Experimental investigation on relationship of preload and displacement output for piezoelectric ceramic actuator

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Piezoelectric ceramic actuator is widely used to produce micro or nano level output displacement in the fields of precision measurement technology and intelligent instruments, micro/nano manufacturing, Micro-electro-mechanical system(MEMS) and etc due to its advantages of compact structure, high displacement resolution, high frequency response, no heat generation and etc. Now we have been developing a two dimensional micropositioning stage for nano imaging lithography(NIL), and selected 2 piezoelectric ceramic actuators as drivers to produce about over 150 microns displacement in X, Y axial directions with lever amplifiers, respectively. In order to add a suitable preload to the piezoelectric ceramic actuator, we have to know the relationship of preload and output displacement for piezoelectric actuator. So in this paper, firstly, piezoelectric effect is introduced. Then the preloading device is designed to test the relationship of preload and maximum displacement. Experiments were carried out under several preload values from 0N to 800N. The relationship curve of preload-maximum displacement was obtained by data processing. Finally, some conclusions were given out. The result indicates that adding preload to piezoelectric actuator can enhance its output displacement in some extent, and a suitable preload can make piezoelectric actuator produce a maximum displacement output.

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1. Introduction

In the fields of precision measurement technology and intelligent instruments, micro/nano manufacturing, Micro-electro-mechanical system (MEMS) and etc, smart materials drivers are usually used as actuators to produce micro or nano level displacement output. For this kind of actuators there are giant magnetostrictive actuator, electrostrictive actuator, electrostatic actuator, piezoelectric ceramic actuator and so on. Of them the piezoelectric actuator is concerned widely due to its advantages of compact structure, high displacement resolution, high frequency response, no heat generation and etc.

When piezoelectric ceramic actuator is used in micro/nano positioning stage, the basic characteristics of the actuator are closely related with the performance indexes of the micro/nano positioning stage. The main basic characteristics of piezoelectric ceramic actuator are force - displacement relationship, voltage - displacement characteristics, repeatability, creep property and temperature characteristic.

In recent years, some researchers have studied the basic characteristics of piezoelectric ceramic actuator. H. Jung and J. Y. Shim did theoretical analysis and experimental research about hysteresis nonlinearity characteristics and creep characteristics of piezoelectric ceramic actuator, and put forward a driving method which can reduce hysteresis nonlinearity and creep at the same time in open-loop control by using the similarities of these two characteristics [1]. T. Zhang and L. N. Sun did a relatively deep theoretical analysis about piezoelectric ceramic actuator's output displacement curve, force- displacement relationship, temperature properties and hysteresis nonlinearity characteristics including the displacement characteristics of several typical piezoelectric ceramic actuators both home and abroad based on the analysis of polarization mechanism of piezoelectric ceramic actuator and electrostrictive actuator, and deduced the normalized model of these two actuators[2]. K. Zheng and S. Z. Yan designed the preload device of intelligent active member, and studied the influence of preload on actuator's properties as well as analyzed the experimental results on the theoretical basis of the impact of piezoelectric ceramic's internal crystalline structure change on converse piezoelectric effect[3]. W. Fan and X. F. Yu did the experimental research of creep characteristics of a piezoelectric ceramic driven stage, and got the creep regularity of the actuator and the creep characteristics curve of the actuator [4].

Now we have been developing a two dimensional micropositioning stage for nano imaging lithography(NIL) [5], and selected 2 piezoelectric ceramic actuators as drivers to produce about over 150 microns displacement in X, Y axial directions with lever amplifiers, respectively. The preload force is needed to eliminate the machinery clearance and to ensure reliable installation. In order to research the effect of preload force on output displacement of piezoelectric ceramic, and determine the value of the preload force and the appropriate installation method of piezoelectric ceramic actuator, the preloading device is designed and the force - displacement characteristics of piezoelectric ceramic actuator is studied.

2. The working principle of piezoelectric ceramic actuator

When dielectric is put into electric field, there are two kinds of effects: electrically induced telescopic effect and piezoelectric effect which are collectively referred to as electromechanical coupling effect. Piezoelectric effect refers to the electric polarization happened on dielectric under mechanical force. The amount of electric polarization is proportional to the value of the stress and the direction of the electric polarization changes with the direction of the stress. When piezoelectric ceramics is used as micro-actuator, the working principle is converse piezoelectric effect. Converse piezoelectric effect means the dielectric produces strain under the effect of outer electric field. The value of the strain is proportional to the value of the electric field and the direction of the strain changes with the direction of the electric field. The value of the piezoelectric coefficient of the material used in making piezoelectric ceramic actuator is much higher than the electrically induced telescopic coefficient, so electrically induced telescopic effect can be ignored. The relationship between strain and electric field when piezoelectric ceramic actuator is under the action of outer electric field is as following [6]:

$$s = dE \tag{1}$$

Where s is the strain, E is the electric field and d is piezoelectric coefficient.

