Design and Performance Analysis of Precision Micro-drive Amplification Mechanism

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Abstract. At present, there are shortcomings in the research of micro-drive amplification mechanism, such as insufficient precision and additional force. In this paper, a kind of micro-drive amplification mechanism is designed and its positioning accuracy is simulated. Firstly, a kind of micro-drive amplification mechanism is designed, which can accurately transform the input displacement of piezoelectric ceramic actuator (PZT) into the output displacement of a certain number of amplification. The theoretical motion magnification ratio of the mechanism is 3:1. Secondly, the kinematics and simulation of the mechanism were studied, and the conversion performance of the mechanism was analyzed. The results showed that the micro-drive amplification mechanism has the advantage of high positioning accuracy (maximum positioning error is 4.67%). Finally, through strength analysis and modal analysis, the performance of micro-drive amplification mechanism is studied. This study has some reference value for the research and application of precision micro-drive amplification mechanism.

1. Introduction
With the continuous improvement of modern industry's requirements for the accuracy of mechanical systems, the requirements for the machining accuracy and motion accuracy of mechanical system equipment manufacturing also increase [1-3]. At present, precision and ultra-precision machining technology is an important realization method of precision manufacturing of mechanical equipment [4-15]. However, how to transfer, guide and amplify the precise output displacement has become a hot topic in the field of precision positioning.

The flexure hinge has the advantages of no hysteresis, high precision, and can realize the functions of accurate displacement guidance, transmission, conversion. The micro-drive amplification mechanism designed based on the flexible hinge technology has the characteristics of simple structure, easy to implement, small stiffness, high amplification ratio and easy to process. By adjusting the structure of the micro-drive amplification mechanism, different amplification ratio can be obtained [16-19]. The technology has been used widely in fields such as biological medicine, Military industry, precision
electronics [20-25]. In the micro-drive amplification mechanism, the parasitic motion will occur due to the force in the non-moving direction. Parasitic motion causes non-kinematic force and displacement of the mechanism, which leads to the decrease of kinematic precision and affects the safety of the mechanism. Therefore, it is of great significance to study the elimination of parasitic motion of micro-mechanism.

Q.M.Zhang designed a single-stage lever amplification mechanism, which is used to clamp tiny devices and achieve accurate amplification of tiny displacement to complete various tasks of micro-assembly [26]. H.Q.Ma designed a new single-degree-of-freedom flexure hinge mechanism suitable for non-circular turning to amplify the output displacement of the piezoelectric actuator, theoretically analyzed the static and dynamic characteristics of the structure, established the differential equation of the structure, and verified it with the finite element method [27]. E.J.Hwang derived the displacement amplification ratio formula of precision positioning platform with lever flexure hinge first-stage amplification mechanism under the consideration of lever bending deformation [28]. J.H.Qu designed a kind flexible micro-drive amplification mechanism with two direction rotary motion driven by Giant Magnetostrictive Actuator, the dynamic model of mechanism parameters is given based on dynamic model establishment [29]. G.P.Xue designed a new chip-level comb-drive magnify micro-drive drive platform with the three degree of freedoms, and the maximum displacement of platform with three directions are 25.2μm in X-axis, 20.4μm in Y-axis, 58.5μm in Z-axis [30].

At present, parasitic displacement exists in the motion of the micro-drive amplification mechanism, which leads to inaccurate motion and affects its safety. In order to solve the problem of limited amplification ratio and parasitic motion of the micro-mechanism, a micro-drive amplification mechanism is designed. Based on the analysis of the working principle of the micro-drive amplification mechanism, the kinematic theory of the micro-drive amplification mechanism was analyzed, and the kinematic performance, strength and modal performance of the micro-drive amplification mechanism were analyzed by finite element method.

