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Energy harvesting with magneto-mechano-electric harvester for AC circular magnetic fields

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ABSTRACT

As the industry on Internet of Things continues to expand, the demand for sustainable energy solutions to power numerous sensors and devices increases. One promising approach is energy harvesting from stray magnetic fields. In this paper, we investigated an energy harvesting with a magneto-mechano-electric (MME) energy harvester, designed for circular magnetic fields. Magnetic simulation using 3D finite element method yields optimum design for the operation at a frequency, 60 Hz. Under the influence of a 5.39 G AC circular magnetic field, the energy harvester successfully harvested energy at a frequency of 60 Hz, and operating with a maximum power of 1.92 mW and a power density of 25.2 mW/cm^3. Additionally, the performance has been enhanced by placing the magnetic flux concentrator parallel and even perpendicular to the piezoelectric sheet. This study underlines the necessity for further research on the structural design of MME harvesters in environments with various types of stray magnetic fields.

1. Introduction

The Internet of Things (IoT), which connects various household devices to mobile devices, and eventually links the entire city to the internet, is considered a core component of future industries [1–3]. As the importance of the IoT environment increases, there is increasing attention on research into establishing Wireless Sensor Networks (WSNs) to detect the status of each device. By establishing such networks, WSNs play a crucial role in building IoT environments, as they can easily monitor or predict the energy consumption and remaining capacity of numerous connected devices [4,5].

However, the extensive deployment of sensing environments requires enormous energy consumption. Sustainable energy harvesting offers a compelling solution by providing a self-replenishing power supply derived from wasted energy in our daily environment. This approach not only reduces pollution associated with battery disposal but also enhances the applicability and lifespan of devices. Energy harvesting is also crucial for the operation of devices in dangerous or inaccessible environments where regular maintenance is challenging [6–9]. In military applications, for example, energy harvesting can significantly extend the operational lifespan of monitoring equipment, unmanned robotic systems, and wearable devices. This reduces the logistical burden of battery supply and disposal [6,7,10–12]. Additionally, it enables the deployment of devices and robots in harsh environments where traditional power supply systems are impractical [13,14].

Among the diverse sources available for energy harvesting, ambient stray magnetic fields generated by currents through power cable receive attention for their accessibility [15–19]. The frequency of AC current in power cables varies based on national power standards. In North America, South America, and South Korea, the standard frequency is 60 Hz, while in Europe, Africa, China, Japan, India, and Russia, it is set at 50 Hz [20]. Consequently, harvesters designed to capture magnetic fields from power cables need to operate at the frequencies to be universally available [19,21,22]. Compared to inductive harvesters, magneto-mechano-electric (MME) energy harvesters offer several advantages, including a lightweight, compact, and straightforward design, with high energy conversion efficiency [23,24] for ac ambient magnetic field. MME harvesters utilize magnetic forces between permanent magnets and ambient AC stray magnetic fields to generate mechanical vibrations. These vibrations are subsequently converted into electrical energy through piezoelectric materials, making MME harvesters well-suited for a variety of applications [23–25].

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As the development of MME energy harvester advances, numerous designs aimed at higher energy harvesting efficiency have been introduced. Initially, the predominant design was the cantilever type, featuring a clamped end with a permanent magnet attached at the free end [23]. This design harnesses energy as the cantilever vibrates in response to specific frequencies of AC magnetic fields, with power being generated via the piezoelectric material affixed to the cantilever beam. Subsequent research has led to innovative structural modifications aimed at improving efficiency, including the distributed-mass type [25], fork type [26,27], clamped-clamped type [28], and dragonfly-wing type [29]. The summary of the MME harvesters using various designs are shown in Table 1.

As indicated in Table 1, recent studies have successfully generated substantial power from low-frequency and low-strength stray magnetic fields by modifying structural designs [28–33]. However, the majority of research have focused on harvesting energy from unidirectional magnetic fields that align parallel to the harvester. This method can impose serious limitation in the application, where the magnetic stray field is not unidirectional. For example, circular magnetic fields, typically generated by currents flowing through power cables, are not suitable for existing structure. 22.9 kV power lines typically have a diameter of around 20 mm, which can limit the size of energy harvesters. In addition, the amplitude of the circular magnetic field decreases significantly with increasing distance from the cable core. An MME energy harvester tailored for circular magnetic fields would be highly beneficial in applications such as powering devices in the miniatured military drones (as illustrated in Fig. 1) or IoT sensor systems near power poles. Recent research has developed a T-shaped MME harvester that can operate under magnetic fields in the x, y, and z directions simultaneously [30]. However, there is still limited study on harvesting energy from circular stray fields.

