Design and Control of 3DOF High Precision Positioning System With Double L Type Flexure Hinge Module

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Abstract: High-precision position system is widely used in lots of fields such as semiconductor industry, biotechnology, display and other up-to-date industry field. One of the main issues is to have a long traveling range with precision. There are a few solutions. For instance, there are inchworm methods, lever principle. In this study, we use lever principle to amplify output displacement with a new mechanical amplification structure. We designed new type 3DOF stage with PZT actuator and capacitive sensor. Non-monolithic structure is suggested to obtain the convenience of assembly and modification. Driving parts are designed as modules that generate displacement amplification of each axis. Designed motion module consists of 3 flexure hinges and a PZT actuator with double L lever structure.

Keywords: High-precision, positioning, stage, flexure hinge, double L type lever

1. INTRODUCTION

Ultra precision positioning system is widely used in lots of manufacturing process of display such as pattern generation, LIGA process etc. The positioning accuracy level of semiconductor manufacturing machines comes to be more important because semiconductor chip size is getting smaller rapidly and high quality display resolution is demanded in the display market. In addition, precision positioning system will be key element in the emerging industry such as BT, IT and NT. Many researchers have studied small application such as AFM, micro griper and small size stage [9] [11] [12].

Concept of dual servo is widely studied for a high precision positioning system. For instance, hard disk head control system uses as dual servo[7]. Combined coarse and fine motion system has a large stoke and enhanced precision[10]. In dual servo system, high resolution servo motor system is need in coarse motion resulting in high cost. However, to increase fine motion stroke can reduce the whole system cost. We decrease coarse motion resolution adequately and increase traveling range of fine motion system to coarse resolution. The output displacement of PZT actuator is very small in the range of 10~100um. So there have been many researches to amplify the displacement of PZT. In this study, we designed the mechanical module using the lever principle with double ‘L’ type for this purpose.

Most high precision positioning system using PZT and flexure hinge mechanism is for small application. The more stiffness difference between mechanical system and PZT module, the better performance can come out. Because flexure hinge stiffness depends on the dimension parameter such as thickness, radius and width of hinge. Actually large size precision system building is difficult due to PZT actuator stiffness limits. In the past, numerous micro stages were constructed in monolithic structure. Monolithic structure is recommended as precision positioning system because of reduced assemblage error. However, it has some problems. It is difficult to build complex stage. It also demands high price 3D manufacturing machine. In this study, we show the benefit of module instead of monolithic type and overcome assemblage error by closed loop control.

In this study, we suggest the new type flexure hinge module with double L lever and 3DOF mechanical structure that has large size loading area and doesn’t cause the stiffness reduction of flexure hinge. In section 2, new flexure hinge mechanism with PZT actuators are explained. In section 3, the modeling and control of the stage are shown with several dynamic characteristics.

2. HIGH PRECISION POSITIONING SYSTEM DESIGN USING THE AMPLIFICATION MODULE

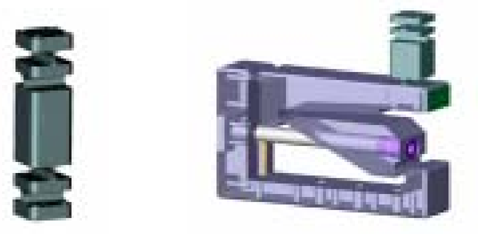
2.1 PZT actuator and Flexure hinge mechanism

Nowadays PZT (lead zirconate titanate) is mostly used for piezoelectric material. PZT actuator has no stick slip, so it has infinite resolution theoretically. Actual resolution, however, is limited by electrical noise in sensor, controller and electrical interference occurred by unexpected output displacement of PZT actuator. Piezoelectric phenomenon doesn’t generate magnetic field and isn’t interfered by magnetic field. It also has fast response characteristic and generates a lot of force. And it is useful in clean environment because it does not need lubricant.

On the contrary, the disadvantages of PZT actuator are just tens micro meter short traveling range and hysteresis. Short traveling range can be overcome by lever principle and hysteresis can be overcome by closed loop control [8].

Until now many precision positioning system have been applied to screw and ball bearing type. We can find examples in lots of industry fields. However, such a mechanism has some problems like stick slip, back lash and friction. Such mechanical problems cause the whole system resolution and accuracy to be decreased. If the system design leads to the desired accuracy, it will be expensive.

Solution for these problems is to use the PZT actuator and flexure hinge or leaf spring mechanism. These mechanisms are simple with continuous driving. Without mechanical friction, it is proper for high precision positioning system. However, small stroke of PZT actuator needs an amplification module. There are several ideas to this. One is to use a leverage based on a monolithic structure. But, this has the reduced stiffness and amplification effect. The other one is to use a L type lever for amplification.



