Experimental investigation of optimal damping ratio for magnetostrictive energy harvester under free vibration

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ABSTRACT

The energy-harvesting efficiency of a magnetostrictive energy harvester feeding a load with a resistive input impedance is described with four non-dimensional parameters: electromagnetic-mechanical spring constant ratio, primary damping ratio, coil damping ratio, and damping ratio of input resistance. Among the parameters, the damping ratio of input resistance has an optimal value while the energy-harvesting efficiency becomes high as the electromagnetic-mechanical spring constant ratio increases or as the primary damping ratio or the coil damping ratio decreases. This paper presents experimental investigation methods to find and validate the optimal damping ratio of a magnetostrictive energy harvester under free vibration. It was found that the unimorph magnetostrictive energy harvester investigated in this study can harvest 10.1% of given mechanical energy with the optimally tuned damping ratio of input resistance.

Keywords: Efficiency maximization, Energy harvesting, Free vibration, Magnetostriction, Optimal damping ratio

1. INTRODUCTION

Energy harvesting is a method that captures ambient energy from the environment and converts it into usable electrical power. For energy harvesting, possible energy sources are mainly solar radiation, heat, electromagnetic waves and mechanical motion. Mechanical vibration belongs to kinetic energy and since it is the most ubiquitous energy in the environment, vibration energy harvesting has increased research interest in recent decades in line with the development of Internet of Things.[1–4] For the conversion from kinetic energy into electrical energy, electromagnetic induction, piezoelectric effect, or electrostatic induction is used.[1,5,6]

Magnetostriction is a phenomenon in which the magnetic flux inside a magnetostrictive material varies depending on the internal mechanical stress. Voltage is induced in the pickup coil wrapped around the magnetostrictive material, and thus magnetostrictive energy harvesting is categorized to an energy harvesting using electromagnetic induction. Fe-Ga alloys are materials with large magnetostriction. Since their machinability and environmental durability are much superior to piezoelectric material,[7,8] Fe-Ga alloys are often used as transducers of vibration energy harvesters.

Unlike solar or thermal energy harvesting, vibration energy harvesting produces AC voltage which needs to be rectified and fed to a DC-DC converter to be converted to appropriate voltage for storage. These procedures are generally integrated into a power management integrated circuit (PMIC), and several PMICs for vibration energy harvesting are currently commercially available. Jung et al.[9] used LTC3588-1 from Analog Devices for power management of a piezoelectric wind energy harvester. In the PMIC, the voltage from a vibration energy harvester is rectified with a full-bridge rectifier. The efficiencies of the piezoelectric energy harvester and the PMIC were 26.1% and 35.7%, respectively. Since the voltage drop and resulting power loss in the rectifier diodes are critical problems in low-voltage electronics, Magno et al.[10] developed the AC-DC converter by using MOSFETs in parallel with Schottky diodes. The developed AC-DC converter was coupled with Texas

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Instruments BQ25570 which is a commercially available PMIC generally for DC-output energy harvesters. With the energy harvesting system consisting of a commercially available electromagnetic energy harvester Kinetron MSG 26.4, the developed AC-DC converter, and the BQ25570, they experimentally investigated optimal input resistance and input capacitance, and they achieved 84% of efficiency in the power management under a single free vibration of the electromagnetic energy harvester.

Investigations to identify the optimal input impedance of vibration energy harvesting systems have been conducted in several studies. Kong et al.[11] investigated the optimal input resistance and input inductance for a piezoelectric energy harvester excited by harmonic vibration. The output power of the piezoelectric energy harvester was maximized based on impedance matching. Liu et al.[12] derived the optimal parameters for an electromagnetic energy-harvesting tuned-mass-damper based on H_2 criteria to minimize the root-mean-square (RMS) values of the vibration amplitude of the primary structure or maximize the RMS of the harvestable power. In a previous study,[13] we derived the optimal input resistance and input capacitance of a magnetostrictive energy harvester based on impedance matching.

However, in many situations, energy harvesters are not subject to harmonic mechanical inputs, but mechanical impacts. Moreover, even under harmonic oscillations, there have been many studies on energy harvesting with frequency up-conversion in which harmonic mechanical inputs are converted to continuous mechanical impacts.[14–16] There is also a commercially available energy harvester in which mechanical vibration energy is stored as strain energy of a spring by a mechanical rectifier, and once the spring reaches its critical torque, it unwinds and derives the rotor of the harvester.[10] In the aforementioned scenarios, energy harvesters need to be optimized based on the energy obtained during free vibration. While there are several experimental studies on the harvestable energy during free vibration,[10,17] there are hardly any studies with a thorough analytical investigation, only to the extent that we have proposed the energy-harvesting efficiency maximization method for energy harvesters under free vibration.[18] The study revealed that the physical property of the harvester is completely described with four non-dimensional parameters and derived the analytically exact optimal damping ratio which is the non-dimensional design parameter corresponding to the optimal input resistance of the harvester.

