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Structural Design and Performance Analysis of Large stroke Nanoscale Positioning Platform for Objective Lens

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ABSTRACT

This study addresses the demand for high-precision, large-stroke positioning in fields such as ultra-precision manufacturing, optical systems, and micro-nano positioning. A novel micro-nano positioning platform based on flexure hinges and a bridge-type amplification mechanism is proposed. The platform utilizes piezoelectric ceramics for actuation, with the bridge-type amplification mechanism amplifying the displacement. Theoretical analysis, parameter optimization, and finite element simulations were conducted to evaluate the system's performance. The design includes the selection of flexure hinges, development of guiding mechanisms, and analysis of the platform's static, dynamic, and kinematic performance. Results demonstrate that the platform achieves high-resolution, large-stroke positioning, meeting the application requirements of objective lens positioning and other high-precision scenarios. This study employs a piezoelectric objective positioning platform based on a bridge-type amplification mechanism. The platform utilizes piezoelectric ceramics as the driving force and compensates for the small displacement of piezoelectric ceramics through a bridge-type amplification mechanism. It integrates arc-shaped flexure hinges and a symmetric multi-link flexure guiding mechanism to ensure high-precision and decoupled displacement transmission. The platform is compactly designed with dimensions of 70mm × 55mm, achieving a maximum stroke of 0.2mm and a positioning accuracy of 5nm, meeting the requirements for objective lens positioning while accommodating certain load-bearing capabilities.

KEYWORDS

Nano Positioning Stage; Piezoelectric Ceramics; Straight Beam Type Flexible Hinge.

1. INTRODUCTION

The novel micro/nano positioning platform, as an innovative instrument based on flexure hinges and bridge-type amplification mechanisms, addresses the demand for high-precision and long-travel positioning in fields such as ultra-precision manufacturing, optical systems, and micro/nano positioning. These platforms have found applications in lithography machines, ultra-precision machine tools, and scanning microscopes [1]. Piezoelectric ceramics, as the core material of piezoelectric actuation technology, utilize the piezoelectric effect to achieve micro/nanometer-scale positioning. They offer advantages such as ultra-high resolution, high precision, and fast response speed. However, their displacement output is relatively small, typically limited to tens of micrometers, which cannot directly meet the requirements of certain applications. To overcome this limitation, various amplification mechanisms have been developed to enhance the displacement of piezoelectric ceramics, enabling their use in high-tech applications like lithography machines, ultra-precision machine tools, and scanning microscopes. At the same time, traditional transmission mechanisms are often associated with inherent drawbacks, such as backlash and wear. To address these issues, researchers have introduced flexure hinges as a novel mechanism capable of efficiently transferring the input displacement from piezoelectric ceramics [2]. The research on micro/nano positioning platforms can be traced back to the 1980s [3]. Scire and Teague from Stanford University in the United States first developed a one-dimensional micro/nano positioning platform with a travel range of up to 50 μm [4], which was successfully applied in the aerospace industry [5]. Since then, numerous advancements in micro/nano platforms have emerged, with new breakthroughs appearing in recent years [6]. In response to the demand for high-precision and long-travel positioning in fields like ultra-precision manufacturing, optical systems, and micro/nano positioning [7], this paper presents the design of a novel micro/nano positioning platform based on flexure hinges and a bridge-type amplification mechanism. The system achieves displacement amplification through piezoelectric actuation and the bridge-type amplification mechanism, with theoretical analysis and finite element simulation validation [8]. Finally, experimental results confirm that the proposed objective lens positioning platform meets the requirements of practical applications.

2. OVERALL STRUCTURAL DESIGN

The semicircular flexure hinge is a key component known for its high motion precision. Its primary structural parameters include: maximum width, radius of the semicircular flexure hinge, thickness, and elastic modulus. Once the basic parameters and force conditions of the flexure hinge are determined, its deformation behavior can be analyzed and calculated. Since the primary deformation occurs in the curved section, the pseudo-rigid-body method can be employed to analyze its deformation.

Components of the platform include: actuator: piezoelectric ceramic, mechanical structure: semicircular flexure hinge positioning, sensor: capacitive feedback sensor, controller: signal processing and control.

