Study of Energy Harvesting from Low-Frequency Vibration with Ferromagnetic Powder and Non-magnetic Fluid

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Received: 22 July 2019 / Accepted: 3 November 2019 / Published online: 23 November 2019
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Abstract

The movement of the creature and the almost wave in the ocean is a low vibration of random energy with a frequency range of 0.1–10 Hz. Because of its low frequency, the opinion has been that electrical energy generation from this low-frequency wave motion through the electromagnetic induction method is difficult. In this study, an electrical generator was created by the electromagnetic induction method by putting a small mass of ferromagnetic powder in nonmagnetic fluid. A broadband vibration energy harvesting model was created in which vibrations are broadened through a multi-degree of freedom oscillation system using ferromagnetic powder. To generate electricity from low-frequency vibrations (1 Hz or less), a non-resonant type model was created by adding fluid to the ferromagnetic powder model and the simulation results confirmed using computational fluid dynamics by creating a working energy harvesting device.

Keywords Energy harvesting · Ferromagnetic powder · Vibration-driven generator · Renewable energy · Computational fluid dynamics (CFD)

Introduction

As IoT develops in recent years, various sensors have been applied to everyday life and many industrial fields from distribution, traffic, infrastructure maintenance, medical care, healthcare, security, and disaster prevention. In the face of this technological tide, energy harvesting is expected to provide an independent power supply to sensor nodes by acquiring energy from the environment [1–5].

Energy harvesting technologies which generate electricity using naturally occurring energy are classified roughly by the energy source. Sources of energy utilized by energy harvesting include electromagnetic waves [6–9], thermal energy [10–13], chemical energy [14, 15], solar energy [16–19], and kinetic energy [20–23]. Of these, kinetic energy is distributed unevenly throughout the environment and is easy to use. One method of harvesting kinetic energy is to use a trembler to

convert environmental vibrations into electric energy. This is called vibration energy harvesting.

In recent years, several electricity generation mechanisms utilizing vibration energy have been developed: the electrostatic electret [24–26], the piezoelectric element [27–31], the reverse magnetostriction effect [32], and the electromagnetic induction effect [33–37]. In general, electricity generating systems are most commonly based on the electromagnetic induction method, and it is thought that this electricity generating method can achieve the largest output of electric energy.

The movement of sea creatures is within the frequency range of 0.5–3 Hz [38], and ocean waves are low vibration of random energy with a frequency range of 0.1–10 Hz [39]. Despite many studies on vibration energy harvesting [40–46], it has proven difficult to generate electricity using the electromagnetic induction method when vibrations are random amplitude and low frequency [25, 47–49].

Low-frequency power generation in vibration energy harvesting using a magnetic levitation vibration system has been reported [50, 51]. Zergoune et al. [52] also proposed a linear electromagnetic vibration energy harvester with weak magnetic coupling. The power generators in these studies [50–52] were complex in structure and had the disadvantage of generating electricity at one or two narrow resonance points because of a one or two-degree of freedom oscillation system. Therefore, we propose a multi-degree of freedom oscillation

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system broadband power generation mechanism using ferromagnetic powder in this study.

Bassiano et al. [23] also enabled low-frequency vibration power generation by bending motion of the macrofiber composites patch (MFCs), and their power generators generate power by bending motion of 0.5 to 2.5 Hz, but it is considered that their device is disadvantageous at 3 Hz or more, due to the durability of the flat plate composite resin. Furthermore, there is a possibility that heat will be generated due to internal friction of the component even for a bending motion of 5 Hz or more, which is also disadvantageous for durability at a high frequency. In this respect, as described below the structure of the power generator in our research is simple and durable and can generate at wide band at low frequency due to ferromagnetic powder and fluid.

Therefore, we aimed to create an electrical generator that can utilize broadband, low-frequency vibrations by using ferromagnetic powder suspended in fluid. We present the design and energy generation of our resulting generator here. The electrical generator of this study is a simple structure and is easy to create and can generate power at low frequency and broadband.

