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Accelerating the IoT: Magnetostrictive Vibrational Power Generators to Replace Batteries*

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One of the major challenges faced by the Internet of Things (IoT) is the management of power sources (batteries) for wireless communication. The vibrational power generation device that we have developed is simple and robust, characterized by high output and high sensitivity, which is expected to provide a complete solution to the power supply problem. Several companies have embarked on commercialization research in anticipation of the practical application of this technology. The device is developed using a Fe–Ga alloy, that is the basis of its electromechanical energy conversion. This paper describes the device's structure and power generation principle, including the output characteristics of the miniature device that is set to replace the coin battery. We also explain the challenges to the widespread use of the device and the battery-free IoT resulting from this technology, as well as its future prospects.

INTRODUCTION

The Internet of Things (IoT) are technologies that connect various things to the Internet. The IoT, along with artificial intelligence (AI), is set to become part of next-generation information society, contributing to safe and secure daily life and efficient work-related activities. However, the IoT has yet to reach its full potential in terms of widespread use. One reason for this is due to the power supplies that are needed for wireless communication. Currently, there are many communication modules such as Bluetooth Low Energy (BLE) and low-power wide-area (LPWA) that can operate with low power consumption, but the power sources for these modules still rely on the batteries. The need to replace batteries periodically and bothersome battery life management are factors that deter the widespread use of IoT. While the use of one or two batteries is a manageable proposition, if the count increases to 100 or 1000, the labor and cost involved cannot be ignored. This situation remains unaltered even in the case of products that claim to last 3 to 5 years with batteries. Billions or trillions of things are expected to be connected by the IoT, and it is unrealistic to assume that batteries will be the power source for all of those things. An expected alternative solution to this problem is energy harvesting. Energy harvesting is the process of generating electricity from small surrounding physical phenomena such as light and heat. Vibrational power generation is one such technique that is highly versatile and that can be used in many objects. Vibration occurs when a periodic or transient force is applied to an elastic body; to prodcuce vibrations, even a small movement, shock, or flow can be a power source. Simply put, everything from production machinery to electrical equipment, cars, railways, bridges, doors, push button switches, shoes, animals, waves, and water streams can be used as a power source. In addition, vibrational power generating devices function as vibration and motion sensors and are capable of instantaneously extracting large amounts of energy. The magnetostrictive vibrational power generator that we have developed is simple and robust, is characterized by high output and high sensitivity and is expected to provide a complete solution to the power supply problem for the IoT. In this paper, we describe the Fe–Ga alloy that is the basis of such a device, the structure and principle of the developed device, and the characteristics of the miniature device that make it set to replace the coin battery. We also present an over-

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view of the battery-free IoT that can be accomplished through this magnetostrictive vibrational power generator, discuss the challenges in its popularization, and summarize prospects.

THE Fe–Ga ALLOY

Magnetostrictive power generating devices have iron-based magnetostrictive materials as their base. A magnetostrictive material has the property of undergoing deformation when magnetized. The iron gallium alloy is a typical example. This material, also called "Galfenol," was developed by Clark et al. of the Naval Surface Warfare Center in the year 2000 [1, 2]. The nature of the strain generated depends on the gallium content. A peak value of about 250 to 300 ppm is obtained at 18.4 or 18.6 % gallium content. The Young's modulus is 70 GPa; the relative permeability is approximately 100; the Curie temperature is 800 °C; and it can be used from cryogenic temperatures up to 200 °C. Some of the features that make it a suitable material for power generation are its excellent magnetic/elastic energy conversion performance and its large inverse magnetostriction effect, i.e., the change in magnetization with stress. Its sensitivity depends on the magnetostrictive constant d (magnetic flux/stress). When d is 2×10^{-8} T/Pa, the magnetization of 1 T changes with a stress of 50 MPa. The electromechanical coupling coefficient k, which is an index of the conversion efficiency, is 0.7 to 0.8. If used properly, it can convert up to 64% of the mechanical energy, ($= 0.8^2$) into electrical energy. Another characteristic of this alloy is that, being an iron-based material, it is ductile and has good workability as well as mechanical strength. Processes such as cutting and electrical discharge machining can be used for shaping, soldering, and welding for joining. In other words, it is possible to create a strong structure using this alloy and a steel plate. Figure 1 shows a long single crystal ingot with a large diameter developed by the Fukuda Crystal laboratory using the Czochralski (CZ) method [3], indicating that such large pieces of alloy can be manufactured. As mentioned above, the device based on this alloy is robust and has a wide temperature range. Furthermore, it has the potential to allow for large mechanical energy input and efficiently convert that input into electrical energy through the inverse magnetostrictive effect.