The difficulty of the previously proposed analytical optimization method is the complex derivation of generalized mass, generalized spring constant, generalized reluctance, and generalized magneto-mechanical coupling coefficient, and the precise identification of the material parameters such as permeability, Young's modulus, and magnetostrictive constant of the magnetostrictive material. Measurements of those parameters require huge and expensive experimental equipment.[19–22] For those reasons, this paper presents the optimization method for magnetostrictive energy harvesters which does not involve the derivation of the generalized quantities nor the measurement of material parameters by directly identifying the non-dimensional parameters through experiments. The optimal damping ratio is obtained and validated through the measurement of energy-harvesting efficiency.

2. HARVESTABLE ENERGY AND OPTIMAL DAMPING RATIO DERIVED FROM ANALYSIS

This study investigates a unimorph magnetostrictive energy harvester shown in Figure 1. The harvester consists of a cantilever comprising a 1.0 × 6.0 × 60 mm Fe-Ga strip and an equally sized aluminum strip, laminated together by superglue. An enameled copper coil with a diameter of 0.10 mm is wound around a plastic bobbin with a thickness of 1.0 mm. The number of turns in the coil and the resistance of the coil are 2000 and 141.6 Ω, respectively. A 10 mm cubic NdFeB magnet is positioned 6 mm from the free end of the cantilever. A 6.0 mm cubic NdFeB magnet is attached to the fixed end of the cantilever and clamped together with the cantilever by a vise.

This kind of single-degree-of-freedom magnetostrictive energy harvester is represented as an equivalent mechanical model shown in Figure 2. In the equivalent mechanical system, m is the generalized mass of the harvester. k is the generalized spring constant stemming from the mechanical elasticity and $-\frac{\theta^2}{\mathcal{R}}$, where θ and $\mathcal{R}$ are, respectively, the generalized magneto-mechanical coupling coefficient and generalized reluctance, stems from the megnetoelasticity. c is the primary damping coefficient. N, L, R_{coil}, and R are the number of turns in

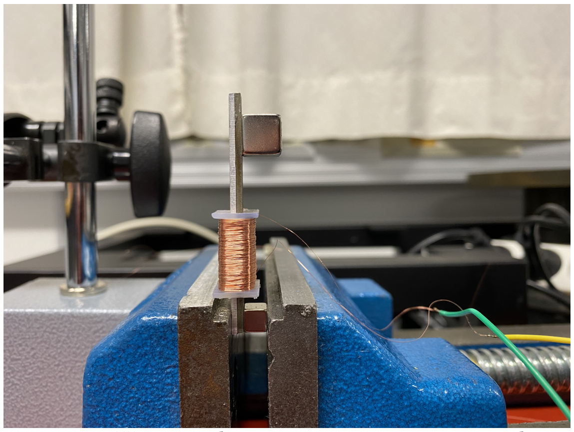


Figure 1: Unimorph magnetostrictive energy harvester

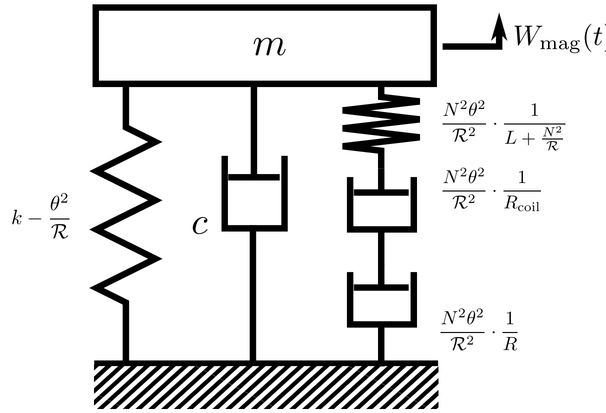


Figure 2: Equivalent mechanical model

the coil, inductance attributable to other than the coil, coil resistance, and input resistance, respectively. The displacement of the equivalent mechanical system is normalized to be the displacement W_{mag} at the tip magnet. In the previous work,[18] we derived the energy-harvesting efficiency under free vibration by integrating the output power P with respect to time t and dividing by the initially given mechanical energy:

$$\begin{aligned}
E_{\mathrm{K}} &= \left.\frac{\displaystyle\int_0^\infty P\mathrm{d}t}{\frac{1}{2}m\dot{W}_{\mathrm{mag}}^2(t)+\frac{1}{2}\left(k-\frac{\theta^2}{\mathcal{R}}\right)W_{\mathrm{mag}}^2(t)}\right|_{W_{\mathrm{mag}}(0)=0} \\
&= \frac{\kappa\zeta_2}{4\zeta_1^2\zeta_2+4\zeta_1^2\zeta_{\mathrm{coil}}+4\zeta_1\zeta_2^2+8\zeta_1\zeta_{\mathrm{coil}}\zeta_2+4\zeta_1\zeta_{\mathrm{coil}}^2+\kappa\zeta_1+\kappa\zeta_2+\kappa\zeta_{\mathrm{coil}}+\zeta_1} \\
E_{\mathrm{U}} &= \left.\frac{\displaystyle\int_0^\infty P\mathrm{d}t}{\frac{1}{2}m\dot{W}_{\mathrm{mag}}^2(t)+\frac{1}{2}\left(k-\frac{\theta^2}{\mathcal{R}}\right)W_{\mathrm{mag}}^2(t)}\right|_{\dot{W}_{\mathrm{mag}}(0)=0} \\
&= \frac{\kappa\zeta_2\left(\zeta_1+\zeta_{\mathrm{coil}}+\zeta_2\right)}{\left(4\zeta_1^2\zeta_2+4\zeta_1^2\zeta_{\mathrm{coil}}+4\zeta_1\zeta_2^2+8\zeta_1\zeta_{\mathrm{coil}}\zeta_2+4\zeta_1\zeta_{\mathrm{coil}}^2+\kappa\zeta_1+\kappa\zeta_2+\kappa\zeta_{\mathrm{coil}}+\zeta_1\right)\left(\zeta_{\mathrm{coil}}+\zeta_2\right)}
\end{aligned} \tag{1}$$

where E_{U} and E_{K} are the energy harvesting efficiencies to potential energy input and kinetic energy input, respectively. The four non-dimensional parameters in Eqs. (1) are defined as follows:

$$\begin{aligned}
&\text{Electromagnetic-mechanical spring constant ratio: } \kappa = \frac{N^2\theta^2}{\mathcal{R}^2\left(k-\frac{\theta^2}{\mathcal{R}}\right)\left(L+\frac{N^2}{\mathcal{R}}\right)} \\
&\text{Primary damping ratio: } \zeta_1 = \frac{c}{2m\omega} \\
&\text{Damping ratio of coil resistance: } \zeta_{\mathrm{coil}} = \frac{R_{\mathrm{coil}}}{2\left(L+\frac{N^2}{\mathcal{R}}\right)\omega} \\
&\text{Damping ratio of input resistance: } \zeta_2 = \frac{R}{2\left(L+\frac{N^2}{\mathcal{R}}\right)\omega}
\end{aligned} \tag{2}$$

where ω is the undamped natural frequency of the mechanical-magnetic system:

$$\omega = \sqrt{\frac{k - \frac{\theta^2}{\mathcal{R}}}{m}} \tag{3}$$

Among the non-dimensional parameters in Eqs. (2), ζ_2 has optimal values to maximize the energy-harvesting efficiencies E_{K} and E_{U}, respectively. For the maximization of E_{K}, the optimal damping ratio $\zeta_{2\mathrm{opt}}$ is obtained in a simple algebraic form as

$$\zeta_{2\mathrm{opt}} = \frac{\sqrt{\zeta_1 \left(4\zeta_1^2\zeta_{\mathrm{coil}} + 4\zeta_1\zeta_{\mathrm{coil}}^2 + \kappa\zeta_1 + \kappa\zeta_{\mathrm{coil}} + \zeta_1\right)}}{2\zeta_1} \tag{4}$$