Materials and Methods

Generator Design

An electrical generator was created by the electromagnetic induction method by putting a small mass of ferromagnetic powder in nonmagnetic fluid (Fig. 1a). In this device, the magnetic flux of the magnetic field created by the permanent magnet shapes ferromagnetic powders into spike-shaped aggregates. Then, the slow vibration moves the fluid, and this motion in the fluid moves the magnetic field in the spike-shaped aggregates of ferromagnetic powder. Thus, electricity is generated in the coil [34, 35].

It is considered that the spike-shaped aggregates of ferromagnetic powder in this electrical generator are a multi-body system model comprised of a mass point, a spring, and a damper (Fig. 1b).

In other words, it may be considered that the tip mass of the spike-shaped aggregates work when they are given low vibrational energy and that the lower part and an overall mass point of the spike-shaped aggregates work when they are given large vibrational energy. The electrical generator encloses the ferromagnetic powder and fluid in a pipe, and the magnetic field in the ferromagnetic powder aggregates, which is induced by a permanent magnet, is moved by reciprocating motion.

Mitcheson [45] and Ju et al. [53] created a motion equation for calculating energy generated in single mass point energy harvesting systems without fluid, and Zhang et al. [49] created an equation for two mass point systems without fluid. To calculate the energy generated by our electric generator, a multiple mass point system in fluid (Fig. 1b), we used the drag equation of fluid dynamics (right side of Eq. (1)). In this case, energy generated was considered equal to drag force.

$$M\ddot{\mathbf{u}}(t) + C\dot{\mathbf{u}}(t) + K\mathbf{u}(t) = \mathbf{f}(t) = \frac{1}{2}\rho SC_{\Gamma}U^2(t) \quad (1)$$

ρ mass density of the fluid
 $\mathbf{U}(t)$ flow velocity relative to the object vector
 S cross-sectional area
 C_d drag coefficient
 T time

$$\text{Displacement vector: } \mathbf{u}(t) = \begin{pmatrix} u_1(t) \\ u_2(t) \\ \vdots \\ u_N(t) \end{pmatrix}$$

$$\text{External force vector: } \mathbf{f}(t) = \begin{pmatrix} f_1(t) \\ f_2(t) \\ \vdots \\ f_N(t) \end{pmatrix}$$

$$= \begin{pmatrix} \frac{1}{2}\rho SC_{\Gamma}U_1^2(t) \\ \frac{1}{2}\rho SC_{\Gamma}U_2^2(t) \\ \vdots \\ \frac{1}{2}\rho SC_{\Gamma}U_N^2(t) \end{pmatrix}$$

Mass matrix: $\mathbf{M}$

$$= \begin{bmatrix} m_1 & 0 & \cdots & 0 & 0 \\ 0 & m_2 & 0 & \vdots & 0 \\ & 0 & \ddots & 0 & \vdots \\ \vdots & \vdots & 0 & m_{N-1} & 0 \\ 0 & 0 & \cdots & 0 & m_N \end{bmatrix}$$

Fig. 1 (a) Vibrating system model with multi-degree of freedom showing a diagrammatic representation of the ferromagnetic powder aggregates by the magnetic field of the permanent magnet in the electrical generator. (b) Vibrating system with multi-degree of freedom model of the spike-shaped aggregate of the ferromagnetic powders by the outside permanent magnet of the electrical generator housing

Damping matrix: C

$$= \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & \cdots & 0 \\ -c_2 & c_2 + c_3 & -c_3 & \cdots & 0 \\ 0 & 0 & \ddots & 0 & \vdots \\ \vdots & \cdots & -c_{N-3} & c_{N-2} + c_{N-1} & -c_N \\ 0 & \cdots & 0 & -c_{N-2} & c_{N-1} + c_N \end{bmatrix}$$

Stiffness matrix: K

$$= \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & \cdots & 0 \\ -k_2 & k_2 + k_3 & -k_3 & \cdots & 0 \\ 0 & 0 & \ddots & 0 & \vdots \\ \vdots & \cdots & -k_{N-3} & k_{N-2} + k_{N-1} & -k_N \\ 0 & \cdots & 0 & -k_{N-2} & k_{N-1} + k_N \end{bmatrix}$$

Because the magnetic flux crosses the coil, an electromotive force (V) is generated by Faraday's law of electromagnetic induction as expressed in Eq. (2). It is thought that if the magnetic flux density and the movement velocity of the conductor are large, and if a conductor is long, the electromotive force becomes large, but the electricity loss is large because the electrical resistance increases.