STRUCTURE AND PRINCIPLE OF A MAGNETOSTRICTIVE VIBRATIONAL POWER GENERATING DEVICE

The upper part of Figure 2 shows the structure of a magnetostrictive vibrational power generating device [4]. In this device, a Fe–Ga alloy plate is attached to a part of a U-shaped steel frame and laminated (unimorph). A coil is wound around the lamination and a permanent magnet is placed inside for bias. The lower part of Figure 2 shows the principle of power generation. The device (end of frame) is fixed to a vibrating object and made to vibrate by attaching a weight to the tip of the frame. The vertical inertial force acting on the weight deforms the frame in such a manner as to make the opening of the frame open and shut and the alloy plate is subjected to alternating tensile and compressive forces in the longitu-

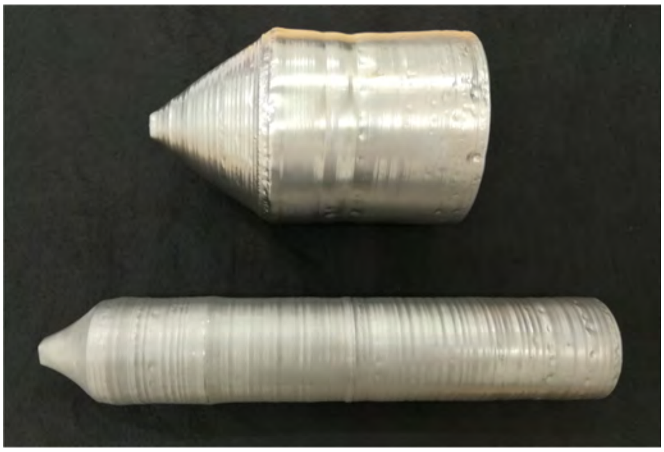

Fig. 1: Single crystal ingots of Fe–Ga alloy (manufactured by Fukuda Crystal Laboratory) fabricated by the CZ method. The diameter of the upper piece is 4 inches and that of the lower piece is 2 inches. It is theoretically possible to manufacture larger-sized ingots.

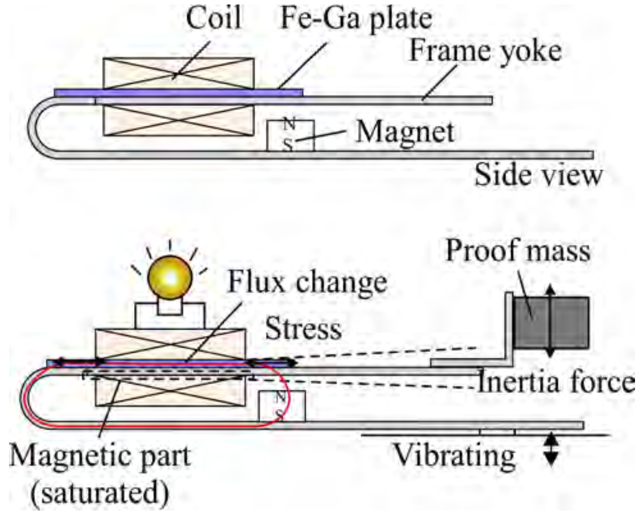

Fig. 2: Structure of power generation device (top) and power generation principle (bottom). The device has a simple structure and can be easily assembled.

dinal direction. Owing to the laminated structure, there is uniform stress in the alloy in the tensile or compressive direction (there is a neutral axis in the frame where the stress is zero). This stress causes a fluctuation in the magnetic flux due to the inverse magnetostriction effect, which flows through the red loop in Figure 2, and an electromotive force proportional to this temporal change is generated in the coil. In general, this vibrational power generator uses the resonance phenomenon. The amplitude can be greatly magnified by matching the resonant frequency of the device with that of the vibration source and a large amount of power can be generated.

