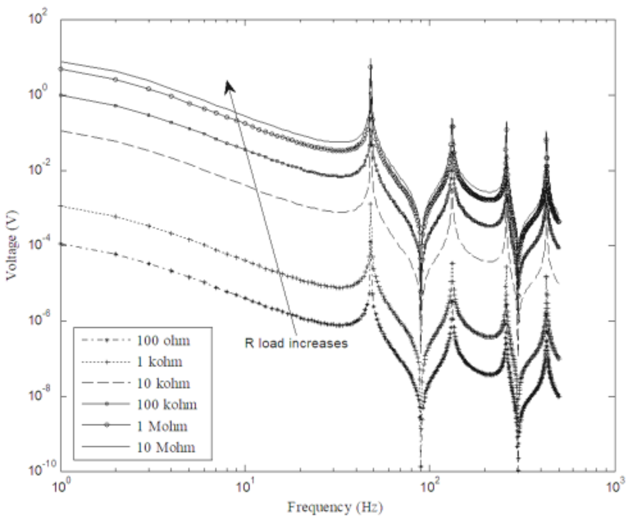

Figure 5. Output voltage of the SDOF vibration energy harvesting system for a broad range of load resistance

As can be seen in Fig. (3) as the resistance load from 10 Mohm decreasing to 100 ohm, the output current of the SDOF energy harvesting system at every frequency consistently decreases. Different with output voltage graph behavior shown in Fig. (4) as the resistance load increase from short circuit to open circuit condition the output voltage is increasing at various frequency range as well. For this reason, the focus is usually placed on close and open circuit conditions for frequency vibration mode in discussion study considerations as well as in the experimental validation cases. The maximum output current for mode 1 excitation is 1.27×10^{-6} A in close circuit conditions and 8.96×10^{-8} A in open circuit condition at 48 Hz frequency. Likewise in same frequency point for first mode output voltage obtained from mathematical models are 8.9 V in open circuit condition and 1.3×10^{-3} V in close circuit condition.

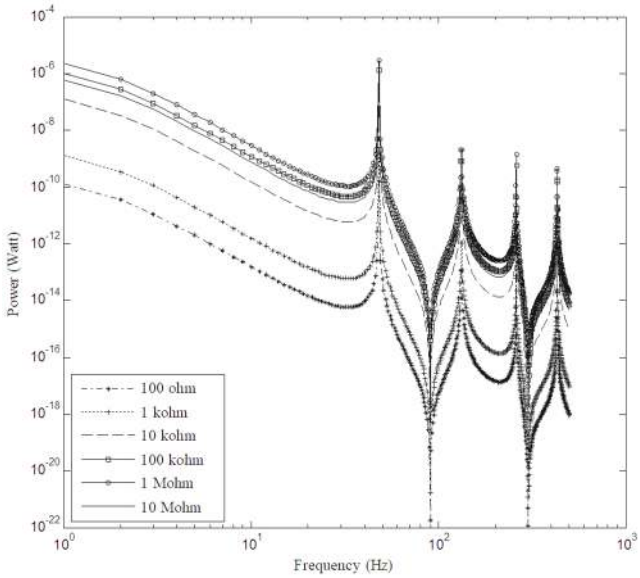

Figure 6. Output power of the SDOF vibration energy harvesting system for a broad range of load resistance

According to the Eq. (23) function of the output power is relative to a power of square of the output voltage and current as plotted at Fig. (5). As the result of two product voltage and current with contrary over with resistance load, from Fig. (5) the output power graph does not showing consistently behavior with the changes of the resistance loads increasing or decreasing for input frequencies. Among the result shown in Fig. (5) the maximum output power has been obtained for mode 1 is 1.63×10^{-10} for close condition and 8.31×10^{-7} W for open circuit condition at 48 Hz.

4. Conclusion

Mathematical modeling of SDOF vibration energy harvesting system is presented in this paper. Based on the Euler–Bernoulli beam theory is employed to calculate the typical vibration modes of SDOF vibration energy harvesting system and obtain the maximum output current, voltage and power of the harvester at several natural frequencies. A mathematical models for SDOF vibration energy harvesting system was developed to predict the performance of the energy harvesting. The output current, voltage and power is a function of various component such as frequency, resistance load, material properties and size of the piezoelectric material. The experimental results are close to mathematical models. Since the spring damping effect the amplitude displacement and frequency of the harvester so the damping effect is interesting to be considered in future study. Further studies of the SDOF vibration energy harvesting that can harvest low frequency vibration energy from environment ambient can be realized.

Acknowledgments

This work was supported by Penelitian Dosen Pemula (PDP) grant scheme from Fakultas Teknik Universitas Sultan Ageng Tirtayasa.

References

[1] Mateu L and Moll F 2005 Review of Energy Harvesting Techniques and Applications for Microelectronics, *Proceedings of SPIE: VLSI Circuits and Systems II*, *359–373. doi:10.1117/12.613046.*.

[2] Sidik S, Azma P, and Kok S L, 2014 *Modeling of Piezoelectric Acoustic Energy Harvester*, (Applied Mechanics and Materials, Vol. 695:757–760).

[3] Spreeman D and Manoli Y 2012 *Electromagnetic Vibration Energy Harvesting Devices* (London: Springer)

Journal of Physics: Conference Series **1477** (2020) 052059 doi:10.1088/1742-6596/1477/5/052059

[4] Tholl M, Haeberlin V, et al., 2018 *An Intracardiac Flow Based Electromagnetic Energy Harvesting Mechanism for Cardiac Pacing* (IEEE Transactions on Biomedical Engineering. Vol. 66) no. 2, pp. 530-538

[5] Williams C, and Yates R. B. 1996 *Analysis of a Micro-electric Generator for Microsystems* (Sensors and Actuators A: Physical, 52(1-3):8–11).