In this study, we designed a center-clamped MME harvester system, which has magnetic masses attached on the end of piezoelectric circular plate along diameter. Significantly high voltage and power was successfully harvested from a circular magnetic field at a specific frequency.

2. Experimental details

Fig. 2(a) depicts the structure of energy harvesting part of energy harvester, consisting of three layers: a base electrode at the bottom (20 mm in radius and 0.4 mm in thickness), a silver electrode at the top (11 mm in radius and 0.2 mm in thickness), and a piezo ceramic at the middle. The permanent magnetic masses are attached at the ends of base electrode along diameter. The harvesting part is clamped in a holder and the holder is assembled with multi-turn coil, as shown in Fig. 2(b). The multi-turn coil produces AC circular magnetic field with a frequency of 60 Hz, induces vibration of the permanent magnets and, as a result, generates electric power through MME conversion. Fig. 2(c) shows the image of a fabricated MME energy harvester. The system holder is fabricated with nonmagnetic poly lactic acid (PLA), stainless steel bolts, and copper electrodes for collecting voltage.

Table 1
Overview of the operating conditions and performance of MME harvesters with various structural designs.

Reference	Piezoelectric	Frequency (Hz)	Magnetic Field (G)	RMS Power (mW)	Power Density (mW/cm^3)
28	PZT-5H	50	0.96	0.97	15.06
29	PZT-5H	50.5	3	25.89	74.81
30	PZT-5H	60	1.75	12.3	73.21
31	PMN-PZT	60	10	2.4	62.56
32	PZT-5H	60	0.8	99	6.86/(4*t)
33	PMN-PZT	60	10	0.38	7.8

3. Results and discussion

As the frequency for transmitting power is set at a specific value, e.g. 50 or 60 Hz, it is necessary to find out the harvester's eigenmodes, corresponding to the eigenfrequency. We performed 3D FEM simulation to design the MME harvester to achieve maximum mechanical vibration at specific frequencies. The mechanical resonance frequency is closely related to the parameters, such as density, Young's modulus, and Poisson's ratio, as shown in Table 2. Fig. 3(a) represents a simulation on the relative displacement of the magnet's center on an exponential scale, with various magnet masses, which shows the accessible eigenfrequencies in a range from 25 Hz to 115 Hz. When the magnet mass changes from 3.75 g to 13.13 g, the eigenfrequency is shifted from 100 Hz to 47 Hz. This confirms that a lighter mass induces a higher mechanical resonance frequency in our system. It is found that stress on the rigid piezoelectric ceramics is primarily concentrated at the edges at a resonance frequency of 60 Hz, as shown in Fig. 3(b). When the frequency deviates slightly from the resonance frequency, the stress is significantly released, resulting in the significant reduction of piezoelectric response.

An eigenfrequency of approximately 60 Hz is achieved by positioning 9.38 g magnets at the ends of the electrode, as specified in the parameters shown in Table 2. Fig. 4 illustrates the displacement of harvester in first, second, and third eigenmodes at the corresponding frequencies. The significant frequency gap between the first mode (59.6 Hz) and the second (681.8 Hz) or third (1.053 kHz) modes allows us to focus on optimizing the first eigenmode for the target frequencies of 60 Hz by setting the magnet's mass and position as above. Thus, the MME system in this study is found to be well designed to operate at the specific frequencies, required to environments.

Based upon the simulation results, we selected magnets with a mass of 8.44 g, achieving a mechanical resonance frequency of around 60 Hz. The discrepancy with the simulation is attributed to slight variations in the magnet's magnetization. Subsequently, the resonance frequency at 60 Hz was verified again through experimental measurements. Voltage generation was demonstrated using a MME energy harvester, working in an eigenmode with a frequency of 60 Hz under unidirectional AC field along the x-axis, as shown in Fig. 5(a). For both magnets magnetized parallel along the (+) z-axis, as shown in Fig. 5(b), the magnetic field induced counterclockwise rotational torque and stress on the piezoelectric plate. This causes the piezoelectric plate to be concave up for one side and down for the other side, and vice versa, with a period of 1/60 seconds. Asymmetric stresses on either side of the piezoelectric plate lead to a neutralization of the generated charges, and only negligible voltage is observed, as depicted in the data (black squares) in Fig. 5(d). On the other hand, for the magnets, magnetized antiparallel along the z-axis, as shown in Fig. 5(c), the magnetic field induces the bending to be concave up or down on both sides of the plates in a periodic time. So, significant AC voltage was observed with the same frequency of 60 Hz, as depicted with the data (red circles) in Fig. 5(d). The resulting root-mean-square voltage (V_{rms}) was presented in Fig. 5(e) as function of the applied field. V_{rms} values increase gradually from 6.04 V to 28.6 V as the field strength increases from 0.21 G to 2.05 G. These results underline the importance of magnetic configuration (antiparallel magnetizations) for efficient energy harvesting in our MME energy harvester under the parallel magnetic field [29]. The output voltage was saturated by the polarization limit of the dipoles in piezoelectric materials, even the bending stress is continuously increased by the external stress [28, 34].