(a) (b)

(a) Spherical joint with flexible structures
(b) Double L type Amplification Hinge Module

Fig. 1 Newly Designed Double L type Hinge Module

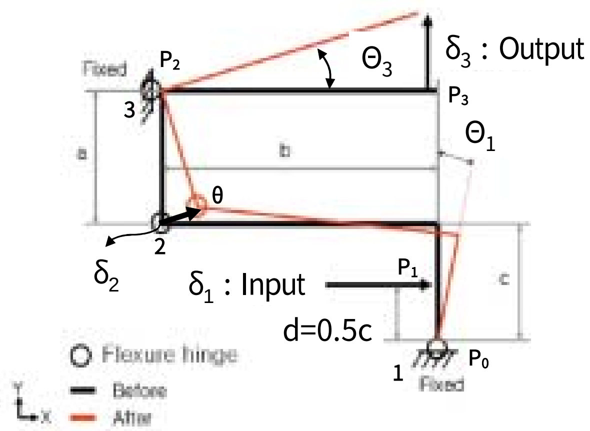


Fig. 2 Principle of Double L type amplification module

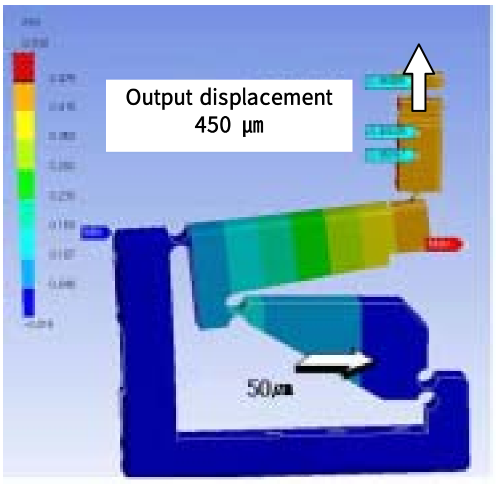


Fig. 3 Simulated Output Displacement of Double L type amplification module by FEM analysis

2.2 Double L Type Flexure hinge module

Overall designed double L type amplification module is shown at Fig.1. It has 3 circular hinges and 2 L shape levers connected in serial.

Lever length can become very long to get the desired amplification ratio in the case of single lever with straight or L type. It causes stiffness and amplification ratio to decrease. Combination of two adequate length L type levers that link in serial shows higher stiffness and amplification ratio than one lever. Hereafter we explain this principle. In Fig.2 if the marked input point (length d) P_1 is given by input displacement δ_1, then L shape hinge rotates by θ_1 and displacement is amplified according to lever principle. Generated displacement δ_1, δ_2 makes the upper L type lever to rotate about P_2. Finally output displacement δ_3 is generated by the same lever principle

$$\begin{aligned} \delta_1 &= d\theta_1 \\ \delta_2 &= \sqrt{b^2+c^2}\ \theta_1 = a\theta_3 \\ \delta_3 &= b\theta_3 = y \\ \frac{\delta_3}{\delta_1} &= \frac{b\sqrt{b^2+c^2}}{a\,d} \end{aligned} \qquad (1)$$

Displacement amplification ratio is derived in Eq. (1). The computed ratio of amplification by hand using Eq. (1) is about 11. On the other hand, the simulation ratio by DesignSpace, the FEM software is about 9 while the single lever case with same parameters of b, c, d shows the ratio of 4 (Fig.3). So, our double L type shows better motion amplification ratio. The difference between 9 and 11 is presumed as added hinge structure at the tip of the hinge module absorbs output displacement and tiny displacement occurs to the module. Equivalent universal or spherical joint at Fig.1 is designed to transform rotation into translation without coupled motion.

2.3 Large Stage Design for Wide and Heavy object

The right circular hinge stiffness of X axis is very high, but the stiffness of Z axis is very small (Fig. 4). In the general monolithic stage machining process we use drilling and wire cutting EDM and then z plane is selected as loading area. If object gets heavy, b and t will be large to endure moment and shear force of y axis. This causes stiffness increase of z axis. So it results in loss of output displacement.

For a right circular hinge, angular deflection α_z about z axis, bending moment M_z about z axis, modulus of elasticity E, hinge thickness t, width b and hinge radius R can be written as Eq. 2 [1]. It is the correlation between the angle displacement to moment and R, b, t in Fig. 4.

$$\frac{\alpha_z}{M_z} = \frac{9\pi R^{\frac{1}{2}}}{2Ebt^{\frac{5}{2}}} \qquad \textbf{(2)}$$

Accordingly it is the better way to load object in X axis direction so that hinge endure heavy load with low stiffness.

