



# Hybrid energy harvesting system under the electromagnetic induced vibrations with non-rigid ground connection

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## ABSTRACT

A hybrid energy harvesting system has been presented in this study by vibrating a beam element with an electromagnetic actuator. With the structure proposed in this article, two different types of energy harvesting concepts were provided with the piezoelectric patch attached to the fixed end of the cantilever beam and the electromagnetic device connected to the free end of the cantilever beam. Generally, in electromagnetic energy harvesting systems, the electromagnetic device is fixed from one end to the ground. The effects of vibration of this fixed surface on energy harvest are being neglected. Electromagnetic devices that provide energy harvesting and vibrate the beam element are of identical structure in the proposed hybrid system. Both devices are mounted at the same point of the beam to face each other. While one of these electromagnetic devices is fixed onto the ground, the other one is assembled to the main beam with a secondary parallel beam element. Therefore, the electromagnetic device that harvests energy or vibrates the beam element can be changed so that it can be either on the lower or upper side of the main beam element. With this designed structure, the behavior of electromagnetic energy harvesting elements and vibration actuators placed on the non-rigid ground has been investigated. Unlike conventional energy harvesting methods, the concept of displacement transmissibility has been discussed in this study. Experimental studies have performed the dynamic conditions to obtain optimum energy harvest in the proposed harvesting system for different frequency inputs. Experimental results revealed the effect of vibrations originating from the non-rigid ground on energy harvesting. It has been observed that the electromagnetic energy harvesting device connected to the non-rigid ground increases the amount of energy collected.

## 1. Introduction

Energy harvesting materials and systems are promising fields of study to meet increasing energy demand today and in the future. The harvested energy is used in many systems that require low power consumption, especially in wireless sensor equipment and embedded integrated circuit systems. As technology progresses, devices with low power consumption will develop, and energy harvesters will be an additional energy source for these devices used in every moment of life. One of the most popular forms of energy harvesting is using piezoelectric materials for mechanical vibrations [1–6]. The other popular form of obtaining energy uses an electromagnetic device as a harvester in the systems subject to mechanical vibrations [7–11]. Although these two popular methods used in energy harvesting have different advantages and disadvantages over each other, they use hybrid structures to increase the amount of energy to be harvested [12]. In general, hybrid energy harvesting (HEH) systems can be collected in two separate groups as

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multi-source hybrid harvesters and single-source harvesters with HEH devices [13]. Sang et al. proposed a vibration-based hybrid energy harvester system with piezoelectric and electromagnetic devices and conducted experimental studies under harmonic excitation [14]. Ping et al used random excitation for governing electromechanical equations of hybrid piezoelectric-electromagnetic energy harvest system to show the mean power and power spectral density with non-dimensional parameters [15]. Dias et al reported the concept of hybrid piezoelectric-inductive harvesting with electroaeroelastic modeling and simulation techniques. They worked on the dimensionless analysis of aeroelastic energy harvesters conducted a scaling and optimization study [16]. Karami and Inman proposed a novel case study for the backward coupling effect in a nonlinear hybrid energy harvester. They used a setup for a hybrid system that includes the equations not only corresponding to the piezoelectric materials but also equations associated with the electromagnetic energy harvesters [17].

As given in the above-mentioned studies, mechanical vibrations are converted into useful energy by using piezoelectric and electromagnetic devices in the energy harvesting concept. These vibrations can be either uni-directional or multi-directional, at different frequencies depending on the system design. On the other hand, many systems that are encountered in daily life, such as the motion of the vehicle, working machine vibrations, flow-induced vibrations, electromagnetic vibrations, and many other mechanical vibrations that occur at low frequencies. Therefore, various methods are investigated to obtain the energy harvest in the low-frequency region. Fan et al have presented a bi-directional hybrid energy harvester encounter ultra-low frequency mechanical excitations in their work. They used two piezoelectric cantilever beams, with a permanent magnet and a set of coils to convert ultra-low frequency, which is lower than 10 Hz, mechanical excitations to the useful energy [18]. Li et al mentioned about the challenge for the different studies to optimize the energy output of energy harvesters work under the low-frequency ambient vibrations. They gave some study and the methods that have been suggested to enhance the power density of the piezoelectric energy harvester systems [19]. Galchev et al worked to design and manufacture of a piezoelectric energy harvesters for harvesting energy from systems that are exposed to low-frequency non-periodic mechanical vibrations using with the electromechanical transducer to decrease the stiffness [20]. Gu and Livermore conducted experiments of an energy harvesting device in the presence of low-frequency vibration and have shown the efficiency of the conveyed electrical power is remarkably improved with the use of coupled vibration technique [21].

Energy harvesting studies that obtained from mechanical vibrations in the low-frequency region are not limited to studies using piezoelectric elements. There are also energy harvesting methods obtained from low-frequency mechanical vibrations using electromagnetic devices. Galchev et al have discussed the modeling and investigation of a vibration generating setup, which is designed for harvesting low-frequency ambient vibrations by using a miniature electromagnetic generator [22]. Rahimi et al have worked on an energy harvesting system, which consists of an electromagnetic generator converting ambient low-frequency vibrations to DC voltage by using a full-wave rectifier and, they proposed a harvesting system that delivers a smooth DC voltage that can directly be utilized by common sensor networks [23]. Jiyang et al have reported the experimental work of a polyvinylidene fluoride cantilever beam element with a magnetic mass for piezoelectric and electromagnetic energy generator systems. They have conducted the study for electromagnetic energy harvesting by locating a coil below the magnetic tip under the vibration with a frequency of 14 Hz [24]. Fan et al have proposed an approach for constructing high-output rotational electromagnetic energy harvesters in two string-suspended and driven rotor which is capable of transforming ultra-low frequency vibrations to fast rotational motion of a rotor [25]. They have successfully demonstrated the low-frequency region vibration and human body vibration can be harvested by an electromagnetic device. Liu et al demonstrated in their study that low-frequency vibrations that are lower than 10 Hz caused by irregular human movements can be collected by using a non-resonant rotational electromagnetic energy harvester [26]. Sardini and Serpelloni have designed an efficient electromagnetic power harvesting device for low-frequency applications and converted mechanical energy in the form of low-frequency vibrations [27].