To investigate energy harvesting from a circular magnetic field around a power cable, we positioned the MME energy harvester directly above the multi-turn coil, as shown in Fig. 6(a), which resembles the energy harvesting condition in a circular magnetic field. Fig. 6(b) represents the magnetic field lines produced by the multi-turn coil. The field lines near the magnetic masses are observed to align not solely along the x-axis but instead along the x- and z-directions as multi-components,

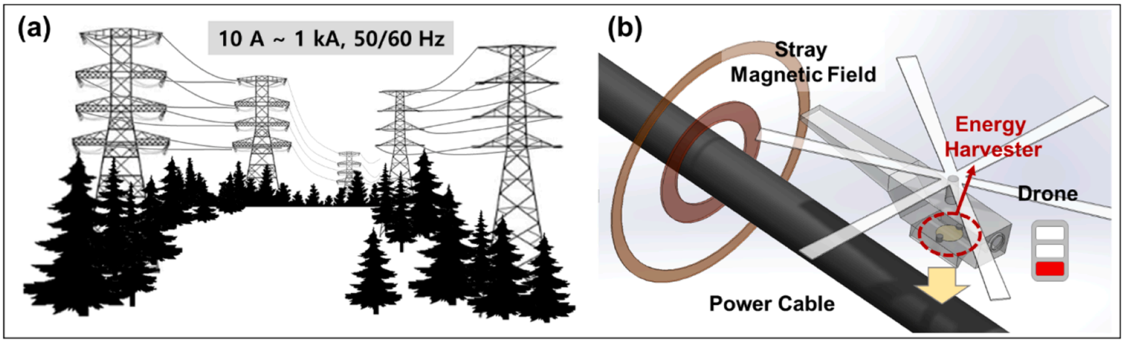

Fig. 1. (a) Illustration of utility power poles and cables under typical operating conditions (b) Potential application of MME harvesters for circular magnetic fields in military drones.

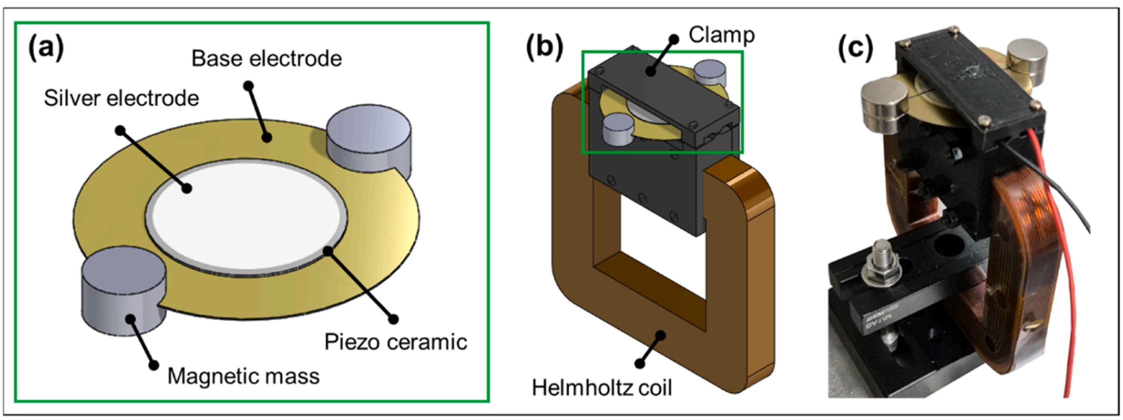

Fig. 2. (a) Structure of energy harvesting part, consisting of piezoelectric plate between base and silver electrodes and magnetic masses on each side of base electrode. (b) Schematic diagram (b) and its picture (c) of the center-clamped energy harvester assembled with the multi-turn coil generating circular AC magnetic field.

Table 2
The key parameters of the FEM 3D simulations for eigenmode of the harvester.