The idea is that appropriately magnetizing the alloy causes the part of the frame where the alloy is attached (the magnetic part) to become magnetically saturated, but not the rest of the structure; hence, the change in magnetic flux generated by vibration circulates well through the frame and links with the coil. In other words, the large inverse magnetostriction effect of the alloy efficiently converts the vibration into electric power via the magnetic circuit. Further, as the free end (the end with the weight) and the fixed end of the U-shaped structure are close to each other, a bending moment is less likely to occur at the fixed end, resulting in less loss and higher sensitivity at the fixed end. A simple structure with no sliding parts and high durability are some of the other major features of this device. Provided that the stress generated by vibration is less than the breaking strength of the material and the bond strength of the laminated part, the device will not break.

DEVICE CHARACTERISTICS

Output characteristics and scale effect

Magnetostrictive vibrational power generating devices can be made in various sizes. The device shown on the left of the photograph in Figure 3 shows a small-sized device. It made of a 4 × 0.5 × 16 mm^3 Fe–Ga alloy plate and has a frame thickness of 0.5 mm, a coil with a wire diameter of 0.05 mm and 3500 turns, and a 4 × 3 × 2 mm^3 neodymium magnet [5]. When a weight of 10.2 g is attached to the end of this device, it resonates at a frequency of 28.5 Hz, generating an open circuit voltage of 1 V with an acceleration of 0.49 m/s^2; an effective power of 0.39 mW can be extracted at 0.75 m/s^2 [6]. When the weight is 1.7 g, it resonates at 88.7 Hz, and a power of 2.0 mW can be extracted at 6 m/s^2. The power density at this time (effective output/volume 0.5 cm^3 of the entire device) is 4.0 mW/cm^3, which is outstanding compared to other vibrational power generation devices. A free-vibration (resonance frequency of 420 Hz) caused by flipping the tip of the device without attaching a weight generates a voltage of 25 V, and 0.5–1 mJ of energy can be extracted at one time. We also conducted fatigue tests which confirmed that the output did not deteriorate even after 100 million vibrations, thus validating the durability of the device.

The magnetostrictive method conforms to the scale effect. If the dimensions of the device are increased K times, the resonance frequency is reduced by $1/K$, the voltage increases K times and, assuming the number of coil turns to be the same, the resistance reduces by $1/K$. As a result, the output is proportional to K^3, or the volume of the device. In the photograph in Figure 3, the devices on the right are respectively twice and four times the size of the above-mentioned small sized model. The operating frequencies are 1/2 and 1/4 times and the outputs are eight times and 64 times that of the small sized

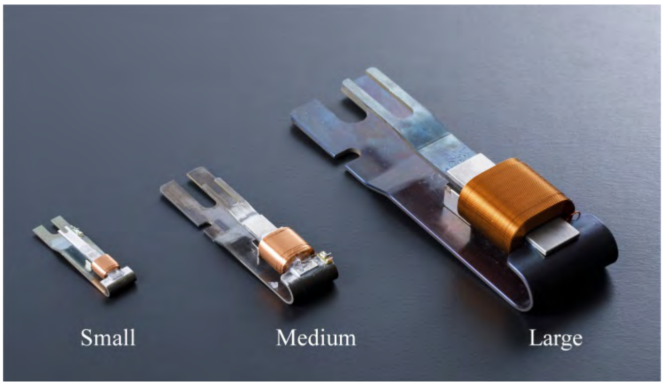

Fig. 3: Photograph of power generation devices. From left to right: small, medium (2 times) and large (4 times).