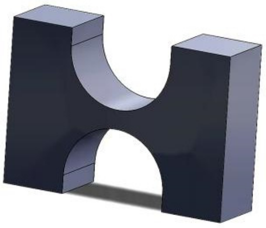

Figure 1. Arc-shaped flexible hinge

Working Principle: When the controller receives a command for objective lens positioning, it sends the corresponding control signals to the actuator. Under these signals, the piezoelectric ceramic actuator generates a small displacement, which is transmitted to the objective lens through the mechanical structure. This allows the objective lens to adjust its position with nanometer-level precision. During operation, the positioning sensor continuously monitors the actual position of the objective lens and feeds the position data back to the controller. The controller processes this feedback and fine-tunes the actuator to ensure that the objective lens remains precisely at the target position. This closed-loop system achieves high-precision positioning and maintains stability throughout the process.

3. BRIDGE-TYPE AMPLIFICATION MECHANISM DESIGN AND ANALYSIS

3.1. Bridge-Type Amplification Mechanism

The principle of the bridge-type amplification mechanism is based on the buckling instability of a compression member in materials mechanics, where the deformation and output displacement are related geometrically to achieve displacement amplification. The bridge-type amplification mechanism offers advantages such as ease of fabrication, compact structure, and high amplification ratio. Here, represents the displacement change of the piezoelectric ceramic in the input direction, is the output displacement of the mechanism, and is the length of the connecting frame. Thus, the output displacement of this amplification mechanism is:

$$\triangle \mathrm{y} = \mathrm{Lsin}\left(\arccos\left(1-\frac{\Delta \mathrm{x}}{2\mathrm{L}}\right)\right) \tag{1}$$

Therefore, the amplification ratio of the bridge-type amplification mechanism can be expressed as:

$$\mathrm{A} = \frac{\Delta \mathrm{y}}{\Delta \mathrm{x}} = \mathrm{Lsin}\left(\arccos\left(1-\frac{\Delta \mathrm{x}}{2\mathrm{L}}\right)\right)/\Delta \mathrm{x} \approx \sqrt{\frac{2\mathrm{L}}{\Delta \mathrm{x}}} \tag{2}$$

3.2. Displacement Calculation of the Piezoelectric Objective Platform

The designed platform has dimensions of 70 mm × 55 mm, with an ideal maximum travel range of 0.2 mm, a travel accuracy of 5 nm, and an emphasis on minimizing torsional deformation errors. After meeting these requirements, considering the operational need to drive the objective lens, the platform must also have a certain load-bearing capacity.

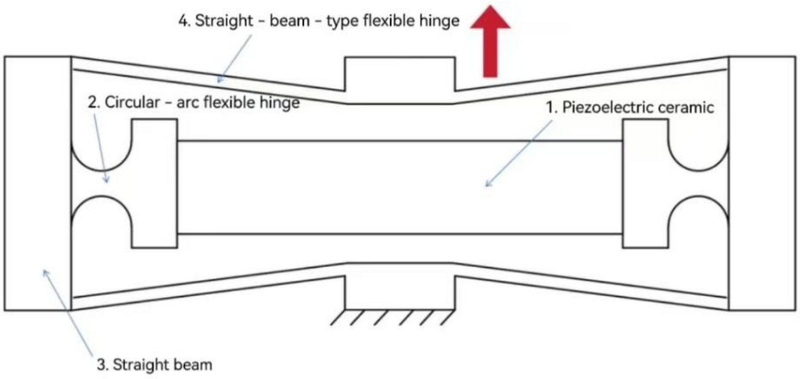

Figure 2. Bridge-type amplification mechanism with piezoelectric ceramic placement

The bridge-type amplification mechanism is separated from the piezoelectric platform for independent analysis, as shown in Figure 2. The initial conditions of the amplification mechanism are that it is subjected to a force along the x-axis, and the flexible hinge is oriented at 0° relative to the x-axis.Under these initial conditions, the strain experienced by the amplification mechanism can be analyzed. The total strain generated can be expressed as:

$$\begin{aligned} U &= \sum_{i=3} (U_a + U_b)_i \\ &= \sum_{i=3} \left(\int_0^{l_i} \frac{N_i^2}{2EA(x_i)} dx + \int_0^{l_i} \frac{M_i^2}{2EI(x_i)} dx \right) \end{aligned} \tag{3}$$

Where is the axial strain of the amplification mechanism, and is the strain caused by the bending moment of the mechanism. In this equation, is the thickness of the flexible hinge, is the Young's modulus of the mechanism, and is the cross-sectional area of the flexible hinge.According to Castigliano's second theorem, the displacement of the mechanism in the x-direction and the torsion occurring around the z-axiscan be simplified into the following equations:

$$\begin{cases} a_{11} = 2C_{x-F_x} + l_1^2 C_\theta + (l_2 + l_3 \sin\alpha)^2 C_\theta \\ a_{12} = -2l_2 C_\theta - l_3 \sin\alpha C_\theta \\ a_{22} = 2C_\theta \end{cases} \tag{4}$$

