Development of a PZT device-based power-generating shoes for disaster-affected areas

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Abstract. A PZT device is an element that generates electric power when an impact is applied by vibration. Currently, PZT devices are installed on the floor near the ticket gates to supply power to station equipment, and on the floor of bridges to turn on LEDs at night. Since the current generated by the PZT device is small, there is a disadvantage that the electric power obtained is small. In this paper, we developed a power-generating shoe using PZT devices for use in disaster-affected areas where power shortages tend to occur. The validity of the developed power-generating shoes is experimentally evaluated under the variation of PZT device, shoes and secondary batteries. At present, the result is that it is possible to charge about 1.5% of mobile phones at the maximum. In order to reduce loss and obtain more power, it is necessary to improve shoes and to build a charge / discharge circuit.

1. Introduction

In recent years, large-scale disasters have often occurred in Japan due to earthquakes and abnormal weather. The national Disaster Medical Assistant Team (DMAT) is a group of professional medical personnel developed in Japan to provide rapid-response medical care or casualties decontamination during a natural disaster or any similar incidents. For DMAT, based on self-sufficiency, it is necessary to bring not only food but also electric power for medical treatment in principle. This principle makes it extremely difficult to secure the power for communication by mobile-devices at nighttime. Rapid transition of disaster information and request for relief supplies are one of the important tasks for DMAT.

If the electric power is generated in shoes and charged to secondary batteries while working in the daytime, the harvested energy could be used for this principle mentioned before. In order to achieve this, the vibration-powered generation that has been used in various situations becomes the focus of the subject [1-3].

In this case, not only do the power generation technology through the shoes matter, but the power management technology is also indispensable. Energy harvesting in shoes based on vibration-powered generation have been studied in various ways [4-6]. However, many of these power-generating shoes possess a specifically designed power generator built into the soles, thus lacking in versatility.

This paper focuses on power-generating shoes with a secondary battery that aims to use in disaster-affected areas. The developed power generator is attached in the insole. Therefore, the advantage of this power generator is the ease of use and the flexibility to be attached to other shoes. The validity of the
developed power-generating shoes is experimentally evaluated under the variation of piezoelectric lead zirconate titanate (PZT) ceramic devices [7-9], shoes and secondary batteries.

2. Structure of power-generating shoes and measurement of generated power

2.1. Structure of power-generating shoes
In this section, the developed power-generating shoes are explained. The power-generating shoes are constructed from insoles, PZT devices, middle shims and metal plates. Table 1 shows the specifications of these devices, and Figure 1 shows an overview of the developed power-generation device. The structure is such that a PZT device, a middle shim, and a metal plate are held between the two insoles, and a hole of 30 mm in diameter is made under the PZT device so that it is easily deformed by the foot pressure [10].

| Material of metal plate | Aluminum |
|-------------------------|----------|
| Material of middle shim | Silicon rubber |
| Size of middle shim [mm] | 12×12×3 |
| Size of PZT device [mm] | Φ35×Φ25×0.53×0.23 |
| (Plate diameter×PZT diameter×Plate thickness×PZT thickness) | |

Table 1. Specifications of power generator.

![Figure 1. Overview of power-generating shoes.](image)

2.2. Experimental conditions
In order to evaluate the electric power generated by the insole equipped with the power generation device, the walking experiments were conducted. In the experiment, the insole was inserted into three types of shoes, working boots, sneakers and sandals. Figures 2 (a), (b) and (c) show the sandals, sneakers and working boots used in the experiment. The generated energy from the PZT device at a resistive load was measured, and the mean value per step was derived when walking 100 steps. The walking speed was about 2.5 km/h. The load resistance was selected to be 1 MΩ which is the matching impedance.
2.3. Experimental results

The mean energy per step of each shoe is shown in Table 2. According to the experimental results, while the generated energy both for the sneakers and for the working boots was about 0.5 mJ, the energy for the sandals was about twice. It may be considered that the power generator in the sneakers and working boots does not vibrate well because the heel is in close contact with the insole. On the other hand, the sandal has a gap between heel and insole; the generator can well deform and vibrate during walking. Therefore, it can be seen that there is a difference in the generated energy depending on the type of shoes.

| Type of shoes | Mean energy per step [mJ] |
|---------------|--------------------------|
| Working boot  | 0.54                     |
| Sneaker       | 0.51                     |
| Sandal        | 1.05                     |

