Self power generating piezoelectric elements applied to switching circuits

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Abstract. In this study, we focused on lead zirconate titanate (PZT) as a power generating piezoelectric element. Niobium was added to each of the PZT elements to improve their power generation characteristics. The purpose of the study was to develop a high-efficiency PZT generator element that utilizes the vibration loads in the support members of a structure. We have previously reported the power generation characteristics of laminated PZT elements under vibration loads. Effect of vibration load, vibration frequency and number of PZT layers on generation characteristics of PZT elements was evaluated in the vibration test. We evaluate the power generation of laminated PZT elements and present the results of an experiment using a switching circuit as a load circuit in order to confirm the suitability of the laminated PZT element as a power source.

Keywords: Piezoelectric element, PZT, Laminating

1. Introduction

The necessity for the development of micro power supply technologies for mobile phones and portable electronics has increased in recent years. Methods of self power generation using the vibration loads of structures and human motion have been receiving significant attention. To this end, the generation of electricity by harnessing vibration forces using piezoelectric elements has been attempted.[1] However, piezoelectric elements only generate power on the order of several microwatts, so improving their power generation capacity is of the utmost importance. The use of lead zirconate titanate (PZT) with high piezoelectric properties and PZT doped with additives is known to improve the electrical properties of piezoelectric elements[2]. Fujimoto et al. have reported the effects of vibration loads on the power generation characteristics of a PZT element doped with niobium (Nb)[3] and have proposed the use of laminated PZT elements to significantly improve the power generation characteristics of PZT elements[4].

2. Electrical Properties and Structure Laminated PZT elements

The structure of the 11-layer PZT element and the appearance of the PZT element and the laminated PZT elements consisting of 3, 5, 7, and 11 layers are shown in Figure 1. Niobium at 1.0 mol% was added to each of the PZT elements to improve their power generation characteristics. Copper electrode plates with a diameter of 16 mm and a thickness of 0.2 mm were inserted between the PZT elements. In addition, a brass plate with a diameter of 16 mm and a thickness of 2 mm was affixed at both ends. Each electrode was divided into a positive electrode and a negative electrode and connected by a wire. The laminated PZT element was covered with a vinyl cover about 1 mm in
thickness on the side for insulation. All of the PZT elements were electrically connected in parallel by these structural electrodes. When a vibration load was exerted axially on the laminated PZT elements, all of the PZT elements emitted an electric charge corresponding to the vibration load. This shows that the laminated (folded) PZT elements are efficient power generation elements. Measurements of the electrical properties of the produced laminated PZT elements are shown in Table 1. The piezoelectric constant was measured by a $d_{33}$ meter (MODELZJ-6B, made by Academia Sinica), and the capacitance was measured by an LRC meter (ZM2353, made by NF Corporation). It was confirmed for the 11-layer PZT element that the values of the piezoelectric constant and the capacitance are related to the number of folds (layers).

![Photographic view and structure of laminated PZT elements.](image)

**Fig. 1.** Photographic view and structure of laminated PZT elements.

| Number of layer | Piezoelectric constant $d_{33}$ (pC/N) | Capacitance $C$ (pF) |
|-----------------|---------------------------------------|---------------------|
| 1               | 320                                   | 1053                |
| 3               | 952                                   | 2843                |
| 5               | 1582                                  | 4790                |
| 7               | 2170                                  | 6726                |
| 11              | 3550                                  | 11560               |

**Table 1.** Specifications of laminated PZT

3. Power generation characteristics of laminated PZT elements

A schematic of the power generation experiment using a vibration load is shown in Figure 2. This experimental device consists of a connection device and a rubber block that transmit the vibration load of the vibration table to the piezoelectric element and a device that holds the piezoelectric element in place. The voltage generated by the PZT element is measured by a voltmeter (Omniaze RA2300, made by NEC). By actuating the vibration table and maintaining the initial compressive load acting on the PZT elements, a vibration test using a sinusoidal vibration load was performed with this device. In this experiment, the initial compression load given was 1000 N. Vibration experiments were conducted at six frequencies (5, 10, 15, 20, 25, and 30 Hz) and eight vibration loads (50, 100, 150, 200, 250, 300, 350, and 400 N). The fluctuating loads and voltage generated from the PZT elements at that time were measured as time history data. As an example of the result of the vibration experiments, the time histories of the load and vibration-generated voltage acting on the 7-layer PZT elements when the amplitude of the vibration load was 400 N with a vibration frequency of 30 Hz are shown in Figure 3. Because it has electric noise, the exciting frequency (30 Hz) has been removed using a band-pass filter. An initial compressive load of 1000 N was applied as the static load, but it is not included in the time histories of the load. In the experiments, it was found that the vibration load and generated voltage had a phase of 30°, and the maximum voltage was about 100 V.

