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Design and Analysis of Large Stroke Piezoelectric Deflection Stage

Jingwei Liu [1], Anna Zhou [1], Chenglong Hao [1], Liangyu Cui [1, 2, *]

[1] School of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin, China

[2] Tianjin Key Laboratory of High Performance Manufacturing Technology & Equipment, Tianjin University of Technology and Education, Tianjin, China

* Corresponding Author: Liangyu Cui

ABSTRACT

In this paper, a deflecton stage, actuated by piezoelectric ceramics actuator and capable of rotating along both the X and Y axes via a Hooke-type flexible hinge mechanism, is meticulously designed. Utilizing three-dimensional modeling software, the flexible mechanism of the piezoelectric deflection stage is modeled in detail. Furthermore, ANSYS software is employed to conduct a finite element analysis (FEA) on the flexible hinge mechanism component of the piezoelectric deflection stage, focusing on characteristics such as stroke, load capacity, stiffness, and Modal and other properties. The analysis reveals that the deflection angles can achieve up to 3.32 mrad and 3.34 mrad respectively, while the first-order natural frequency stands at 385.93 Hz. These specifications adequately fulfill the stringent requirements of high-speed operation for a large-stroke deflection stage.

KEYWORDS

Deflecton Stage; Flexible Hinge; Piezoelectric Ceramic Actuator; Finite Element Analysis.

1. INTRODUCTION

In the context of today's increasingly advanced industrial manufacturing technologies, the demand for high-precision machining equipment has become increasingly urgent. Especially within the automotive, aerospace, medical instrumentation, and automation sectors, the pursuit of large stroke and high precision represents the prevailing trend in current micro-manufacturing industry development[1] . However, these technologies frequently encounter challenges such as positional inaccuracy, limited range of motion, insufficient robustness, and excessive errors, particularly where deflection errors have emerged as a significant impediment to achieving precise platform positioning accuracy[2] . Therefore, investigating methods to enhance positioning accuracy by adjusting and compensating for deflection errors holds significant importance for advancing precision machining technology in China. In this endeavor, piezoelectric deflection stage and their associated technologies have garnered considerable attention due to their distinctive benefits, emerging as pivotal technologies for achieving high-precision positioning. Piezoelectric deflection stage boast nanoscale precision and a high-frequency bandwidth, while also facilitating wear-free and frictionless precision motion through the utilization of flexible mechanisms. Consequently, they satisfy a wide range of high-precision machining and positioning requirements[3] .

Currently, remarkable advancements have been made in domestic and international research concerning piezoelectric deflection stage and flexible mechanisms. For instance, technology enterprises such as Ball Aerospace[4] & Technology Lefch Hand Design[5] have developed a variety of oscillating table products covering a range from small to large angles and frequencies from tens to several kilohertz, which are widely used in optical equipment in aviation and space. In terms of flexible mechanisms, the torsionally flexible hinge proposed by JACOBSEN et al. can use this type of torsionally flexible device even when large translational or rotational displacements are required; Chen Guimin[6] et al. proposed a depth-cut elliptical flexible hinge, and Zong Guanghua et al. developed a flexible hinge with a hyperbolic shape, which enables this hinge to realize a wide range of movement and rotation angles [7]. These provide new ideas for the design of flexible mechanisms. In addition, Li Zongxuan[8] also conducted an in-depth study on the deformation, fracture prevention and size setting of flexible mechanisms by means of finite element analysis and other methods. However, despite these results, there are still some shortcomings in the existing research. For example, the internal structure of piezoelectric deflection stage tends to be more complex with more combinations of parts, which increases the difficulty of design and manufacturing. Meanwhile, the performance of some piezoelectric deflection stage in high frequency and large stroke still needs to be improved. In addition, the dynamic performance of flexible mechanisms under complex loading conditions has not been adequately studied, which limits their application in high-precision machining.

