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Development and Evaluation of Linear Characteristic of a Complex Flexure Hinge

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Summary

This paper concentrates on the development and evaluation of linear characteristics of a complex flexure hinge with high accuracy and large stiffness. The flexure hinge mechanism is used to clamp the shaft of a micropositioning stage based on the inchworm principle. Six key parameters of the flexure hinge are optimized by using finite element method. Developed flexure hinge has very good effects on the clamping and resilience that are accurate and reasonable. The evaluation result shows that the flexure hinge has excellent linear characteristic.

keywords: flexure hinge; micropositioning stage; finite element method; linear characteristic

Introduction

Recently ultra-precision micropositioning stage is becoming one of the most key devices and technological advancement due to its growing applications in many fields of precision engineering, such as scanning tunnel microscope, X-ray lithography, micro-machining, assembly of micro-systems, and biological cell manipulation [1]-[3]. The stage is capable of providing smooth motions through deformations of special material such as piezostacks or shape memory alloy. Many successful applications of micropositioning stages have also been reported [4]-[6].

Generally, a micropositioning stage consists of bases, sliding guides, linkages, flexure hinges, and piezoelectric actuators. Especially, the fexure hinges and piezoelectric actuators are integrated to implement ultra-precision manipulation with high resolution. Compared with conventional motion-transmission mechanisms such as gears or joints, fexure hinge mechanisms have many inherent advantages: no backlash, negligible friction, no lubrication, adequate for magnifying the output displacement of piezoelectric actuators, and free of thermal generation. In addition, it can be monolithically manufactured and applied to reduce the assembly errors and ensure the machining accuracy. Based on the applied voltage, piezoelectric actuator can generate continuous expansion and retraction motions with infinite resolution and wide dynamic response range. Thus, the piezodriven fexure hinge mechanism becomes one of the best choices for ultra-precision manipulation [7].

In 1965, Paros and Weisbord [8] derived the stiffness of a circular hinge theoretically. Smith et al [9] and Lobontiu et al [10] derived that same characteristic

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for an elliptical hinge and a corner-fleted hinge. Based on these researches researchers [7], [11] developed many modeling and analysis methods that were used to estimate and optimize real flexure hinge mechanisms. Xu and King [12] analyzed hinge structure by FEM showing a good agreement with experimental results. Tian et al [13] described a design methodology and dynamic modeling of a piezodriven fexure-based Scott–Russell mechanism for nano-manipulations. Kim et al [7] developed and optimized a piezoelectric actuator using bridge-type fexure hinge mechanisms to amplify the displacement of multilayer piezostacks. In that research, matrix method was used to derive the motion equation of the hinge mechanism and optimize the hinge mechanism developed.

In fact, the aforementioned optimization was mainly used to verify and estimate the results of the matrix method and experiences. The optimization procedure for parameters of the flexure hinge was not in the initial design stage. Thus, that method makes it very difficult and time-consuming to optimize the complex flexure hinge structure.

In this research, a complex flexure hinge is developed and evaluated, which integrate with a piezoelectric actuator for clamping the shaft of a micropositioning stage. Based on the finite element method, the complex flexure hinge that includes six key parameters is optimized. Because linear characteristic is an important performance index for flexure hinges, the characteristic curve is derived by calculating the relations of the force and displacement. The evaluation result shows that the flexure hinge has excellent linear characteristic.

Flexure Hinge Mechanism for Clamping

Working principle of flexure hinge mechanism

The flexure hinge mechanism mainly includes a piezoelectric actuator, a flexure hinge, an adjusting screw and a base. Fig.1 shows the basic topology of the flexure hinge mechanism.

The shaft is a motion element of the micropositioning stage that moves with a micro-scale step in the axial direction of the shaft. Based on the controlling order of the micropositioning stage, it needs to be clamped by the flexure hinge mechanism to keep a fixing state for a short time. The piezoelectric actuator provides clamping force which is transferred to the shaft by the elastic deformation of the flexure hinge. Subsequently the shaft becomes in a free state by elastic resilience of the flexure hinge. As shown in fig.1, the flexure hinge and the piezoelectric actuator are fixed on the top of the base. The adjustable screw and the shim are used to apply the preload, in order to ensure the intimate contact between the flexure hinge and the piezoelectric actuator.

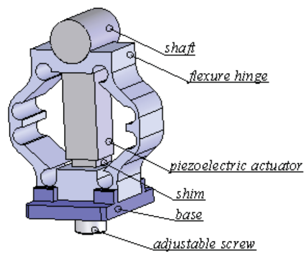

Figure 1: Topology of flexures hinge mechanism for clamping

Modeling of flexure hinge for optimization

In general case, the fexure hinge consists of rigid link parts and fexure parts. The circular, elliptical and corner-flleted shapes are often used as flexure hinge profles. Circular hinges are applied widely because they are easy to be fabricated by conventional machining.

