Optimal Design of Micro/Nano Positioning Stage with Wide Range and High Speed Based on Flexure Structures

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Abstract. To meet the demand of large motion area and high natural frequency of the micro/nano positioning stage used in fast atomic force microscope (AFM), suitable material, actuator and displacement delivering mechanism were chosen and key factors that affected the performance such as input, output, and coupling displacement, driving force and natural frequency were simulated by finite element method (FEM). Finally, we manufactured the micro/nano positioning XY stage actuated by piezoelectric ceramics driver. Experimental results showed that natural frequency was 1.15kHz, maximum displacement was over 60μm along each axis and coupling rate was below 5%.

1. Introduction

Atomic Force microscope (AFM), with high resolution of atomic-scale, not only can be used as a direct observation of the nano scale morphology, but a realization of the process of samples. AFM plays an important role in the field of bioscience, such as observation and operation of DNA, protein macromolecular, cells and biological tissues. Traditional AFM only functions in slow motion, which is due to their low natural frequency and the coupled effect exists amid X, Y, Z axis. However, AFM of high speed usually have a small scanning area, ranging from several hundred nanometers to less than ten microns. Scanning speed and scanning area interact each other. Increase of scanning speed is based on the high natural frequency of the positioning system, eg. up to 1kHz, which requires a compact structure and materials of high Young’s modulus, whereas compact structure conflicts motion area. Present situation is that a general micro/nano-positioning stage is of large motion area and low natural frequency or high natural frequency and small motion area.

In recent years, many scholars and professionals in this areas have made explorations in how to raise motion area and natural frequency at the same time. Bohua Yin, Daixie Chen, proposed a scheme [1] of flexure hinge structure actuated by piezoelectric ceramics which is able to move in the area of 100μm×100μm whereas its natural frequency was just 200Hz, far from enough to the need of fast scan. Z. Guo, Y. Tian, employed a compact and simple 3-DOF (X-Y-θZ) planar flexure-based positioning stage actuated by piezoelectric ceramics.[2] It had enough stiffness(natural frequency were 1130Hz, 970Hz in x, y directions) and limited motion area(12.74μm, 12.22μm in X, Y direction respectively). Brouwer, J.P. Meijaard, have processed characteristics analysis of rigidity and deformation with the result that structure of parallel flexure beams benefit the motion displacement [3].
Based on the existing research results, this paper takes various factors that affect the motion area and natural frequency of the micro/nano positioning stage into account. The finite element method is adopted to optimize the parameters. Experiment will be implemented to verify the scheme.

2. Design of XY micro/nano positioning stage

The design target of this positioning stage was to realize a high natural frequency, large motion area and small coupling rate. The design scheme was based on flexible circular flexure hinge and flexure beam which can produce elastic deformation. The following factors were considered in the design process.

2.1. Materials

Table 1 shows the mechanical properties of common metal materials. Study shows that once the geometrical parameters of the mechanism are decided, the natural frequency is proportional to \( \sqrt{E/\rho} \) (\( E \) is the elastic modulus of the material, \( \rho \) is the density)\[4\]. The greater of \( E/\rho \), the higher of the rigidity and natural frequency. Increase of the rigidity will enforce the requirements for the piezoelectric ceramic driver as well as the amplifying arm, and in order to reduce the mass of the stage, Al7075 (\( E = 71 \text{GPa}, \rho = 2.81 \text{g/cm}^3 \)) material was chosen to build the stage.

| Materials             | Elastic modulus/E(Gpa) | Density/\( \rho \)(g/cm\(^3\)) | \( \sqrt{E/\rho} \) |
|-----------------------|------------------------|----------------------------------|----------------------|
| Ductile iron          | 173                    | 7.3                              | 4.87                 |
| carbon steel          | 206                    | 7.3-7.85                         | 5.21                 |
| Alloy Steel           | 206                    | 7.9                              | 5.11                 |
| Rolled phosphor bronze| 113                    | 8.8                              | 3.58                 |
| 7075 aluminum alloy   | 71                     | 2.81                             | 5.03                 |