In addition, it is understood that if the magnetic induction of the ferromagnetic powders is large and if the magnetic permeability of the permanent magnet is large, the electromotive force is also large.

$$V = -N \frac{\Delta\Phi}{\Delta T} \quad (2)$$

V induced electromotive force
 N the number of the winding of the coil
 Φ magnetic flux density
 T time

Ferromagnetic powders (ferrite of 3.2 μm average particle diameter) composed of Mn-Zn and manufactured by Toda Kogyo Corporation were used as the magnetic powders in this study. Figure 2 is a scanning electron microscope (SEM) photograph of ferromagnetic powders used in this study.

The particle size of the magnetic powder is dangerous to the environment if it is too small (nanometer), and if it is too large, energy is lost due to mechanical loss such as friction, so a particle size of submicron order was used. The average particle size was measured by a laser diffraction/scattering particle size distribution analyzer manufactured by HORIBA, Ltd.

Generator Testing

In this study, a 0.2 mm wire was wound up 3600 times around a 250 mm long polyvinyl chloride pipe of outer diameter 22 mm and inner diameter 16 mm, and a neodymium magnet

Fig. 2 Ferromagnetic powders (ferrite of 3.2 μm average particle diameter) SEM photograph

of magnetic induction 280 mT and dimensions 150 $\times$ 8 $\times$ 8 mm was placed parallel to the coil/wound up wire. 20 cc of water and 5–15 g of magnetic powder were put in a pipe housing to make the electrical generator. The electrical generator was set to the shaker and the following vibrations applied at a 40-mm amplitude: 1.5 Hz = 0.043 G, 2.0 Hz = 0.317 G, 2.5 Hz = 0.469 G, 3.5 Hz = 0.977 G, 4.5 Hz = 1.465 G, 5.0 Hz = 2.002 G. An accelerometer was attached to the electrical generator to measure the acceleration. Since, the frequency of ocean waves is approximately 0.1 to 10 Hz, and the movement of sea creatures is within the frequency range of 0.5–3 Hz.

In this study, magnetic inductions of 13, 23, 48, and 68 mT were created at distances of 7.2, 10.2, 12.3, and 17.4 mm from the permanent magnet and measured by magnetic meter (MG-3003SD, FUSO Co., Ltd.) (Fig. 3).

Therefore, a total of 72 experiments were conducted with frequencies of 1.5, 2.0, 2.5, 3.5, 4.5, and 5.0 Hz (accelerations of 0.043, 0.317, 0.469, 0.977, 1.465, and 2.002 G); magnetic inductions of 13, 23, 48, and 68 mT; and ferromagnetic powder masses of 5, 10, and 15 g. Figure 3 shows the experimental device.

Testing by High-Speed Microscope

The still images are photographed at 1000 fps with the high-speed microscope (VW-9000, Keyence Co., Ltd.). Photography condition of 15 g of ferromagnetic powders and 20 cc of water with the transparent polyvinyl chloride pipe, having a length of 250 mm, outer diameter of 22 mm, and an inner diameter of 16 mm was vibrated with a frequency of 2.8 Hz (vibration amplitude 40 mm) by the shaker.

Simulating Motion of Generator Contents

In the electrical generator of this study, it is thought that the behavior of the fluid and the direction of magnetic induction and the magnetic flux greatly contribute to electrical generation [54]. Therefore, the efficiency of the electrical generation was considered by analyzing the magnetic flux distribution of the electromagnetic permanent magnet and using the data to generate a computer simulation [55].

In the next chapter, the influence of the fluid on ferromagnetic powder aggregates was examined in the electrical generator by fluid analysis using the general-purpose finite element program CFD (computational fluid dynamics).

