Ultra-precise Micro-motion Stage for Optical Scanning Test

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ABSTRACT

This study aims at the application of optical sensing technology in a 2D flexible hinge test stage.
Optical fiber sensor which is manufactured taking advantage of the various unique properties of optical fiber, such as good electric insulation properties, resistance of electromagnetic disturbance, sparkless property and availability in flammable and explosive environment, has lots of good properties, such as high accuracy and wide dynamic range, repeatable, etc. and is applied in 2D flexible hinge stage driven by PZT. Several micro-bending structures are designed utilizing the characteristics of the flexible hinge stage. And through experiments, the optimal micro-bending tooth structure and the scope of displacement sensor trip under this optimal micro-bending tooth structure are derived. These experiments demonstrate that the application of optical fiber displacement sensor in 2D flexible hinge stage driven by PZT substantially broadens the dynamic testing range and improves the sensitivity of this apparatus. Driving accuracy and positioning stability are enhanced as well. [1,2]

Keywords: Optical test, Optical fiber, 2D flexible hinge stage

1. INTRODUCTION

Micro-displacement mechanism normally refers to the equipment working with a displacement within a scale of less than millimeter and micro-positioner is its core component. The mechanism has high sensitivity and prominent accuracy, which make it one of the crucial components of precision mechanism and instrument. Micro/ nano-positioning and driving technology is prerequisite and the basis of achieving the micro / nano-operation and industrialization of micro-nano technology. In many fields such as automated assembly、micro-manufacture system、microelectronic engineering、optics and photonics engineering、precision engineering、biological engineering 、space technology、nanotechnology. The problem of micro/ nano-positioning and driving technology should also be solved.

In the engineering practice of the ultra precise manufacture and measurement, flexible hinge stage driven by PZT is always adopted to achieve nano-driving and positioning technology. Therefore the research on how to precisely control and test becomes the pivotal problem of these applications. However, due to hysteresis, creep, and nonlinearity properties, PZT's precision and positioning stability are limited. For solving the above problems, a stage integrated with high precise displacement sensor for loop-locked control is proposed. Nowadays the stage is always integrated with capacitance displacement sensor .But the capacitance displacement sensor is easy to be affected by the change of the electromagnetic fields, edge effects, temperature of the environment, difficult to ensure accuracy of their own.

Optical fiber has lots of unique characteristics, especially displacement resolution can be achieved sub-nanometer and meet the demands of the driving precision and the positioning stability of the ultra-precise micro-motion stage. Micro-bending deformation structures are set up on the test stage. Making use of the micro-bending loss characteristics the optical fiber is integrated with micro-bending deformation structures .So that the real-time detection of micro displacement can be achieved, and then the test results will be fed back to the system in order to achieve the precise control and detection. [3, 4]

2. THEORETICAL ANALYSIS

2.1 Fiber bending loss analysis

Nowadays one of the most important advantages of fiber is easy bending. If the fiber bending radius of curvature is too small, that may not satisfy the ART conditions. Because of which the light may change its route of transmission infiltrating from the core of the fiber into cladding, even leaking outward through the cladding. Under normal condition,

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the constant β of the light transmission along the axis should meets $n_2k_0 < \beta < n_1k_0$.When the optical fiber bends, light will transmit through the bending part Optical fiber. So if you want keep the same phase of the electric and magnetic fields in a plane, the light speed is rapider when the light is nearer to the outside. When transmit to a particular location, its phase speed will be faster than light, which means that the transmission mode changes into radiation mode. So some part of optical power will lose. This also means that the decay will increase.

According to the theory of D. Marcused, when the bending radius is R, bending loss coefficient is:

$$2\alpha_b = \frac{\sqrt{\pi}u^2}{e_m W^{\frac{3}{2}} V^2 \sqrt{R} k_{m-1}(Wa) k_{m+1}(Wa)} exp[-\frac{2}{3}(\frac{W^3}{\beta^2})R] \tag{1}$$

In the formula (1) u is radial normalization phase constant. W is radial normalization attenuation constant. β is axial propagation constant. 'a' is radius of the fiber core. V is normalization frequency. k_m is m-band modified Bessel function. e_m=2(m=0), e_m=1(m$\neq$0).

Formula (1) is exact for every LP_{mn} mode. Single mode fiber only transmits LP_{01} mode. So we can only consider LP_{01} mode:

$$2\alpha_b = \frac{\sqrt{\pi}u^2}{e_m W^{\frac{3}{2}} V^2 \sqrt{R} k_{-1}(Wa) k_1(Wa)} exp[-\frac{2}{3}(\frac{W^3}{\beta^2})R] \tag{2}$$

Jeunhumme gives a formula as follows for the single mode fiber. If the radius is R, the loss per unit length is:

$$\alpha_c = A_c R^{-\frac{1}{2}} \exp(-UR) \tag{3}$$

$$A_c = \frac{1}{2}(\frac{\pi}{aW^3})[\frac{u}{Wk_1(W)}]^2 \tag{4}$$

$$U = \frac{4\Delta n W^3}{3aV^2 n_2} \tag{5}$$

In the formula (5) Δ n is the difference in refractive index between the core of fiber and cladding of fiber.