2.2. Driver

Piezoelectric ceramic driver is widely applied in micro/nano positioning system on its merits of high displacement resolution, simple structure, little heat, high rigidity, fast response, no wear, no lubrication. Despite that piezoelectric stacks can stroke a large displacement, its own static capacitance is too large to be accepted. In the realization of high-speed scanning, it requires high current drive, which increases the drive power requirements and costs. General piezoelectric stack have defect of short stroke and we must design an amplification mechanism in the practical application. When we choose a driver, the rigidity of the stage structure \( k_s \) must be taken into consideration, which is because the output ability of piezoelectric ceramic driver is given by \[5\]

\[
\Delta L = \frac{k_p}{k_s + k_p} \Delta L_0
\]

where \( \Delta L_0 \) represents the maximum nominal displacement that piezoelectric driver can output without external spring load, \( \Delta L \) is the displacement that piezoelectric driver can output with external spring load, \( k_p \) is the rigidity of piezoelectric ceramic actuator.

For the sake of improving the natural frequency of the positioning stage, \( k_s \) should be set as large as possible, but at the same time \( \Delta L \) will reduce. To achieve the best compromise, the value of \( k_s \) is set to be 40% of \( k_p \). After comparing mainstream piezoelectric ceramic drivers, we selected German company PI production P-887.91 as our driver. Its nominal stroke is 32\( \mu \text{m} \) and maximum force is 1850N at 100V.
2.3. Amplifying arm and flexure structure

In spite that flexure hinge has high accuracy, its motion range is limited, while the flexure beam can provide greater deformation. In the simulation, we applied identical pulling force on the small edge of flexure hinge as well as flexure beam as shown in Figure 1. They were of approximately same size and the simulation results is presented in Table 2 where we can clearly see great advantages of flexure beam in output displacement, stress and natural frequency. We select flexure beam as the displacement delivering mechanism.

![Figure 1 Simulation of the deformation between the two structures with same size when applying identical pulling force](image)

**Table 2** Contrast of the performance between flexure hinge and flexure beam

|                | Size (mm) | Material | Pulling force | Maximum displacement | Maximum stress | Natural frequency |
|----------------|-----------|----------|---------------|----------------------|----------------|------------------|
| Flexure beam   | 50×10×1   | Al7075   | 100N          | 17.1mm               | 1.7 GPa        | 526.8 Hz         |
| Flexure hinge stick | 50×10×4.5 Thinness in the curve:0.5,Radius:2 | 100N | 10.9mm | 3.87 GPa | 349.2 Hz |

Because of the rigidity of the metal system, deformation of the amplifying arm cannot be neglected. To obtain a stiffer amplifying arm, a stable novel triangular beam were adopted to weaken the deformation of the arm. The optimized final design is shown in Figure 2.

![Figure 2 Layout of micro/nano positioning stage (final design)](image)

There are a few details having been taken into consideration. In order to increase the natural frequency of the stage, the central part was designed to be very small to reduce the mass. Simulation
results showed that the width of the flexure beam was positively correlated with the natural frequency, and the mass of the central part was negatively correlated with the natural frequency.

As the piezoelectric ceramic driver is very weak withstanding torque and bending moment, we introduced a flexure hinge node between the driver and the lever, taking advantage of the flexure hinge’s feature of easy to bend to avoid the bending moment that may be harmful to piezoelectric ceramic driver. It was completely symmetric in X, Y direction which reduced the coupling between the two axes. The central part of the stage was supported by four pairs of flexure beams, and this structural arrangement well controlled the rigidity and flexibility of the stage [6].

In order to extend the life of the stage, the connections between flexure beams and other parts were rounded. The thickness of the stage was 7mm and the length of one side was 140mm. Magnification of the lever was set to be 4.765

3. Simulation analysis

Fix the stage and apply finite element static analysis and modal analysis in the X, Y direction.