The energy harvesting studies given above show that different harvesting materials and devices are implementable to different structural systems and various mechanical vibration scenarios. The combination of two different energy harvesting mechanisms provides not only improvement in efficiency but also gives a significant increase in power output. In many researches, the coupling of energy harvesting mechanisms is used to increase the energy output for the given vibration sources [28–42].

When the literature mentioned so far is examined, it is seen that the vibration effect of the ground is ignored in the energy harvesting systems established to the conversion of the mechanical vibrations to useful energy. However, displacement transmissibility, a known mechanical vibration phenomenon, has been experimentally introduced to show how it affects the amount of energy to be obtained in energy harvesting systems. A novel HEH system is presented in this study by vibrating a beam element with an electromagnetic actuator. This proposed system also examines the potential of transforming ground vibrations into useful energy under different dynamic conditions. Two identical electromagnetic devices were used in this study to provide energy harvesting, as well as to vibrate the beam element, and they were mounted at the same point of the main beam to face each other. While one of these electromagnetic devices is fixed onto the ground, the other one is assembled to the main beam with a secondary parallel beam element. There are studies on energy harvesting methods in which two beams are used on the same system [43–45]. However, the secondary beam element used in these studies was used to connect a second piezoelectric element to increase the amount of power obtained from energy collection. In this study, the effect of a non-rigid surface on energy harvesting was experimentally investigated. By applying the piezoelectric and electromagnetic energy harvesting methods, the hybrid energy structure is obtained. In addition, the concept of displacement transmissibility emphasized for the proposed system. The secondary beam element in proposed system is used to demonstrate the displacement transmissibility. With this designed structure, the behavior of the electromagnetic energy harvesting element and the vibration actuator placed on the non-rigid ground has been investigated. The HEH system with a non-rigid ground connection exposed to electromagnetically induced vibrations has been investigated by experimental studies, and results presented.

The paper is organized as follows: Section 2 gives the details of the proposed HEH structure. Section 3 presents the energy harvesters of the system and gives formulation for the electromagnetic model, piezoelectric model and, coupled model. The next section's

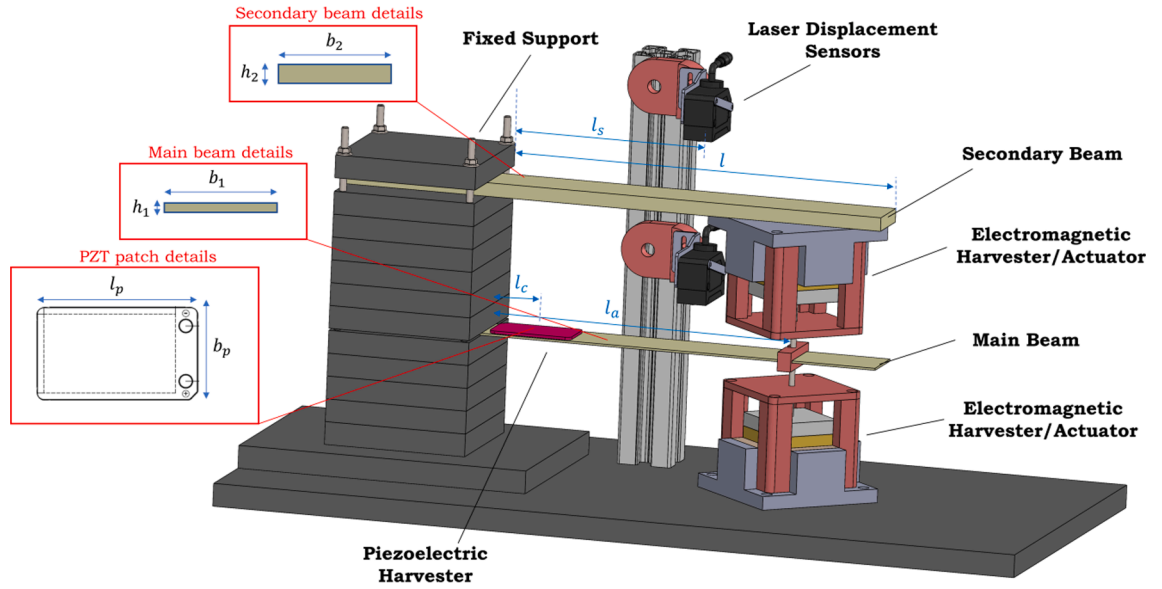


Fig. 1. Dual beam HEH system schematic view.

**Table 1**  
Dual beam HEH system parameters.

Name	Symbol	Value	Unit
PZT patch dimensions	$l_p \times b_p \times h_p$	$61 \times 35 \times 0.5$	[mm]
Main beam dimensions	$l \times b_1 \times h_1$	$280 \times 40 \times 1.5$	[mm]
Secondary beam dimensions	$l \times b_2 \times h_2$	$280 \times 40 \times 10$	[mm]
Density of the main and secondary beam (Aluminum)	$\rho$	2700	[kg/m <sup>3</sup> ]
Mass of the main beam	$m_1$	$4.53 \times 10^{-2}$	[kg]
Mass of the secondary beam	$m_2$	0.302	[kg]
Distance between the fixed support and piezoelectric harvester center point	$l_c$	36	[mm]
Distance between the fixed support and electromagnetic harvester/actuator	$l_a$	235	[mm]
Distance between the fixed support and laser displacement sensor	$l_s$	160	[mm]
PZT coefficient	$d_{31}$	$-180 \times 10^{-12}$	[C/N]
Electromagnetic device resistance	$R_{em}$	3.05	[ $\Omega$ ]
Electromagnetic device inductance	$L_{em}$	1674.5	[ $\mu$ H]
Electromagnetic device coil number of turns	$N$	200	[-]

topic is the experimental implementation of the designed HEH system. In addition, the response of electromagnetic energy harvesting element and vibration actuator placed on the non-rigid ground is presented. Finally, the concluding remarks are included.