Based on aforementioned advantages and working conditions of the flexure hinge. In this research, the circular shape is selected as flexure hinge profiles that are laid out symmetrically, as shown in fig.2.

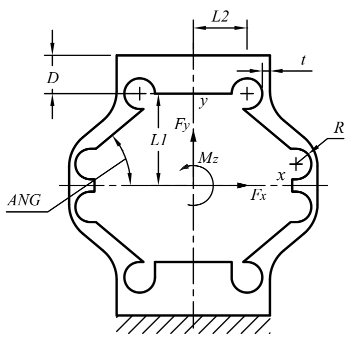

Figure 2: Flexure hinge geometry parameters

Optimization

Optimizatin parameters

Based on the simplified equations of Paros and Weisbord [8], the hinge compliance equations are as follows.

$$\frac{\alpha_z}{M_z} = \frac{9\pi R^{1/2}}{2Ebt^{1/2}}, \tag{1}$$

$$\frac{\Delta y}{F_y} = \frac{9\pi}{2Eb}\left(\frac{R}{t}\right)^{1/2}, \tag{2}$$

$$\frac{\Delta x}{F_x} = \frac{1}{Eb}\left[\pi\left(\frac{R}{t}\right)^{1/2} - 2.57\right]. \tag{3}$$

In (1)-(3), R is the radius of flexure hinges, t is the neck thickness of flexure hinges, b is the thickness of the flexure hinges in the z direction. E is the elastic modulus. It can be seen that the parameters, R and t are the most important which obviously affect the deformation abilities of the flexure hinge. Thus, the parameters R and t need to be designed and optimized. The definition of the overall parameters is as shown in fig.2. The length $L2$ of the top link, the angle ANG between the middle link and x axis, and the horizontal distance $L1$ between the top link and x axis, are also the optimization parameters. The stiffness of the flexure hinge is determined by all of these parameters. therefore, the stiffness is defined as the object function of the optimization.

To refer the geometrical parameters of other similar structure related to the flexure hinge, the value ranges of these optimization parameters are listed in Table 1.

Table 1: Optimization Parameters

Parameters	L1 (mm)	L2 (mm)	D (mm)	t (mm)	R (mm)	ANG (degree)
Lower	10	5	5	0.6	0.5	15
upper	13	8	8	1.6	2.0	45

Material of the flexure hinge

In order to optimize these parameters precisely, it is necessary to pay attention to the material factors. 65Mn is often used as flexure hinge material, because it has smaller elastic modulus and higher allowable stress. All of the parameters are as shown in Table 2.

Table 2: Parameters of the Flexure hinge Material

Material	Elastic modulus	Allowable stress
65Mn	200 GPa	400 MPa

Object function

The output force of the piezoelectric actuator may be divided two components, one part provides to the flexure hinge as expanding force, the other part to the shaft as clamping force. When voltage V is applied to the piezoelectric actuator, the output force is inversely proportional to the deformation, as shown in fig.3.

According to the output force-displacement curve in fig.3, the object function of the optimization for the flexure hinge is as follows

$$\frac{(\Delta L_0 - \Delta L)\,K_b - F}{K_s} \geq \Delta L. \tag{4}$$

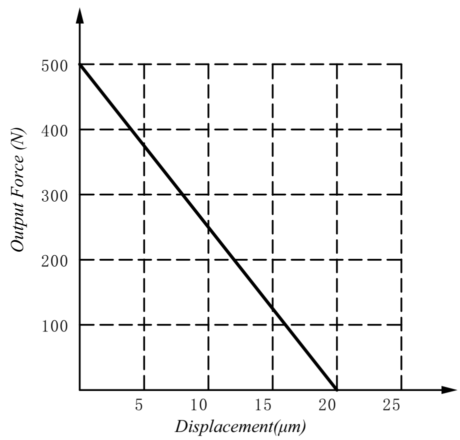

Figure 3: Output force-displacement curve of the piezoelectric actuator

In (4), ΔL_0 is the maximum displacement of the piezoelectric actuator without any load, ΔL is the maximum displacement of the piezoelectric actuator with clamping load, K_b is the stiffness of the piezoelectric actuator, K_s is the monolithic stiffness of the flexure hinge, and F is the clamping force.