In response to the above deficiencies, by optimizing the design of the flexible mechanism and the driving method of piezoelectric ceramics actuator, a large-stroke piezoelectric deflection stage with a closed-loop stroke of not less than 3mrad and a no-load frequency of not less than 300Hz is designed, and the maximum load of 1kg is also set to improve the positioning accuracy and stability. Through this study, it is expected to promote the development of high-precision machining technology and provide more accurate and stable positioning solutions for related industries.

2. STRUCTURAL DESIGN OF A PIEZOELECTRIC DEFLECTION STAGE

The piezoelectric deflection stage is mainly composed of piezoelectric ceramics actuator, flexible hinge, housing, sensors and their internal alignments, as shown in Fig. 1. Among them, the driving element is the piezoelectric ceramics actuator, the transmission mechanism is the flexible hinge, the measuring element is the strain gauge, and the reflector is mounted on the motion platform of the piezoelectric deflection stage in the form of threaded connection or adhesive bonding to deflect the angle determined by the laser reflected from the mirror, thus realizing the high-precision positioning.

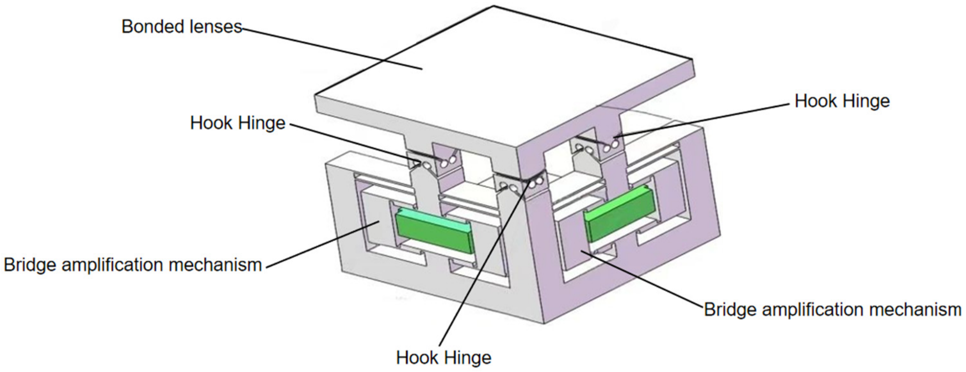


Fig 1. Simplified schematic of a piezoelectric deflection stage

Due to the use of flexible and metal-made mechanical drives there is a certain degree of energy loss, which prevents them from achieving perfect transmission. Flexible hinges produce a considerable amount of springing in their external dimensions, in the form of openings and under pressure, so that the pressure inside them can be determined by means of equations. Using two-dimensional piezoelectric technology driven by piezoelectric ceramics actuator, it is possible to achieve control of the stroke amplification of the flexible hinge, thus allowing the moving platform to make rotational movements in the X-axis. Since each piezoelectric deflection stage is powered by two mutually perpendicular piezoelectric ceramics actuator and positional transfer is accomplished with the aid of three sets of Hooke's hinge structures, in this rotational study on the X-axis, the moving platform of the piezoelectric deflection stage is deformed in the direction of the Z-axis at all other points as it is moved around the X-axis.

3. FLEXIBLE MECHANISM DESIGN AND ANALYSIS

3.1. Hook Hinge Design

Hook hinge, also known as limit hinge, is a special hinge structure, as shown in Fig. 2. It is mainly composed of two parts, the outer circle bending hinge block and the inner circle bending hinge block; the bending angle of these two parts should be kept consistent, and the hinge surface gap is small. The main features are: small size, light weight, high torque transfer precision, high transfer efficiency, good accuracy and characterization, good stability, high load carrying capacity and long life. It is more suitable for the design of this piezoelectric deflection stage; it is characterized by small volume, light weight, high torque transfer precision, high transfer efficiency, strong load-bearing capacity and long life.