## 2. Dual beam hybrid energy harvesting system

Dual beam HEH system is shown schematically in Fig. 1. In this system, two separate beam elements of the same width and length but different thicknesses were used. While the thin one of these beams is used as the element which is exposed to vibration and obtains energy harvest on it, the thick one is used to represent the non-rigid ground connection. Both beam elements are assembled by fixed support. There are two electromagnetic devices on the system that are connected to the main beam element at the same point. These devices are identical Lorentz type electromagnetic devices that can operate in both actuator mode and harvester mode. In addition, a piezoelectric patch is affixed to the main beam element around the fixed end location and piezoelectric energy harvesting is achieved. Two laser displacement sensors have been used to measure the displacements on the main beam and on the secondary beam. The secondary beam has represented for the non-rigid ground connection exposed to some small vibration that affects the harvested energy in the main system. The basic dimensions and physical parameters of the system are presented in Table 1.

## 3. Dynamics of the energy harvesters

Upper electromagnetic device base support of the energy harvesting system undergoes harmonic motion due to the non-rigid ground. The dynamics of the harvester is described as;

$$m_e \ddot{x} + c_e \dot{x} + k_e x = k_e y + c_e \dot{y} = A \sin(\omega t - \alpha) \tag{1}$$

where  $m_e$  represents the seismic equivalent mass,  $k_e$  stiffness coefficient,  $c_e$  damping coefficient,  $x$  shows the displacement of the main beam,  $y$  shows the displacement of the secondary beam,  $A = Y \sqrt{k_e^2 + (c_e \omega)^2}$ , and  $\alpha = \tan^{-1}(-c_e \omega / k_e)$ . The ratio of the amplitude of the response  $x(t)$  to that of the base motion  $y(t)$ ,  $X/Y$ , is called the displacement transmissibility [46]. The variation of the displacement transmissibility can be written as follows;

$$\frac{X}{Y} = \sqrt{\frac{k_e^2 + (c_e \omega)^2}{(k_e - m_e \omega^2)^2 + (c_e \omega)^2}} \tag{2}$$

Displacement transmissibility is generally used in the design of the vibration systems to indicate the vibration transmission at different frequencies. In this study, an additional upper beam element is used, which is thicker than the main beam element and represents the ground connection. Therefore, a setup has been obtained in which the ground displacements are not taken as zero and the displacement transmissibility effect can be observed.

### 3.1. Electromagnetic model

The mathematical expression of the motion for the displacement of the electromagnetic energy harvesting system can be given as follows;

$$\begin{aligned} m_e \ddot{x}(t) + c_e \dot{x}(t) + k_e x(t) + BI(t) &= F(t) \\ B\dot{x}(t) - (R_1 + R_{em})I(t) - L_{em}\dot{I}(t) &= 0 \end{aligned} \tag{3}$$

where  $L_{em}$  is the electromagnetic device inductance,  $B$  is the electromagnetic coefficient,  $R_1$  is the load and  $R_{em}$  is the electromagnetic device self-resistance. When a closed-loop coil passes through a magnetic flux, an electric current is induced according to Faraday’s law of electromagnetic induction. The main idea in the electromagnetic model is to scavenge electrical energy by induction over a closed-loop coil circuit element that is moved in a magnetic field caused by mechanical vibrations. The voltage induced by the electromagnetic device according to Faraday’s law can be given by;

$$V(t) = -N \frac{d\varphi}{dt} \tag{4}$$

where  $N$  is the number of turns of the closed loud coil and,  $\varphi$  is the total flux in the coil. The equation for the obtained power when the voltage ( $V$ ) scavenged by an electromagnetic device is passed over an electrical load ( $R_1$ ) (see Fig. 4) and internal resistance of the electromagnetic device ( $R_{em}$ ) can be written as follows.

$$P_{em} = \frac{V^2}{R_1 + R_{em}} \tag{5}$$

### 3.2. Piezoelectric model

Piezoelectric patch transducers are the smart materials that transform electrical energy into mechanical energy and vice versa. The piezoelectric effects can be given by the piezoelectric constitutive equations as follows;

$$\begin{bmatrix} T \\ D \end{bmatrix} = \begin{bmatrix} s^E & -d^t \\ d & \epsilon^S \end{bmatrix} \begin{bmatrix} S \\ E \end{bmatrix} \tag{6}$$

where  $S$  represents the strain,  $T$  represents the stress components,  $E$  is given for the electric field, and  $D$  is the electric displacement.  $s$ ,  $\epsilon$ , and  $d$  are given for the elastic compliance, dielectric constant, and piezoelectric coefficients respectively. Finally,  $E$  and  $S$  superscripts are stand for evaluated constants under constant electric field and constant stress, respectively and finally  $t$  indicates the transpose of the matrix. This model describes a linear mathematical relationship between the electrical and the mechanical domain. In the literature that consider piezoelectric nonlinear situations in certain models can be found [47]. The general equation of the motion related to the displacement of piezoelectric energy generation structure can be given as follows;

$$\begin{aligned} m_e \ddot{x}(t) + c_e \dot{x}(t) + k_e x(t) + \theta V(t) &= F(t) \\ -\theta \dot{x}(t) + C_{pzt} \dot{V}(t) &= -I(t) \end{aligned} \tag{7}$$

where  $\theta$  represents the piezoelectric coefficient,  $C_{pzt}$  represents the capacitance of the piezoelectric material and  $x(t)$  is the displacement of the effective mass of the system. The piezoelectric element adhered to a beam element provides energy harvesting by converting the mechanical vibrations exposed by the beam to electrical energy. The power equation obtained when the voltage ( $V$ ) scavenged by a piezoelectric element is passed over an electrical load ( $R_2$ ) (see Fig. 4) can be written as follows.

