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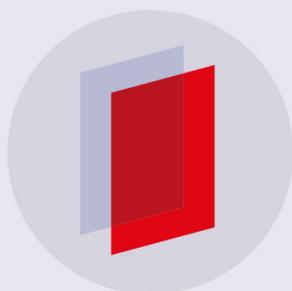
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A Novel Design to Increase the Power Output of an Electromagnetic Vibration Energy Harvester Using Finite Element Analysis

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Abstract. The concept of Internet of Things has prompted the need for a sustainable energy source to power wireless sensor networks. Vibration energy harvesting emerges as an applicable option. This paper presents a finite element analysis of a new electromagnetic vibration energy harvester design aimed to increase the power output of an electromagnetic vibration energy harvester by making the coil and a pair of magnets vibrate in the opposite direction, hence increasing the speed of the coil cutting through the magnetic flux of the magnets. The design consist of a regular cantilever beam And one uniquely shaped cantilever beam designed to move in the opposite direction to the regular beam under the same base excitation. Results show that due to the opposite motion, the speed of the coil moving through the magnetic flux for the new design is equal to the sum of velocities from the two individual beams. This lead to a 99.3% increase in power output generated from the new design when compared with the sum of the individual power outputs produced by the two beams. Further analysis demonstrates that the maximum power decreases if a time lag was introduced between the two beams, hence stating the importance of matching their natural frequencies.

1. Introduction

Industry 4.0 envisions the revolution of a ‘smart factory’, where cyber-physical systems monitor physical processes and make decentralized decisions through automation and data exchange. This vision is usually associated with the concept of the Internet of Things, where cyber-psychical devices embedded with sensors are able to communicate and exchange useful data with each other and with humans in real time through a wireless sensor network (WSN).

A WSN is a network built upon a large number of sensor nodes, with each node functioning as a physical measurement device to detect phenomena such as light and heat. Over the past decade, advancement in WSN technologies have allowed the development of low powered WSNs [1]. Hence, research in energy harvesting aimed at finding a sustainable source of power for WSN has become increasingly popular, as a WSN powered by conventional batteries has many constraints, such as large size, limited life and high maintenance cost [2–4]. One of the most promising sources of energy, which was initially proposed by William and Yates [5], is vibrations.

Vibration energy harvesting has emerged as a promising energy source due to its high power density in terms of electrical conversion and its abundance in the surroundings [6]. Many transduction methods exist to convert mechanical vibration energy into electrical power, with the two most common methods being piezoelectric conversion and electromagnetism. Piezoelectric conversion has demonstrated a higher power density at small volumes whereas electromagnetism conversion is more



favorable when space is not a constraint [7]. However, Beeby et al. [8] argued that the power density of an optimized electromagnetic vibration energy harvester can surpass that of a piezoelectric harvester at small volumes.

Much research has been conducted over the past decade to increase the power output and frequency bandwidth of a vibration energy harvester. Thein et al. [9] employed a finite element optimization algorithm to determine the optimum topology for a piezoelectric vibration energy harvester that would result in the maximum power output. Ooi and Gilbert [10] proposed a dual-resonator design consisting of two cantilever beams facing each other, where a pair of magnets is attached to one beam and a coil is attached to the other. It was shown that under dissimilar resonant frequencies, the bandwidth between the two resonant frequencies was improved. However, the maximum power recorded is equal to that of a conventional design. Other researchers have explored the effect of a hybrid energy harvesters where the piezoelectric and electromagnetism transduction method have been combined into a single harvester [11,12]. While an increase in power output was observed, the recorded power output was less than the sum of the power outputs from the two individual transduction methods.