As mentioned in the preceding section, though the downward power of gravity and the power of adsorption of the permanent magnet produces the spike-shaped aggregates of the ferromagnetic powders by the magnetic field of permanent magnet, it was observed that the spike-shaped aggregates of ferromagnetic powder are transformed, inclined, moved, and they float in the fluid as observed with the high-speed microscope in simple harmonic oscillation at the vibration frequency of 2.8 Hz. Because the

Fig. 3 Measurement image of the magnetic induction in the electrical generator

maximum inflow velocity of the simple oscillation of amplitude 40 mm and the vibration frequency 2.8 Hz is 0.703 m/s, a CFD simulation was performed to determine the effect that a fluid of inflow speed 0.703 m/s would produce in the spike-shaped aggregates of ferromagnetic powder.

CFD of Boundary Conditions

An initial condition for the computer simulation of five cones (spikes) of the spike-shaped aggregates of ferromagnetic powder was set by the magnetic field of the permanent magnet in the electrical generator housing (Fig. 4). The boundary condition of the CFD was defined by the top surface opening model with the same flow velocity model, except for a wall at inflow, a free outflow condition, and the non-slip model at the wall

surface (Fig. 4a). In addition, it was assumed that the pressure incline of the normal direction in the wall surface and in the inflow is zero, and that the pressure at the exit is the same, i.e., 0 Pa: the numerical computation of convenience.

The even velocity in the entrance by a simple oscillation of amplitude 40 mm of the frequency 2.8 Hz is expressed as maximum velocity in Eq. (3).

$$V_{\max} = A \times 2\pi f \quad (3)$$

$V_{\max}$ maximum velocity of the simple oscillation
 A the amplitude
 f frequency

Fig. 4 Initial condition image of the fluid analysis simulation of the electrical generator using ferromagnetic powder and the non-magnetic fluid. (a) Device whole view image. (b) The case of without the fluid

pressure. (c) The case of the fluid pressure from the left to the right. (d) The case of the fluid pressure from the right to the left

The entrance fluid velocity in Fig. 4 is calculated with the maximum velocity of Eq. (3), and the inflow velocity at the frequency of 2.8 Hz is calculated as 0.703 m/s. Furthermore, water was used for the experiment, so the fluid viscosity was set at 0.001 Pa s, the fluid density at 998.2 kg/m³, and the thermal conductivity at 0.6 W/m, K. In addition, the spike-shaped aggregates of the ferromagnetic powder are the conic obstacles in the duct; thus, we simulated the flow in electrical generator with a turbulence mode.

The agreement of (A–E) distinguishes the positions of the spike-shaped aggregates of ferromagnetic powder in Fig. 4, indicating the initial condition of the CFD.

In this research work, we used analysis application ANSYS Academic Teaching Advanced of the supercomputer of ACCMS, Kyoto University.

Results

Generator Testing

At a vibration frequency of 2.0 Hz (acceleration, 0.317 G), when the magnetic powder weight is 5, 10, and 15 g, relatively large power generation is observed only when the magnetic flux density is as low as 13 mT (Fig. 5a).

At the frequency 3.5 Hz (acceleration, 0.977 G), the generated voltage decreases with increasing magnetic flux density when the magnetic powder weight is 5 and 15 g, but this tendency is not observed when the magnetic powder weight is 10 g (Fig. 5b).

At the frequency 5.0 Hz (acceleration, 2.002 G), this tendency becomes even stronger. When the magnetic powder weight is 5 and 15 g, the generated voltage tends to decrease as the magnetic flux density increases. In the case of 10 g, it is recognized that the generated voltage increases as the magnetic flux density increases. It is recognized that the largest power generation is possible at a magnetic powder weight of 10 g (the magnetic flux density 48 mT) (Fig. 5c).

At a frequency of 2.0 Hz = 0.317 G and 3.5 Hz = 0.977 G, the lateral force of the fluid due to acceleration is smaller than the vertical attraction due to the magnetic flux of the permanent magnet, so magnetic powders accumulate and are hard to move. Therefore, it is considered that the electrical generation voltage becomes small (Fig. 5a, b).

On the other hand, at the frequency 5.0 Hz = 2.002 G, when the magnetic flux increases from 13 to 23 mT, the lateral force of the fluid due to acceleration is larger than the attraction force of the permanent magnet, and the spike-shaped aggregates of ferromagnetic powder move easily. Therefore, the generated voltage increases. However, if the magnetic flux is increased to 68 mT, it is considered that the attraction force of the magnet is stronger to the lateral force of the fluid due to the acceleration, and the magnetic powder is accumulated, so that it is difficult to move, and the generated voltage decreases (Fig. 5c).