For the maximization of E_{U}, the optimal damping ratio $\zeta_{2\mathrm{opt}}$ is the solution of the following quartic equation:

$$\begin{aligned}
&4\zeta_1\zeta_{2\mathrm{opt}}^4 + \left(8{\zeta_1}^2 + 8\zeta_1\zeta_{\mathrm{coil}}\right)\zeta_{2\mathrm{opt}}^3 + \left(4{\zeta_1}^3 + 8{\zeta_1}^2\zeta_{\mathrm{coil}} - \kappa\zeta_{\mathrm{coil}} - \zeta_1\right)\zeta_{2\mathrm{opt}}^2 \\
&+ \left(-8{\zeta_1}^2{\zeta_{\mathrm{coil}}}^2 - 8\zeta_1{\zeta_{\mathrm{coil}}}^3 - 2\kappa\zeta_1\zeta_{\mathrm{coil}} - 2\kappa{\zeta_{\mathrm{coil}}}^2 - 2\zeta_1\zeta_{\mathrm{coil}}\right)\zeta_{2\mathrm{opt}} \\
&- 4{\zeta_1}^3{\zeta_{\mathrm{coil}}}^2 - 8\,{\zeta_1}^2{\zeta_{\mathrm{coil}}}^3 - 4\,\zeta_1\,{\zeta_{\mathrm{coil}}}^4 - \kappa\,{\zeta_1}^2\zeta_{\mathrm{coil}} - 2\,\kappa\,\zeta_1\,{\zeta_{\mathrm{coil}}}^2 - \kappa\,{\zeta_{\mathrm{coil}}}^3 - {\zeta_1}^2\zeta_{\mathrm{coil}} - \zeta_1\,{\zeta_{\mathrm{coil}}}^2 = 0
\end{aligned} \tag{5}$$

Equation (5) can be algebraically solved by Ferrari's method:

$$\zeta_{2\mathrm{opt}} = \frac{1}{2}\left(\sqrt{2\Lambda - p_1} + \sqrt{-2\Lambda - p_1 - \frac{2p_2}{\sqrt{2\Lambda - p_1}}} - \zeta_1 - \zeta_{\mathrm{coil}}\right) \tag{6}$$

where

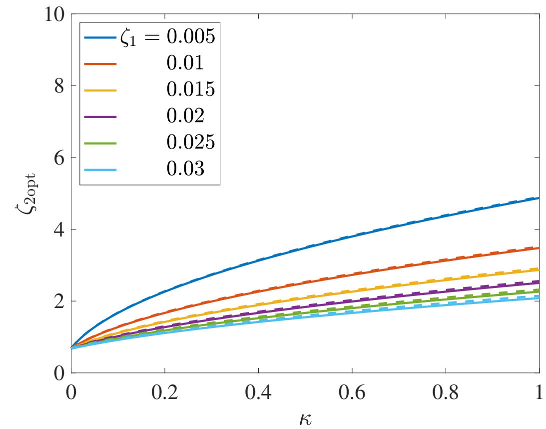
$$\Lambda = \frac{p_1}{6} + r - \frac{w_1}{3r} \tag{7}$$

$$r = \sqrt[3]{-\frac{w_2}{2} + \sqrt{\frac{w_2^2}{4} + \frac{w_1^3}{27}}} \tag{8}$$

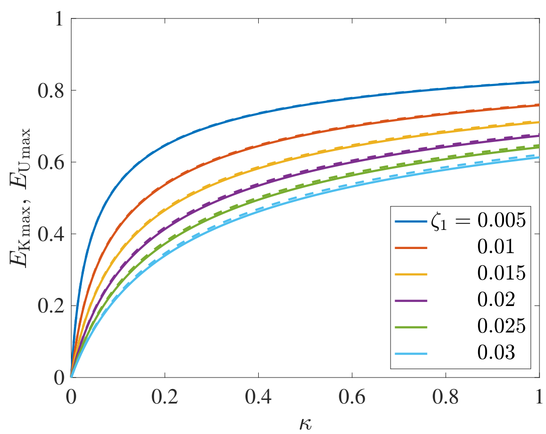
$$\begin{aligned}
w_1 &= -\frac{p_1^2}{12} - p_3 \\
w_2 &= -\frac{p_1^3}{108} + \frac{p_1 p_3}{3} - \frac{p_2^2}{8}
\end{aligned} \tag{9}$$