Part	Density (kg/ m^3)	Young's Modulus (GPa)	Poisson's ratio
Base electrode	8960	130	0.34
Piezo ceramic [35]	7500	63	0.3
Magnet Mass /each side	6218	160	0.24

depending on their position relative to the top of the multi-turn coil. The angle of the magnetic field applied to the center of the magnet was 45.6°, which is almost same as the angle in the circular field (46.4°), This indicates that the environment is nearly identical to the circular magnetic field generated by the wire. In this field condition, harvesting voltage was successfully observed. The V_{rms} value increases as the field increases (Fig. 6(c)) and reaches a maximum value at a frequency of 60 Hz, exhibiting a 3 dB bandwidth of 1.88 Hz (Fig. 6(d)). This indicates that the MME energy harvesting system in this study is optimized for energy harvesting from circular magnetic fields at a 60 Hz frequency, similar to the system in a unidirectional magnetic field. The x-component of the magnetic field induces a torque on the magnet aligned along the z-axis, serving as the main source of vibration. This behavior was corroborated by observing that the V_{rms} graph exhibited a consistent pattern under both parallel magnetic field condition and circular magnetic field condition. Theoretically, a perpendicular magnetic field ($\overrightarrow{B}$) to the magnetization of the magnet ($\overrightarrow{M}$) is required to produce the maximum torque ($\overrightarrow{\tau} = \overrightarrow{M} \times \overrightarrow{B}$). However, the optimal position of the MME energy harvester within a circular magnetic field can be limited. In this work, the MME energy harvester is positioned where the magnetization of permanent magnet and the incident field align at approximately 45°. To achieve the study's goal of harvesting ambient circular magnetic fields from power lines, the MME energy harvester was designed with a smaller size and a first resonance mode at 60 Hz.

To evaluate the power harvested by the MME, a diode bridge rectifier circuit was employed [29,32], as shown in Fig. 7(a). The average power (P_{avg}) was calculated as $P_{avg} = {V_{rms}}^2/R_L$, where R_L represents the load resistance connected to the rectifier. The V_{rms} and P_{avg}, shown in Fig. 7 (b) and (c) respectively, were plotted as a function of the load resistance under the indicated fields. With an AC circular magnetic field of 5.39 G, V_{rms} value increases as R_L increases and levels off, yielding a saturation voltage of ≈ 28.4 V. The calculated P_{avg} was found to have a maximum power of 1.92 mW near $R_L = 70$ kΩ. The corresponding average power density was calculated to be 25.2 mW/cm^3, by dividing the average power with the volume of piezoelectric component. The performance of MME harvester in this study highlights its potential for harvesting energy from both linear and circular AC magnetic fields.

To enhance the harvesting efficiency, a magnetic flux concentrator (MFC) was fabricated with a parallelepiped shape ($16 \times 40 \times 0.7$ mm^3) of $Ni_{80}Fe_{20}$ alloy, which has a high magnetic permeability (0.12 H/m). First, MFC was placed to be parallel to the piezoelectric sheet and at a distance, d_{mfc}, from the magnets edge, as shown in Fig. 8 (a). Fig. 8(c) represents the average power and power density as a function of road resistance at $d_{mfc} = 6, \quad 8,$ and10mm. The power is achieved to be 0.55, 2.04, and 2.31 mW for $d_{mfc} = 6, \quad 8,$ and10mm, respectively, resulting in an enhanced harvesting efficiency by 20.2 % for $d_{mfc} = 10$mm, compared to the value of no MFC system. The MFC concentrates the magnetic flux, especially along the x-axis, and then