$$P_{pzt} = \frac{V^2}{R_2} \tag{8}$$

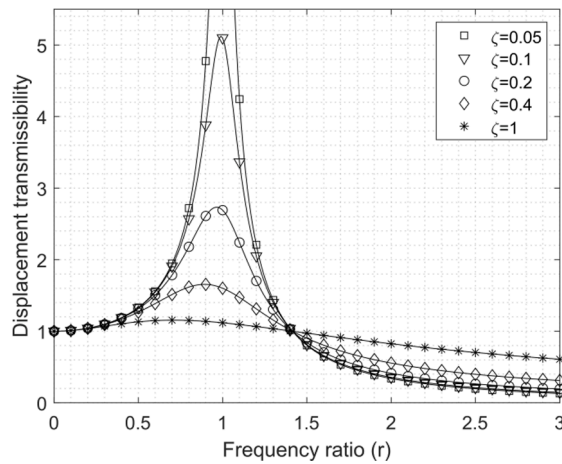


Fig. 2. Variation of the displacement transmissibility.

### 3.3. Hybrid model

Hybrid energy harvesters with the coupled model structure are generally used to increase the energy to be harvested. The piezoelectric and electromagnetic harvesting system equations given separately in Eqs. (4) and (7) can be expressed as a governing equation of the hybrid system as follows.

$$m_e \ddot{x}(t) + c_e \dot{x}(t) + k_e x(t) + BI(t) + \theta V(t) = F(t)$$

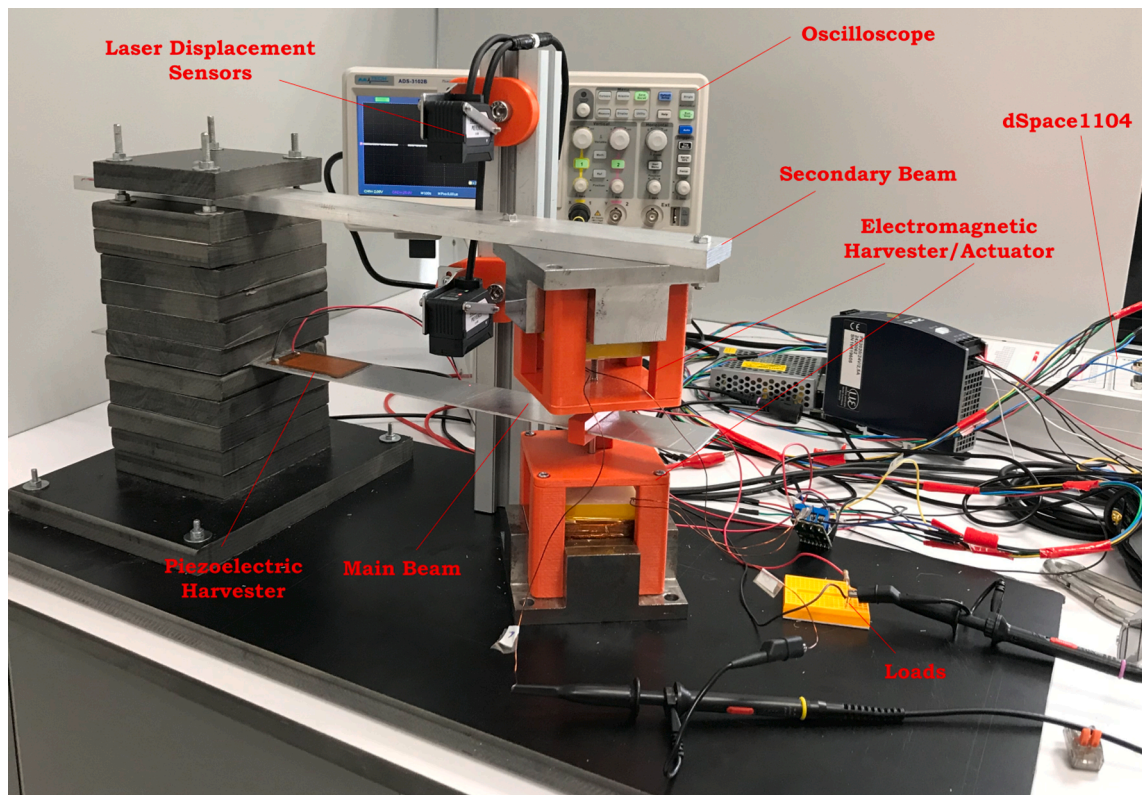


Fig. 3. Experimental setup.