$$\begin{aligned}
p_1 &= -\frac{1}{4\,\zeta_1}\left(2\,{\zeta_1}^3 + 4\,{\zeta_1}^2\zeta_{\mathrm{coil}} + 6\,\zeta_1\,{\zeta_{\mathrm{coil}}}^2 + \kappa\,\zeta_{\mathrm{coil}} + \zeta_1\right) \\
p_2 &= -\frac{1}{4\,\zeta_1}\left(4\,{\zeta_1}^2{\zeta_{\mathrm{coil}}}^2 + 4\,\zeta_1\,{\zeta_{\mathrm{coil}}}^3 + \kappa\,\zeta_1\,\zeta_{\mathrm{coil}} + \kappa\,{\zeta_{\mathrm{coil}}}^2 - {\zeta_1}^2 + \zeta_1\,\zeta_{\mathrm{coil}}\right) \\
p_3 &= \frac{1}{16\,\zeta_1}\left({\zeta_1}^5 + 4\,{\zeta_1}^4\zeta_{\mathrm{coil}} + 2\,{\zeta_1}^3{\zeta_{\mathrm{coil}}}^2 - 4\,{\zeta_1}^2{\zeta_{\mathrm{coil}}}^3 - 3\,\zeta_1\,{\zeta_{\mathrm{coil}}}^4\right. \\
&\qquad \left. -\kappa\,{\zeta_1}^2\zeta_{\mathrm{coil}} - 2\,\kappa\,\zeta_1\,{\zeta_{\mathrm{coil}}}^2 - \kappa\,{\zeta_{\mathrm{coil}}}^3 - {\zeta_1}^3 - 2\,{\zeta_1}^2\zeta_{\mathrm{coil}} - \zeta_1\,{\zeta_{\mathrm{coil}}}^2\right)
\end{aligned} \tag{10}$$

Figures 3 and 4 show the optimal damping ratio $\zeta_{2\mathrm{opt}}$ of the input resistance and the maximized energy-harvesting efficiencies E_{Kmax} and E_{Umax} with the variation of the primary damping ratio ζ_1 and the damping ratio of the coil resistance, respectively. The higher the electromagnetic-mechanical spring constant ratio, the greater the energy-harvesting efficiency. Conversely, higher primary damping ratio or coil damping ratio results in lower energy-harvesting efficiency. It is also noteworthy that there is almost no difference between the optimal damping ratios Eqs. (4) and (6) and the maximized energy-harvesting efficiencies E_{Kmax} and E_{Umax}.

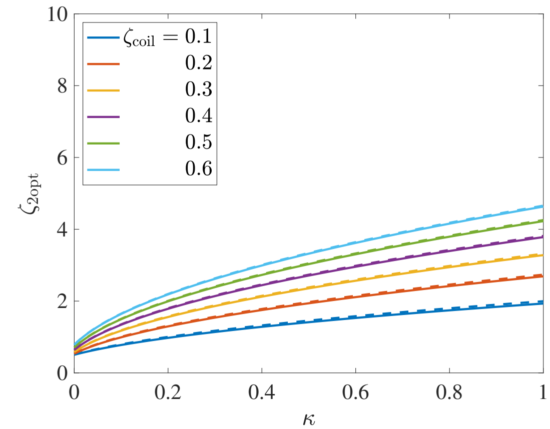


(a) Optimal damping ratio of input resistance

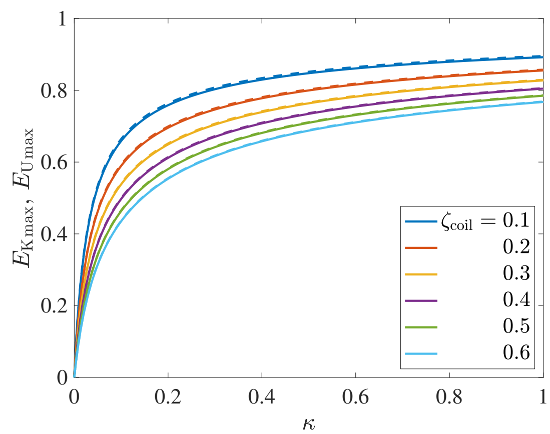


(b) Maximized energy harvesting efficiency

Figure 3: Optimal damping ratio and maximized energy harvesting efficiency to kinetic energy (solid line) and potential energy (dashed line) of magnetostrictive energy harvester with input resistance varying with primary damping ratio ζ_1 ($\zeta_{\text{coil}} = 0.4656$)