To ensure the effectiveness of the clamping, the clamping force F is assumed to be more than 100N, the displacement ΔL_0 is assumed to be more that 10 μm. Thus, the stiffness of the flexure hinge is as follows

$$K_s \leq \frac{(\Delta L_0 - \Delta L)\, K_b - F}{\Delta L} \approx 15N/\mu m. \tag{5}$$

The flexure hinge mechanism transfer the displacement of the piezoelectric actuator by elastic deformation of the material. When the flexure hinge is applied the external load, the maximum stress must be less than the allowable stress as follows

$$\sigma_{\max} \leq [\sigma]\,. \tag{6}$$

In (6), $\sigma_{\max}$ presents the maximum stress, $[\sigma]$ presents the allowable stress of the material.

Optimization results

The finite element method is used to optimize the parameters of the flexure hinge. The initial values of optimization parameters of the flexure hinge obtain from Table 1, depending on the experiences and the geometrical structure of the other parts.

Optimization of parameters L1,L2,D.

From (1)-(3), it can be seen that the compliance/stiffness is insensitive to the parameters, $L1$, $L2$, D. Three optimizations procedures are performed. Table 2 shows the optimization results. Fig.4 shows the relationship between stiffness and parameter D. The trends of the results of the other two parameters are similar with this one. Because the maximum stress of the flexure hinge is far less than the allowable stress in the optimization process, the maximum stress may be negligible in the subsequent optimization working.

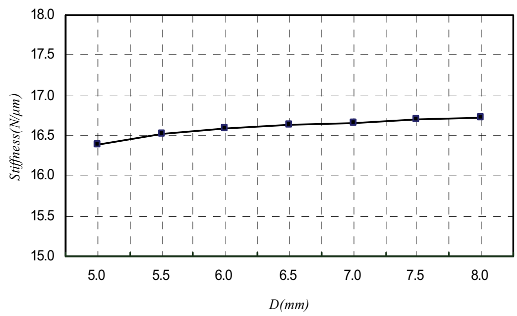

Figure 4: Optimization result of stiffness-parameter D

Optimization of parameters t, R, ANG.

Fig.5 shows that the stiffness of the flexure hinge is directly proportional to the neck thickness t of the flexure hinge. The stiffness $K_s$is less than 14.5 N/μm, when the neck thickness t is less than 1.0 mm and the radius R is less than 2.0 mm. The trend of the result of the parameter R is similar with this one. The calculation results show that the stiffness of the flexure hinge is inversely proportional to the angle ANG between the middle link and x axis. The stiffness $K_s$is less than 14.4 N/μm, when the angle is more than 40 degree. Table 2 shows all the optimization results.

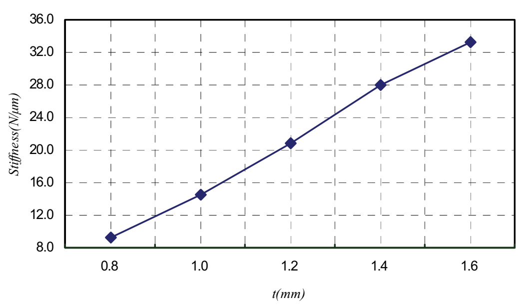

Figure 5: Optimization result of stiffness-parameter t

Evaluation of Linear Characteristics

The maximum working displacement of the flexure hinge is 20 μm. The flexure

Table 3: Optimization Results

Parameters	L1 (mm)	L2 (mm)	D (mm)	t (mm)	R (mm)	ANG (degree)
value	10	5	5	1.0	2.0	40

hinge is applied the load from 10N to 290N respectively within the allowable load. The force-displacement curve is as shown in fig.6. From the curve it can be seen that the flexure hinge has excellent linear characteristic.

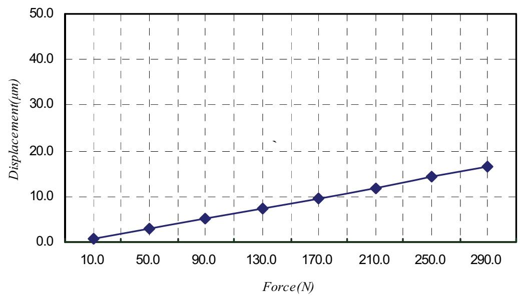

Figure 6: Force-displacement curve of the flexure hinge

Conclusion

In this paper, a complex flexure hinge is developed, which integrate with a piezoelectric actuator for clamping the shaft of a micropositioning stage. The monolithic stiffness of the flexure hinge included six key parameters is defined as object function. Finite element method instead of traditional methods, e.g. matrix method and experience method that are time-consuming or imprecise, and be used to optimize the six key parameters of the flexure hinge. The characteristic curve is derived by calculating the relations of the force and displacement. The evaluation result shows that the flexure hinge has excellent linear characteristic.

Developed flexure hinge has very good effects of the clamping and resilience that are accurate and reasonable. The optimization approach can also be applied to design other types of complex flexure hinge mechanisms for micropositioning stages.

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