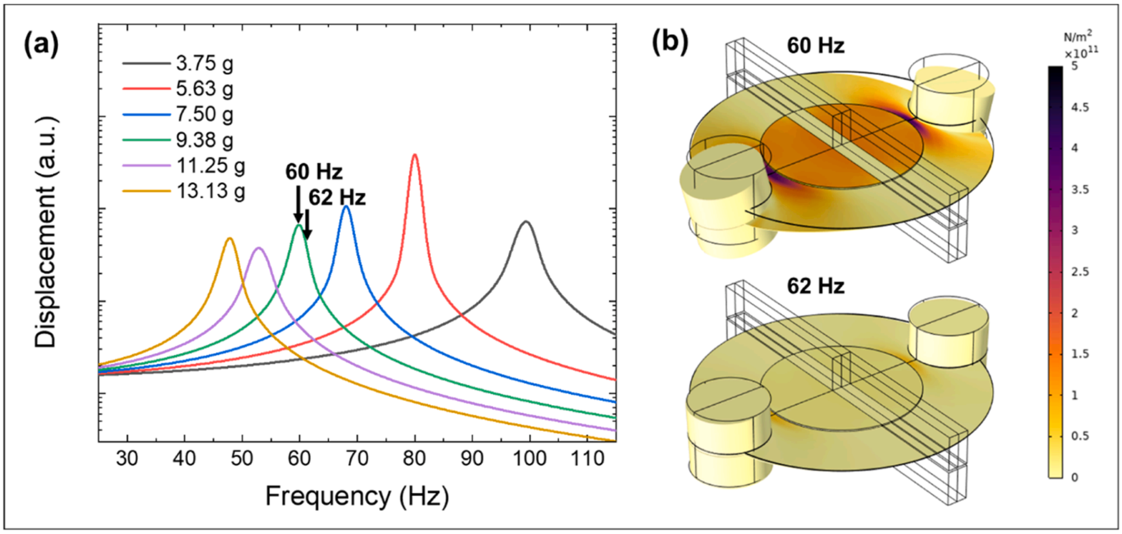

Fig. 3. (a) Displacement of the end of base electrode with various masses of magnet as a function of frequency, representing the resonance frequencies depending upon masses, (b) Stress profiles on the base electrode and piezoelectric ceramic plates at frequencies of 60 Hz and 62 Hz, with the magnet mass of 9.38 g.

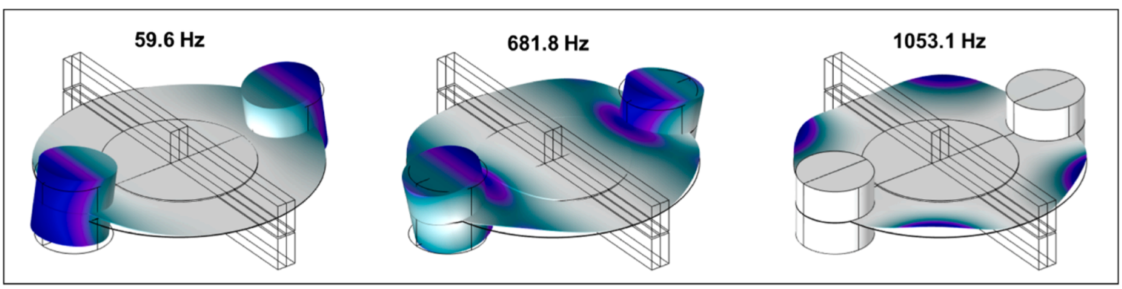

Fig. 4. The harvester in first (left), second (center), and third (right) eigenmodes and corresponding frequencies of the MME harvester are shown, with the color representing the normalized displacement.