In this paper, a finite element analysis (FEA) was conducted to analyse the power output of the electromagnetic vibration energy harvester design in Figure 1. The purpose of the design is to increase the speed of the coil cutting through the magnetic flux of two permanent magnets by making the coil and the magnet vibrate in opposite directions under the same base excitation. The design consists of two smaller beams (beams B and C) that are clamped to one end of a primary cantilever beam. The other end of the primary beam is clamped to a vibrating base. When the primary beam vibrates, the free ends of the two smaller beams move in the opposite direction to the primary beam due to the amplitude gradient of the primary beam. The new design is paired with a regular cantilever beam (beam A) to generate power. A coil is attached to one of the smaller beams and a pair of magnets is fixed onto the regular beam. A mass or another coil can be added onto beam C depending on application. To simplify analysis, beam B was modelled as a regular cantilever beam similar to Beam A. However, the base motion of beam B is opposite to beam A. Using the results of the FEA, further analysis was conducted to investigate the effect of time lag on the cutting speed of the coil.

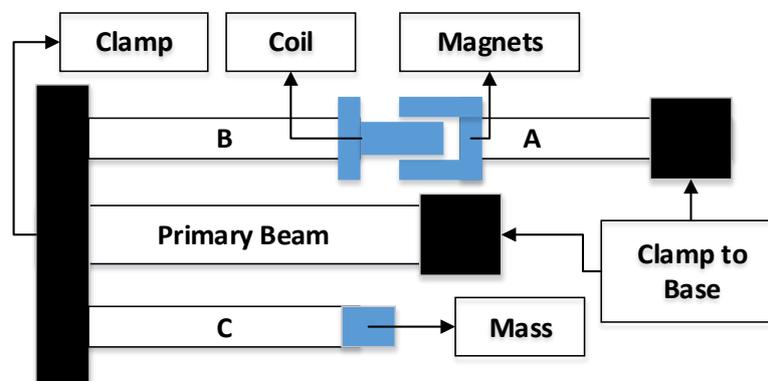


Figure 1. Design of a cantilever beam to make the magnet and the coil vibrate in the opposite direction (top view).

2. Power output of an electromagnetic vibration energy harvester

Figure 2 illustrates the mechanism of a typical electromagnetic vibration energy harvester. The mechanism exhibits a forced vibration motion, in which the base vibration induces the vibration of the coil. When the coil vibrates, the coil cuts through the magnetic field produced by the two permanent magnets. According to Faraday's law of induction, this will result in the generation of an induced current within the coil, hence producing power.

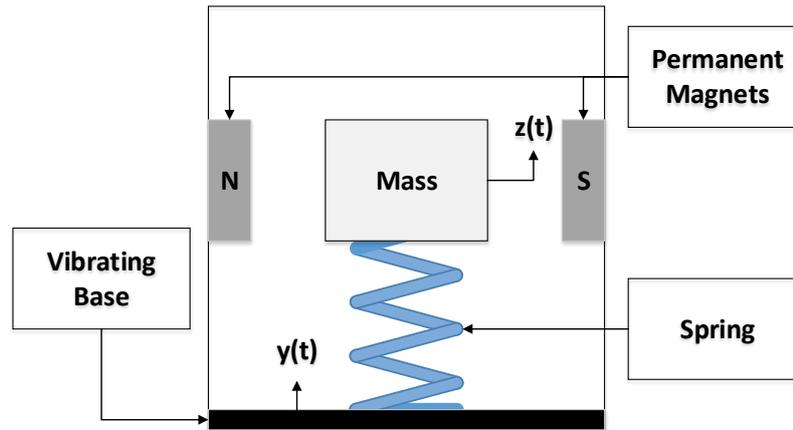


Figure 2. A schematic of an electromagnetic vibration energy harvester.

In Figure 2, $z(t)$ represents the relative vertical motion of the vibrating coil at time t and $y(t)$ is the motion of the vibrating base at time t . The governing equation relating the two variables can be described by [13]

$$z(t) = \frac{\omega^2}{\omega_n^2 - \omega^2 + 2(\zeta_m + \zeta_e)\omega_n\omega} y_0 e^{i\omega t} \quad (1)$$

where ω is the driving frequency, ω_n is the natural frequency of the system, ζ_m is the mechanical damping of the system, ζ_e is the induced electrical damping and y_0 is the maximum amplitude of the base excitation. Differentiating equation (1) with respect to t results in the velocity of the coil:

$$v(t) = z(t)\omega \quad (2)$$

where $v(t)$ is the velocity of the coil at time t . Based on Faraday's law of electromagnetism, the magnitude of the induced voltage generated within a coil when the coil cuts through a magnetic field is:

$$V_i = NBl_c v_c \quad (3)$$

where V_i is the induced voltage, N is the number of turns of the coil, B is the magnetic flux density between the two permanent magnets, l_c is the effective length of the coil and v_c is the relative speed of the coil cutting through the magnetic field, otherwise referred to as the cutting speed. By substituting equation (2) into equation (3) and applying Ohm's law, the average power produced by the coil of an electromagnetic vibration energy harvester at time t can be determined. In this paper, the phrase 'average power' refers to the root-mean-square value of the power.

$$P_{avg}(t) = \frac{[NBl_c z(t)\omega]^2}{4R_T} \quad (4)$$

Here, $P_{avg}(t)$ is the average power generated and R_T is the total resistance of the system, which is conventionally the sum of the coil resistance and the load resistance. If the electrical components of the harvester is fixed, equation (4) becomes

$$P_{avg}(t) = P[z(t)\omega]^2 \quad (5)$$

where P is a constant representing the harvester's electrical components. From equation (5), the only non-electrical contribution to the power output of the energy harvester is the cutting speed of the coil. Since the average power is proportional to the square of the velocity, a small increase in velocity will result in a significant increase in power. In addition, the equation also states that the power output generated from an individual harvester having a cutting speed of $v_1 + v_2$ would be higher than the sum of the two power outputs generated from two individual harvesters having cutting speeds of v_1 and v_2 , respectively. This statement is represented by:

$$P(v_1 + v_2) > P(v_1) + P(v_2) \quad (6)$$

where $P(v_1 + v_2)$ is the power output corresponding to a cutting speed of $v_1 + v_2$ and $P(v_1)$ and $P(v_2)$ are the power outputs for a cutting speed of v_1 and v_2 . This is because $(v_1 + v_2)^2$ is always higher than $v_1^2 + v_2^2$. Therefore, it is more efficient to increase the cutting speed of a single electromagnetic harvester than to use multiple harvesters having lower cutting speeds

3. Methodology

In this section, the coil's cutting speed and power output of the beam design was investigated through finite element analysis as shown in Figure 1. From this point forward, the design in Figure 1 will be referred to as Design 1. To simplify analysis, beams A and B from Design 1 were modelled as two individual cantilever beams subjected to opposite base excitation motion. Beam A was modelled as an aluminium beam and beam B was modelled as a steel beam. One end of both beams were clamped while additional mass were added to the other end to match their natural frequencies. The specifications of the modelled beams are tabulated in Table 1. All FEA was conducted using Abaqus.

Table 1. Specifications of beams A and B modelled in Abaqus.

	Beam A	Beam B
Young's Modulus (GPa)	69	200
Density (kgm ⁻³)	2700	7800
Width (mm)	12	12
Length (mm)	80	80
Thickness (mm)	1.2	1.2
Added mass (g)	18.24	2.84
Damping ratio	0.015	0.015
Natural Frequency (Hz)	33.237	33.237

An eight node linear brick reduced integration element with hourglass control (C3D8R) was used to model both beams. A base excitation acceleration magnitude of $0.5g$ was applied at the clamped end of the aluminium beam. Here, $1g$ is equal to an acceleration of 9.81ms^{-2} . The FEA model was simulated under nine different driving frequencies, including the beam's natural frequency. Figure 3 illustrates the FEA model generated. The maximum power output produced by the beam A alone was then determined using equation (5) based on the maximum velocity recorded from the FEA model. Here, it is assumed that the maximum velocity of beam A will correspond to the cutting speed of beam A.