Output voltage increases with higher magnetic flux and larger ferromagnetic powders mass. In addition, the standard partial regression coefficient of magnetic flux density is low (− 0.17) (Table 1).

It is suggested that when acceleration is low and magnetic flux density is low, the spike-shaped aggregates of ferromagnetic powder are difficult to move due to their attraction to the permanent magnet magnetic field. Thus, the electricity generated decreases.

When the weight of ferromagnetic powders increases, generated voltage increases. However, after the weight increases above a certain fixed value, voltage starts to decrease, possibly because it becomes hard to physically move the ferromagnetic powder in the pipe. Therefore, the standard partial regression coefficient of the ferromagnetic powders mass is low (− 0.05). On the other hand, the standard partial regression coefficient of the frequency was 1.23, suggesting that most of the increase of voltage generation is caused by the frequency. Thus, the effects of magnetic flux density and ferromagnetic powders mass on electricity generation are low under the acceleration level (2.002 G) used in this experiment. Future study is needed to understand the effect of these two variables on electricity generation under greater acceleration (3 G).

Acceleration (vibrational frequency) significantly affected generated voltage. Therefore, we performed a simple linear regression analysis to find the relationship between generated voltage and vibrational frequency level. The contribution of the frequency in the electricity generation showed high value of 0.89 (Table 2). Simple linear regression analysis (without considering the effects of ferromagnetic powder mass and magnetic flux density) showed a highly linear relationship between vibrational frequency and output voltage. Actual and predicted values (by single regression analysis, frequency vs output voltage) of output voltage depending on frequency are shown in Fig. 6.

If magnetic flux density is low (13 mT), and frequency is 2.0 Hz (acceleration, 0.317 G) or 3.5 Hz (acceleration, 0.977 G), the spike-shaped aggregates of ferromagnetic powder are easy to move. Even with 10 g of magnetic powders and a high magnetic flux density (48 mT), if acceleration is high (1.465 G, 2.002 G), the spike-shaped aggregates of ferromagnetic powder are moved, and generated voltage is high (the maximum generation in Fig. 6). In the case of much quantity of magnetic powders (10 or 15 g), 2.0 Hz (acceleration, 0.317 G), the low frequency of 3.5 Hz (acceleration, 0.977 G), and large magnetic flux density (68 mT), the spike-shaped aggregates of ferromagnetic powder are hard to move, and generated voltage is low (the minimum generation in Fig. 6).

Result of High-Speed Microscope Observation

With the average particle diameter of the ferromagnetic powders at 3.2 μm, the phenomenon could not be observed clearly

Fig. 5 Output voltage plot and frequency (acceleration) against ferromagnetic powders weight and the magnetic flux density by the distance of the permanent magnet

(Fig. 7a). Thus, average particle diameter (3.2 and 419 μm) ferromagnetic powders were photographed. A photograph of average particle diameter 419 μm is very clear (Fig. 7b). It is seen that the ferromagnetic powders stick out like the spike form as a result of the magnetic field of the outside permanent magnet of the pipe by the high-speed microscope photograph. Furthermore, it is seen that these spike-shaped aggregates of ferromagnetic powder are transformed or moved by the lateral pressure of the non-magnetic liquid (water).

In the stationary state, the spike-shaped aggregates of ferromagnetic powder are pressed down on the inside wall of the electrical generator housing by the gravity of the spike-shaped aggregates and by the magnetic power of adsorption of the permanent magnet. But it was observed that the spike-shaped aggregates of ferromagnetic powder float in the fluid if moved by the vibration of the electrical generator. Therefore, it was speculated that the vibration from the electrical generator nullified the friction between the housing wall surface of the

Table 1 Results of multiple regression analysis

Factor	Partial regression coefficient	Standard partial regression coefficient
Sections	30.5	
Vibration acceleration (G)	89.5	1.23**
Magnetic flux density of the container inner wall surface (mT)	− 0.39	− 0.17
Weight of ferromagnetic powders (g)	− 0.6	− 0.05
Contribution ratio	0.84	

** $P < 0.01$

Table 2 Results of single regression analysis

Factor	Partial regression coefficient
Section	0
Acceleration	55.77
Contribution ratio	0.89
Significant	1.36E–35

electrical generator and the spike-shaped aggregates of ferro-magnetic powder.