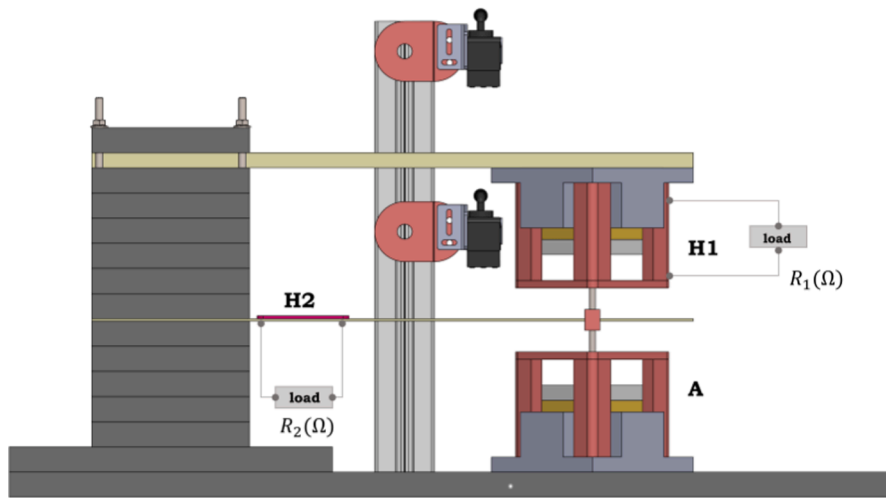
$$B\dot{x}(t) - (R_1 + R_{em})I(t) - L_{em}\dot{I}(t) = 0$$

$$-\theta\dot{x}(t) + C_{ps}\dot{V}(t) = -I(t) \tag{9}$$

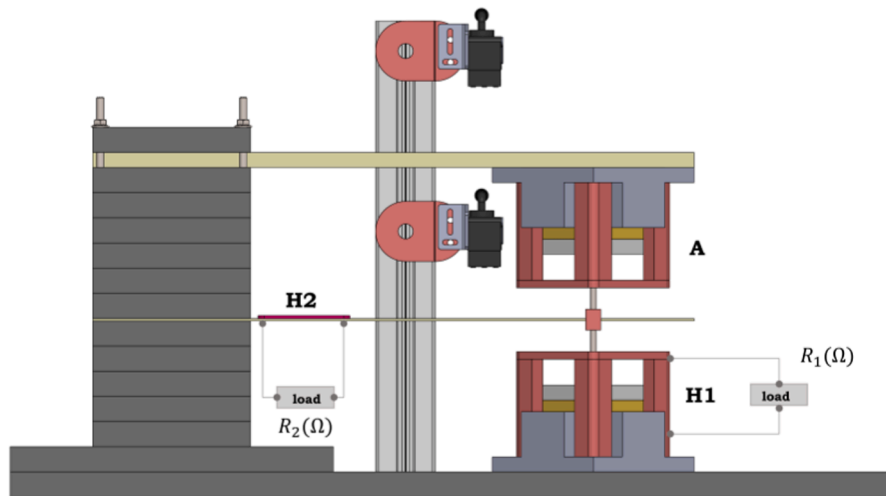
In the proposed HEH system, the base of the electromagnetic actuator is represented by a secondary beam element that allows the base motion. The ratio of the amplitude of the base and system motion gives the displacement transmissibility defined in Eq. (2). This equation can be expressed in terms of the damping ratio ( $\zeta$ ) and the frequency ratio ( $r = \omega/\omega_n$ ) for a typical vibration system as follows:

$$\frac{X}{Y} = \sqrt{\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}} \tag{10}$$

The correlation between the displacement transmissibility and frequency ratio is given in Fig. 2. The displacement transmissibility value converges to one when the frequency ratio ( $r$ ) is close to zero as can be seen from Fig. 2. It is also known that the resonance occurs when the natural frequency of the system ( $\omega_n$ ) and the excitation frequency ( $\omega$ ) coincide. In this case ( $r = 1$ ), the displacement transmissibility value converges to infinity. The frequency value of the main beam used in the proposed HEH system is found to be equal to  $\omega_n = 15.8$  Hz according to the finite element analysis. The electromagnetic device on which vibrate was given for the system has a working range of 0.5–6 Hz. Therefore, the displacement transmissibility amplitude ratio is expected to occur as given in Fig. 2 and



(a)



(b)

Fig. 4. Two different cases for the HEH system (a) Case-1 (b) Case-2.

remain on the left side of the resonance value ( $r = 1$ ). The effect of this situation on the energy harvest is examined experimentally in the next section.

#### 4. Experimental study

Experimental setup of the parallel beam HEH system is shown in Fig. 3. To measure the displacements of the beam element, two non-contact laser displacement sensors are used. A discrete Mosfet H-bridge driver is used for the electromagnetic device in actuator mode to drive the rotor at a specific frequency. A PWM signal generated by a host computer with dSpace 1104 hardware configuration. A two-channel oscilloscope is used for voltage measurements from the electromagnetic device and piezoelectric material. DuraAct P-876 piezoelectric patch transducer with electrical load resistance is attached to the beam element to convert the mechanical vibrations into electrical power. A custom-made electromagnetic device is used in the system in both actuator and harvester modes.

By changing the operating modes of identical electromagnetic devices in the system, the behavior of the electromagnetic energy harvesting element and the vibration characteristics of the actuator which is placed on the non-rigid ground has been investigated. Fig. 4 shows two different operating modes. As the first case in Fig. 4(a), while the electromagnetic device at the top is in energy harvesting mode (H1), the device at the bottom is used as the main beam vibration source (A). In Case-2, as shown in Fig. 4(b), the electromagnetic device at the top of the system is the source of vibration for the main beam (A), while the device at the bottom works in the energy harvesting mode (H1). In both cases, the piezoelectric element adhered to the main beam operates in energy harvest mode.

