

# Design and analysis of a 3D Elliptical Micro-Displacement Motion Stage

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**Abstract.** Micro-displacement motion stage driven by piezoelectric actuator has a significant demand in the field of ultra-precision machining in recent years, while the design of micro-displacement motion stage plays an important role to realize a large displacement output and high precision control. Thus, a 3D elliptical micro-displacement motion stage driven by three PZT actuators has been developed. Firstly, the 3D elliptical trajectory of this motion stage could be adjusted through the form of the PZT actuators input signal. Then, the desired trajectory was obtained by adjusting the micro displacement of the motion stage in 3D elliptical space. Finally, the trajectory simulation and the finite element simulation were applied in this motion stage. The experimental results shown that, the output displacement of the three directions under the input force of the 1600N were 14 $\mu$ m, 16 $\mu$ m and 74 $\mu$ m, respectively. And the first three modes were 1471.6Hz, 2698.4Hz and 2803.4Hz, respectively. Analysis and experiments were carried out to verify the performance, result proved that a large output displacement and high precision control could be obtained.

## 1. Introduction

In recent years, the micro-displacement mechanism driven by PZT actuator has been widely used in precision machining field due to its high precision and strong structural variability, such as ultra-precision machining, micro/nano-motion stage and other precision machining fields [1]. Meanwhile, the requirement of high-precision motion stage for large-size workpiece machining has also been increased gradually. At present, many experts and scholars have devoted themselves to the research on the micro/nanoprecision control stage with multi-degree of freedom to meet the complex operation. These researches are mainly focused on the design of the micro-displacement motion stage, the motions modeling and the precision control. These researches were mainly focused on the micro-displacement motion stage design, the motions modeling and the precision control [2]. The current design of the structure is divided into two types based on the structure design of the micro-displacement stage, e.g. series and parallel structure of hinge [3]. The shape of hinge is divided into round flexible hinges, oval flexible hinges, rectangular flexible hinges, and Z-shaped flexible hinges. In this paper, the micro-displacement motion stage was actuated by the high-frequency reciprocating telescopic of piezoelectric drive, and the guide direction was provided by the flexible hinge. The precise control of micro-displacement stage system was obtained by controlling the piezoelectric



telescopic motion. Guo et al. designed a U-shaped micro-vibration stage to amplify the displacement, and the different vibration trajectory has acquired by adjusting the input voltage phase [4]. Yong et al. designed a compact parallel motion based on the XYZ scanning stage, the scanning range can reach  $3.5\mu\text{m} * 3.5\mu\text{m}$  in 625Hz [5]. Wan et al. designed a micro-displacement flexible platform with XY modeling, and studied its quantitative analysis model for the pseudo-rigid body model. Meanwhile, the motion performance was analyzed by finite element method. When the stage is in no-load, the single direction error of epiphytic motion was less than 1.7% [6]. Huang et al. proposed a series motion XYZ nano-motion stage, the theoretical maximum displacement in all directions could achieve 9.7-12.5 $\mu\text{m}$ , but the frequency of series motion was smaller, less than 10Hz [7].

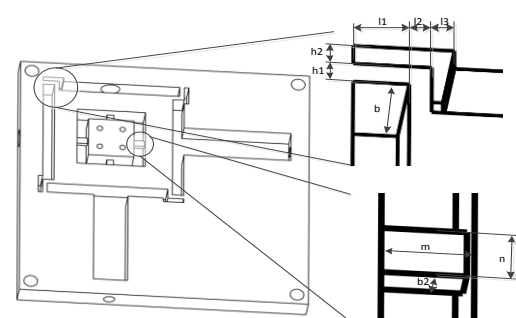
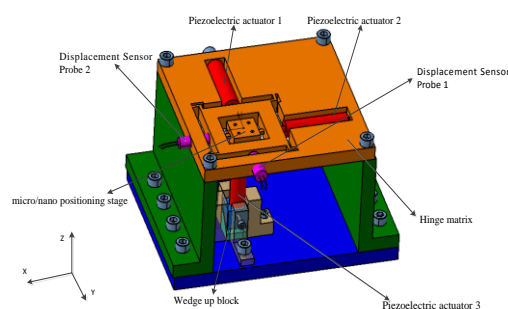
A lot of achievements of the research on micro-displacement motion stage has been achieved in recent years, but there were still existed some problems. For example:

- (1) it is not easy to get a larger bandwidth of the complex motion stage structure;
- (2) There is crosstalk between the axis among different modeling of the motion stage, and the size of the crosstalk is related to the modeling of the motion axis;
- (3) The dynamic performance of each motion axis is difficult to unify.