Simulating Motion of Generator Contents

Figure 8 a shows fluid pressure distribution when a generator housing moved from a stationary state laterally. When the fluid moves from the left to the right, the pressure occurs at the left side of spike-shaped aggregate (A) and the negative pressure occurs between the spike-shaped aggregates. It is seen that when the spike-shaped aggregate inclines, the negative pressure of the gap domain of the spike-shaped aggregates increases more, and more lateral fluid pressure occurs on the aggregates. In other words, the aggregates' lateral transformation becomes pronounced as the aggregates incline.

In addition, when aggregate (A) inclines aside, the negative pressure of the upward fluid pressure increases, and the power to rise above occurs (Fig. 8b). This phenomenon propagates like a chain reaction instantly in aggregates B–E. Furthermore, it is understood that because motion of fluid is reciprocating motion, reverse lateral fluid pressure occurs with the opposite edge spike E after a half cycle (0.18 s) and that ascending power occurs on the spike-shaped aggregate E (Fig. 8c).

This phenomenon propagates like a chain reaction instantly from aggregate D to A also. Figure 9 presents a contour showing the speed distribution of the fluid of this phenomenon. It is seen that the negative pressure occurs in the point where the fluid velocity becomes larger (Figs. 8 and 9).

Discussion

Generator Testing

Figure 5a indicates that if the external force is small (acceleration, 0.317 G), the magnetic flux density needs to be reduced. Figure 5b considered that when the magnetic powder weight is 5 g, the magnetic powder spikes are small and difficult to move due to the attractive force of the magnet when the magnetic flux density from the permanent magnet increases.

Furthermore, it can be understood that when the frequency is as fast as 5.0 Hz (acceleration, 2.002 G) and the magnetic powder weight is moderate at 10 g, the generated voltage increases even if the magnetic flux density is large (Fig. 5c).

Therefore, the relationships between quantity of ferromagnetic powders, strength of magnetic induction, and vibration frequency (acceleration) are important to maximizing electrical generation.

Within the vibration frequency in the experiment, the generation peak at the resonance point accepted in other energy harvesting methods is not recognized. Thus, it was concluded that in this study, the electricity is generated by the multi-degree of freedom oscillation system because it has many resonance points owing to the use of ferromagnetic powders.

Fig. 6 Output voltage plot against actual (diamond) and predicted (red square, by single regression analysis) frequency values. The partial regression coefficient of the frequency was 0.80. The output voltage and the frequency showed high linear relationship under the condition of the experiment in this study by single regression analysis (frequency vs output voltage)

Fig. 7 Photography image with a high-speed microscope at 1000 fps. The polyvinyl chloride pipe (length = 250 mm, diameter = 20 mm) was vibrated (at frequency = 2.8 Hz, vibration amplitude = 40 mm, acceleration = 2.7 G) by a shaker. Enclosed magnetic powders (mass = 15 g), in 20 cc of water. The magnetic flux density from a permanent magnet = 28 mT. (a) Average particle diameter = 3.2 μm . (b) Average particle diameter = 419 μm

As for the vibration models in vibrational energy harvesting, the one mass point and two mass point systems are mainstreams and the resonance frequency is one or two and thus they cannot generate electricity by larger broadband vibrations [56–58]. Furthermore, the generation at the low frequency is very difficult in the study of vibrational energy harvesting [59].

Therefore, the flexibility system vibration model using ferromagnetic powders has many resonance points, and thus, broadband vibration electrical generation become possible. The technical problem in vibrational energy harvesting is electrical generation via the broadband vibration frequency and the low frequencies [48]. The ferromagnetic powders enable the generation of electrical energy from the broadband vibration frequency. In addition, using the non-magnetic fluid in the vibration electrical generator of this study enables low-frequency electrical generation.

If the frequency is much lower than the resonance frequency in the one mass point system model, the exercise is not handed down to a mass point. Instead, the generation energy becomes zero [45]. However, in the case of a mass point in the fluid, the drag on the mass point from the fluid for low kinetic

energy at a low frequency is shown in Eq. (4) derived from Newton's law of resistance.

