Fundamental Study on Hysteresis Reduction of Piezoelectric Actuators by Preload Control

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Abstract. Piezoelectric actuator is usually used in feedback system because of the hysteresis non-linearity of between input voltage and output displacement. The aim of this paper is analysis of the hysteresis to reduce cost of high precision positioning system by piezoelectric actuator with open-loop control. Ratio of max hysteresis to max displacement, RHD, has been proposed as an evaluation indicator for the hysteresis. Effects of compressive stresses, i.e. preload, in two directions on RHD were investigated and bulk and stacked piezoelectric actuators with low RHD have been studied experimentally.

1. Introduction

Piezoelectric actuator with less hysteresis can be applied to high precision open-loop control. Open-loop control is not costly, compared to closed-loop one. It is possible for less hysteresis piezoelectric actuator with open-loop control to reduce the cost of positioning systems [1]. In this paper, effects of a stress onto a bulk and stacked piezoelectric actuators on the hysteresis are studied. Unruan M et al. described preload to a piezo lessens hysteresis because of domain wall suppression [2] and Yimmirun R showed that dielectric properties were lowered by a stress [3]. New hysteresis indicator, RHD, was introduced to evaluate hysteresis of both a bulk and a stacked piezoelectric actuators. Preload effects on RHD have been studied for a bulk and stacked piezoelectric actuator. Although application of some control theories to piezoelectric actuators in order to reduce piezoelectric actuator’s hysteresis nonlinearity have been studied [4][5][6], the control systems become complicated.

2. Experiment

2.1. Experimental Configuration

Figure 1 shows a configuration of an experiment equipment. Two kinds of specimens, i.e. a bulk and a stacked piezoelectric actuators, were used in the experiment. Size of each piezoelectric actuator is 10(width)×10(depth)×40mm(height). Table 1 shows the piezoelectric actuator specifications. The actuator was under the preload up to 4.9 [MPa] in X and Y direction, shown in figure 1, where X is a polarized direction of the piezoelectric actuator. A stacked type couldn’t be at a large compressive stress in Y direction because of its configuration of stacked thin PZT plates in X direction. Actually the preload in Y-direction for a stacked piezoelectric actuator was limited up to 0.09 [MPa]. The preload was generated by two air cylinders in X and Y directions and the compressive stresses were
applied to the actuator through floating joints. Max voltage to a bulk and a stacked piezo was 500[V] and 100[V] respectively. The voltage was applied through high voltage supply using ramp output function. Time of up and down ramp was 20 [s]. The input signal rate is small enough for piezoelectric actuators. Halt time between the ramps was 1[s]. Displacement of the bulk and the stacked piezoelectric actuator was measured by laser interferometer system (5519A, Agilent Technologies) with 5 nm resolution and electric micro (E-M5R, Tokyo Seimitsu) with sensitivity of 0.01 V/μm respectively. Figure 2 shows a block diagram of the experiment. Open-loop control was adopted with stresses in X and Y directions to evaluate hysteresis of piezoelectric actuator.

**Figure 1.** Experimental configuration: Stress in X and Y directions were applied to a piezoelectric actuator using air cylinders

**Figure 2.** Block diagram of experiment apparatus: Open-loop control was adopted with stress in X and Y directions to evaluate hysteresis of piezoelectric actuator

2.2. **RHD Definition**

Figure 3 shows a relationship between input voltage and output displacement of a stacked piezoelectric actuator in X direction. Ratio of max hysteresis to max displacement, i.e. operating range, RHD, has been defined newly as an evaluation indicator for the hysteresis.

| Parameter       | Bulk                  | Stacked              |
|-----------------|-----------------------|----------------------|
| Size (width x Depth x Height[mm]) | 10 x 10 x40           | 10 x 10 x40          |
| Material        | PZT                   | Stacked PZT          |
| Sensitivity[V/μm] | 3000                  | 4                    |
| Response [kHz]  | 39                    | 34                   |
| Manufacturer    | Fuji Ceramics         | NEC Tokin            |

**Functional voltage supply**

**Piezoelectric actuator**

**Position sensor**

**Preload mechanism**

**PC**

**Sensor controller**
RHD = \frac{\text{Max hysteresis}}{\text{Max displacement}} \tag{1}

It is difficult to compare hystereses of bulk and stacked piezoelectric actuators because there are large differences between operating ranges of bulk piezoelectric actuator and stacked one, for example, 30μm and 0.1μm respectively. RHD indicator makes it possible to compare hysteresis of bulk and stacked piezoelectric actuators. Since RHD is a kind of normalized estimate indicator, characteristics of hysteresis for bulk and stacked piezoelectric actuators can be discussed using RHD.