(a) Optimal damping ratio of input resistance



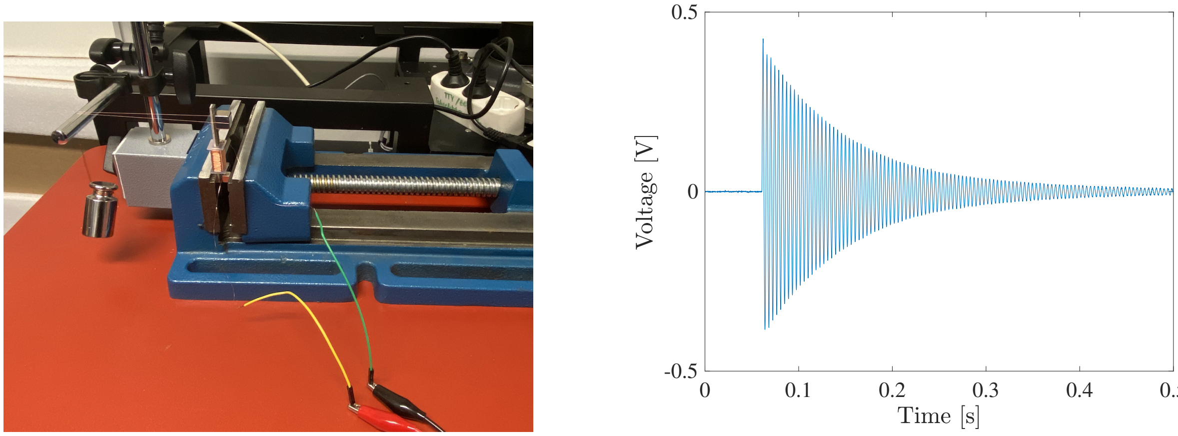
(b) Maximized energy harvesting efficiency

Figure 4: Optimal damping ratio and maximized energy harvesting efficiency to kinetic energy (solid line) and potential energy (dashed line) of magnetostrictive energy harvester with input resistance varying with damping ratio ζ_{coil} of coil resistance ($\zeta_1 = 0.0072$)

3. EXPERIMENTAL PARAMETER IDENTIFICATION FOR ANALYSIS

As seen from Eqs. (2), energy-harvesting efficiency can be determined once the electromagnetic-mechanical spring constant κ, primary damping ratio ζ_1, resistances R_{coil} and R, inductance $L + \frac{N^2}{\mathcal{R}}$, and natural frequency ω are experimentally measured. The natural frequency ω and primary damping ratio ζ_1 of the cantilever were measured by the free vibration experiment shown in Figure 5(a). A 100 g weight was hung on the magnet at the free end by a copper wire with a diameter of 0.05 mm. When the copper wire breaks, free vibration is induced due to the potential energy given by the weight. The voltage induced in the pickup coil was measured by a data acquisition device (NI USB-6251 from National Instruments). Figure 5(b) shows the obtained open-circuit free voltage response. From the period of the damped oscillation and the logarithmic decrement, $\omega_1 = 1502$ rad s^{-1} and $\zeta_1 = 0.0072$ were calculated, respectively.

The inductance $L + \frac{N^2}{\mathcal{R}}$ was determined from frequency response measurements. Figures 6(a) and (b) show the experimental setup and its circuit diagram, respectively. A series-resonant circuit was made by connecting a



(a) Experimental setup (b) Open-circuit free voltage response

Figure 5: Free vibration experiment to measure natural frequency ω and damping ratio ζ_1 of cantilever

resistive load ($R = 99.4\ \Omega$), a capacitor ($C = 1.00\ \mu$F), and an AC voltage supply with 5 V to the pickup coil of the magnetostrictive energy harvester. In this series-resonant circuit, the amplitude of the voltage V_{load} across the resistive load is given as follows:

$$|V_{\mathrm{load}}| = \frac{R}{\sqrt{\left[\frac{1}{\omega C} - \left(L + \frac{N^2}{\mathcal{R}}\right)\omega\right]^2 + \left(R_{\mathrm{coil}} + R\right)^2}} |V| \tag{11}$$

where V and ω are the voltage from the AC voltage supply and its frequency. From Eq. (11), it can be seen that regardless of the resistance values of the pickup coil and resistive load, the resonant frequency ω_{n} of the series-resonant circuit is determined by the values of the inductance and capacitance:

$$\omega_{\mathrm{n}} = \frac{1}{\sqrt{\left(L + \frac{N^2}{\mathcal{R}}\right) C}} \tag{12}$$