The main shortcoming of piezoelectric ceramic actuator is the small output displacement and the solution is to adopt piezoelectric ceramic stack as shown in Fig. 1. The total deformation ΔL of piezoelectric stack can be expressed as:

$$\Delta L = n\Delta l \tag{2}$$

Where n is the number of ceramic pieces and Δl is the deformation of one ceramic piece.

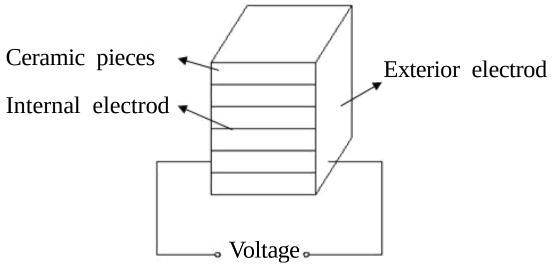


Fig. 1 The schematic of piezoelectric stack

The selected piezoelectric ceramic actuator is PST/150/5×5/20 as shown in Fig. 2. This actuator is piezoelectric ceramic stack and the main parameters are introduced in Table. 1.

Fig. 2 The piezoelectric ceramic actuator

3. Design of the preloading device

Dimensions a×b×L (mm)	Nominal displacement (μm±10%)	Blocking force (N)	Stiffness (N/μm)	Capacitance (nF)	Resonance frequency (KHz)
5×5×18	20	1800	60	1800	50

Table. 1 Main parameters of the piezoelectric ceramic actuator

The preloading device is consist of base frame, preloading screw, slider, a pole with flexure hinge, cylindrical helical spring and bracket of the sensor and is shown in Fig. 3.

The working principle of the preloading device is as follows: The

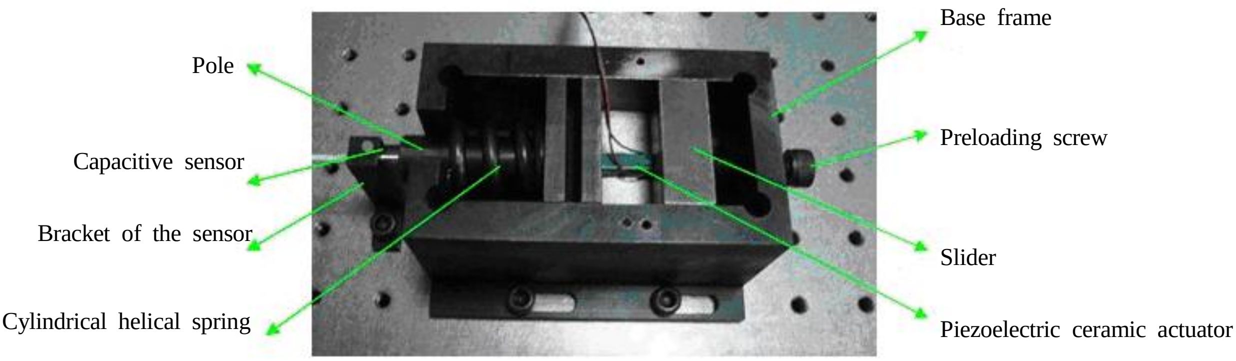


Fig. 3 The preloading device

piezoelectric ceramic actuator is put between the slider and the pole while the cylindrical helical spring is put between the pole and the base frame. Turning the preloading screw can promote the slider to make the piezoelectric ceramic actuator be pressured in the rooms between the slider and the pole. When applying voltage to piezoelectric ceramic actuator to make it elongate, the piezoelectric ceramic actuator pushes the pole to make the cylindrical helical spring be compressed further, and then the output displacement of the actuator can be obtained by the sensor from the front-end plane of the pole.

The type of the preloading screw is M8 and the value of its pitch is p=1.25mm. The type of the cylindrical helical spring is 5×25×30 (diameter of the line × middle diameter × free height) and the value of stiffness is $K = 158N/mm$, while the largest compression value is 7mm.