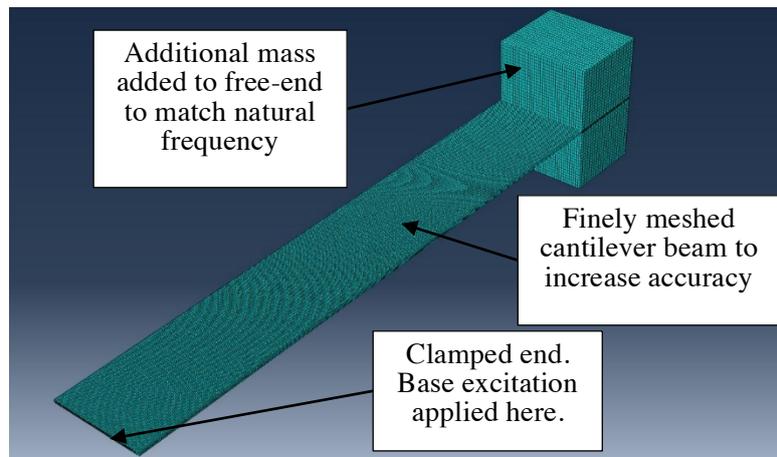


Figure 3. FEA model of beam A.

The same procedure was repeated for the steel cantilever beam model. However, the magnitude of the base excitation acceleration input was changed to $-0.5g$ instead. The negative sign indicates that the motion of the base for the steel beam is opposite to that of the aluminium beam. The maximum power output of beam B alone was then calculated, assuming that the cutting speed is equal to the maximum velocity of beam B. For Design 1, the maximum power output was determined by taking the maximum resultant velocity between beams A and B. This is because in Design 1, the total cutting speed is equal to the difference in velocity between beams A and B due to their opposite motion, hence their resultant velocity. A time lag was then introduced into the results from Beam B to observe the effect of the time lag on the maximum cutting speed and power output of Design 1.

4. Results and Discussion

Figure 4 below describes the cutting speed response curves of beams A and B obtained from the FEA model and Design 1 calculated by subtracting the velocity of beam A with B (resultant velocity). A Gaussian curve was fitted to the FEA results for beams A and B. The velocity measurements for beams A and B were taken from the centre of the free-end tip of the beam.

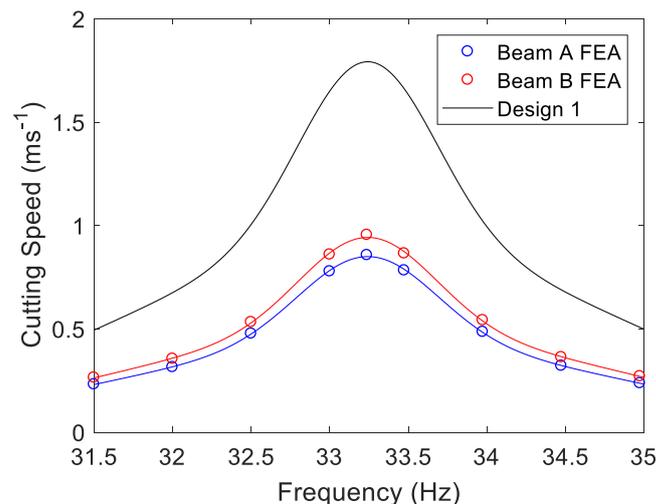


Figure 4. Cutting speed response curves of beams A and B and Design 1.

The power response curve of beams A and B and Design 1 were then calculated using equation (5) based on the results from Figure 4 and plotted as shown in Figure 5. Since the electrical components

of the harvester were not modelled in FEA, the power was calculated in terms of constant P . Table 2 tabulates the maximum velocity and power of Design 1 and beams A and B.