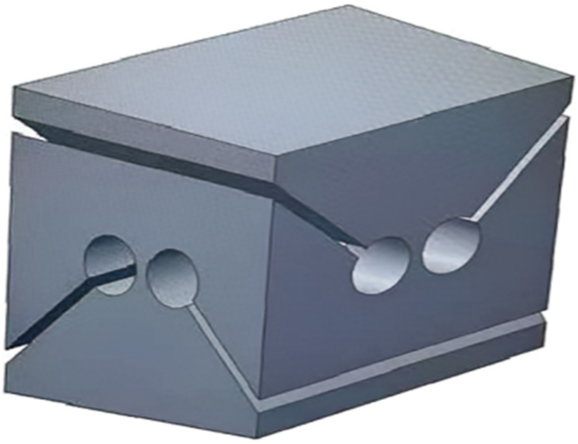


Fig 2. Flexible Hook Hinge

3.2. Bridge Amplification Mechanism Design and Analysis

The structure of the bridge amplification mechanism is symmetrical, as shown in Fig. 3, consists of 8 flexible hinges, 4 connecting beams, 2 translation rods, 1 output block and 1 fixed block This is composed of beams with different sizes; the width of the two beams in contact with the piezoelectric ceramics actuator cannot be too small, to prevent deformation during the work process, affecting the analysis results. As the piezoelectric ceramics actuator produced by the stroke is relatively small, the role of the bridge amplification mechanism is to amplify the piezoelectric ceramics actuator produced by the stroke, through the applied displacement and force to make the bridge amplification mechanism, flexible Hooke hinge to produce elastic deformation, transferred to the deflection table, so that you can better observe the deflection of the piezoelectric deflection stage, the detailed structure as shown in Fig 3.

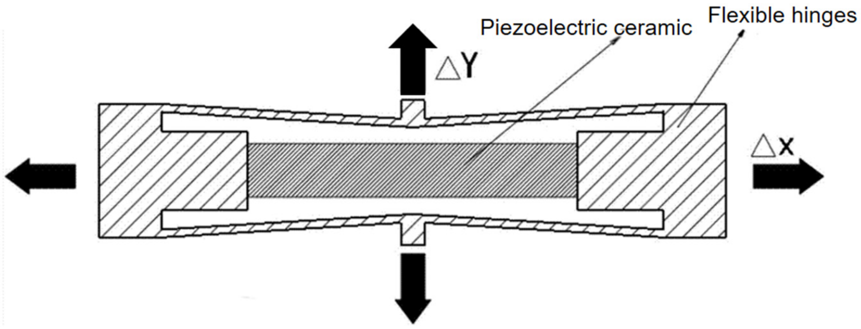


Fig 3. Bridge amplification structure

4. FINITE ELEMENT ANALYSIS

4.1. Maximum Stroke

In exploring the mechanism of operation of the piezoelectric deflection stage, the focus was on how to precisely rotate the moving stage around the x-axis and y-axis by manipulating the two piezoelectric ceramics actuator. Specifically, the same input displacement, i.e., 0.01 mm, was applied to each of the two piezoceramic actuators located at the axial end to drive the rotation of the piezoelectric deflection stage. It is observed experimentally that when the actuators are operated in the manner described above, the output displacement of the piezoelectric deflection stage along the z-axis reaches a maximum value of about 0.171 mm, which, combined with the calculation of the radius of rotation of 50 mm, results in an x-axis deflection angle of about 3.42 mrad. The y-axis deflection is determined by the same method, and similar results are obtained, with the output displacement along the z-axis reaching a maximum value of about 0.172 mm, the y-axis deflection angle is about 3.44mrad.

At an axis input displacement of 0. 01mm, Fig. 4 illustrates the displacement in the x-direction, with the output displacement reaching a maximum value of about 0.171mm and the x-axis deflection angle of about 3.42mrad.