In Equation 2, represents the length of component2 of the amplification mechanism, and represents the length of the straight beam 3 of the amplification mechanism. From this, the stiffness of the mechanism can be derived.

$$K_e = \frac{F_{0x}}{u_{0x}} = \frac{2}{4C_{x-F_x} + l_3^2 \sin^2\alpha C_\theta} \tag{5}$$

When the mechanism is subjected to the input displacement from the piezoelectric ceramic, the output displacement is , and the amplification ratio is given by:

$$A1 = \frac{\Delta y}{\Delta x} = \frac{(L_3^2 - h^2)\sin\alpha\cos\alpha}{h^2\cos^2\alpha + 6L_3^2\sin^2\alpha} \tag{6}$$

The deformation in the x and y directions is given by and , respectively.

$$\Delta x = \frac{\Delta y}{\Delta x} = \frac{(L_{AB}^2 - h^2)\sin\alpha\cos\alpha}{h^2\cos^2\alpha + 6L_3^2\sin^2\alpha} \tag{7}$$

$$\Delta y = \frac{\partial E}{\partial F_y} = \frac{L_{AB}^3}{12EI}\left(F_x\cos\alpha - F_y\sin\alpha\right) \times \sin\alpha\cos\alpha \tag{8}$$

4. FINITE ELEMENT ANALYSIS

4.1. Static Analysis of the Piezoelectric Objective Platform

The deformation of the motion-guiding mechanism can be regarded as the force response of a statically indeterminate beam subjected to support displacements. By superimposing and, the deflection and rotation angle generated by the flexible hinge can be obtained.

$$u_y = u_y^{Fa} + u_y^{Ma} = \frac{4Fal_4^3}{Eht_2^3} - \frac{6Mal_4^2}{Eht_2^3} \tag{9}$$

$$\beta = \beta^{Fa} + \beta^{Ma} = \frac{6Fal_4^2}{Eht_2^3} - \frac{12Mal_4}{Eht_2^3} \tag{10}$$

Where represents the length of the flexible hinge, denotes the deflection generated by the flexible hinge, and represents the rotation angle produced by the flexible hinge. By solving Equations (10) and (11) simultaneously, the values of and can be obtained.

$$\mathrm{Fa} = \frac{\mathrm{E}h - \mathrm{t}_2^3 \mathrm{u}_\mathrm{y}}{\mathrm{l}_4^3} \tag{11}$$

$$\mathrm{Ma} = \frac{\mathrm{Fal}_4}{2} \tag{12}$$

By obtaining and the deflection, the stiffness of the multi-link motion-guiding mechanism can be determined.

$$\mathrm{k_g} = 4\mathrm{k} = 4\frac{\mathrm{F}}{\mathrm{u_y}} = \frac{4\mathrm{E}h\mathrm{t}_2^3}{\mathrm{l}_4^3} \tag{13}$$

From Equation (13), it can be concluded that the stiffness of the mechanism increases most rapidly as increases, and it is inversely proportional to the length of the flexible hinge. In the finite element analysis, displacement constraints of 10 μm are applied to both ends of the inner side of the amplification mechanism. The maximum displacement is found to be 166 μm, resulting in an amplification ratio of 8.3, as shown in Figure 3.