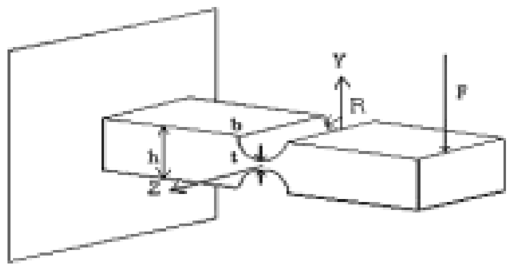


Fig. 4 Right Circular hinge

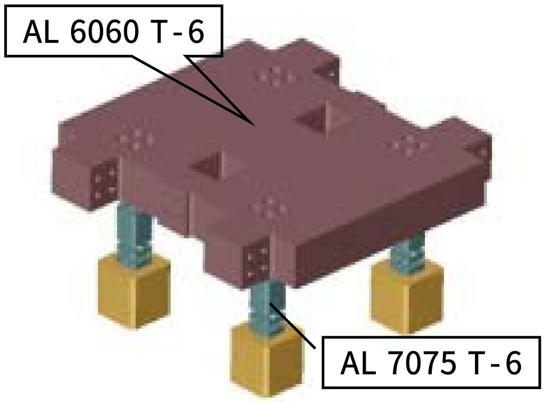
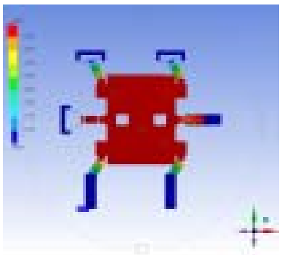
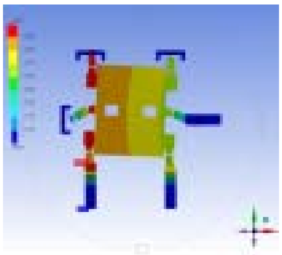


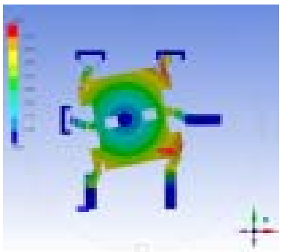
Fig. 5 3D CAD model of our stage with four separable spherical joints



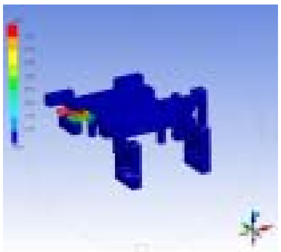
(a) mode 1 : 123.57 Hz



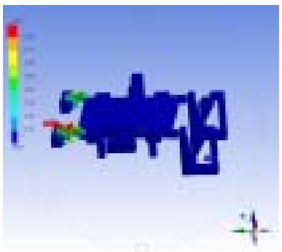
(b) mode 2 : 172Hz



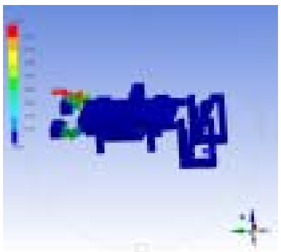
(c) mode 3 : 195.6 Hz



(d) mode 4 : 402 Hz



(e) mode 5 : 558.22 Hz



(f) mode 6 : 558.95 Hz

Fig. 6 Vibration Analysis of Assembled stage

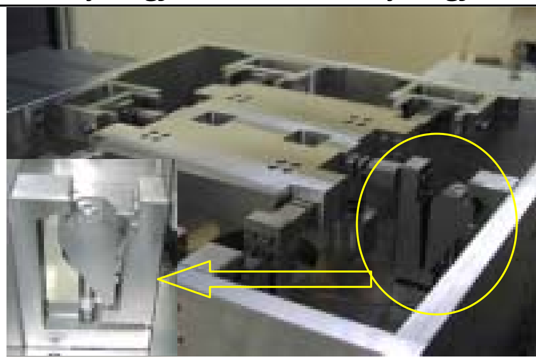


Fig. 7 Photo of Prototype of Assembled Stage

Fig.5 shows the stage to load a wide object on the upper face and Fig.7 shows the photo of assembled Stage. This stage has 300×300 (mm^2) loading area. Flexure hinge material is AL 7075-T6 and the other load face is AL 6061 T-6.

If ceramic material is used for the load plane of the stage, it will be less influenced by temperature change.

3. MODLEING AND CONTROL OF THE STAGE

3.1 Modeling of stage

We referred a numerical model in [5]. Eq. (1) shows the relationship between translation output displacement of each flexure hinge and angle displacement.