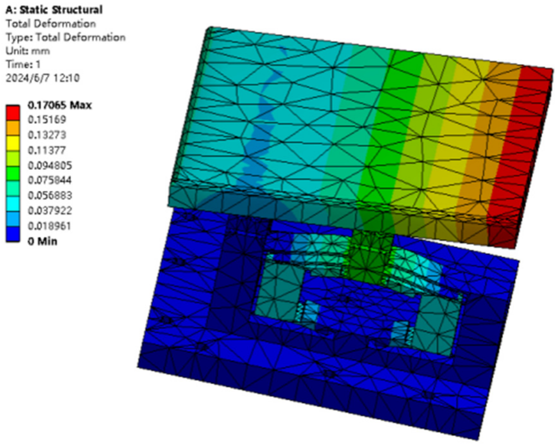


Fig 4. Displacement analysis in x-direction

With an axis input displacement of 0. 01mm, Fig. 5 illustrates the displacement in the y-direction, where the output displacement reaches a maximum value of about 0.171mm and the x-axis deflection angle is about 3.42mrad.

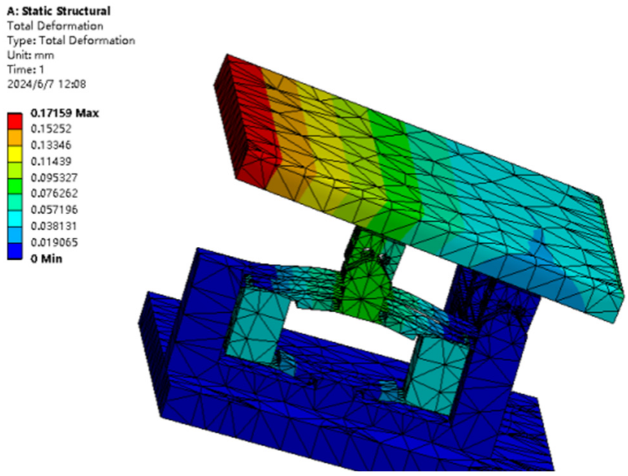


Fig 5. Displacement analysis in y-direction

After obtaining the maximum output displacement, we can calculate that the magnification (maximum output displacement/input displacement) is about 8.5 times. According to the conversion formula between radian and angular systems, the X-axis is deflected by approximately 1.90° and the Y-axis is deflected by approximately 1.91°.