**Figure 3.** Definition of RHD: In order to compare hysteresis of both bulk and stacked piezoelectric actuator, RHD was defined as max-hysteresis/max-displacement

### 3. Experimental Results

Experimental data were analyzed statistically. Figure 4 shows results of RHD by multiple regression analysis. When the significance level was 0.05, the null hypothesis that RHD is not influenced by X and Y preload is rejected because the P values are smaller than 0.05. On the other hand, RHD was not affected by type of the piezoelectric actuators. Figure 5 and figure 6 shows relationship between preload and RHD in X and Y direction. Figure 5 shows that RHD decreases with an increase of X-preload. Y preload had effects on RHD too, however there were no clear trends like X-preload. Type did not influence RHD statistically because statistics P value of type was more than 0.05.

**Figure 4.** Multiple regression analysis: Multiple regression analysis shows that X preload influenced RHD most
4. Discussion

Preload influences a max displacement as well as RHD. It is important to take into consideration actuator stroke from viewpoint of actual positioning specifications on positioning travel. Figure 7 shows a relationship between a max displacement and RHD. Displacement of stacked piezoelectric actuator was much larger than bulk’s, so there are two groups in figure 7. RHD for bulk piezoelectric actuator was not clear in figure 7.

![Figure 5](image1.png)  
**Figure 5.** Relationship between X preload and RHD: There was a trend that RHD decreased as X preload increased

![Figure 6](image2.png)  
**Figure 6.** Relationship between Y preload and RHD: There was a not clear trend between Y preload and RHD

![Figure 7](image3.png)  
**Figure 7.** Relationships between max displacement and RHD: different displacement range between bulk and stacked piezoelectric actuator resulted in two groups

Preload influences a max displacement as well as RHD. It is important to take into consideration actuator stroke from viewpoint of actual positioning specifications on positioning travel. Figure 7 shows a relationship between a max displacement and RHD. Displacement of stacked piezoelectric actuator was much larger than bulk’s, so there are two groups in figure 7. RHD for bulk piezoelectric actuator was not clear in figure 7.

To study RHD of bulk piezoelectric actuator in detail, the bulk data were only analyzed in figure 8. Both preload groups of High (more than 1.5 [MPa]) /Low X-preload, High (more than 1.2 [MPa]) /Low Y-preload, are plotted in figure 8. Points with high X-preload and high Y-preload data seem to cluster in A (figure 8) and points with high X-preload and low Y-preload seem to cluster in B. A has a condition of open-loop high accuracy positioning with low RHD and small stroke. B has a condition of open-loop control with a relatively large stroke.
Figure 8. Relationships between max displacement and RHD for bulk piezoelectric actuator: Points with high X preload and high Y preload cluster in A and points with high X preload and low Y preload clustered in B.

Figure 9. Relationships between max displacement and RHD for stocked piezoelectric actuator: Chart didn’t agree with hyperbola chart, which shows that there was a complicate hysteresis is trend fo stacked piezoelectric actuator.

Figure 9 suggests that hysteresis in stacked piezoelectric actuator changed greatly, compared to those of bulk piezoelectric actuators. High X-preload tends to make RHD low for a stacked piezoelectric actuator, too. However, there was no clear relationship between displacement and RHD for a stacked piezoelectric actuator as shown in figure 9.

As stated in Chapter 2, large preload in Y-direction, for example more than 0.09 [MPa], can’t be stressed to a stacked piezoelectric actuator. Limited preload in Y-direction onto a stacked piezo might cause the unclear. Nevertheless the stroke is very small, for example, less than 100 [nm], low RHD and small stroke condition, that is, large preloads in X and Y directions are good for high precision positioning with open-loop control because hysteresis error can be estimated from equation (1) and figure 8 as follows:
Positioning error due to hysteresis is evaluated approximately to be 5 [nm] with large preloads in X and Y directions. Considering engineering applications, dynamics of a piezoelectric actuator with X and Y preload should be investigated in detail. For example, RHD of piezoelectric actuator in actual servo system should be looked into. Frequency response of a piezoelectric actuator with X and Y preload should be investigated, too. Especially the dynamics of a bulk piezoelectric actuator with large X preload, which has low RHD as shown in figure 8, are interesting.

5. Summary
New indicator for hysteresis, RHD, has been introduced to evaluate the hystereses of both a bulk and a stacked piezoelectric actuators. Experimental results demonstrated that high X and Y preload was good for precision positioning with open-loop control for a bulk piezoelectric actuator. Although feasibility is influenced by required positioning accuracy, it can be seen that open-loop positioning by a bulk piezoelectric actuator can be applied to precision positioning with high preloads in X and Y directions. The authors are currently investigating dynamics of open-loop precision positioning on the condition.

6. References
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