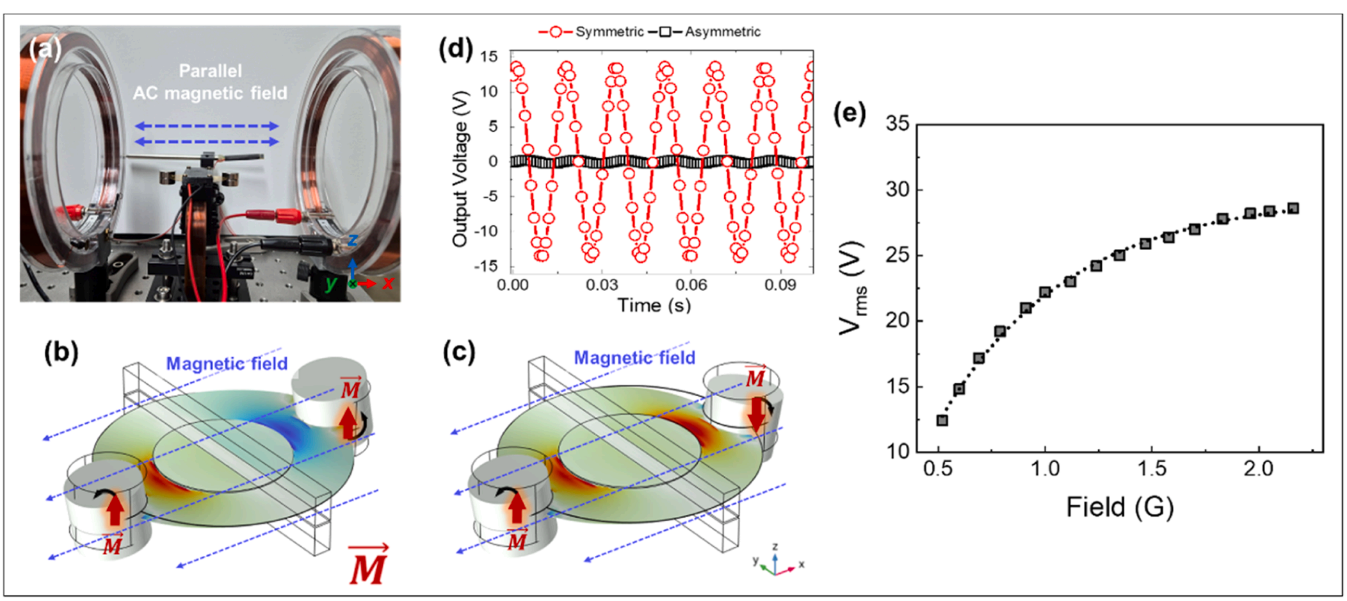

Fig. 5. (a) Experimental setup for the harvester under magnetic field along the *x*-direction. (b) Schematic illustration of magnetic torque and stress profile when the magnets are aligned parallel along the + *z*-axis under uniform external field along the *x*-axis. (c) The same illustration as (b) when the magnets are aligned anti-parallel. (d) Time-dependent output voltage: black and red symbols for magnetic configuration in (b) and (c), respectively. (e) Output root mean square voltage, V_{rms}, as a function of magnetic field.

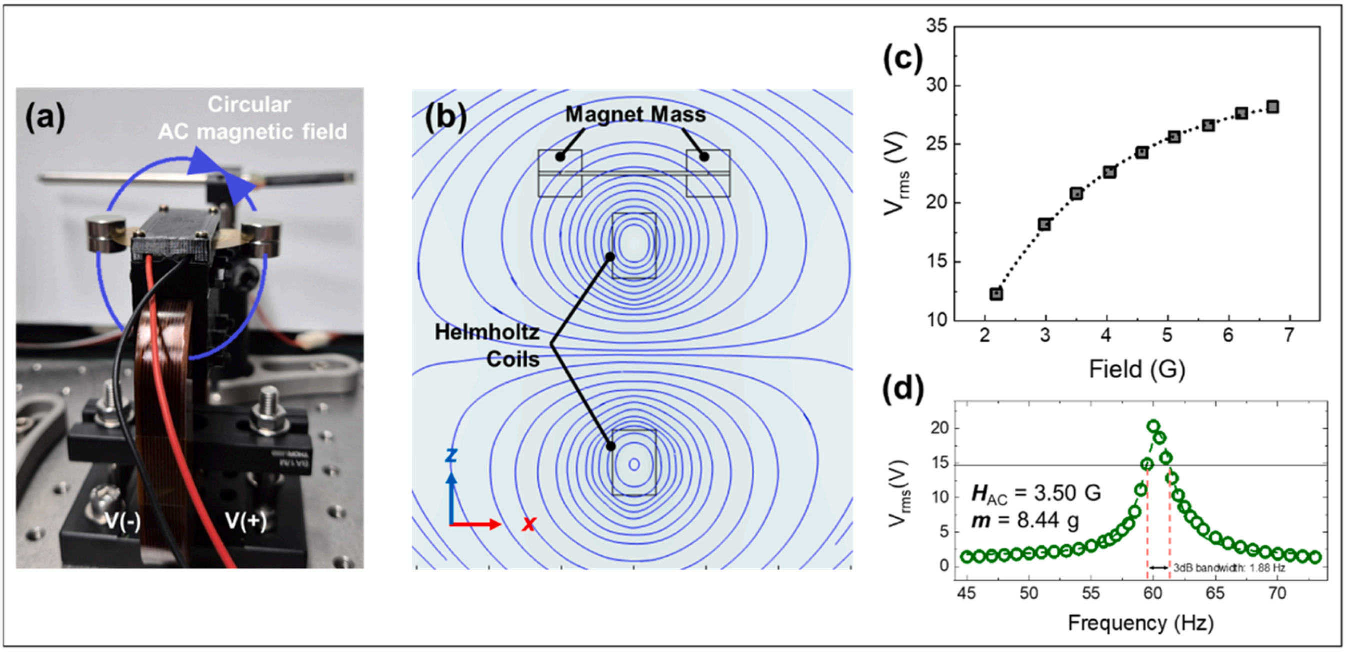

Fig. 6. (a) Experimental setup for the MME harvester under circular AC magnetic field. (b) Magnetic field distribution produced by the multi-turn coil. (c) Output root mean square voltage, $\boldsymbol{V}_{\mathbf{rms}}$, as a function of magnetic field. (d) Output $\boldsymbol{V}_{\mathbf{rms}}$ under an AC circular field of 3.50 G as a function of frequency.