The main beam element vibrated at different frequencies between 0.5 Hz and 6 Hz with the electromagnetic device driven by different input frequencies produced on the dSpace system. With the vibration inputs in this frequency range, were repeated for both cases, the displacement data on the beam elements and the voltage data without an electrical load on the energy harvesting equipment were recorded. The displacement results on the beams and the voltage output values obtained from the electromagnetic and piezoelectric elements for Case-1 and Case-2 are shown in Figs. 5 and 6 respectively, for 0.5 Hz vibration frequency. From these given figures, Fig. 5 (a) and Fig. 6 (a) show the displacement results recorded by the laser displacement sensor over both beam elements. In the figures shown in Fig. 5 (b) and Fig. 6 (b), voltage values obtained from the electromagnetic harvester and piezoelectric harvester are given. For 0.5 Hz vibration frequency in Case-1, the RMS value of the voltage harvested in the electromagnetic device has measured as 0.3783 V, and in the piezoelectric material has measured as 25.521 V. These values have measured as 0.3764 V for the electromagnetic device and 23.285 V for the piezoelectric material in Case-2. Similarly, the displacement results on the beams and the voltage output values obtained from the electromagnetic and piezoelectric elements for Case-1 and Case-2 are shown in Figs. 7 and 8 respectively, for 6 Hz vibration frequency. For 6 Hz vibration frequency in Case-1, the RMS value of the voltage harvested in the electromagnetic device has measured as 2.2542 V, and in the piezoelectric material has measured as 24.718 V. These values have measured as 2.088 V for the electromagnetic device and 21.677 V for the piezoelectric material in Case-2. As shown in Figs. 6 and 8, it is seen that the electromagnetic actuator being on the upper side of the system, that is, a non-rigid ground connection causes a decrease in the obtained voltage values.

For comparison, the voltage variation obtained from energy harvesting devices in all frequency regions without any electrical load is shown in Fig. 9 for both cases. Fig. 9 (a) represents Case-1, Fig. 9 (b) represents Case-2, and the left axis of these figures shows the voltage range obtained from the piezoelectric material, while the right axis shows the voltage range obtained by the electromagnetic device.

Experimental results were also obtained with the selected electrical charges of various sizes for two different cases in all frequency regions. Resistors with values 1 m $\Omega$ , 820 k $\Omega$ , 68 k $\Omega$ , 6.8 k $\Omega$ , 1 k $\Omega$ , 680  $\Omega$ , 330  $\Omega$  and 4.7  $\Omega$  were used for the piezoelectric load ( $R_2(\Omega)$ ), in descending order. Similarly, the resistance elements with values 200  $\Omega$ , 150  $\Omega$ , 47  $\Omega$ , 33  $\Omega$ , and 10  $\Omega$  was used as the electrical loads for the electromagnetic device.

It is seen from Figs. 10 and 11 that, as the excitation frequency increases, the converted power is continuously increased. However, this increase is more pronounced in low resistance values ( $R_2 < 33\Omega$ ) for the electromagnetic device, while it is more pronounced around for the 20 k $\Omega$  value for the piezoelectric harvester.

As a result, it has been shown experimentally that the displacement transmissibility effect has an undeniable effect on energy harvesting systems. In a typical vibration system, the displacement transmissibility value depending on the frequency ratio between natural frequency of the system, and the frequency of the excitation source. In addition, this value is evaluated with the damping ratio of the system. It has been seen that the connection of the electromagnetic harvester to a non-rigid ground and the vibration caused by the displacement transmissibility on this ground affect the total energy harvested in the system relevant from the outcomes of the experimental studies.

#### 5. Conclusion

In this study, a novel hybrid energy harvesting system configured in a different structure is proposed. In the structure used in the study, two identical electromagnetic devices were used, one was operated in actuator mode and the other in harvester mode. These two electromagnetic devices are placed opposite to each other on the main beam element. While one of them has a rigid ground connection, the other is mounted on a secondary beam placed parallel to the main beam in the system. In this way, a non-rigid ground connection was provided for the second electromagnetic device and the effect of this situation on energy harvest was examined. As a result of the experiment obtained, it was seen that the amount of energy obtained was higher when the rigid ground connection was provided for the actuator mode of the electromagnetic device and the non-rigid ground connection was provided for the harvester mode of the electromagnetic device. It is seen that the non-rigid connection of the device that provides vibrations to the main beam causes displacement transmissibility.

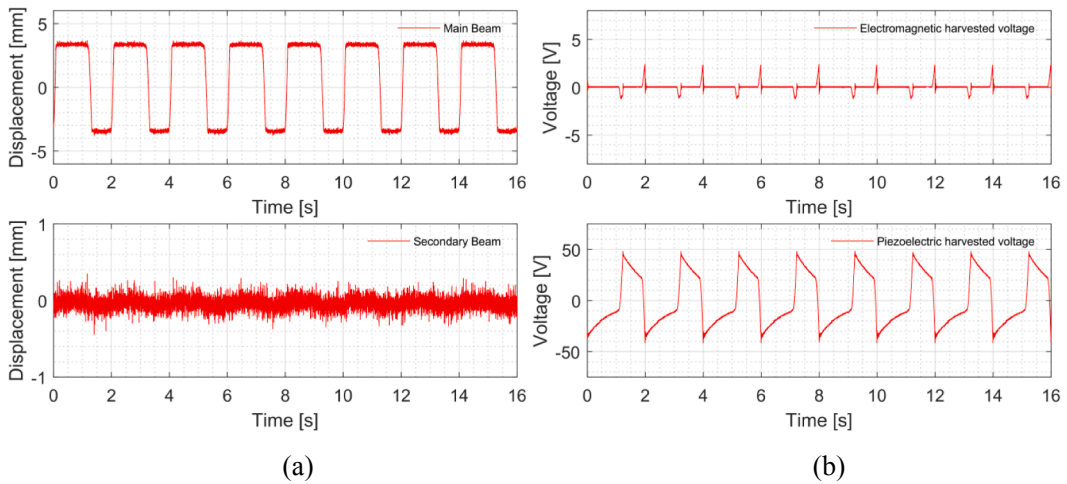


Fig. 5. Vibration at 0.5 Hz for Case-1 (a) Beam element displacements (b) Electromagnetic and piezoelectric voltage output.