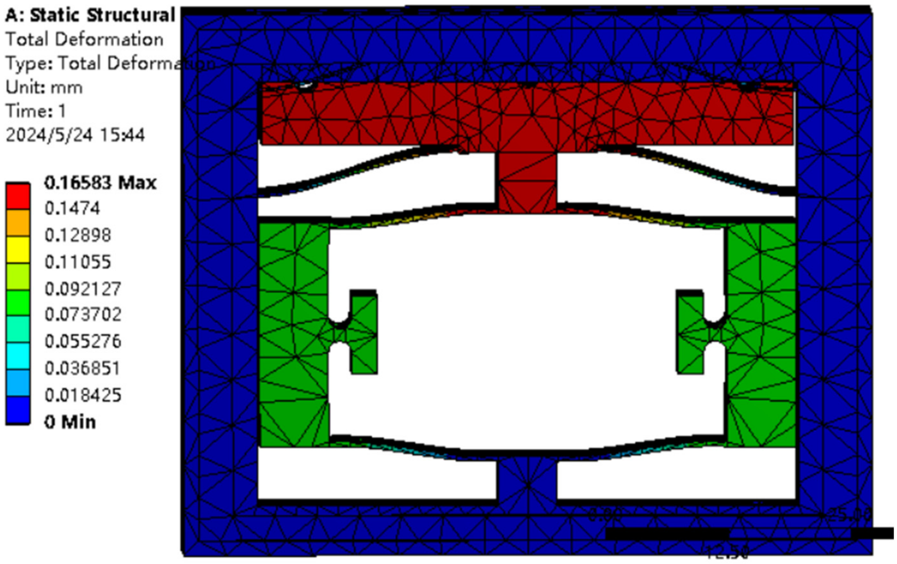

Figure 3. Maximum stroke of the bridge-type amplification mechanism

Under a no-load condition, when a displacement of 20 μm is applied to the bridge-type amplification mechanism as described in Section 4.1.1, the maximum stress is 37.7 MPa, as shown on the left in Figure 4, which is significantly lower than the yield strength of AL7075 (505 MPa).Based on this, an objective lens mounting frame is added to the platform. In the finite element analysis, the mounting frame is set as a 1 kg load. The analysis results indicate that when a displacement of 20 μm is applied to the bridge-type amplification mechanism, the maximum equivalent stress is 60.58 MPa, which satisfies the yield strength requirement of AL7075 (505 MPa), as shown on the right in Figure 4.

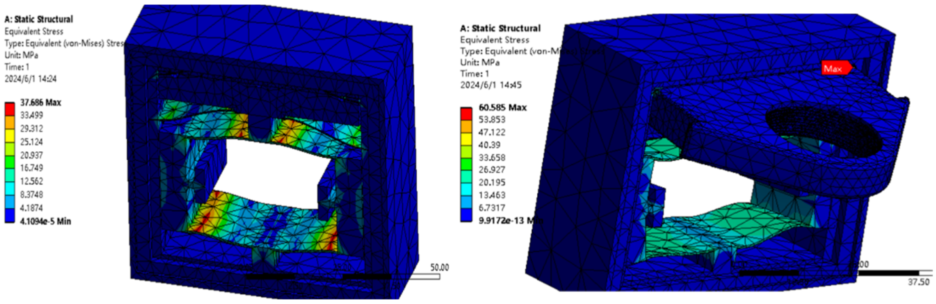

Figure 4. Equivalent stress of the bridge-type amplification mechanism under no load and 1 kg load conditions

4.2. Modal Analysis of the Bridge-Type Amplification Mechanism2.5.Special Signs

To evaluate the dynamic performance of the piezoelectric objective platform, a modal analysis of the amplification mechanism is conducted. This analysis provides insight into the platform's dynamic characteristics. In this study, the first six modes of the bridge-type amplification mechanism are analyzed, yielding the natural frequencies and mode shapes for these modes. The natural frequencies of the first six modes are as follows: First mode: 223.04 Hz Second mode: 424.82 Hz Third mode: 472.73 Hz Fourth mode: 1622.3 Hz Fifth mode: 2055.2 Hz Sixth mode: 2511.4 Hz

(a) First-order mode shape

(b) Second-order mode shape

(c) Third-order mode shape

(d) Fourth-order mode shape

(e) Fifth-order mode shape

(f) Sixth-order mode shape

Figure 5. Mode shapes of the bridge-type amplification mechanism piezoelectric objective platform for each order

5. SUMMARY

This paper presents the design of a piezoelectric-driven, large-stroke objective positioning platform based on flexible hinges and a bridge-type amplification mechanism. Through the selection of flexible hinges, the design of the bridge-type amplification mechanism, theoretical analysis of its amplification ratio and stiffness, and the modeling and optimization of the motion-guiding mechanism, the platform's performance characteristics were comprehensively studied. Finite element simulation was used to verify the platform's displacement amplification ratio, maximum stress, and modal characteristics under both no-load and loaded conditions. The results indicate that the platform achieves large-stroke, high-resolution positioning, meeting the high-precision requirements for objective positioning in optical systems. Compared with traditional designs, the proposed dual-stage bridge-type amplification mechanism demonstrates superior performance in terms of amplification ratio and dynamic characteristics, making it an effective improvement in the field of micro-nano positioning technology.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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