We set up the equation of kinetic energy and potential energy to be used for Lagrange equation, Eq. (3).

Effective stiffness is computed by using [1]. The computed natural frequency is 109Hz and it is close to the 123 Hz that is computed by FEM software in Fig. 6.

For the double L type module, polar moment of inertia J_1 about 1 hinge, polar moment of inertia J_3 about 3 hinge, mass of object and angular displacement θ_1, θ_2, θ_3 about each right circular hinge 1,2,3 used for modeling process in the following

Kinetic Energy

$$
\begin{aligned}
T &= \frac{1}{2}J_1\dot{\theta}_1^{\,2} + \frac{1}{2}J_3\dot{\theta}_3^{\,2} + \frac{1}{2}M\,\dot{y}^2 \\
&= \frac{1}{2}J_1\frac{a}{b\sqrt{b^2+c^2}}\dot{y}^2 + \frac{1}{2}J_3\frac{1}{b}\dot{y}^2 + \frac{1}{2}M\,\dot{y}^2 \\
&= \left(\frac{1}{2}J_1\frac{a}{b\sqrt{b^2+c^2}} + \frac{1}{2}J_3\frac{1}{b} + \frac{1}{2}M\right)\dot{y}^2 \\
&= A\dot{y}^2
\end{aligned}
$$

Potential Energy

$$
\begin{aligned}
V &= \frac{1}{2}K_{\theta_1}\theta_1^{\,2} + \frac{1}{2}K_{\theta_2}\theta_2^{\,2} + \frac{1}{2}K_{\theta_3}\theta_3^{\,2} + \frac{1}{2}Ky^2 \\
&= \left(\begin{array}{c}\frac{1}{2}K_{\theta_1}\left(\frac{a}{b\sqrt{b^2+c^2}}\right)^2 + \frac{1}{2}K_{\theta_2}\left(\frac{a+\sqrt{b^2+c^2}}{b\sqrt{b^2+c^2}}\right)^2 \\ +\frac{1}{2}K_{\theta_3}\left(\frac{1}{b}\right)^2 + \frac{1}{2}K\end{array}\right)y^2 \\
&= B\,y^2
\end{aligned}
$$

Lagrange Equation

$$L = T - V = A\dot{y}^2 - By^2 \qquad (3)$$

$$\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{y}}\right) - \left(\frac{\partial L}{\partial y}\right) = 2A\ddot{y} + 2By = F$$

$$2A\ddot{y}^2 + 2By = F$$

$$M_{eff}\,\ddot{y}^2 + K_{eff}\,y = F$$

$$M_{eff} = 2A = 0.066kg$$

$$K_{eff} = 2B = 31220 \;\; mN/mm$$

$$f = \frac{1}{2\pi}\sqrt{\frac{K_{eff}}{M_{eff}}} = 109 \; Hz$$

3.2 Feed back control

Representation of dynamic system about the double L type hinge module is Eq. (4).

$$\ddot{y} + \frac{K_{eff}}{M_{eff}} y = \frac{1}{M_{eff}} F \qquad (4)$$

The output displacement and velocity are a set of state variables. Butterworth configuration [6] is applied to get proper poles placement. Gain values are determined by using the MATLAB. It is modified by trial and error because of the difference between actual dynamics and theoretical model.

Fig.8 describes a feedback control system. Controller is Turbo PMAC that is commercial product made by Delta-Tau and consists of 16 bit AD and DA converter. Displacement is measured by capacitive sensor and sensor resolution is 1nm in specification however actual resolution is about 30 nm in our experiment environment because of external disturbance like building vibration and electrical noise.

PZT actuator has maximum 60㎛ traveling range. Normally PZT actuator intends to be inverse proportion between output displacement and stiffness [4]. Programming tool is used to PLC program which is supplied by PMAC.

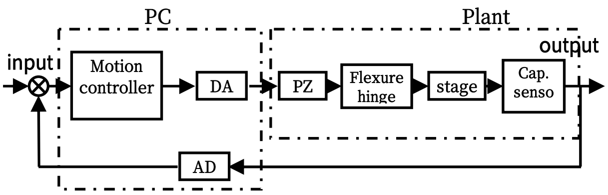


Fig. 8 Control System of 3 DOF precision positioning system

Fig. 9 shows single open loop step response. That is capacitive sensor signal measured while control input voltage increases 1 V per each step from 0V to 10V. Initial starting point was changed to 2㎛ by process to preload. We can recognize full stroke as 95 ㎛ in single axis. It is interesting that the step response is different in each step. This means that system dynamics is changing as the PZT actuator displacement varies. We presume that the reason is hysteresis of PZT actuator and stiffness change. However, we assumed that system model is constant in whole traveling range.