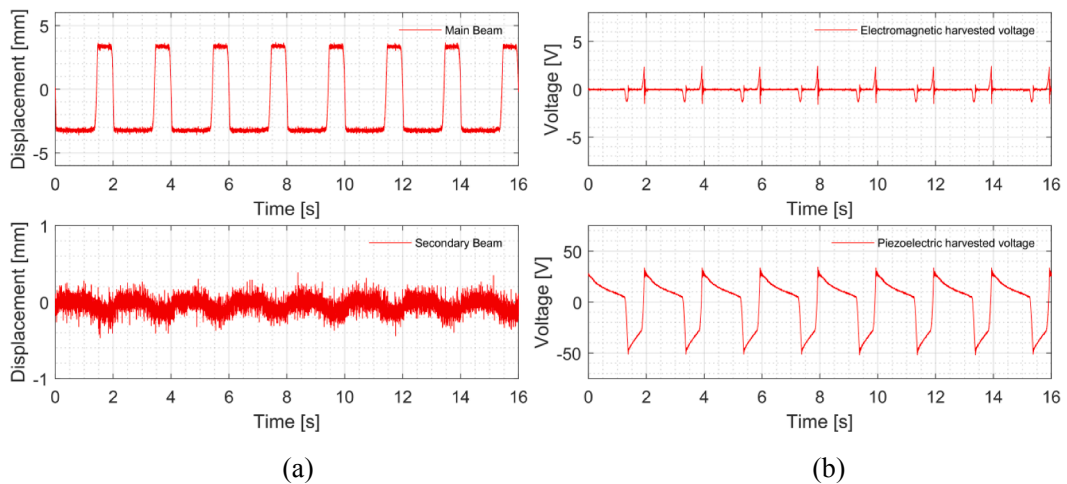


Fig. 6. Vibration at 0.5 Hz for Case-2 (a) Beam element displacements (b) Electromagnetic and piezoelectric voltage output.

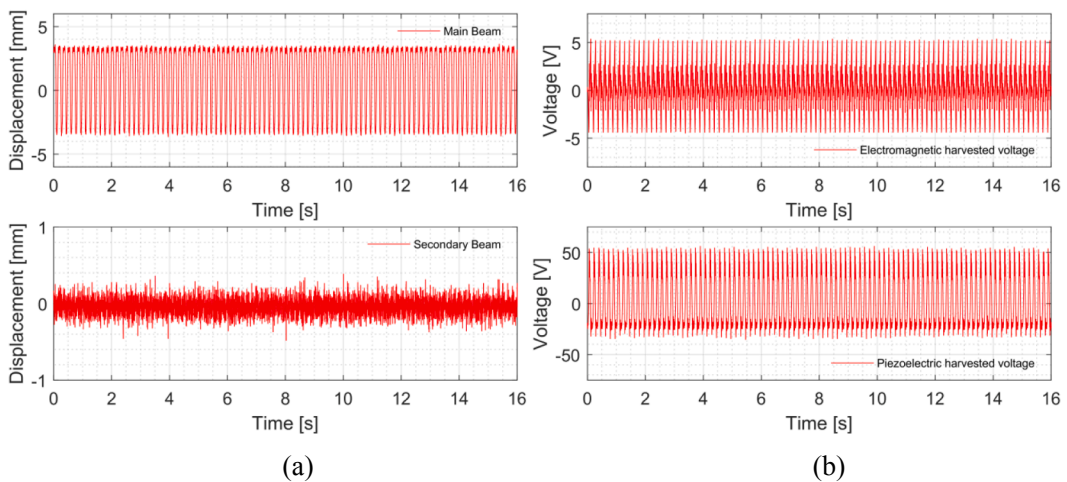


Fig. 7. Vibration at 6 Hz for Case-1 (a) Beam element displacements (b) Electromagnetic and piezoelectric voltage output.

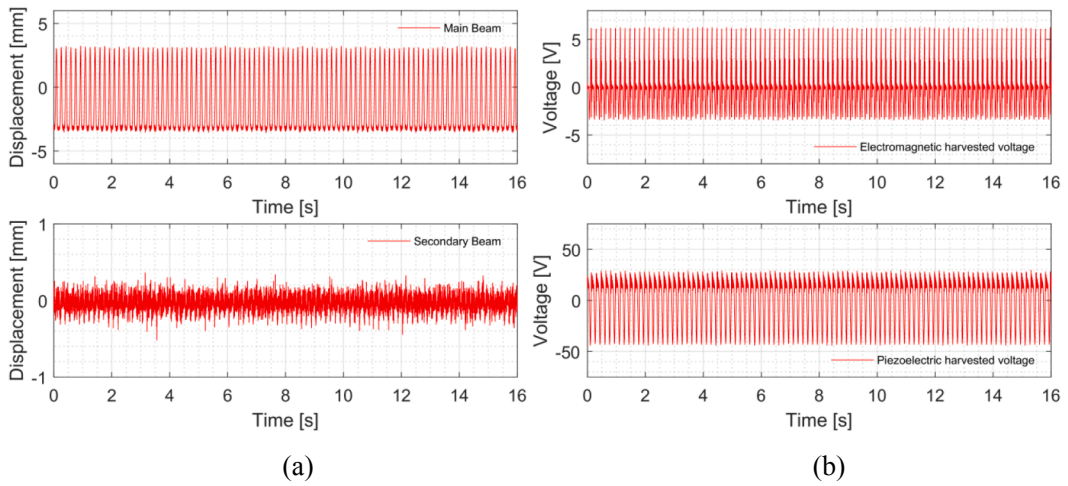


Fig. 8. Vibration at 6 Hz for Case-2 (a) Beam element displacements (b) Electromagnetic and piezoelectric voltage output.