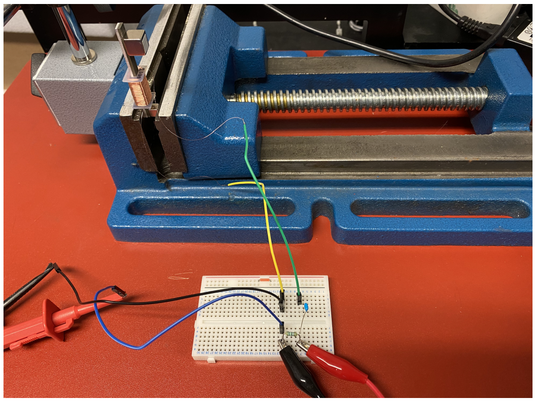
Therefore, the inductance can be obtained by measuring the resonant frequency ω_{n}. Figure 6(c) shows the two types of frequency responses of the voltage V_{load} across the resistive load. The frequency responses were measured for two cases: one with the tip of the cantilever mechanically fixed to avoid interaction with mechanical vibration, and the other without fixing the tip. Even though there is a clear difference between the two frequency responses around the resonance of the cantilever, both frequency responses show the electrical resonance at $\omega_{\mathrm{n}} = 3142$ rad s^{-1}. Therefore, the inductance of the magnetostrictive energy harvester can be estimated as

$$L + \frac{N^2}{\mathcal{R}} = \frac{1}{\omega_{\mathrm{n}}^2 C} = 0.101 \text{ H} \tag{13}$$

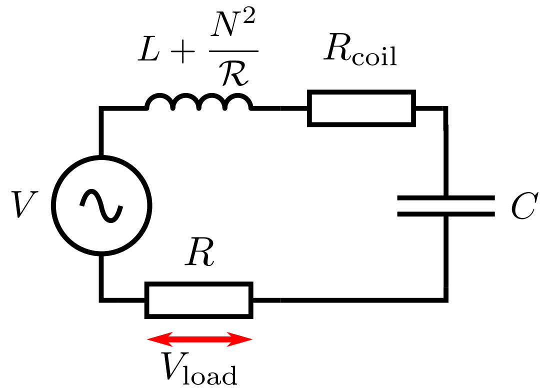
The electromagnetic-mechanical spring constant ratio κ was estimated from the energy harvesting efficiency of the magnetostrictive energy harvester connected to a resistive load of $R = 140\ \Omega$. The free vibration was induced by the 100 g weight. In the experiment, the energy harvesting efficiency E_{U} was obtained as

$$E_{\mathrm{U}} = \frac{\displaystyle\int_0^{\tau} \frac{V_{\mathrm{load}}^2}{R} \mathrm{d}t}{M g W_{\mathrm{mag}}(0)} \tag{14}$$

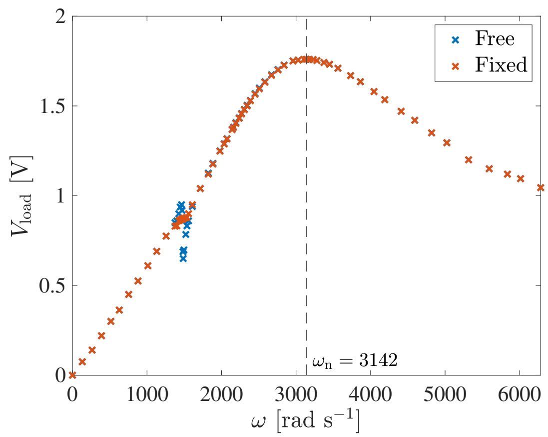
where M and g are the mass of the weight and graviational acceleration, respectively. τ is the finite time until the induced free voltage response is sufficiently damped. In this study, the free voltage response was integrated



(a) Experimental setup

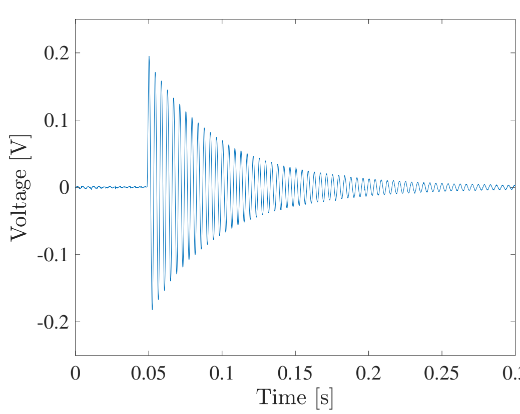


(b) Circuit diagram

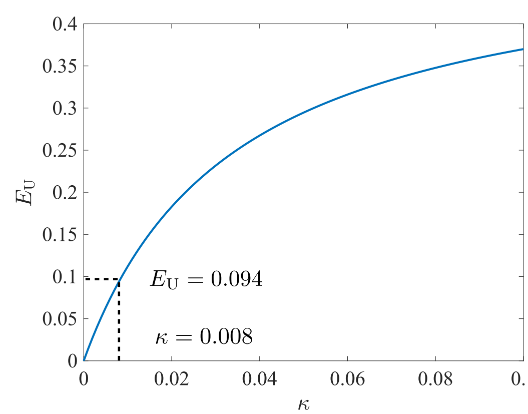


(c) Frequency responses of voltage across resistive load

Figure 6: Frequency response measurements to identify inductance $L + \frac{N^2}{\mathcal{R}}$