Furthermore, the fluid energy per unit time required to impact the mass point in Eqs. (4) and (5) is derived in Eq. (6) based on the Reynolds number expressed in Eq. (5). Thus, for the electrical generator in this study, the amount of energy required to impact the spike-shaped aggregates of ferromagnetic powder is influenced by fluid viscosity and fluid velocity.

$$D = \frac{1}{2} \rho V^2 S C_d \quad (4)$$

ρ mass density of the fluid

V flow velocity

S cross-sectional area

C_d drag coefficient (a vertical angle 30° circular cone: 0.34)

$$Re = \frac{\rho V L}{\mu} \quad (5)$$

Fig. 8 Fluid pressure distribution (fluid velocity = 0.703 m/s, frequency = 2.8 Hz). (a) The case without the fluid pressure. (b) The case of the fluid pressure from the left to the right. (c) The case of the fluid pressure from the right to the left

Fig. 9 Fluid velocity: inflow fluid velocity = 0.703 m/s, vibration frequency = 2.8 Hz. (a) The case without the fluid pressure. (b) The case of the fluid pressure from the left to the right. (c) The case of the fluid pressure from the right to the left

Re Reynolds number (a vertical angle 30° circular cone $Re > 10^4$)

L characteristic length (constant value)

μ coefficient of viscosity

Eq. (6) is derived from Eq. (5).

$$\rho = \frac{Re\mu}{VL} \quad (6)$$

Substitute Eq. (6) for Eq. (4)

$$D = \frac{Re\mu VSC_d}{2L} \quad (7)$$

The movement length of the fluid at 1 s, V .

Therefore, the fluid energy reaching the spike-shaped aggregate per unit time is expressed by Eq. (8):

$$D \times V = \frac{Re\mu V^2 SC_d}{2L} \quad (8)$$

The electric generation of the electrical generator in this study happens by changes of the magnetic flux density in the coil in accordance with Faraday's law stated in Eq. (2). The pressure of the fluid in the electrical generator greatly contributes to the movement or transformation of the spike-shaped aggregates of ferromagnetic powder. In other words, it is understood that the fluid velocity considerably influences the electrical generation by Eq. (8).

When the electrical generator having a gross weight of 370 g is vibrated at an amplitude of 40 mm, a voltage of 180.2 mVp-p and an electric current of 2 mA at a frequency of 5.0 Hz are generated. Consequently, from Eq. (9), the input energy is 0.292 J.

$$E = 2\pi^2 mf^2 A^2 \quad (9)$$

m mass

A amplitude

f frequency

$$E = 0.292 \frac{Kgm^2}{s^2} = 0.292 J$$

The execution voltage is calculated from measured values as follows.

$$\text{Actual voltage value} = (180.2 \text{ mVp-p}/2)/\sqrt{2} = 63.7 \text{ mV}$$

$$\sqrt{3} \times 63.7 \text{ mV} \times 2 \text{ mA} = 221 \mu\text{W} = 0.221 \text{ mW} = 0.000221 \text{ W}$$

$$\text{Power factor} = 0.9$$

$$\text{Effective generation electricity } P: 0.000221 \times 0.9 = 0.000200 \text{ W} = 0.200 \text{ mW} = 200 \mu\text{W}$$

$$\text{Electric energy of 1 s: } 0.200 \text{ mW} \times 1000 \text{ ms} = 200 \mu\text{J}$$

$$\text{The volume of the electrical generator: } 3.14 \times 11^2 \times 250 = 94985 \text{ mm}^3$$

The generated electricity per volume of the electrical generator at vibration frequency of 5.0 Hz in this study is $2.11 \mu\text{W}/\text{cm}^3$, and this value is at the same level as article of the vibration energy harvesting [40, 60].

