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Force Sensing in a Multilayered Ceramic Actuator Using a Piezoelectric Ceramic Plate

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A method of sensing the force of a multilayered ceramic actuator using a piezoelectric ceramic plate is described. The newly developed system consists of a mutually bonded piezoelectric actuator and a piezoelectric ceramic plate, which are interposed between nonlinear elastic elements. The graphical analysis suggested that a small signal superimposed on the driving voltage of the actuator makes it possible to detect the force and a subsequent experiment confirmed thus.

1. Introduction

In recent years, multilayered piezoelectric ceramic actuators driven by a small voltage, which have a fast response without electromagnetic noise, have been proposed,(1,2) thus receiving increasing attention as a fundamental element in precision mechanical engineering. However, they have some puzzling problems in terms of nonlinear and hysteresis displacement response due to creeping movement of domain walls in ferroelectric materials.(3,4) In order to overcome such disadvantages, the actuators usually have to be used together with a rather complicated negative feedback system.(5,6)

The multilayered ceramic actuators are often used with the application of a pre-stress. In such cases, the pressure sensor is an appropriate element for detecting how the system works. Although the piezoelectric ceramics have an excellent sensitivity for pressure, they only respond to the rate of pressure change, in other words, they work in a differential mode, making it difficult to apply them to the sensor for the quasi-static pressure. We have therefore developed a new sensing system which consists of a piezoelectric ceramic plate combined with a nonlinear elastic spring.

In the following, we first describe the operation of the system by analyzing it graphically and then report the experimental results of the newly devised system.

2. Operation of the Sensor System

The model under consideration consists of a multilayered ceramic actuator adhered to a piezoelectric ceramic plate and this composite system, which we call an intelligent actuator, was uniaxially bound with a nonlinear elastic spring (Fig. 1). A hard sphere and a strain-gauge-type load cell were inserted for realizing the nonlinear characteristic and for calibration, respectively. According to Hertz's theory on elastic contact, the relationship between the displacement X and the applied mechanical force F is

$$X=kF^{2/3}, \tag{1}$$

where k is the coefficient determined from both the sphere's dimension and its material constant.

The multilayered ceramic actuator deforms as the sum of each elemental layer with an applied driving voltage V but without an external force, as

$$X_0=d_{33}\cdot n\cdot V, \tag{2}$$

where X_0 is the displacement of the actuator, d_{33} is the piezoelectric strain constant in the thickness direction and n is the number of stacked layers. Based on the elastic property of the actuator, we obtain its displacement X_1 against the external force F,

$$X=a\cdot F$$

$$a = s_{33}^{E}\cdot\frac{l}{A}, \tag{3}$$

where a is a constant, s_{33}^{E} is the elastic compliance in the length direction, l is the length and A is the cross section of the actuator. Then the total displacement of the actuator under the operating conditions is

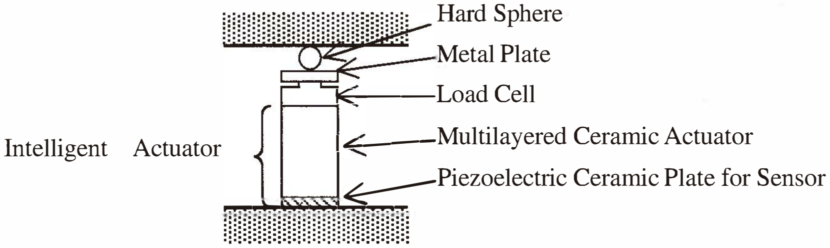

Fig. 1. Construction of the actuator system.

$$X = -X_1 + X_0$$
$$= -a \cdot F + d_{33} \cdot n \cdot V. \tag{4}$$

If one superimposes this actuator characteristic on the elastic property of the nonlinear binding system, one obtains Fig. 2. The operating point is designated by the intersection of the nonlinear binder curve with the actuator line and at this point the following relationship should be maintained.

$$kF^{2/3} + aF - d_{33}nV = 0 \tag{5}$$

This relationship gives the variation of the force ΔF with a small fluctuation of the applied voltage to the actuator ΔV.

$$\Delta F = \frac{d_{33}n}{\frac{2}{3}kF^{-1/3} + a}\Delta V \tag{6}$$

Equation (6) represents the principle of the present sensing system. When the driving voltage fluctuates, the instantaneous force varies about the operating point; if the applied voltage moves from V_1 to V_2, the resultant force upon the same voltage variation ΔV changes from ΔF_1 to ΔF_2, reflecting the difference of the operating point. It goes without saying that the sensor's output signal is proportional to this force variation.

