Magnetostrictive low-cost high-performance vibration power generator

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Abstract. A high-sensitivity, high-durability, low-cost vibration power-generating device using a magnetostrictive element (Fe-Ga alloy) is proposed. The device comprises a unimorph layer having a magnetostrictive element attached to a U-shaped frame with a permanent magnet for magnetic bias wound about by a coil. By magnetically saturating the part to which the frame element is affixed, an electromotive force is generated in the coil by vibration according to the change in the magnetic flux generated by the inverse magnetostrictive effect of the element. An evaluation of a prototype device (4 g) using an element of 4 × 0.5 × 16 mm is performed. With a weight of 1.7 g attached, an open-circuit voltage of 4 V at an oscillation of 88.7 Hz and 6 m/s² yields the effective power of 2.0 mW. With a weight of 10.2 g, an effective power of 0.39 mW is generated at a frequency of 28.4 Hz and an acceleration of 0.075 G. After repeated oscillation at 420 Hz and 8 G for 100 million times, the resonant frequency and voltage remain unchanged.

1. Introduction
The main problem with Internet-of-Things (IoT) and wireless sensor modules is battery power. Modules are said to work for several years with button batteries, but when the number of modules reaches 100 or 1,000, battery exchange becomes a very troublesome task. In addition, batteries lose charge capacity without using them, and their disposal is also troublesome. Batteries could be replaced with vibrational power generation. By replacing batteries with non-electrochemical power sources, the use of IoT devices and sensor modules could become far easier. At present, a vibration power-generating device using a Fe-based magnetostrictive material is under investigation. General environmental vibration occurs at frequencies of 20 to 100 Hz and accelerations of 0.05 G to 1 G. The device is required to generate power from mild to high-intensity vibrations. In this study, a power-generation device satisfying the criteria of high sensitivity, high durability, and mass productivity is proposed and tested to demonstrate these features.

2. Structure and principle of device
The structure of the device is shown in Fig. 1. The device has a unimorph base with a plate-like magnetostrictive element (Fe–Ga alloy [1]) adhered to a U-shaped magnetic frame (Fig. 1 top). A coil is wound around the unimorph and permanent magnet is arranged in the space within the frame. The frame is designed so that the part where the magnetostrictive element is bonded becomes magnetically saturated by magnetic bias; the other parts remain unsaturated, and a uniform stress is applied in the longitudinal direction of the element when the unimorph is bent [2].

The principle of power generation is shown in Fig. 2. The device is fixed to a vibration source, weight is attached to the tip of the frame, and the device is shaken. At this time, the device deforms such that the inertial force of the weight opens and closes the opening of the frame, uniform tensile and compressive stresses are generated in the longitudinal direction of the element, and the magnetic
flux is increased or decreased by the inverse magnetostrictive effect. Figure 2 shows the cases for which the inertial force of the weight is downward (top) and upward (bottom). The change in the magnetic flux generated by the inverse magnetostrictive effect circulates in the closed magnetic circuit in series with the element, frame, magnet, and gap. The magnetic portion is magnetically saturated and, therefore, high in magnetic resistance, and the change in the magnetic flux of the device does not backflow through the magnetic portion. Therefore, an electromotive force proportional to the temporal change of the magnetic flux of the element is generated in the coil.

The critical design feature of this structure is the easily molded frame, which can be cut out and bent from a Fe plate, thereby significantly reducing the cost. The element can be fixed to the frame and the air-core coil can be fitted later, suitable for mass production. The generated power can be significantly increased by manipulating the layer thickness of the coil, while the generated voltage and resistance can be adjusted by manipulating the wire diameter. Furthermore, the unimorph is more easily vibrated by uniform curving compared to the conventional parallel-beam type [3], and also highly durable. Thus, the proposed structure satisfies both mass productivity and high performance.