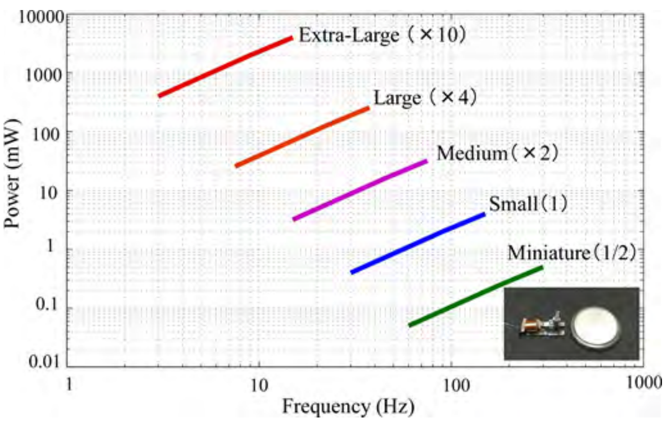

Fig. 4: Relationship between operating frequency and generated power (effective value). The larger the size, the lower the operating frequency range. The magnetostrictive type can be made in various sizes and can generate power of the order of milliwatts.

model, respectively. The relationship between the operating frequency of the device and the (effective) power generated considering the scale effect is shown in Figure 4. We are also developing extra-large and microminiature devices that are 10 times and 1/2 the size of the small sized device.

Output characteristics of a microminiature vibrational power generating device

Here, we describe the output characteristics of a microminiature magnetostrictive vibrational power generating device that can replace coin batteries [6]. This device is shown in the photograph at the bottom right of Figure 4. The device is made up of a 2 × 0.25 × 8 mm^3 Fe–Ga alloy, a 0.5 mm thick frame, a coil with a wire diameter of 0.03 mm and 3500 windings with a 2 × 2 × 1 mm^3 neodymium magnet. It has a mass of approximately

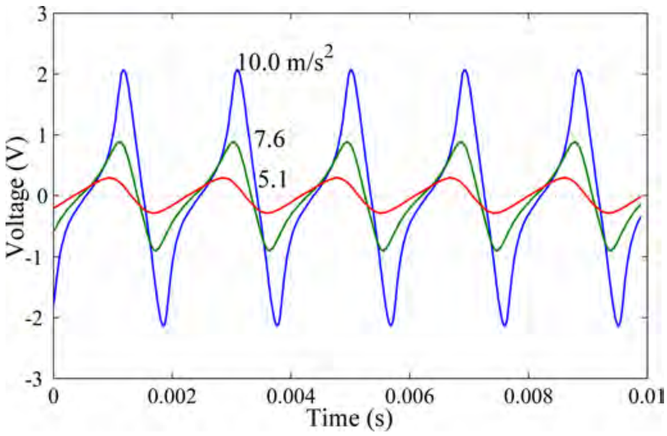

Fig. 5: Generated voltage (522.2 Hz). A voltage of about 1 V is required for wireless communication operation. The microminiature device generates more than that.

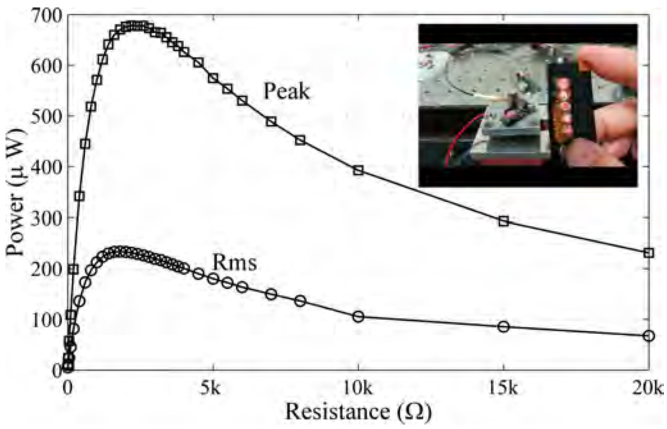

Fig. 6: Generated power (522.2 Hz, 1.0 G). Maximum peak power (Peak) is 670 μW, maximum effective power (Rms) is 234 μW. Top right: 5 LEDs flash with power generated from a microminiature vibrational power generating device.

