Micro Power Generation using Magnetic Elastomer for Energy Harvest

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Abstract
This paper presents a method of energy conversion for an electromagnetic oscillation to electrical micro-power using magnetic-elastomer, and this method can efficiently scavenge power generator from low-frequency external vibration. In the present study, we focused on comparing experimental data to theoretical analysis in newly made experimental set up with various magnetic-elastomers. The theoretical analysis is based upon the law of Faraday’s electromagnetic induction, in which the induced electromotive force can be estimated from the vibration of the magnetic-elastomer under the magnetic field. From the result of experiment, it was found that the measured peak output power was 5.64 μW at 1.6 Hz. The theoretical analysis revealed that data obtained in the experiment are well explained by means of alternating internal magnetization. Also in the present study experimental results are correlated with non-dimensionalized parameters, which involve all essential material parameters and governing dynamic properties.

Key words
Magnetic-Elastomer, Micro Power Generation, Electromotive Force, Magnetic Field, Low frequency

1. Introduction
The global electrical energy consumption is rising and there is a steady increase of the demand on the power capacity, efficient production, distribution and utilization of energy. The increasing energy demand in near future will force us to seek environmentally clean alternative energy resources. In energy scavenging technique, power can be generated from various environmental sources such as ambient heat, light and vibration. In particular, several scavenging techniques using vibration based on piezoelectric, electrostatic and electromagnetic transduction have been reported in recent years [1-6]. In order to realize the power generation from various available energy resources, an electromagnetic power generation using magnetic-elastomer, which has been newly introduced in industrial applications such as the flow control valve and artificial muscles in robot etc.[7-14], is one of a promising candidate for the demand.

This paper reports a new application of micro-electromagnetic power generation using a magnetic-elastomer with low frequency oscillation. Fig. 1 shows the magnetic-elastomer used in this study. Magnetic-elastomer adapted in the present study is a new class of stimuli-responsive polymeric materials, in which their properties can be controlled by magnetic field. Such materials can be utilized in various engineering applications in which large deformation with elastic character can exert substantial magnetic force due to internal structural change. The theoretical back ground of the present power generation method is based upon the law of Faraday’s electromagnetic induction, that is, an externally forced vibration of magnetic-elastomer under a given magnetic field induces the electromotive force.

Fig.1 Magnetic-elastomer

Fig.2 Schematic diagram of deformation of magnetic-elastomer under given magnetic field; (a)→(b) Oscillation
2. Principle of this Method
In magnetizable body, the magnetic flux density \( B \) [T] is given by the following formula in general:

\[
B = \mu_0 (H + M)
\]  

(1)

where \( \mu_0 \) is the permeability [-], \( H \) is the magnetic field [A/m] and \( M \) is magnetization [A/m]. The magnetic flux density \( B_{fg} \) [T] in magnetic-elastomer can then be written by the following magnetic polarization formula, based on an assumption that distribution of deformation and volume void distribution of magnetization are equivalent.

\[
B_{fg} = \mu_0 \left\{ H + (1 - q) M_{fg} \right\}
\]  

(2)

where \( q \) is the volume void of magnetite-elastomer [-] and \( M_{fg} \) is the magnetization of magnetic-elastomer [A/m]. It is noted that the change of magnetic susceptibility in deforming magnetic-elastomer is neglected. Based on the Faraday’s law, the induced electromotive force generated in an induction coil (winding turn is \( n \) [turns]) is then written by

\[
V = -n \frac{\partial}{\partial t} \int \left\{ \mu_0 \left\{ H + (1 - q) \chi H \right\} \cdot \hat{n} \right\} dS
\]  

(3)

where \( \chi \) is the magnetic susceptibility [-]. Fig.2 illustrates schematic diagram of deformation of magnetic-elastomer under a given magnetic field, which is imposed by an external solenoid coil. With deformation of magnetic-elastomer by oscillatory external force, the electromotive force is generated in an induction coil. Fig.3 shows a represent signal of electromotive force recorded from the induction coil, with the sampling rate of 514 /sec. From the RMS (root mean square) value of the waveform, we can find the time-average-power generation.

3. Test Specimens and Experimental Set Up
3.1 Test specimen
In the present study, in manufacturing a test specimen of magnetic-elastomer, silicone gel as base material and ferromagnetic particles as dispersant are used. For base material the silicone gel elastic modulus can be treated as a soft material linear elastic material (with first response function) within the experimental condition. Table 1 shows basic properties of silicone gel used in the present study. In this study, Carbonyl iron powder (SQ: BASF Japan Ltd.) is used as dispersant particles. Wave signal is recorded by oscilloscope from the pick-up electric current, with the sampling rate of 514 /sec. Table 2 shows basic properties of the magnetic particles, whose mean diameter is approximately 5.40 μm. In preparation of test specimen, silicone gel was stirred with different concentration of the magnetic particles by mixture ratio of 20wt.% and 30 wt.%. Synthesizing the

| Table 1 Property of silicone gel |
|-------------------------|------------------|------------------|
| Silicone gel           | Density [kg/m³] | Penetration[JIS K 2530] | Curing condition [K,h] |
| TSE3062                | 970              | 55               | 343.15 , 0.50          |

<table>
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<th>Table 2 Property of magnetic particles</th>
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<td>Magnetic particles</td>
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<td>Carbonyl SQ</td>
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<th>Table 3 Properties of magnetic-elastomer</th>
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<td>Mixture ratio[wt.%]</td>
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magnetic-elastomer, the test specimen, was carried out at heating temperature of 343.15 K with conditions for 30 minutes harding time, using a homoeothermic machine. In the present study, two kinds of the aspect ratio (1.2 and 1.8 aspect ratio) of magnetic-elastomer are manufactured and tested. Table 3 shows properties of the magnetic-elastomers.