3. Prototype evaluation

3.1. Prototype

In the prototype device, the magnetostrictive element was a 4 × 0.5 × 16-mm plate cut from a single-crystalline bulk Fe_{81.4}Ga_{18.6} material by wire discharge machining. The frame was wire discharge machined from a 0.5-mm plate of cold-rolled Fe and then bent. The element was adhered to the frame with an epoxy-type structural adhesive. The coil had a wire diameter of 0.05 mm and 3500 turns (520 Ω), and the magnet was Nd–B–Fe measuring 4 × 3 × 2 mm. The coil was fixed in the unimorph section with silicone rubber. The weight of the device was 4 g.

3.2. Voltage characteristics

The power generation characteristics were measured with the system shown in Fig. 3. The device was fixed to the exciter with screws and vibrated. The vibration acceleration was measured by an acceleration pickup, while the displacement of the frame was measured with a laser displacement sensor. Weights of 1.7 g, 3.2 g, and 10.2 g were attached to the tip of the frame. Figure 4 shows the frequency response results of open-voltage/acceleration measured with white noise excited with a fast Fourier transform (FFT) analyzer. When the weights are 1.7, 3.2, and 10.2 g, the resonance frequencies are 89.8, 57.9, and 28.9 Hz, respectively, and the Q values are 185, 196, and 195, respectively.
The voltage waveform is shown in Fig. 5 under the weight of 1.7 g and sinusoidal wave oscillation of 88.7 Hz frequency and accelerations of 3.0, 6.0, and 9.0 m/s². The maximum voltage of 5.4 V is generated at the acceleration of 9.0 m/s². The relationship between the displacement of the tip of the frame and the change in the magnetic flux density of the element, as calculated by the time integration of the voltage waveform, is shown in Fig. 6. A magnetic flux density change of 1.3 T, equivalent to that of the conventional parallel-beam type [3], occurs. Under 6.0 m/s² acceleration, a resistance is connected as a load and the relationship between resistance and power (Joule loss) is measured and shown in Fig. 7. A maximum power of 5.1 mW and an effective power of 2.0 mW are obtained at approximately 1000 Ω. Figure 8 shows the relationship between the resistance and the displacement amplitude of the frame, and reduced vibration of the device by power consumption occurs.

Figure 3. Prototype device and measurement system.

Figure 4. Frequency response of voltage/acceleration with varied weight.

Figure 5. Open voltages (88.7 Hz).

Figure 6. Flux density variation vs. displacement.

Figure 7. Power vs. resistance (0.6 G).

Figure 8. Amplitude vs. resistance (0.6 G).
Next, the voltage waveforms at the weight of 10.2 g, the frequency of 28.4 Hz, and accelerations of 0.34, 0.49, and 0.61 m/s² are shown in Fig. 9. A voltage of 1 V is generated at an acceleration of ~0.05 G and a practical voltage could be extracted with minimal vibration. Figure 10 shows the relation between the resistance and electric power at 0.75 m/s² acceleration. The maximum electric power of 1.05 mW and the effective electric power of 0.39 mW are obtained at a resistance of approximately 520 Ω. The difference in the matching resistance arises from the degree of coupling between electricity and machinery.

![Figure 9. Open voltages (28.4 Hz).](image)

![Figure 10. Power vs. resistance (0.075 G).](image)

3.3. Fatigue test

Fatigue tests were performed with the apparatus shown in Fig. 11. Without weight on the tip, the device was shaken 0.1, 1, 10, and 100 million times at a resonance frequency of 420 Hz and an acceleration of 8 G at room temperature (25 °C). The resonance frequency was finely adjusted at the appropriate times, and the frequency characteristic of the voltage (1-G and 8-G frequency sweeps) was measured after each given number of cycles. Figure 12 shows the results. The frequency characteristics remain almost unchanged from the first cycle, even after 100 million cycles. After the test, neither the separation of elements nor metal fatigue is observed.

![Figure 11. Apparatus for fatigue test.](image)

![Figure 12. Frequency characteristics of voltage after cyclic vibration.](image)

Acknowledgments

This work was supported by JST CREST Grant Number JPMJCR15Q1, Japan. The fatigue tests were conducted by Toyo Tire & Rubber Co., LTD.

References

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