(a) Free voltage response



(b) Analytical relationship between energy harvesting efficiency E_{U} and electromagnetic-mechanical spring constant ratio κ based on Eqs. (1)

Figure 7: Energy efficiency measurement to estimate electromagnetic-mechanical spring constant ratio κ

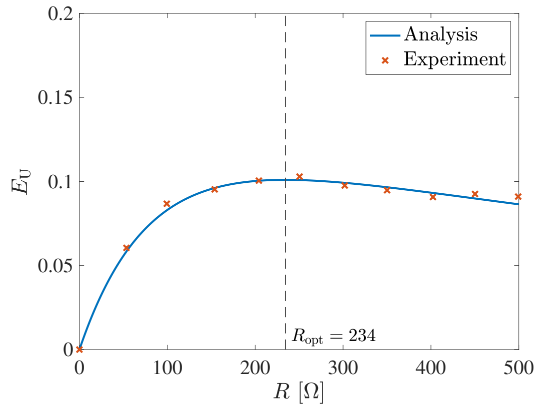


Figure 8: Changes in energy harvesting efficiency of magnetostrictive energy harvester with a pure resistive circuit

for $\tau = 5$ s. The initial displacement $W_{\mathrm{mag}}(0) = 0.034$ mm was measured by a laser displacement sensor (optoNCDT 1900 from Micro-Epsilon). Figure 7(a) shows the obtained free voltage response. From Eq. (14), $E_{\mathrm{U}} = 0.094$ was calculated. The energy harvesting efficiency E_{U} is a monotonically increasing function with respect to the electromagnetic-mechanical spring constant ratio κ, thus there is only one κ corresponding to $E_{\mathrm{U}} = 0.094$. Figure 7(b) shows the analytical relationship between E_{U} and κ based on Eqs. (1). From the relationship, $\kappa = 0.008$ was estimated.

4. EXPERIMENTAL VALIDATION OF OPTIMAL DAMPING RATIO

The experimental validation was performed by measuring the changes in the energy harvesting efficiency Eq. (14) due to variations in the input resistance R and comparing them with the analytical results. Figure 8 shows the changes in energy harvesting efficiency of the magnetostrictive energy harvester connected to a resistive load. The experimental results are in good agreement with the analytical results. According to the impedance matching, the optimal resistance value is expected to be equal to the coil resistance $R_{\mathrm{coil}} = 142\ \Omega$. However, both experimental and analytical results in this study revealed that the optimal resistance value is greater than the coil resistance. The analytical energy harvesting efficiency at the optimal resistance $R_{\mathrm{opt}} = 234\ \Omega$ is $E_{\mathrm{U}} = 0.101$.

5. CONCLUSION

This paper presented experimental parameter identification methods for the non-dimensional parameters describing the energy-harvesting efficiency of a magnetostricitive energy harvester. The proposed methods do not include measurements of dimensions, Young's modulus, permeability, or magnetostrictive constant which is generally obtained from the combination of mechanical stress and magnetic measurements. They are thus more feasible with general laboratory equipment.

An experiment to validate the obtained optimal damping ratio was also conducted by measuring the energy-harvesting efficiency at different load resistances. The analytical results and experimental results show good agreement, and both show that the optimal damping ratio of the magnetostrictive energy harvester is higher than the one obtained from impedance matching ($\zeta_{2\mathrm{opt}} = \zeta_{\mathrm{coil}}$) in which the harvester is assumed to be a constant AC voltage source. The optimal damping ratio of the magnetostrictive energy harvester is $\zeta_{2\mathrm{opt}} = 0.769$. The maximum energy-harvesting efficiency at the optimal damping ratio is 10.1%.

Finally, it is highly noteworthy that as the presented equivalent mechanical model of a single-degree-of-freedom magnetostrictive energy harvesters is identical to that of an electromagnetic-mechanically coupled system,[23] the proposed methods in this study are also applicable to the investigation of electromagnetic energy harvesters.

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