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A study of the electric power generation properties of a lead zirconate titanate piezoelectric ceramic

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Electric power generation characteristics of lead zirconate titanate (PZT) piezoelectric ceramic have been investigated experimentally and numerically. A thin PZT ceramic plate attached to a thin brass plate was used to examine the electric voltage generated during cyclic loading. On increasing the number of PZT ceramic plates combined together in the longitudinal direction, the electric voltage increases with the highest electric voltage being obtained for four PZT ceramic plates; and the maximum electric voltage becomes almost constant even if the number of PZT ceramic plates combined together increases more than four. This is attributed to the low strain level and the mixed strain (compressive and tensile strain). The effect of strain characteristic on the electric voltage value was analyzed numerically using our strain definition, and a clear correlation between the extent of compressive strain and generated electric voltage is clarified. A different electric generation characteristic was further observed depending on the stress conditions: generation of positive and negative electric voltage occurs when the PZT ceramic is subjected to mainly compressive and tensile stress, respectively.

1. Introduction

Since piezoelectric ceramics were developed in the middle of the twentieth century, their material properties have been studied by a large number of researchers around the world. In recent years, one of the popular piezoelectric ceramics is that made of lead zirconate titanate (PZT), which consists of a perovskite structure providing the ability to transform mechanical strain energy into electrical charge (piezoelectric effect) or applied electrical energy into mechanical strain (inverse piezoelectric effect). With the piezoelectric effect, generation of electric power has been considered to make a clean energy system, i.e., harvesting of energy [1]. Piezoelectric energy harvesters, consisting of vibrating devices, convert mechanical strain energy into electricity [2]. This energy system for use in numerous microelectronic elements has received special attention in our society. In these energy harvesting systems, a number of PZT ceramic plates are set simply in parallel under a floor or in a floor panel. It has been expected that related systems will be employed widely in society. In recent years, associated trials have been carried out using the energy harvesting systems. However, the extent of the electric power generation of the energy harvesting systems may not be enough. Thus, an improvement of the system is required.

To improve the efficiency of electric power generation from PZT ceramics, a study of piezoelectric energy harvesting devices has been conducted experimentally and theoretically, and a discussion on the associated research has been presented [3]. In this instance, the effect of mechanical loading conditions on the electric power generation characteristics has been investigated using commercial PZT ceramic plates under various cyclic loading conditions. Shu and Lien [4] have reported that the harvested power depends on the input vibration characteristics (frequency and acceleration), the mass of the generator, the electrical load, the natural frequency, the mechanical damping ratio and the electromechanical coupling coefficient. Moreover, they have proposed several design guidelines for devices with large coupling coefficient and quality factor [4]. Kim et al. [5] have examined electric generation properties using cymbal transducers created as a promising structure for piezoelectric energy harvesting under high force at high cyclic frequency. Electric power of about 52 mW was obtained under a pre-stress load of 67 N at 100 Hz [5]. With piezoelectric and electromagnetic systems, portable generators with human mechanical energy harvesting systems have been proposed [6], and Sudevalayam and Kulkarni have surveyed various aspects of energy harvesting sensor system architecture, energy sources and storage technologies and examples of harvesting-based modes and

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applications [7]. Although there are several experimental works involving development of energy harvesting systems, there is apparently a lack of information to achieve high-efficiency energy harvesting power generation, where determination of suitable loading conditions would be required. This is especially true, because power generation from a piezoelectric material could come with low current and high impedance [8]. Thus, in the present work, an attempt was made to investigate the effects of the loading conditions on the electric voltage using our original testing systems.

2. Experimental procedures

2.1. Piezoelectric ceramic

Fig. 1 shows the commercial circular membrane PZT ($PbZrTiO_3$) ceramic used in the present work [9]. This PZT ceramic has been employed widely for buzzers and ultrasonic sensors. The nominal grain size of this PZT is about 1 μm. The PZT ceramic is formed with dimensions of ϕ9.0 mm × 0.12 mm, which is attached to a thin brass plate (ϕ12.0 mm × 0.10 mm), where special adhesive was employed. Silver-based electrode plating was applied to the PZT ceramic surface by a firing process in atmosphere. The PZT ceramic consists of a tetragonal structure with an aspect ratio $c/a = 1.014$.