Supposing the force applied on cylindrical helical spring is F when the preloading device is working and the preload force of piezoelectric ceramic actuator is F_0. According to force analysis of the preloading device, we can get:

$$F_0 = F \tag{3}$$

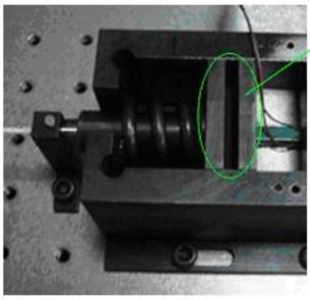
Combining the Hooker Law, formula (3) can be expressed as:

$$F_0 = F = K\Delta x \tag{4}$$

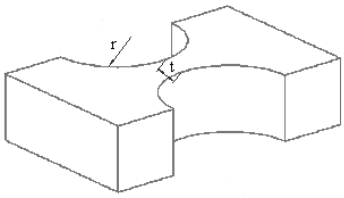
Where Δx is the compression value of the spring. According to formula (4), the turning laps *n* of preloading screw when the preload force increases $\Delta F_0 = 100N$ can be calculated:

$$n = \frac{\Delta F_0}{K \times p} \approx 0.5 \tag{5}$$

It can be seen from formula (5) that when the preloading screw turn every half circle, the preload force of piezoelectric ceramic actuator increases about 100N, so the preloading device realizes approximate quantitative loading. The piezoelectric ceramic stack can not bear bending moment, torque and tension and the preloading device should ensure the stack only under pressure along the axis. Therefore, there is a flexure hinge mechanism on one end of the pole as shown in Fig. 4 to guarantee the safety. The key parameters of the flexure hinge is: $r = 2mm$ and $t = 0.8mm$.



(a) Flexure hinge mechanism on the pole



(b) Parameters of the flexure hinge

Fig. 4 The flexure hinge mechanism on the pole

4. Experiments

In the experiments, the force - displacement characteristics of piezoelectric ceramic actuator PST/150/5×5/20 is studied in the designed preloading device. The type of the drive power of the actuator is HPV-1C015010500 whose output voltage range is -10V~150V and the voltage resolution is 5mV. Capacitive displacement sensor of LION PRECISION Company in American is used in displacement measurement whose range is 0~250μm and the sensitivity is 80.000mV/μm.

The experimental steps are as follows:

(1) Install the piezoelectric ceramic actuator into the preloading device. Load the preload force from 0N and increase 100N (rotating the screw about half circle)every time until 800N. Repeat the experiment 5 times at each different preload force. The process of each experiment is to make the driving voltage rising from 0V to 130V then dropping from 130V to 0V and write down the output displacement at 130V.

(2) Repeat step (1) three times and write down the records.

Preload force（N）	Output displacement（μm）		
	First Group	Second Group	Third Group
0	16.025	16.375	15.525
100	16.800	17.050	17.525
200	18.225	18.425	18.425
300	19.250	19.100	18.950
400	19.075	19.825	19.675
500	19.875	19.525	19.650
600	19.475	19.825	20.025
700	20.200	19.625	19.825
800	19.625	19.825	19.700

Table. 2 The experimental data of force - displacement characteristics

The experimental results are shown in Table. 2. The output displacement in each group and at each preload force is the average value of the 5 times experimental records. Fig. 5 is the force – displacement curve according to data in Table. 2.

It can be seen from Table. 2 and Fig. 5 that the value of preload force has a influence on the maximum output displacement of piezoelectric ceramic actuator. When the preload force is in the scope of 0N-700N, the maximum output displacement of piezoelectric ceramic actuator is generally increased with the increasing of preload force. In the scope of 0N-400N, the maximum output displacement increases quickly while in the scope of 400N-700N, the maximum output displacement increases relatively slowly. When the preload force is in the scope of 700N-800N, the maximum output displacement of piezoelectric ceramic actuator declines slightly with the increasing of preload force.

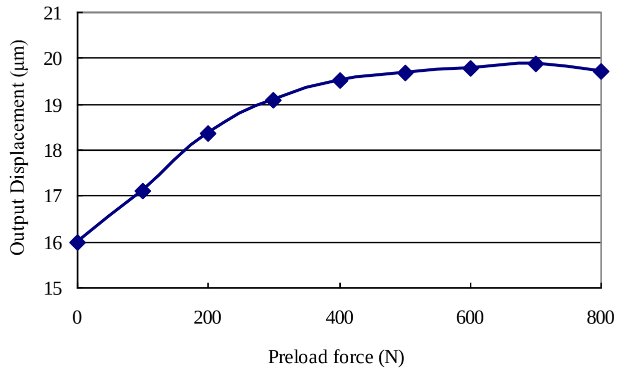


Fig. 5 The force – displacement curve

Therefore, in order to make full use of the output capacity of piezoelectric ceramic actuator and considering the convenience of loading, the preloading force can be set to be slightly higher than 400N.

5. Conclusions

When piezoelectric ceramic actuator is used in micro/nano positioning stage, the value of the preload force and the appropriate installation method should be considered carefully. A preload device which can realize safety and quantitative loading is designed and a series of experiments are carried out. From the experimental results, we can conclude that the preload force has a influence on the maximum output displacement of piezoelectric ceramic actuator and slightly higher than 400N is a relatively appropriate value of the preload force.

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