3. Comparison of various sizes of PZT devices

3.1. Shape of PZT devices

In this section, in order to improve power generation, PZT devices with different sizes are compared. The mean energy is measured and evaluated in terms of size. As for the PZT device, the differences in the plate diameter, the plate thickness, the PZT diameter and the PZT thickness were compared. Moreover, depending on the size of the PZT device used, the size of the middle shim and the size of the insole’s hole below the PZT device were changed. The specifications of the PZT devices are shown in Table 3. Table 4 shows the size of the middle shim between two plates and the hole below the PZT
device corresponding in each PZT device shown in Table 3. In the following section, the PZT device, middle shim and hole are referred to using the number, as shown in Table 3 and Table 4.

| PZT device | Size of PZT device [mm] |
|------------|-------------------------|
| (a)        | Φ20×Φ14×0.22×0.12       |
| (b)        | Φ20×Φ14×0.42×0.22       |
| (c)        | Φ27×Φ19.7×0.54×0.24     |
| (d)        | Φ41×Φ25×0.63×0.23       |

Table 4. Size of middle shim and hole.

| PZT device | Middle shim diameter [mm] | Hole diameter [mm] |
|------------|---------------------------|--------------------|
| (a)        | Φ5                        | Φ17                |
| (b)        | Φ5                        | Φ17                |
| (c)        | Φ10                       | Φ24                |
| (d)        | Φ12                       | Φ36                |

3.2. Experimental conditions
In order to evaluate the generated energy when using the four types of power generators shown in the previous section, experiments were carried out. The experimental conditions were the same shown in section 2.2. In addition, the tested shoe was selected as the sandal that generated the largest amount of generated energy, as described in section 2.3. The insole with the power generator was inserted into the sandal, and the mean energy per step was calculated.

3.3. Experimental results
The mean energy of each power generator per step is shown in Table 5. The generator (a) could not withstand the stress applied when walking and was broken. This is because both the plate and the PZT device were too thin. Comparing the generated energy when using (b) to (d), it can be seen that the energy becomes larger as the size of the generators gets larger. Moreover, comparing the energy when using the PZT device of (d) with the experimental results shown in section 2.3, it is noticed that the generated energy becomes slightly larger when using (d). The generated voltage and power for the resistance load when using (d) is shown in Figure 3. This is considered due to the fact that the PZT device was strained with the increase of the PZT size and the hole below it.

Table 5. Mean energy of power generator per step.

| PZT device | Mean energy per step [mJ] |
|------------|---------------------------|
| (a)        | broken                    |
| (b)        | 0.098                     |
| (c)        | 0.25                      |
| (d)        | 1.10                      |
4. Charging of mobile phones using secondary battery

4.1. Types of secondary batteries
According to Table 5, the power generating shoes with a currently developed PZT device attached to the insole can generate 1.1 mJ per step, which corresponds to about 52.8 J in 8 hours walking (48,000 steps). In this experiment, considering the capacities for the generated energy as well as the easiness of installation, three types of batteries were conducted for charging mobile phones. Table 6 shows the specifications of utilized secondary batteries. These secondary batteries are numbered as in Table 6 and will be compared in the following section.

| Battery Type | Product number | Capacity [mAh] | Output voltage [V] |
|--------------|----------------|---------------|-------------------|
| (e)          | EFL700A39      | 0.7           | 3.7               |
| (f)          | MS414GE        | 2.0           | 3.0               |
| (g)          | MS621FE        | 5.5           | 3.0               |

4.2. Experimental conditions
The charging energy to a mobile phone when using the three types of secondary batteries is evaluated. Each secondary battery was, at first, fully charged, and then the energy is re-charged to the mobile phone through the developed management circuit.

The mobile phone used in this experiment was the Nokia 105 SIM-Free mobile phone with a battery capacity of 800 mAh. Minimum charging voltage is 4.3 V DC across the battery terminals. From Table 6, since the output voltage of any secondary batteries is not higher than 4.3 V, charging cannot be performed. Therefore, in the secondary battery (e) of Table 6, the boost converter is incorporated in the circuit to set the output voltage up to 5 V. Moreover, for the batteries (f) and (g), the same two batteries are connected in series to set the output voltage up to 6 V. A shunt resistor with 10 Ω was connected in series to measure the current flowing to the mobile phone.

4.3. Experimental results
The applied voltage and current to the mobile phone when the secondary battery of (e) is used is shown in Figure 4. When (e) was used to charge the mobile phone, the charging time was instantaneously ended, and the charged energy was 0.122 J. It corresponds to $8.47 \times 10^{-4}$% compared to the total capacity 800mAh of the mobile phone.