2.2. Experimental conditions

Fig. 2 displays schematic illustrations of the test apparatus and testing methods. Two main experimental approaches were used for investigation of the electric power generation characteristics, where the effects of (i) number of PZT ceramic plates and (ii) stress conditions were investigated. Electric voltage generation was examined during cyclic loading. In this case, cyclic loading was conducted by varying the following conditions: loading value (1–20 N), frequency (0.1–2 Hz), load waveform (square or triangular waveforms), number of PZT ceramic plates (N = 1–5) and stress condition (compressive and tensile stress). Furthermore, to investigate the effect of stress intensity on the electric generation characteristics, different hole size of the test fixture, i.e., the span of the specimen for the bending load, was changed: a_1, a_2, a_3 and a_4, as shown in Fig. 2. The electric voltage was continuously monitored for 10 cycles using a digital multimeter (8846A, Fluke). It should be noted that the 10 cycles used for this examination was a smaller number compared to related previous work (300 cycles) [10]. This is due to a reduction in the sample damage, e.g., domain switching and cracking.

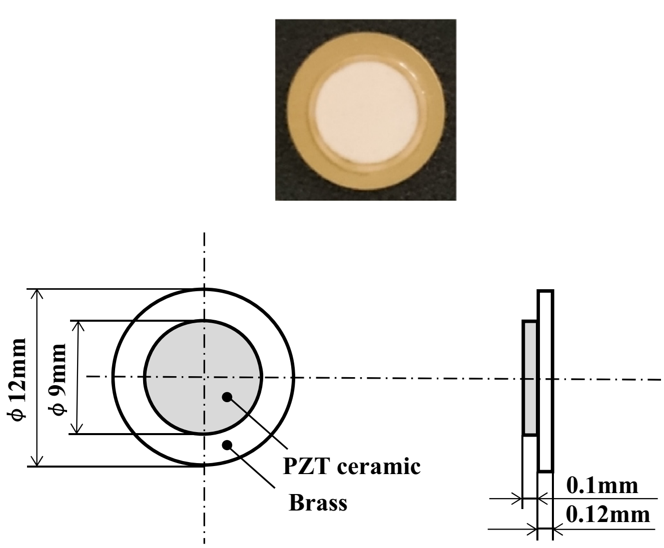

Fig. 1. PZT ceramic plate for investigation of electric power generation characteristics.

2.3. Finite element analysis

Finite element (FE) analysis was executed to analyze the influence of the stress–strain characteristics on the electric power generation. Fig. 3 displays the model of the test samples, consisting of PZT ceramic and brass plates, which was designed on the basis of the geometry of the actual PZT ceramic plates (Figs. 1 and 2). Due to the change of sample span shown in Fig. 2, the stress area generated by the applied bending loading was altered. In this approach, two- and three-dimensional FE simulations with 8-noded quad elements were employed. The mesh size of the ceramic plate was determined to be less than 0.01 mm. The following material properties were selected: elastic constant (E) of 82 GPa and Poisson's ratio (ν) of 0.3 for the PZT ceramic and $E = 103$ GPa and $\nu = 0.35$ for the brass plate.

3. Results and discussion

3.1. Effect of the number of PZT ceramic plates

Fig. 4(a) shows the relationship between the applied load and the maximum electric voltages for square-wave mode. As seen, the electric voltage value increases with increasing loading value, where no clear frequency effects on the electric voltage are observed. With an increasing number of PZT ceramic plates, the electric voltage level overall increases, and the highest increment rate of the electric voltage is obtained for the sample with four PZT ceramic plates. For five PZT ceramic plates, the maximum electric voltage seems to decrease slightly compared to the four-plate case. Fig. 4(b) displays the results of the maximum electric voltages for triangular-wave mode. The electric voltage value increases with increasing frequency and applied load value. Moreover, similar to the square-wave mode, a higher electric voltage value is obtained for a larger number of PZT ceramic plates, in which the peak electric voltage is detected for three PZT plates. Fig. 5 shows the variation of the electric voltage with time for various numbers of PZT ceramic plates obtained under cyclic loading with the square- and triangular-wave modes. It is clear that the maximum electric voltage increases with an increasing number of PZT ceramic plates. Furthermore, the generation characteristics of the electric voltage between the square- and triangular-wave modes are different, which may be attributed directly to the loading speed [11,12], where the higher the loading speed, the greater the electric voltage. Interestingly, time lags can be observed between the electric voltage generation and applied load especially for the samples with a large number of PZT ceramic plates, i.e., electric voltage does not rise even if the mechanical loading is applied, as indicated by the dashed circles. It is clear from Fig. 5 that a longer time lag is obtained for the large number of PZT ceramic plates: 0.025 s and 0.08 s for five PZT plates under square and triangular waveforms, respectively. This occurrence would be caused by the low strain because of the high rigidity of the test samples, as many PZT ceramic plates are attached in the longitudinal direction.

Fig. 6 displays variations of the mean maximum electric voltage and strain value as a function of the number of PZT ceramic plates. To understand clearly the electric generation characteristics, their strain values are also examined using a commercial strain gauge attached behind the PZT ceramic plate. In this case, the strain value was examined by the simple bending loading. It is clear that the