The generated voltage and electric power as functions of the vibration load are shown in Figure 4 for each laminated PZT element. The generated voltage is increased 2.9-fold for the 3-layer PZT
element, 4.1-fold for the 5-layer PZT element, and 4.8-fold for the 7-layer PZT element. In addition, although a 5.1-fold voltage increase was noted in the 11-layer PZT element compared with the single-layer PZT element, the generated voltage and electric power tended to become saturated with an increase in the number of laminated layers. The generated voltage of all of the laminated PZT elements was found to increase proportionally under load, and the generated electric power was found to increase proportionally to the square of the number of layers. In the case of the 11-layer PZT element, this corresponded to about 5 mW when the vibration load was 400 N, and the generated power increased about 25-fold compared to the single-layer PZT element.

The effects of the vibration frequency on the generated voltage and electric power for each of the laminated PZT elements when vibrated at 400 N are shown in Figure 5. The generated voltage and electric power for all of the laminated PZT elements increased almost proportionally to the load. However, the capacitance of the PZT elements was proportional to the number of layers, the resistance of the voltmeter was much larger, and the power generation characteristics of each of the laminated PZT elements became saturated.

**Fig. 2.** Experimental setup for self power generation using a vibration load.

**Fig. 3.** Time histories of generated voltage and load for 11-layer PZT (30 Hz, 400 N).

**Fig. 4.** Generated voltage and electric power functions of the vibration load for each PZT element (vibrated at 30 Hz).
4. Experiment of laminated PZT elements applied to switching circuits

In an experiment, we applied the 11-layer laminated PZT elements to switching circuits (Kyowa Electric Instruments) that were turned on when they reached the driving voltage. The generated voltage for the 11-layer PZT elements was converted to 3.4 V by a constant voltage module (LTC3588, Strawberry Linux Corporation). The circuit diagram for the laminated PZT element and the switching circuit with an LED lamp are shown in Figure 6. The voltage generated by the laminated PZT element using the experimental setup (Figure 2) was rectified and smoothed and reached the LED lamp through the switching circuit. The capacity of the condenser used was 470 μF. In this experiment, we measured the on-off frequency of the LED lamp using the switching circuits set at 2.5 V. This experiment was conducted at five frequencies (10, 15, 20, 25, and 30 Hz) and four vibration loads (50, 100, 150, and 200 N). The time history of the voltage of the laminated PZT with the switching circuit at a vibration load of 200 N vibrated at 30 Hz is shown in Figure 7. The generated voltage of the laminated PZT elements was about 3.4 V. It is assumed that the generated voltage was affected by the constant voltage module. The time history of the LED lamp voltage using the 2.5 V switching circuit (30 Hz, 200 N) is shown in Figure 8. It shows that the voltage fluctuated and that the LED lamp was lit when the voltage was at or above 2.5 V. The LED lamp was turned on and off at a frequency of 1.4 Hz.

Fig. 5. Effect of frequency on generated voltage and electric power for each of the laminated PZT elements (vibrated at 400 N).

Fig. 6. Circuit diagram for a laminated PZT element and a switching circuit with an LED lamp.
5. Conclusions

The following conclusions were made from this study.

- The power generation characteristics were greatly improved by increasing the number of layers. The generated voltage of all of the laminated PZT elements was found to increase proportionally under load, and the generated electric power was found to increase proportionally to the square of the number of layers. In the case of the 11-layer PZT element, this was about 5 mW when the frequency was 30 Hz and the vibration load was 200 N, and the generated power increased about 25-fold compared to a single-layer PZT element.

- The generated voltage and electric power of all of these test pieces increased almost proportionally to the load. However, it is assumed that the capacitance of the PZT elements is proportional to the number of layers.

- The LED lamp was turned on and off at a frequency of 1.4 Hz when the frequency was 30 Hz and the vibration load was 200 N.

Based on these results, the laminated PZT elements can be applied to monitoring sensors and other applications.

References

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