Figures 5 and 6 show the applied voltage and current when (f) and (g) are used, respectively. When (f) was used for charging the mobile phone, the charge time of 40 seconds could be confirmed, and then
it was observed that charge and non-charge states repeated after 50 seconds. The charged energy was 0.393 J, and about 3 times of energy when using (e) could be confirmed. However, this is still a small value of $2.73 \times 10^{-3}$ % compared to the total capacity of the mobile phone.

When (g) was used, the charging time of 450 seconds was confirmed, and it was observed that the charged state and the uncharged state frequently repeated after 500 seconds. The charged energy was 1.921 J, which was 0.013% in comparison with the total capacity of the mobile phone.

In this experiment, a shunt resistance of 10Ω was connected in series to the mobile phone and a circuit in which a logger for voltage measurement with an internal impedance of 1MΩ was connected in parallel to it. Therefore, it is considered that there is a loss of energy in the shunt resistance and the internal impedance of the logger. In addition, when the output voltage of batteries becomes lower than the minimum voltage that can charge the mobile phone, the periodic switching such as charging and non-charging states appeared. As a result, the charging ends before releasing all the energy.

Moreover, when (e) is used, the energy is lost even in the boost converter incorporated in the circuit. Since the capacity of the secondary battery is small and the energy that can be charged to the mobile phone is limited, it is considered that (e) where loss is performed by the boost converter is not suitable for phone charging. Considering the charged energy and the capacity of the secondary battery, the most practical secondary battery could be (g). Therefore, the characteristics of the secondary battery (g) are considered in the following section.

![Figure 4](image-url). Applied voltage and current with secondary battery (e).

![Figure 5](image-url). Applied voltage and current with secondary battery (f).
4.4. Comparison with theoretical value

In this section, it is assumed that the theoretical value is the electric energy in secondary battery fully charged to the mobile phone. In this condition, the electric energy actually charged to the mobile phone shown in the previous section is evaluated. In addition, by using the developed power-generating shoes, how much energy can be charged on the mobile phone is shown. Table 7 shows the relationship between the number of PZTs attached to the power-generating shoes, the generated energy per step, and the total energy after 8 hours of walking. Table 8 shows the relationship between the number of the battery (g) used, the total energy when (g) is fully charged, and what percentage of the mobile phone can be recharged.

When comparing the energy actually charged in the mobile phone shown in the previous section (1.921 J), the theoretical value of the energy is 59.4 J. This value corresponds to 3.23%. The energy is lost for the reasons given in the previous section.

From Table 8, if four PZTs are attached to one insole of the power generating shoes and all of them can generate the same amount of power, the energy per step becomes 4.4 mJ. Moreover, if 8 hours walking is taken, the energy of 211.2 J can be generated. This means that four batteries of (g) are required, and the mobile phone can be charged 1.467% under the ideal conditions without losses.

| Table 7. Generated energy per step and total energy in an 8-hour walk with respect to the number of PZTs. |
|---|---|---|
| Quantity | Amount of power generation per step [mJ] | Amount of power generation in 8-hour walk [J] |
| 1 | 1.1 | 52.8 |
| 2 | 2.2 | 105.6 |
| 4 | 4.4 | 211.2 |

| Table 8. Secondary battery energy and percentage of mobile phone’s battery with respect to the number of (g). |
|---|---|---|
| Quantity | Electric energy [J] | Percentage [%] |
| 1 | 59.4 | 0.4 |
| 2 | 118.8 | 0.8 |
| 4 | 237.6 | 1.6 |
| 6 | 356.4 | 2.4 |
5. Conclusion
In this paper, a power generating-shoe with a PZT device-based power generator built into an insole is proposed for the purpose of utilization in disaster-affected areas. First, the mean generated energy per step was verified by experiments using three types of shoes. It has been confirmed that a large difference occurs in the generated energy due to the structure of shoes. Next, the experiments were carried out by changing various dimensions of the PZT device. In these experiments, the mean energy per step increases accordingly, parallel to the device size.

Moreover, the comparative verification of three types of secondary batteries has been investigated for the charging of the mobile phone. In these verifications, the secondary battery suited for practical use has been evaluated, and the electric energy and the theoretical value were quantitatively compared.

As for future works, improvement of the generated energy with the optimization of structure design, reducing the differences in energy across various type of shoes and verification of the durability of the power generator is expected. In addition, it is necessary to develop a power-management circuit that can perform charging with little loss from a PZT to a secondary battery.

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