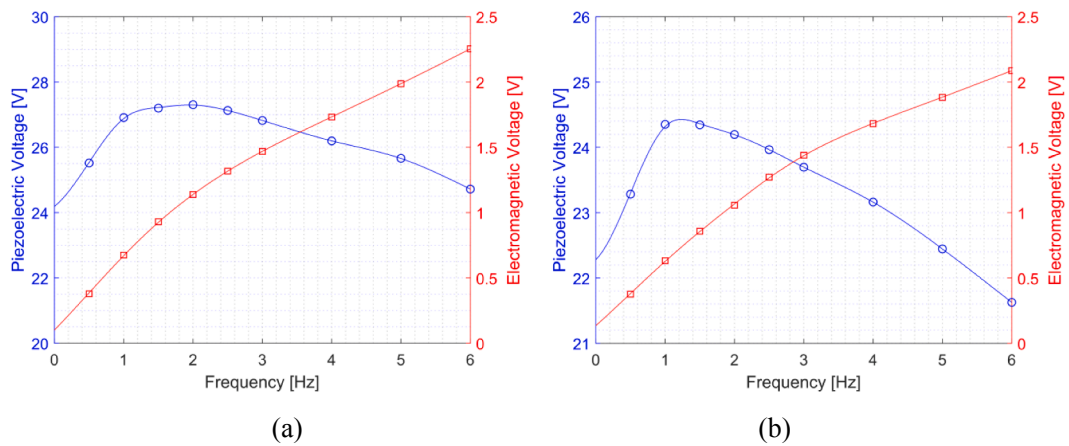


Fig. 9. The effect of vibration frequency on the piezoelectric and electromagnetic harvested voltage (a) Case-1 (b) Case-2.

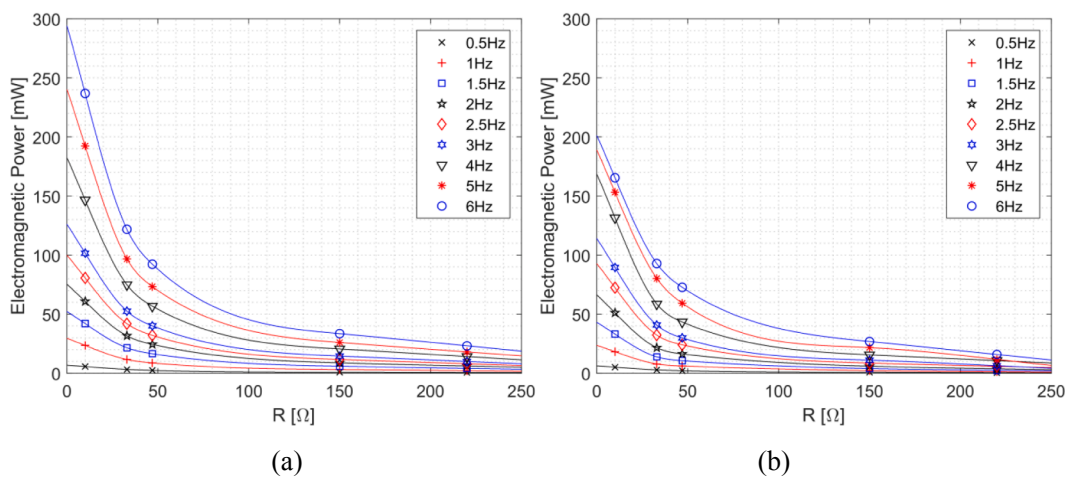


Fig. 10. The effect of vibration frequency on the electromagnetic harvested power variation for different electrical loads (a) Case-1 (b) Case-2.

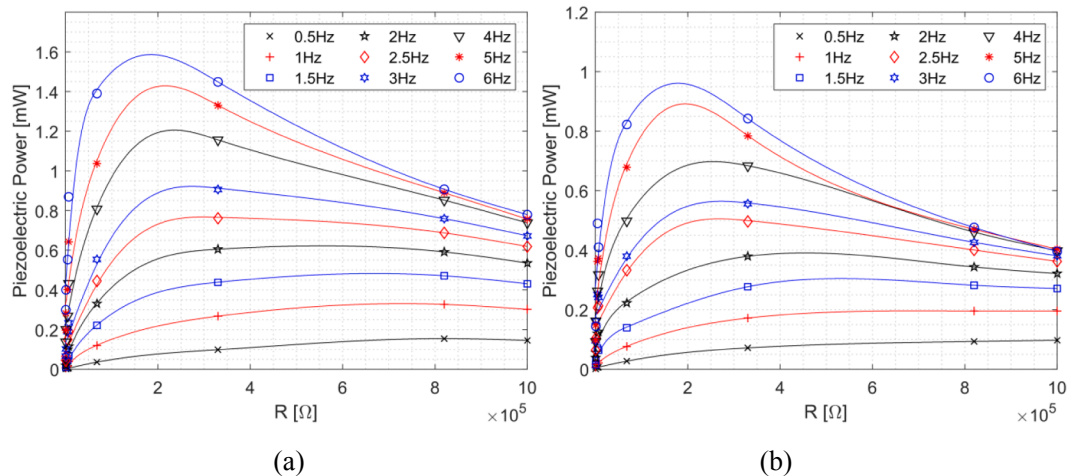


Fig. 11. The effect of vibration frequency on the piezoelectric harvested power variation for different electrical loads (a) Case-1 (b) Case-2.

### CRedit authorship contribution statement

**Sinan Basaran:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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