1 g, and the size is comparable to the adjacent coin battery (CR2032, diameter 20 mm, mass 3 g). The capacity of a CR2032 coin battery is 3 V, 225 mAh. The output of the battery, when continuously used for 3 years, is 26 μW, which is the guideline value for an output that can replace batteries. Figure 5 shows the voltage when a 0.3 g weight is attached to the tip of the device and a vibration at the primary resonance frequency of 522.2 Hz is made. A voltage of approximately 2 V is shown to be generated at an acceleration of 10.0 m/s^2. Figure 6 shows the result of evaluating the power using Joule loss of resistance. An effective power of 234 μW can be extracted with 1.5 kΩ. This can be confirmed from the photograph at the top right of Figure 6, where the LEDs connected to the device blink. A power of 234 μW is approximately nine times 26 μW and four to five times higher than the actual power obtained by multiplying the efficiency of the AC/DC power conversion circuit (estimated to be 0.5–0.6). The frequency band of the vibration generated in a machine tool is around 500 Hz, which can be used, for example, as a power source for the wireless sensors used for predictive maintenance of these machines. We have succeeded in wirelessly transmitting, every few seconds, the temperature and illuminance sensor information by using a wireless communication module (TWELITE) [7] with this vibrational power.

BATTERY-FREE IOT AND ITS APPLICATIONS

While the maintenance of a power supply is a challenge to the IoT, we are surrounded by objects that generate vibrations or motions that excite vibrations. By using vibrational power generators, the motions and vibrations of those objects can be used as a power source. There are many systems for crime prevention, monitoring, and predictive maintenance of machines, in which motion and vibration are used as the basis for decision making. Figure 7 shows an overview of the battery-free IoT that could be realized through vibrational power generation [8].

In Figure 7, group (1), power is generated by a "one-time" movement or impact of a person or thing and wirelessly transmitted over a short distance.

In Figure 7, group (2), power is generated by the vibration of machinery or infrastructure and the sensor signal is wirelessly transmitted periodically over a long distance. These signals are received by terminals such as personal computers or Raspberry Pi, which are connected to the cloud.

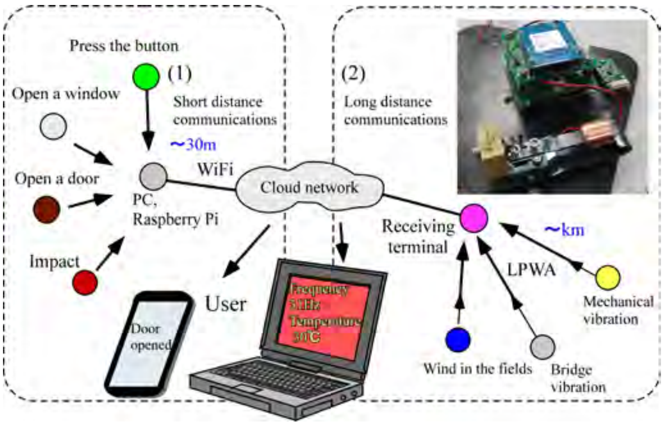

Fig. 7: Overview of the battery-free IoT realized with magnetostrictive vibrational power generation. They are roughly classified into short-distance and long-distance transmitters and are operated by different device sizes, circuits, and communication modules. If a power supply for communication can be secured, the environment for battery-free IoT could become an instant reality.

The basic idea in group (1) is wireless transmission through a single movement. By using a magnetostrictive vibrational power generator and exciting it through various movements and impacts, such as the push of a button, the opening of a door, or the hitting of a board with a ball, more than 0.5 mJ of energy can be generated for each movement or impact. We have demonstrated that signals can be transmitted by a short-range wireless module (BLE and 315 MHz short-range communication module [9], for example). By using a medium-sized device, it is possible to extract about 5 mJ of energy in a single movement and do away with the sensor signal. For instance, it is possible to build a system where power is generated by the opening of a door and information about the temperature of the room is transmitted. (This operation has been verified through a prototype experiment and a demonstration).