2. Micro-drive amplification mechanism

2.1 Flexible hinge selection
Flexure hinge can transmit force and displacement by using plastic deformation of its weak part, and has good driving and guiding function. It can be applied to many high technology fields of high-precision or ultra precision sports fields. According to the composition and shape of the weak part of the flexure hinge, the common flexure hinge can be divided into straight circular flexure hinge (Figure 1(a)), circular arc flexure hinge (Figure 1(b)), parabolic flexure hinge (Figure 1(c)), rectangular flexure hinge (Figure 1(d)). The flexibility, transmission accuracy and maximum stress of various flexure hinges are different. Rectangular flexure hinge has the best flexibility and rotation range, but the transmission accuracy is low, and the rotation center of this kind flexure hinge is mobile during the motion. Circular arc flexure hinge has very high motion precision, but its flexibility is very poor, its motion is limited to a small range. The performance of straight circular flexure hinge and parabolic flexure hinge is between the two kinds of flexure hinge, which can take into account the requirements of motion precision and motion range. Straight circular flexure hinge has the advantages of simple structure and convenient processing, so it is the most commonly used flexible hinge.
2.2 Design of micro-drive amplification mechanism

According to the principle of parallelogram and flexure hinge function, design a micro-drive amplification mechanism, and its structure is shown in figure 2. The micro-drive amplification mechanism consists of 18 same straight circular flexure hinges, the length of radius and the minimum distance for each flexible hinge respectively is 3mm and 1mm. The mechanism can be driven by the micro actuator which is placed at the hollow body of the mechanism, and 6 M4 countersunk head screws are used outside the mechanism to be fixed when moving. The magnification ratio can be adjusted according to the need. This design is a specific proportion.

The flexures hinge of the mechanism are symmetrically distributed on the y-axis. The structure size is 160mm×196mm×50mm(length × width × height ), including 18 same straight circular flexible hinges with symmetric distribution. And a piezoelectric ceramic actuator(PZT) is placed at the hollow body of the mechanism as the micro actuator. When the mechanism is fixed by six M4 countersunk head screws, the micro-drive amplification mechanism input point V has the motion input displacement ∆u driven by the PZT in the hollow part. Under the transmission and amplification of ten flexure hinges(A, B, C, D, E, I, F, H, G, and J), the output point W of the micro-drive amplification mechanism has a certain displacement ∆δ with respect to the initial position, and the ∆δ is the output displacement of the micro-drive amplification mechanism. During the micromotion process, as the eight flexure hinges (K, L, O, P, M, N, Q, and R) on both sides of the micro actuator are symmetrically distributed to ensure that the micro actuator does not bear the force or torque in the direction of non-motion in the process of movement. Since the mechanism is vertical (with y direction), the force and displacement in the non-
moving direction cancel each other out, so there is no non-moving direction displacement in the process of motion.

2.3 Material selection
The micro-drive amplification mechanism can transmit force and displacement by using plastic deformation of flexure hinge. And the elasticity and plasticity of flexure hinge material are the decisive factors affecting the function of micro-drive amplification mechanism, therefore, the material selection of the micro-drive amplification mechanism is very importance for its performance.

The micro-drive amplification mechanism which includes 18 symmetrically distributed flexure hinges. Material selection should comprehensive consider two factors, include provide the more deformation within the plastic limited deformation and the material is easy of processing. Current research generally believes that 60Si2Mn, 65Mn and QBe2 are relatively ideal materials for flexure hinge, and the material parameters of the three materials are shown in Table 1. Various parameters of the three materials and experience with flexure hinge materials are considered, the spring steel 60Si2Mn is used as the machining material of the micro-drive amplification mechanism, and in order to ensure the motion precision of micro-drive amplification mechanism, the wire cutting machining method is adopted.

| Material name | Young's modulus (MPa) | Yield limit (MPa) | Tensile strength (MPa) | Poisson ratio | Density (g/cm³) |
|---------------|-----------------------|-------------------|-----------------------|---------------|----------------|
| 60Si2Mn       | 2.06×10⁵              | 1176              | 1274                  | 0.26          | 7.85           |
| 65Mn          | 2.00×10⁵              | 784               | 980                   | 0.3           | 7.81           |
| QBe2          | 1.26×10⁵              | 725               | 945                   | 0.3           | 8.3            |

3. Kinematic analysis of the micro-drive amplification mechanism
The accuracy and rationality of the mechanism design can be verified by kinematic analysis of the micro-drive amplification mechanism.