3.2 Experimental set-up
Fig.4 illustrated the schematic diagram of the experimental set-up. Oscillation given to the magnetic-elastomer was achieved through external mechanical force. The external force, applied to the magnetic-elastomer by rod, is driven and transmitted by crank-gear mechanism connected to a driving motor. External magnetic field is then applied by an external solenoid coil, which is controlled by a DC power supply unit, to yield constant magnetic field intensity of 140 mT. Fig.5 displays the magnetic field distribution from the external solenoid coil, at the position of the magnetic-elastomer. The pick-up signal, the electromotive force, is amplified, recorded and displayed with an oscilloscope, the dimension of induction coil is such that; diameter of 40 mm, thickness of 0.1 mm, winding turns of 1500 turns and copper wire diameter of 0.5 mm. Magnetic-elastomer was placed in an acrylic container, on which the induction coil was winded. The periodic displacement perpendicular to the magnetic-elastomer was executed by external force through the driving unit, and the connecting rod as shown in Fig.4. In experiments, the oscillating motion to magnetic-elastomers was given at low frequency range from 0 to 1.6 Hz. The alignment of imposed external force and strain of the magnetic-elastomer is set meticulously to yield constant strain of ε=8.0 mm, which gives q constant value.

4. Results and Discussion
4.1 Comparison of experimental value with theoretical estimation

Fig.6 and Fig.7 show representative data of the induced electromotive force in the case of 30 wt.% mixture ratio and 20 wt.% mixture ratio respectively for the same magnetic-elastomer of aspect ratio of 1.8. In both figures of Fig.6 and Fig.7, the theoretical prediction from Eq.(3) and experimental results are also compared for the frequency range up to 1.6 Hz.

In both cases (Fig.6 and Fig.7), the comparison between the theoretical prediction and experimental results indicates good qualitative agreement. The deviations from the theoretical prediction and experimental results, in Fig.6 and Fig.7, are tended to be widened (maximum 29 % at 1.6 Hz for 20 wt.% mixture ratio in Fig.7, and 20.2 % at 1.6 Hz for 30 wt.% mixture ratio in Fig.6) as the imposed frequency is increased, though at lower frequencies the differences are
so as to determine the performance of power generation. With \( l=0.6 \) and \( m=-0.6 \), as seen Fig.8, the experimental results are found to be correlated very well by the relation of Eq.(4) and Eq.(5), indicating that the frequency and aspect ratio have effect on the power generation (the electromotive force) with almost the same order of magnitude \((l=0.6 \) and \( m=-0.6 \)). It has clearly shown (in Fig. 8) that the power generation (at low frequency range) increases with increasing the frequency and aspect ratio within the range adapted in the present study.

The above results show that the magnetic elastomer generates an electric power with its deformation in the low frequency condition (1.6 Hz), the maximum power is 5.64\( \mu \)W. Therefore the test carried out in the present investigation revealed that the new application of energy harvest using magnetic elastomer.

### 5. Conclusion

Experimental studies are conducted to verify the performance of power generation of magnetic-elastomer under oscillatory deformation in a given magnetic field. Theoretical analysis is given to estimate the experimental results.

It was found that the theoretical analysis can predict the results obtained from the experiments fairly well. The errors (deviation from experimental results) are thought to be chiefly due to estimation of deformation degree of magnetic-elastomer, considering visco-elastic dynamics. A correlation relation is proposed to evaluate the performance of power generation. The proposed correlation can yield good estimate of the experimental results by choosing approximate value of the correlation constants (index value of \( l \) and \( m \)).

### Nomenclature

\(|B|\quad\text{magnetic flux density}\quad[T]

\(|B_{fg}|\quad\text{magnetic flux density of magnetic elastomer}\quad[T]

\(|H|\quad\text{magnetic field}\quad[A/m]

|i|\quad\text{current value}\quad[A]

|M|\quad\text{magnetization}\quad[A/m]

|M_{fg}|\quad\text{magnetization of magnetic elastomer}\quad[A/m]

|n|\quad\text{winding turns}\quad[\text{turns}]

|P|\quad\text{electricity generated}\quad[\text{W}]

|q|\quad\text{volume fraction of magnetic elastomer}\quad[-]

|V|\quad\text{electromotive force}\quad[V]

|V_{rms}|\quad\text{RMS value of electromotive force}\quad[-]

|\kappa|\quad\text{specific electric conductivity}\quad[\text{V}]

|\mu_0|\quad\text{permeability}\quad[-]

|\chi|\quad\text{magnetic susceptibility}\quad[-]

|L|\quad\text{aspect ratio}\quad[-]

|l, m|\quad\text{conflation index}\quad[-]

### Subscripts

|\bar{\mu}_\text{fg}|\quad\text{ferrogel}

|\text{rms}|\quad\text{root mean square}
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References