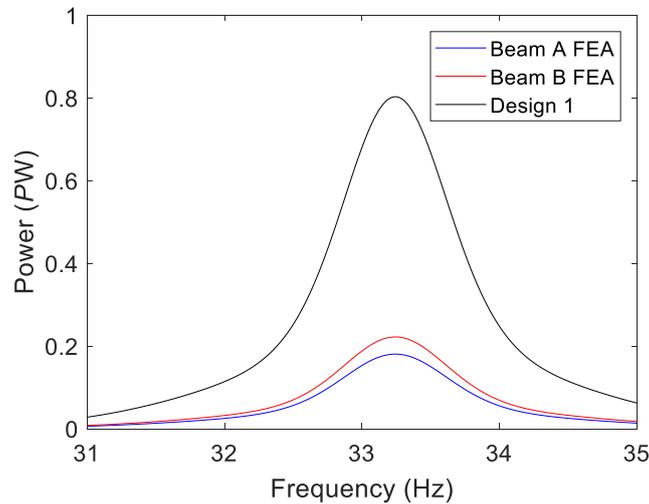


Figure 5. Power response curves of beams A and B and Design 1.

Table 2. Maximum velocity and power of beams A and B and Design 1.

	Maximum velocity (ms^{-1})	Maximum power (W)
Beam A	0.86	$0.185P$
Beam B	0.95	$0.226P$
Design 1	1.81	$0.819P$

Results from Figure 5 describes a significant increase in power for Design 1 compared to the individual power outputs from Beams A and Beam B, especially at resonance. In addition, the maximum power output of Design 1 was recorded to be 99.3% higher than the sum of power from beams A and B, which is in agreement with equation (6). The power output recorded in Table 2 corresponds to the case in where the natural frequencies of Beams A and B are equal. If Beams A and B have dissimilar natural frequencies, a time lag would occur between the two beams. The effects of time lag on the power output of Design 1 is plotted in Figure 6.

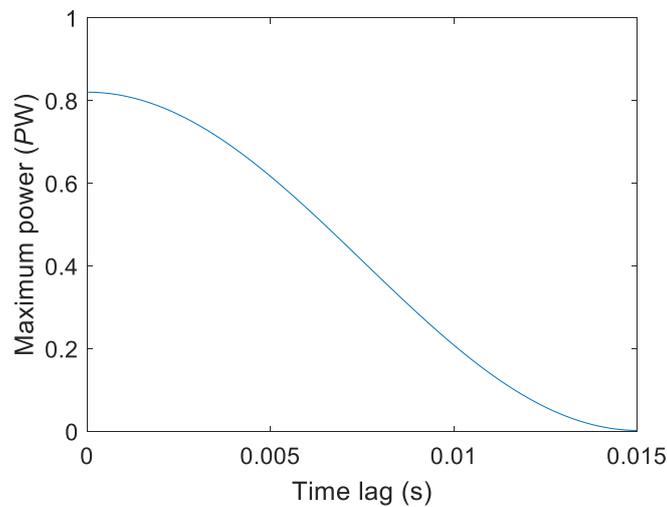


Figure 6. Effect of time lag to the maximum power output of Design 1.

The curve in Figure 6 states that increasing the time lag between beams A and B will decrease the maximum power output of Design 1. For Design 1 to remain efficient in terms that the power output of Design 1 is higher than the sum of power outputs from beams A and B, the time lag between beams A and B cannot exceed 0.0075 seconds. This value may differ if a different cantilever beam specification were used for beams A and B. Nevertheless, Figure 6 shows the importance of matching the natural frequency of beams A and B in Design 1 to maximise the efficiency of the design.

5. Conclusion

This paper investigates the cutting speed and power output of a new electromagnetic vibration energy harvester design (Design 1) through finite element analysis. Beams A and B from Design 1 were simulated using FEA and the maximum velocity of both beams were recorded. The cutting speed of Design 1 is equal to the resultant velocities from beams A and B. Since beams A and B move in the opposite direction, the maximum cutting speed of Design 1 is equal to the sum of the maximum velocities from beams A and B. Analytical results show that the maximum power output of Design 1 is 99.3% higher than the sum of the maximum individual power outputs from beams A and B. If the natural frequency of beams A and B are not matched, a time lag will occur between the two beams. Further analysis was conducted to analyse the effect of time lag on the maximum power output of the Design 1. It was found that increasing the time lag between the two beams decreases the maximum power output of Design 1. Hence, it is important to ensure that the natural frequency of beams A and B are equal to maximise the efficiency of Design 1. Future works include experimental validation of the results presented in this paper.

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