Therefore, A 3D elliptical micro-displacement motion stage device driven by piezoelectric actuator is designed. Which can minimize the generation of epiphytic motion, at the same time, the building stiffness modeling is relatively simple of folded flexible hinge. The simulation of trajectory and finite element were applied in this developed stage, it can be seen that the micro - displacement motion stage designed in this paper can realize the micro - displacement motion with high precision and large bandwidth.

## 2. The whole design of micro-displacement motion stage

The 3D elliptical micro-displacement motion stage structure has shown in Fig.1. The device driven by three vertical piezoelectric, where the piezoelectric actuator 1 and the piezoelectric actuator 2 are respectively installed in the Y-direction and the X-direction of the flexible hinge base, by the preload screw. The piezoelectric actuator 3 is installed in the vertical Z direction of the flexible hinge base, by the preload wedge-shaped block. Further, the top of the piezoelectric actuator 3 is directly in contact with the lower end of the micro/nano-motion stage, the displacement sensor probe is installed on the flexible hinge base. The displacement of the piezoelectric actuator 1 is measured by the probe 1, and the displacement of the piezoelectric actuator 2 is measured by the probe 2. The main function of the displacement sensor is to provide feedback data for subsequent closed loop control.



**Figure.1** The structure diagram of the mechanism. **Figure.2** Schematic of the compliant mechanism.

The displacement and the whole bandwidth of the 3D elliptic micro-displacement stage is related to the flexible hinge structure. Fig. 2 shows that the thickness of the flexible hinge driven by piezoelectric actuator 1 and 2 in the flexible hinge base is  $b$ , the width is  $h1$ . The folding flexible hinge parameters were  $l1$ ,  $l2$ ,  $l3$ , and the flexible hinge structure of the piezoelectric actuator 3 is relatively simple, the length is  $m$ , the width is  $n$ , and the thickness is  $b2$ . In this paper, the design of the Three

PZT vertical drive micro-displacement driving for 3D elliptical micro-displacement stage flexible hinge size parameters are shown in Table 1.

**Table 1.** The dimension parameters of the two type flexure hinges.

b(mm)	b2(mm)	l1(mm)	l2(mm)	l3(mm)	h1(mm)	h2(mm)	m(mm)	n(mm)
10	3	5	2	2	2	2	5	5

The stiffness model was built by the flexible hinge. Then, optimize the device's bandwidth by adjusting the parameter settings.

### 3. Simulation Analysis of Micro - Displacement Motion Stage

#### 3.1. Motion simulation analysis of the Mechanism

The input signal of 3D elliptical micro-displacement motion stage with three PZT actuators are:

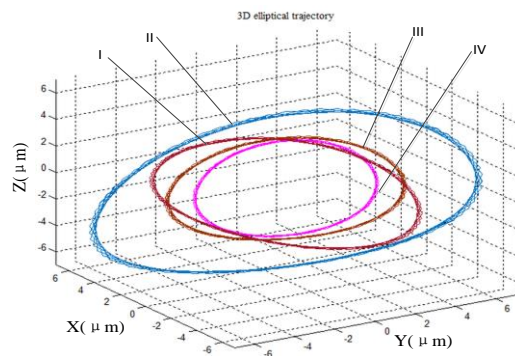
$$\begin{cases} u_x(t) = V_x \sin(2\pi ft + \varphi_x) \\ u_y(t) = V_y \sin(2\pi ft + \varphi_y) \\ u_z(t) = V_z \sin(2\pi ft + \varphi_z) \end{cases} \quad (1)$$

Where  $v_x$ ,  $v_y$  and  $v_z$  are the amplitudes of motion trajectories generated by three piezoelectric actuators in direction  $X$ ,  $Y$  and  $Z$ , respectively;  $u_x$ ,  $u_y$  and  $u_z$  are the input signals in three directions;  $\varphi_x$ ,  $\varphi_y$  and  $\varphi_z$  are the phase angle of the piezoelectric actuator signal;  $f$  is the driving frequency. The driving signal of three piezoelectric actuators output displacement under the Cartesian coordinate system are:

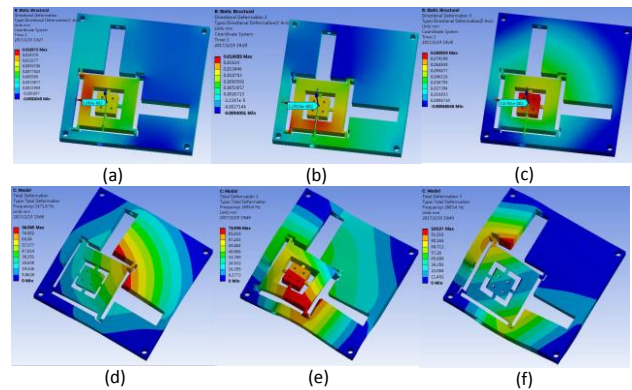
$$\begin{cases} x(t) = A_x \sin(2\pi ft + \psi_x) \\ y(t) = A_y \sin(2\pi ft + \psi_y) \\ z(t) = A_z \sin(2\pi ft + \psi_z) \end{cases} \quad (2)$$

Where  $A_x, A_y$  and  $A_z$  are the output displacements amplitude,  $\psi_x, \psi_y$  and  $\psi_z$  are the phase difference of the output displacement.

The 3D elliptic micro-displacement stage trajectory by different parameters to simulate. Figure 3 shows that the trajectory I:  $A_x=2\mu m$ ,  $A_y=2\mu m$ ,  $A_z=1\mu m$ ,  $\psi_x=0^\circ$ ,  $\psi_y=45^\circ$ ,  $\psi_z=90^\circ$ , by changing the amplitude and phase of the output displacement, the 3D elliptical trajectories of different spatial positions can be obtained. the trajectory II:  $A_x=2\mu m$ ,  $A_y=4\mu m$ ,  $A_z=1\mu m$ ,  $\psi_x=0^\circ$ ,  $\psi_y=45^\circ$ ,  $\psi_z=90^\circ$ . the trajectory III:  $A_x=2\mu m$ ,  $A_y=2\mu m$ ,  $A_z=1\mu m$ ,  $\psi_x=30^\circ$ ,  $\psi_y=45^\circ$ ,  $\psi_z=150^\circ$ . trajectory IV:  $A_x=3\mu m$ ,  $A_y=2\mu m$ ,  $A_z=3\mu m$ ,  $\psi_x=0^\circ$ ,  $\psi_y=60^\circ$ ,  $\psi_z=120^\circ$ . Figure 3 shows that, the study aims to development of a 3D elliptical micro-displacement motion stage that enables the ideal elliptical trajectory, by the set each parameters.



**Figure.3** The three PZT vertical drive micro-displacement driving for 3D elliptic micro-displacement stage trajectory.



**Figure. 4** Finite element analysis of the Three PZT vertical drive micro-displacement driving for 3D elliptic micro-displacement stage.

### 3.2. Finite element analysis of the Mechanism

In this paper, reliability and structural resonances of the device all depend on the performance of the flexure hinge, static and dynamic performance of the hinge need to be taken into consideration. Finite element analysis is carried out to evaluate the static and modal responses of the hinge. The adopted software is ANSYS Workbench 14.0. The stage material selection is spring steel 65Mn, In the model, three piezoelectric actuators the input force applied to the driving position of the 1600N, the micro-displacement motion stage in three directions of output displacement can reach 14μm, 16μm and 74μm. As shown in Figures 4 (a) - (c), the output displacement can be adjusted by adjusting the size of the input force.

The first three order modal analysis results of the Three PZT vertical drive micro-displacement driving for 3D elliptic micro-displacement stage are shown in Fig. 4 (d) - (f), where the first-order mode can reach 1471.6HZ and the second-order mode is 2698.4 HZ, the third-order mode is 2803.4HZ, micro-displacement motion stage in the course of motion, and convenient for the precise control within 0-500HZ bandwidth.

## 4. Summary

The apparatus of a 3D elliptical micro-displacement motion stage driven by piezoelectric actuator is designed. Three piezoelectric actuators are surrounded by a closed-annular folding flexure hinge to improve the strain and stress amplitudes of the specimen. The design procedures and basic working performances, such as static and modal responses of the flexure hinge. Also, detailed analysis and experiments, such as the simulation of trajectory and finite element, result proved that high precision control could be obtained and large output displacement.

## Acknowledgments

This work was financially supported by the “Chunhui Plan” Project of Ministry of China Education (Z2016024) and the development Program of Scientific and Technological of Jilin Province (20160520072JH, 20160101340JC, 20150623024TC-08).

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