The other big issue of the multi DOF stage with flexure hinge is the coupling problem. In the actuation test, interference about another axis represented no more than 4%. It can be overcome through closed loop control and model compensation.

A step response with 10 ㎛ command in closed loop control is represented in Fig. 10. Fig.11 shows settling time is about 1.3 second. The steady state output is shown in Fig. 12 to check positioning accuracy in each step. The accuracy in whole stroke is about 60 nm. High quality environments and high resolution AD, DA converters are needed for the better accuracy.

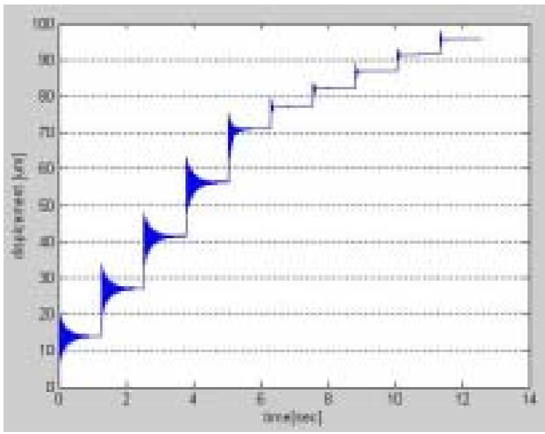


Fig. 9 Open loop Step response

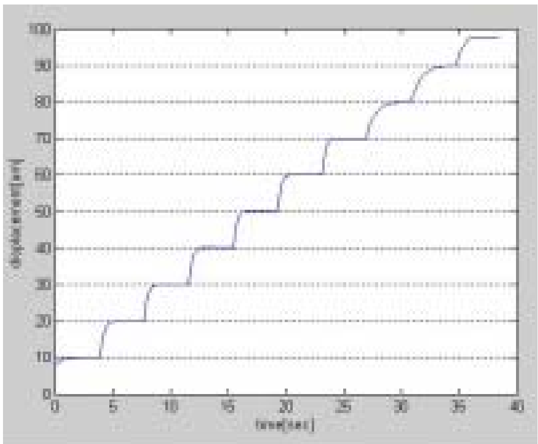


Fig. 10 Closed loop Step response

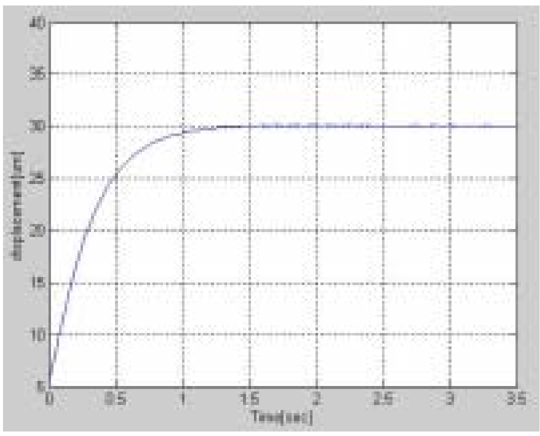


Fig. 11 Closed loop One Step response

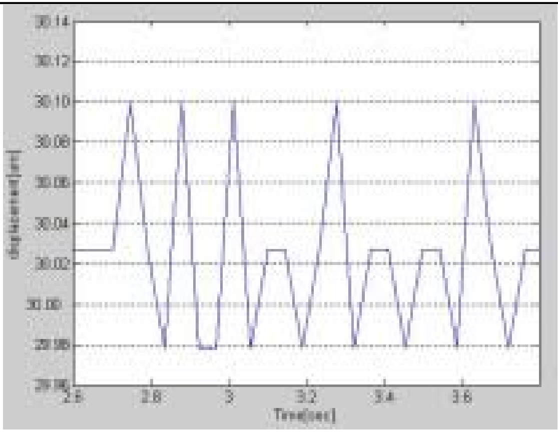


Fig. 12 Resolution

4. CONCLUSION

New type of flexure hinge module with double L type lever shows the higher motion amplification ratio. This will be cost saving factor in a dual servo positioning system.

The 3DOF stage with separate flexure hinge module has large loading area with little dependence on hinge stiffness. In addition, it has the advantage of easy modifying and tuning the stage structure. The stiffness difference between PZT actuator module and flexure hinge module or other stage part should be compared carefully. Otherwise, this will reduce the output motion range. It is to worth to note that the open loop step response of the stage with PZT actuator shows the varying dynamics as the displacement changes. This should be considered in the strict control conditions.

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