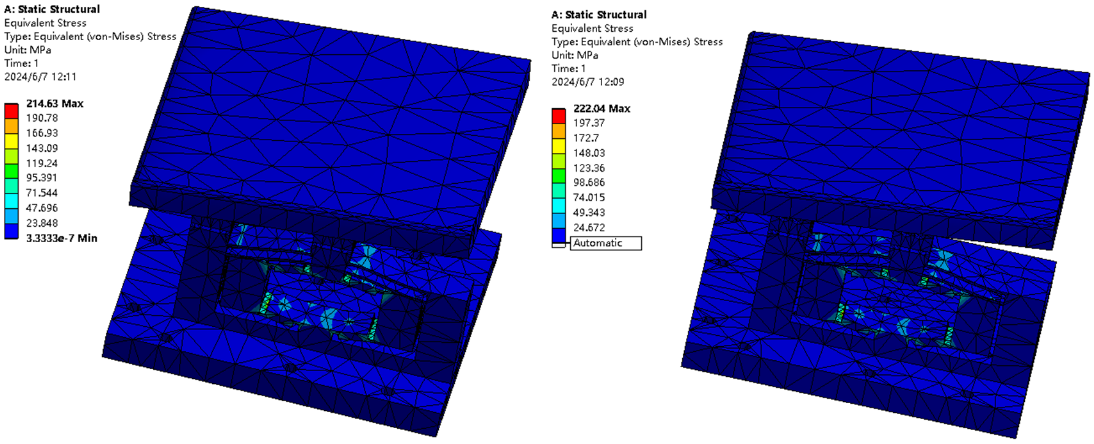
4.2. Maximum Load

Due to the use of flexible and metal-made mechanical drives there is a certain degree of energy loss, which prevents them from achieving a perfect transfer. In fact, the amount of movement received by flexible hinges is not always accurate, and only under certain ideal conditions can they approximate the pressure allowed by the material. In addition, the springing phenomenon produced by flexible hinges in their external dimensions, in the form of openings and under pressure is quite pronounced, so that the pressure inside them can be determined by means of a formula. However, the quality of the hinge material and its processing in actual production may differ from the theoretical model, thus causing a gap between the real situation and the expected theoretical result. If the pressure exceeds the limit, it will lead to broken and damaged hinges. In order to minimize this effect, it is necessary to study the maximum amount of pressure that can be carried by the piezoelectric deflection stage, and this maximum amount of pressure is the maximum load of the piezoelectric deflection stage. After the static solution, it can be learned that the equivalent pressure without burden is 222.04 MPa. When the maximum weight (1KG) is put on the piezoelectric deflection stage and the hydrostatic equivalent pressure solution is carried out, the maximum equivalent pressure reaches 214.63 MPa, which meets the permissible pressure specified by the material A17075. Fig. 6 shows the equivalent pressure of the piezoelectric deflection stage with and without load.

4.3. Modal Analysis

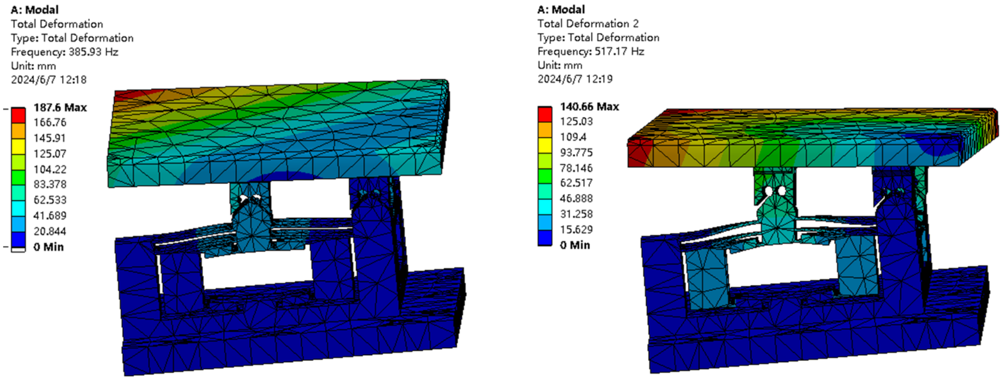
After the implementation of the model study on the dynamic characteristics of the piezoelectric deflection stage, numerical simulation tools were used to obtain the first six levels of stationary frequency points and a series of kinematic features corresponding to these levels. The designed and fabricated two-dimensional piezoelectric deflection stage contains the following built-in component properties: diameter $r = 1$ mm, thickness $b = 7$ mm, and height $h = 10.5$ mm; and the constructional factors within the Hooke's elastic joints, which are the key components of the device, including the aforementioned dimensional information *(i.e.*, r, b, and h) and other relevant data have also been determined. have also been determined. According to the results obtained, a detailed description and understanding of the characteristics of the device can be obtained from the kinetic energy states of the first to the sixth level (Fig. 7); the first level of the intrinsic frequency is equal to about 385.93

Hz per second, and the second level of the intrinsic frequency occurs about 517.17 Hz, which are both in compliance with the preset no-load frequency of not less than 300 Hz.



(a) Without load (b) With load

Fig 6. Equivalent force with and without load condition



(a) First-order intrinsic frequency (b) Second-order intrinsic frequency

Fig 7. Individual mode vibrations of the piezoelectric deflection stage

5. SUMMARY

The research introduces an innovative design scheme that utilizes a flexible mechanism to achieve rotation of the tip-tilt mirror along the x-axis and y-axis. This piezoelectric deflection stage is driven by piezoelectric ceramics actuator parallel to the dynamic platform and achieves x-axis and y-axis rotation of the dynamic platform through deformation of Hooke's joints, thereby enabling the piezoelectric deflection stage to deflect at various angles.

Through analysis of the collected data, it was found that under the application of safe voltages, the maximum stroke along the x-axis and y-axis results in deflection angles of 3.32 mrad and 3.34 mrad, respectively. Furthermore, based on modal analysis, the natural frequency in the primary direction of motion was obtained as 385.93 Hz. The above data indicates that the design meets the requirements.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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