Simulating Motion of Generator Contents

Figure 10 shows the exercise process of the spike-shaped aggregates by the fluid pressure. Aggregate A rises from the generator housing wall surface by the fluid pressure (Fig. 10a) and aggregates B–E rise from the housing wall surface like a chain reaction (Fig. 10b). When the reciprocating

Fig. 10 Image of the power to appear in each spike-shaped aggregates of ferromagnetic powder. (a) The case without the fluid pressure. (b) The case of the fluid pressure from the left to the right. (c) The case of the fluid pressure from the right to the left

motion of the generator turns into reverse motion, the aggregate E of the opposite direction is raised from the wall surface of the electrical generator by the fluid pressure. The aggregates D–A in a chain reaction are then raised from the housing wall surface by the fluid pressure (Fig. 10c).

An electromagnetic analysis was conducted by running a computer simulation in ANSYS simulating the distribution state of the magnetic flux density induced in the spike-shaped aggregates of ferromagnetic powders by the permanent magnet. Shirai et al. [55] showed that the magnetic flux density concentrates on the tip of the aggregates of the ferromagnetic powders.

Because the motion at the tip of the spike-shaped aggregates of ferromagnetic powder is largest during the reciprocating motion, as shown in Fig. 7, it indicates that the electrical generator in this study generates electricity efficiently. From even very slow speed motion, the electrical generator generates electricity efficiently from the changes on the analyzed magnetic flux density per Faraday’s law of electromagnetic induction.

In the spike-shaped ferromagnetic powder aggregates due to the magnetic flux of the permanent magnet, the magnetic particles can be oriented by the magnetic flux. Thus, the spike-shaped aggregates of ferromagnetic powder can capture the magnetic flux efficiently.

The energy of the fluid causes the spike-shaped ferromagnetic powder aggregates to move flexibly, and even with a small fluid energy, the magnetic flux in the spike-shaped aggregates of ferromagnetic powder can efficiently generate electric energy in the coil.

Conclusion

The resonance model of the broadband vibration frequency that made the flexibility vibration system using ferromagnetic

powders in vibrational energy harvesting was created. Furthermore, a non-resonance type model of this device was suggested and may be achieved by adding a fluid to the designed model which enables it to handle vibrations at very slow motion.

In this study, we use computer simulation to study the efficiency of our electrical generator and the influence of fluid on the movements of the spike-shaped aggregates of ferromagnetic powder, and therefore on energy generated.

We found that the shape of the ferromagnetic powder aggregates is significant, and that the efficiency of electricity generation is greatly influenced by fluid movement. It is likely that the ferromagnetic powder aggregates are moved upward by the action of the fluid when the electrical generator is shaken, and that the friction loss due to the housing disappears, contributing to generation efficiency.

The electric generator in this study can convert motion into electric energy using ferromagnetic powders and fluid from the naturally occurring low-intensity, slow kinetic energy. Therefore, this electric generator could generate energy from a variety of energy sources such as animal body movements and could be applied to numerous purposes.

The characteristics of the electrical generators obtained in this study are summarized as follows.

1. The electrical generator converts a reciprocating motion into electrical energy.
2. Because there are no mechanical parts, in particular sliding parts, there is no source of abrasion or noise.
3. In this electrical generator, fluid is used to influence the magnetic field of a permanent magnet using ferromagnetic powders. This creates a highly flexible vibration system where voltage generated is linearly dependent on vibration frequency.

4. The use of ferromagnetic powders made it possible to generate electricity flexibly from broadband vibrations.
5. The use of fluid in this device made it possible to generate electricity from very slow motion.
6. The device in this study is highly adjustable and thus can be applied in many environments. By regulating magnetic flux density (by adjusting the distance between the permanent magnet and the generator contents) and ferromagnetic powder weight, this generator can generate electricity using a wide range of vibration frequencies.
7. The materials used in this study are environmentally harmless.
8. The spike-shaped ferromagnetic powder aggregates can capture the magnetic flux efficiently. Even with a small fluid energy, the magnetic flux in the spike-shaped aggregates of ferromagnetic powder can efficiently generate electric energy in the coil.

The electrical generator in this study, without its fluid component, is also suitable for use with vibrations in the range of 10–500 Hz, which are faster than the range considered in. A subsequent study will report on this separately.

It is thought that this study can become the breakthrough of the technical problem in energy harvesting. For practical use, it is thought that a further study must be conducted in the future.

Acknowledgments The supercomputer of ACCMS, Kyoto University was used for this research. The authors thank Jason Hideki Preble (Kyoto University) for this study.

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