3.1 Analysis of the mechanism magnification ratio
The different magnification ratio of the mechanism can be designed according to the need, and this paper only give the magnification ratio analysis procedure of one mechanism as an example. The micro-drive amplification mechanism motion diagram as shown in figure 2, when the input displacement Δu delivered by side V to the flexure hinge G and flexure hinge J, through flexure hinge A to flexure hinge J(including A, B, C, D, E, I, F, H, G, and J), the displacement is transmitted and amplified, then the side W has a magnification displacement Δδ along the y direction. As the mechanism is symmetrical, only the left part of the mechanism is analyzed. As the input displacement Δu is passes from point G to point C, the ratio between the displacement Δδ at the point E and the displacement Δu at the point C is equal to the ratio between the length of the EC to the length of the EF, according to the lever principle and the parallelogram amplification principle. The ratio is:

\[
\frac{\Delta \delta}{\Delta u} = \frac{L_{EC}}{L_{EF}} \tag{1}
\]

The output displacement of the point E is as follows:

\[
\Delta \delta = \frac{L_{EC}}{L_{EF}} \Delta u \tag{2}
\]

In the micro-drive amplification mechanism design, \(L_{EC}=45\text{mm}, L_{EF}=15\text{mm}\), according to the above equation(2), work out \(\Delta \delta\) equal to 3 times of \(\Delta u\).

According to the driving and guiding function of the flexure hinge and the mechanism has symmetrical distribution structure, it can be known that the output displacement \(\Delta \delta\) of the output end side of the micro-drive amplification mechanism is equal to 3\(\Delta u\) in the vertical direction(y-axis direction), and the displacement is zero in the horizontal direction(x-axis direction). Therefore, the
magnification ratio of the micro-drive amplification mechanism is 3, and not bear the force or torque in
the direction of non-motion in the process of movement. In addition, the micro-drive amplification
mechanism can achieve different magnification ratio according to the need, get through adjusting the
design structure.

3.2 Simulation analysis of the micro-drive amplification mechanism
The 3D model of the micro-drive amplification mechanism was imported into the finite element software,
and the radius and minimum thickness of the flexure hinge were 3mm and 1mm respectively. 60Si2Mn
was selected as the material property parameter of the mechanism. In order to facilitate the loading of
the mechanism, surface imprinting was made on the inner surface between the mechanism and PZT.

When meshing, the method of free meshing is adopted to complete the meshing of the whole
mechanism. Then, Then the mesh refinement of 36 flexure hinges was carried out and the optimization
parameter was set to 3. After the completion of meshing, the number of nodes of the model is 1465330
and the number of meshes is 930746, the meshed model is shown in figure 3(a). The mesh division of
the curved part of the flexure hinge is fine and the meshing quality is good.

During loading, fixed constraints were applied to the six threaded holes, and displacements in
different positive y directions were loaded at the V-side position as input displacements, as shown in
Figure 3(b). An output displacement can be get by every input displacement is loaded. The input
displacement is set to 1-15μm, and the interval is 1μm. The output displacement of the center position
of W side is detected by probe function, and solution dates is shown in table 2.

![Figure 3](image_url)

Fig. 3 The preparation for finite element analysis. (a) Meshing; (b) Constraint condition.

3.3 Comparison with two kinematic analysis methods
To analyze the transformation performance accurately, two methods are used in this paper, the theory
analysis of theory model equation (2) of transformation performance in section 3.1, the simulation
analysis in section 3.2. The maximum output displacement of finite element method and theoretical
analysis results are 45μm and 43.047μm. And the results of the above two methods to analyze the
relationships between Δu and Δδ are contrasted, as shown in Figure 4.
Tab. 2 kinematic analysis of the micro-drive amplification mechanism.

| Serial number | \(\Delta u (\mu m)\) | Theory analysis value \(\Delta \delta (\mu m)\) | Analysis results of FEM value \(\Delta \delta (\mu m)\) |
|---------------|-----------------|---------------------------------|---------------------------------|
| 1             | 1               | 3                               | 2.8693                          |
| 2             | 2               | 6                               | 5.7386                          |
| 3             | 3               | 9                               | 8.6086                          |
| 4             | 4               | 12                              | 11.477                          |
| 5             | 5               | 15                              | 14.348                          |
| 6             | 6               | 18                              | 17.215                          |
| 7             | 7               | 21                              | 20.085                          |
| 8             | 8               | 24                              | 22.954                          |
| 9             | 9               | 27                              | 25.823                          |
| 10            | 10              | 30                              | 28.693                          |
| 11            | 11              | 33                              | 31.562                          |
| 12            | 12              | 36                              | 34.431                          |
| 13            | 13              | 39                              | 37.302                          |
| 14            | 14              | 42                              | 40.169                          |
| 15            | 15              | 45                              | 43.047                          |

Fig. 4 The results of the above two methods in analyzing the relationships between \(\Delta u\) and \(\Delta \delta\).