Figure 7, group (2) requires the design of a rectifier, a storage circuit, and a constant voltage circuit. In fact, we are developing a wireless sensor system that uses the medium-sized device shown in the photograph in Fig. 7. With this device, the microcomputer is activated every 2 minutes by 30 Hz, 0.1–0.2 G vibrations and the vibrational frequency, acceleration (calculating the effective value), and temperature can be transmitted by LPWA module A similar transmission using vibrational power generation by wind [10] is possible.

In magnetostrictive vibrational power generation, the mechanical and electrical systems are strongly linked together through the power generation section and vibration is simultaneously attenuated with power consumption. Furthermore, the mechanical resonance can be adjusted and controlled by electrical characteristics. It has been demonstrated that the resonance frequency can be adjusted and controlled up to about 10 % by connecting capacitors to the device and changing the capacitance. Because the generated voltage is caused by vibration and motion, the device also functions as a sensor. In Figure 7, group (1), the device also serves as a motion sensor and in group (2), it is theoretically possible to identify the speed and frequency of vibration of the device from the generated voltage. In other words, the sensor is not needed. In predictive maintenance, the signal changes are often more important than absolute values and hence there is a demand for such simple and low-cost systems. Therefore, the technology for utilizing the mechanical-electrical linkage not only as a power source, but also for sensing and controlling objects attached to the device will be developed.

CHALLENGES

A magnetostrictive device is a simple and robust device. It is smaller than a battery in size but is capable of improved output. Hence, it is superior to conventional vibrational power generators such as piezoelectric materials, microelectromechanical systems, and batteries. The generated voltage being a speed electromotive force, mechanical energy is the input, and based on this, electrical energy is extracted. The upper limit of this input is determined by the weight, the Q value (sensitivity of resonance), frequency of the vibration source, and acceleration. Considerable weight and vibrations are required to obtain milliwatts of electricity. In vibrational power generation, it is essential to develop a structure that utilizes the resonance phenomenon from input vibration (mechanical energy) to efficiently extract energy, and the circuit must be designed to integrate the device with the power conversion and wireless sensor modules. Compared to batteries, magnetostrictive vibrational power generation has one definite disadvantage, which is the rather cumbersome process at the time of initial introduction. Once a battery is set in place, it begins to work immediately; in contrast, in the case of vibrational power generation, it is essential to carry out on-site adjustment work such as measurement of mechanical vibration, selection of the device, and weight according to the data, before operations can begin. Overcoming this hurdle is the key to the widespread use of this technology. Furthermore, as these magnetostrictive vibrational power generating devices have semi-permanent lives, it is important to ensure heat resistance and durability, and to provide measures against fluctuations in vibrational frequency (band widening).

CONCLUSION

This paper describes the characteristics of magnetostrictive vibrational power generating devices and a battery-free IoT system that can be realized by this technology. The future outlook for magnetostrictive vibrational power generation is described. First, the problems of initial introduction and reliability will be resolved in stages and device performance and usability will be improved through verification tests and monitoring. We have been promoting commercialization of the devices in various fields and several trials for social implementation are in progress. There are companies that are conducting research on mass-production of Fe–Ga alloys, and inexpensive Fe–Al alloys are being developed in the United States [11]. In the future, the price of the device will be nearly the same as a battery and the environment to utilize the vast amount of data sent by devices has already been set up in the form of the cloud, AI, etc. Vibrational power generation is a multiple billion dollars market, and once a technical model becomes established, beginning with a product, it will not be long before the battery-free IoT becomes widespread.

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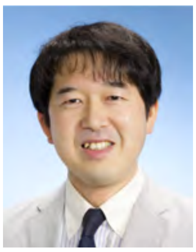

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