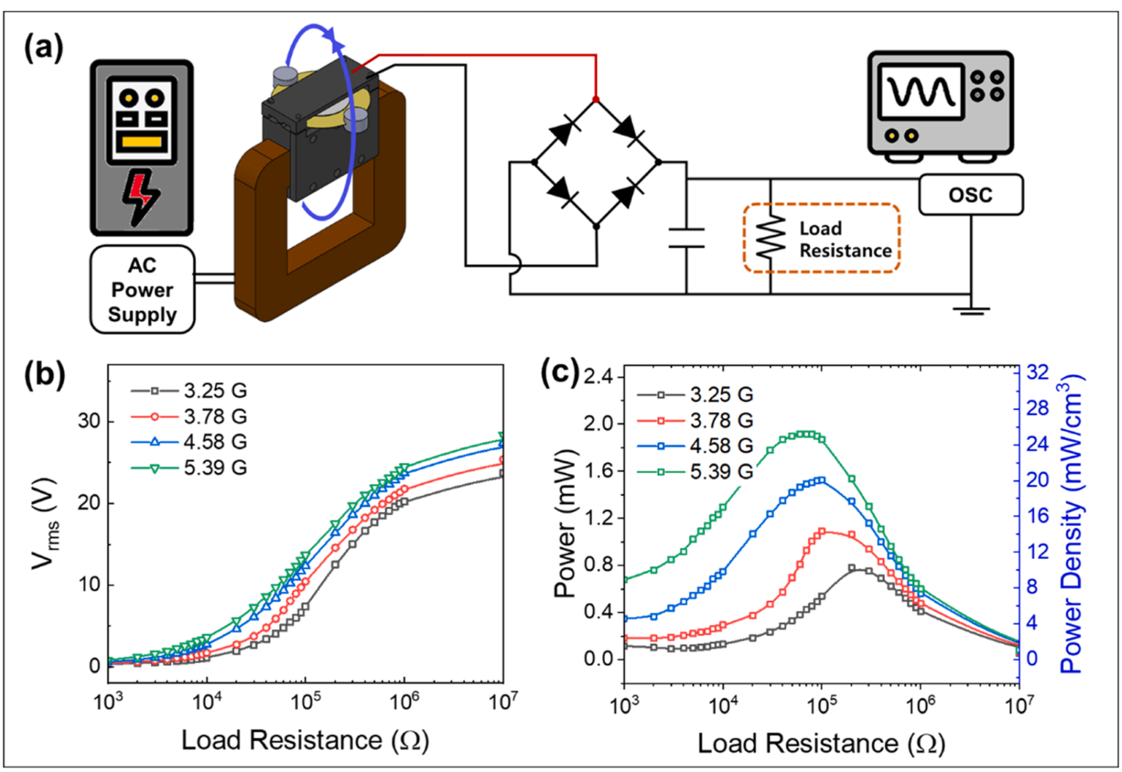

Fig. 7. (a) Schematic diagram of electrical circuit of a diode bridge rectifier for the measurement of output power. (b) Measured output root mean square voltage, $\boldsymbol{V}_{\mathbf{rms}}$, under various fields as a function of load resistance. (c) Calculated average power and power density as a function of load resistance.

increases the net field on the magnets, as depicted in Fig. 8(e). The field at the magnet was observed to be raised up by 17.3 % along the *x*-axis, compared to that without MFC. Therefore, the MFC can amplify the vibration amplitude of the magnets and harvested energy. Next, the MFC was placed to be perpendicular to the piezoelectric sheet below the magnet at a distance of 10 mm, as shown in Fig. 8(b). Fig. 8(d) represents the average power and power density as a function of road resistance. The power increases to be 2.26 mW, resulting in an enhanced harvesting efficiency by 17.7 %, compared to the value of no MFC system. The modified field distribution by the perpendicular MFC was plotted in Fig. 8(f). The field at the center of magnet was observed to be raised up by 12.4 % along the *x*-axis, compared to that without MFC.