The linear equation fitted to the kinematic theoretical analysis is

\[
\Delta \delta = 3 \Delta u \tag{3}
\]

And the linearity of the linear equation is 1.

The linear equation fitted to the kinematic finite element method is

\[
\Delta \delta = 2.869\Delta u - 0.0007467 \tag{4}
\]

And the linearity of the linear equation is 1.
Through equation (3) and equation (4), it can be calculated that the motion error of the mechanism is 4.67%. And from figure 4, we can see that the fitting lines the kinematic theoretical analysis and the kinematic finite element method are very close and both have high linearity. Therefore, the mechanism motion has high accuracy and linearity.

4. Performance analysis of the micro-drive amplification mechanism

4.1 Strength analysis

The strength analysis of the micro-drive amplification mechanism mainly analyzes whether it is damaged under the drive of the PZT, so it is necessary to calculate the maximum simulated stress of the micro-drive amplification mechanism under the maximum drive displacement of the PZT.

The strength analysis of the micro-drive amplification mechanism is carried out by the finite element method. Input the maximum displacement (the maximum elongation of PZT is 15μm) on the V-side of the mechanism, and the maximum simulated stress of the micro-driven amplification mechanism is shown in Figure 5. From Figure 5, we can see that the maximum stress of the micro-drive amplification mechanism is 81.613 MPa.

Fig.5 The maximum simulation stress analysis of micro-drive amplification mechanism.

The allowable stress of the material is:

\[
[\sigma] = \frac{\sigma_1}{\lambda}
\]  

The yield limit of 60Si2Mn \( \sigma_1 \) is 1176MPa and the safety factor \( \lambda \) is 1.5. By substituting \( \sigma_1 \) and \( \lambda \) values into equation (5), the allowable stress \( [\sigma] \) of the material is 784MPa. The maximum stress of the micro-drive amplification mechanism is 81.613 MPa, which is far less than the allowable stress of the material.

The results of static finite element analysis show that the system is safe and reliable in the process of movement, and the maximum stress of the micro-mechanism meets the requirements of material checking strength. Therefore, the system strength meets the design requirements, and the system has good strength performance.

4.2 Modal analysis

In order to ensure good dynamic performance of the system in the process of motion, it is necessary to analyze the natural frequency of the micro-drive amplification mechanism to judge whether the system will resonate in the process of motion. The finite element Modal module is used in the analysis to conduct free modal analysis of the micro-drive amplification mechanism without constraints. The first 6 order inherent frequency of the mechanism is shown in figure 6.
Fig. 6 The first 6 order natural frequencies of the micro-drive amplification mechanism.

The mechanism is driven by PZT with the P225.10 model, and the maximum speed of the piezoelectric actuator is 2r/s, therefore, the maximum vibration frequency is 2Hz. And the first order inherent frequency is 333.12Hz, so it will not occur to resonance between the micro-drive amplification mechanism and piezoelectric actuator during the motion.

Therefore, the mechanism has excellent dynamic performance.

5. Conclusion

Based on parallelogram principle and flexure hinge function, a micro-drive amplification mechanism is designed in this paper.

The micro-drive amplification mechanism can accurately magnify the linear displacement with a certain magnification ratio, and the mechanism will have not bear the force or torque in the direction of non-motion in the process of movement. The magnification of the mechanism can be adjusted according to the need.

The kinematic performance, strength performance and dynamic performance of the micro-drive amplification mechanism are analyzed by finite element method. The analysis shows that the maximum motion error value of the mechanism is 4.36%, the mechanism strength meets the design requirements, and it has good dynamic performance. The results show that the mechanism design is accurate and effective.

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