3. Experimental Results and Discussion

By using a commercially available piezoelectric ceramic actuator (Tokin Ceramics Co. Ltd., AE1424D16), an experiment for the confirmation of the preceding analysis was

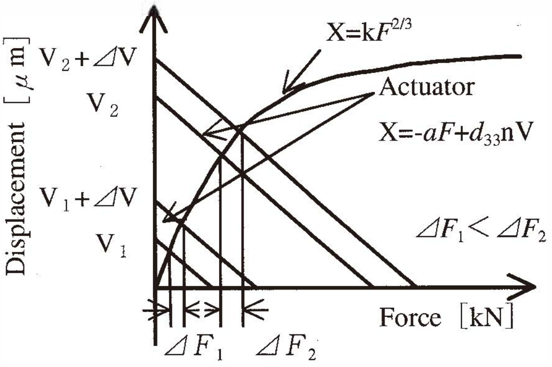

Fig. 2. Elastic characteristics of the actuator system where a multilayered ceramic actuator is bound with a nonlinear elastic spring.

carried out. Figure 3 shows the displacement vs. force characteristics for various driving voltages. As can be seen from the figure, a significant hysteresis phenomenon is observed. A piezoelectric ceramic plate for the force sensor, 14×14×0.1 mm^3, was adhered to the actuator. It was then inserted in the binding system with a ϕ3 mm hard sphere together with a load cell for monitoring (VALCOM,VLC-10KNE159).

An example of the voltage waveform applied to the actuator and resultant output signal is shown in Fig. 4. In this figure, a small square wave voltage of 1 V for sensing is superimposed on the driving voltage of 59 V. The cycle period and duty ratio of the square wave are 0.5 s and 50%, respectively. The output signal gives an exponential response with a small variation of the driving voltage, whose peak value corresponds to the operating force.

Figure 5 shows the output signal voltage vs the force to which the actuator is subjected.

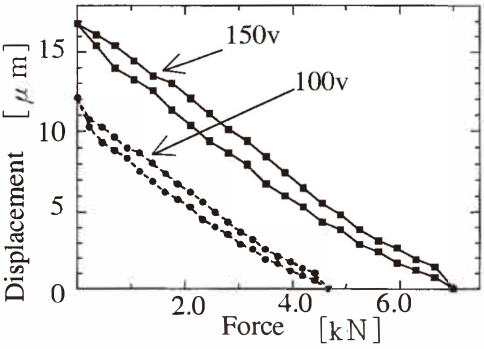

Fig. 3. Displacement vs force characteristics.

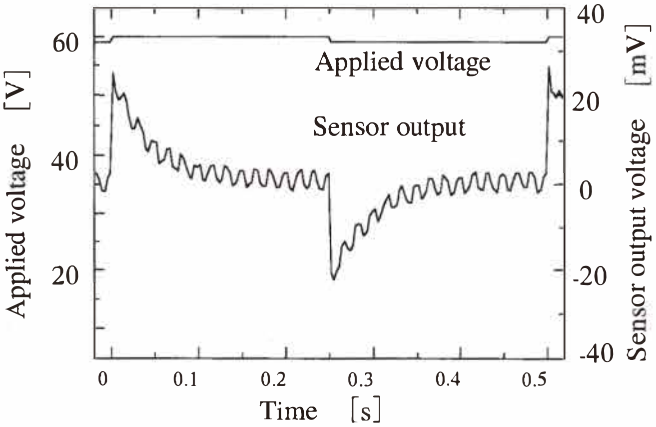

Fig. 4. Output signal of the sensor piezoelectric plate in case a small square voltage of 1 V is superimposed on the driving voltage of 59 V under the initial binding force of 0.75 kN.

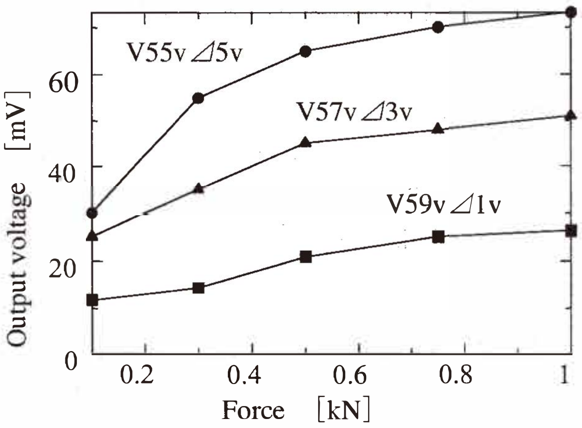

Fig. 5. Output signal vs force characteristics.

It should be said, at least in principle, that we can detect the force of the actuator using the piezoelectric ceramic plate. The saturation tendency in the figure may be caused by the deviation from the assumed nonlinear elastic property of eq. (1). The minimum detectable force, of course, should be limited by the signal/noise ratio.

4. Conclusions

The newly devised force sensing system for the multilayered ceramic actuator was shown to work well using a piezoelectric ceramic plate. Further efforts of our group will be directed at developing an automatic pressure controller for high-pressure gasses.

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