The displacement and driving forces were applied at the flexure hinges which were in contact with the piezoelectric ceramics, respectively. Results showed that the input displacement, output displacement, driving force were interacted proportionately. Magnification was about 2.45. Coupling rate was below 1%. When the input displacement in X-direction was 32μm, the maximum stress, 92.3MPa, occurred at the lever fulcrum. Similarly, when the input displacement in Y-direction was 32μm, the maximum stress was 87.9MPa. They were much smaller than the yield strength of the Al7075 material 455MPa. According to Figure 3 we can work out that the input rigidity is 19.5N/μm. Based on the input and output displacement, the rigidity of the stage’s output part is about 8.0N/μm.

First-mode shape through modal analysis is shown in Figure 4. It shows that the first-mode natural frequency in the X and Y direction are 1338Hz and 1408Hz respectively. The results of the finite element simulation analysis accord with our demands.

**Figure 3** Relationship between output and input displacement, input displacement and driving force in X and Y directions

**Figure 4** First-mode vibration shape Natural frequency in X direction: 1338Hz, in Y direction: 1408Hz
4. Experimental verification

4.1. Experimental device
The material of positioning stage was Al7075 and it was processed by wire cutting. The driving power of piezoelectric ceramic was PI company's products, of which the maximum output voltage was 100V. Inductance micrometer of DGB-5B Type produced by Sanmenxia Zhongyuan Meter Company was utilized to measure the displacement, with which we can achieve accurate measurement within 300μm and in ±30μm gear, the indication error was less than 0.5μm, in ±100μm gear, the indication error was less than 2.5μm. We used Polytec's laser vibrometer and an oscilloscope for the amplitude measurement. We applied sine wave signal to drive the piezoelectric ceramic to avoid the impact of sharp signal. The principle of natural frequency measurement is shown in Figure 5.

![Figure 5 Principle of natural frequency measurement](image)

4.2. Experimental process and results analysis

4.2.1 static performance test. First we carried out experiments in X direction. Raise the driving voltage applied to piezoelectric ceramic driver slowly from zero, and recorded the displacement of the central part every 5V rise. After reaching 100 V, lower the voltage gradually and recorded the displacement every 5V lowered. Repeated this process for 3 times, collected the data and plotted a curve as shown in Figure 6. From the curve we can see that when the voltage was raised, the experimental results were reproducible. Because of the piezoelectric ceramics features of creep, hysteresis and non-linearity, different groups appeared deviation when the driving voltage decreased. The X direction average value of the maximum output displacement in the central part of the stage was 64.2 μm.

![Figure 6 Relationship between changing voltage and output displacement in X direction](image)
In the same way, when we recorded input displacement at different voltages, we found that the displacement magnification at different voltages was roughly equal, and the average value was 3.10, slightly larger than the simulation results.

Experiments in Y direction showed similar results. When the driving voltage was 100V, the output displacement in the Y direction was 62.8μm, and the average value of the magnification was 3.05, which was in good agreement with the experimental results in X direction.

Within the experimental voltage range, the actual coupling displacement was between 0.1μm and 0.6μm, and the coupling rate was less than 5%, both agreeing with the design requirements.

4.2.2 Natural frequency test. Adjust the position of the laser vibrometer’s measuring head so that it focused at the central part of the stage precisely. Generate sine signal of 100Hz, 5V by the function signal generator which would make the positioning stage under forced vibration. Laser vibrometer detected the amplitude of the stage and displayed the waveform through the oscilloscope. In the frequency range of 100~1800Hz, look for the frequency point corresponding to the maximum amplitude and this frequency is exactly the actual natural frequency. Experimental results are shown in Figure 7. Natural frequency in X direction was 1155Hz, and the maximum amplitude was 61μm. Natural frequency in Y direction was 1163Hz, and the maximum amplitude was 62.2μm.

Figure 7 Relationship between driving frequency and displacement in each axis

5. Conclusion
An micro/nano-positioning stage with relatively large motion area, high natural frequency and low coupling rate is presented in this paper. In the design process, finite element method played a good role in guiding us to build an optimized stage. In the experiment, the static features of the positioning stage were measured by PI high-voltage power supply and inductance micrometer. Natural frequency was observed by signal generator, laser vibrometer and oscilloscope. The experimental results showed that it well balanced large motion area and high natural frequency, which met the demands of rapid scanning of atomic force microscopy.

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