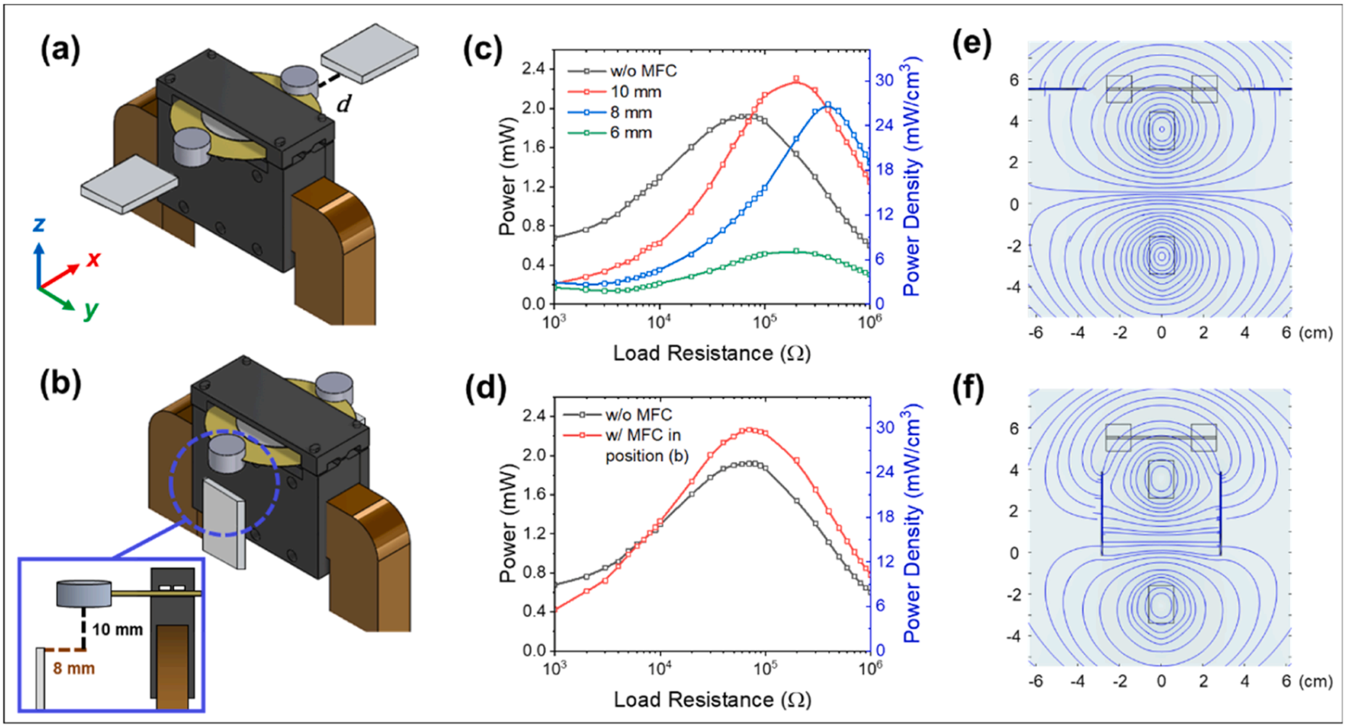

Fig. 8. Schematic diagram of energy harvester with magnetic field collector plates, parallel (a) and perpendicular (b) to electrode plate. Average power of harvesting voltage as a function of load resistance of energy harvester with MFCs in parallel position with different *d* and (d) perpendicular position to piezoelectric sheet with 5.39 G of circular field. (e) Simulation of magnetic field distribution with MFCs in parallel and (f) perpendicular position.

Although the MFC is expected to concentrate the field mainly along the *z*-axis, there is still field-up effect even along the *x*-axis at the center of magnet. Therefore, we observed significant harvesting efficiency enhancement with MFC even perpendicular to the harvesting plate in a circular field.

4. Conclusion

We have investigated energy harvesting capability of the MME harvester, designed to be optimized for continuous symmetric vibrations under circular AC magnetic field. The MME energy harvester comprises a single piezoelectric plate with magnetic masses positioned at both ends. By orienting the magnets in opposite directions and exposing them to AC magnetic fields in either parallel or circular directions, we achieved symmetric bending motions of the piezoelectric plate, which maximizes energy harvesting efficiency. We achieved an average power density of 25.2 mW/cm^3 under a circular AC magnetic field of 5.39 G, which is comparable to previous reports, conducted in uniaxial AC magnetic fields. This amplitude of magnetic field is commonly observed around typical 22.9 kV power cables when carrying a current of approximately 50 A. The energy harvesting efficiency was enhanced by 20.2 % and 17.7 % by using MFC plate, aligned parallel and perpendicular to the piezoelectric plate, respectively, compared to that of harvester with no MFC integration.

These promising results are achieved using accessible and cost-effective materials, highlighting the potential of energy harvesting from AC circular magnetic fields around power cables for various applications, such as military drones or IoT sensors, enabling wireless sensing and sustainable operations.

Author contributions

S. Y., B.K.C. and D.S. conceived the project idea and planned the experiment. D.S. and S. Y. fabricated samples and performed the analytical calculation. D.S. and B.K. performed the measurement. D.S., M. H., S.Y., and B.K.C. analyzed the data. S. Y. and B.K.C. led the work and wrote the manuscript with D.S. All authors discussed the results and commented on the manuscript.

CRediT authorship contribution statement

Seo Dongpyo: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kim Byungro:** Software, Methodology, Investigation. **Cho B.K.:** Writing – review & editing, Writing – original draft, Visualization, Validation, Funding acquisition. **Ha Minjeong:** Writing – original draft, Visualization, Validation, Investigation, Conceptualization. **Han S.H.:** Visualization, Validation, Methodology, Investigation. **Yoon Seungha:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization.

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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Data availability

No data was used for the research described in the article.

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