If the difference in refractive index, and the deadline for work at wavelengths have been given, and there is a critical radius of curvature R_c, when the actual radius of curvature at the close, bending loss can be sharply increased to intolerable value form insignificant numerical value. [5, 6]

2.2 Design of the integrated structure of optical fiber sensor and 2D stage

For making use of the advantages of the optical fiber, fiber is applied to two-dimensional flexible hinge stage. As fig.1, '1' is two-dimensional flexible hinge stage, and 2、3 are PZT connectors. When displacement takes place due to deformation of the stage, the fiber is squeezed, that will cause deformation of fiber and loss of light, so as to achieve micro-displacement detection.

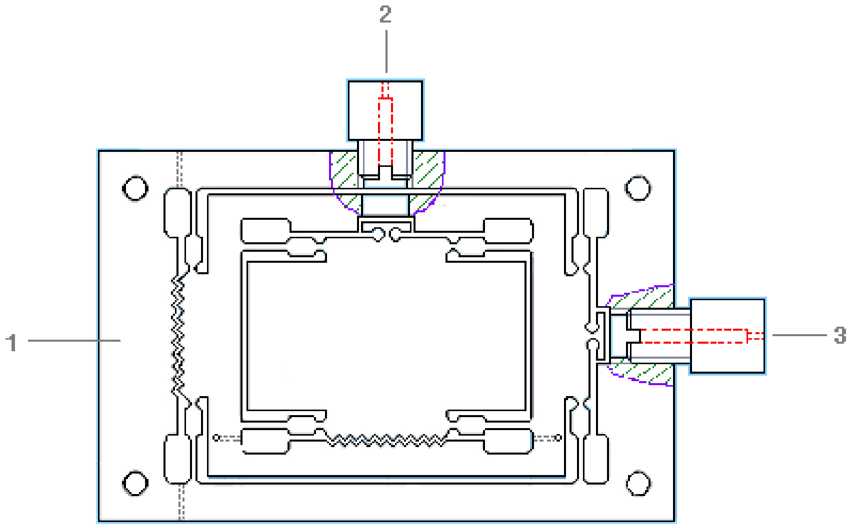

Fig.1. Two-dimensional flexible hinge stage

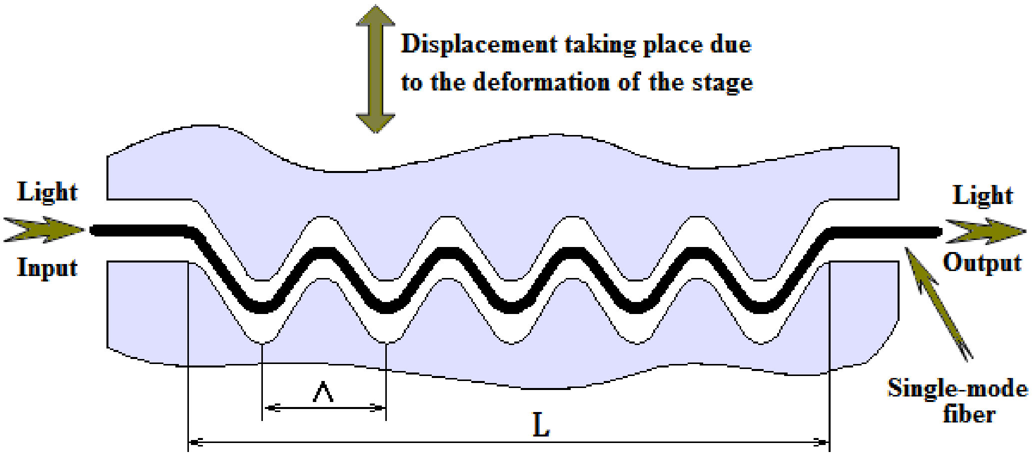

Fig.2. Structure of the micro-bend tooth

The design principle of best tooth spacing of micro-bend tooth(Λ): [7] Because of the different cycle of the bending loss is different and modulation of the sensitivity is also not the same too. The fiber will have the greatest bending loss at the best tooth space. That is the most sensitive modulation. In the case of the fiber of which the refractive index profile is $n^2(r) = n_0{}^2[1-2\Delta(r/a)^{\alpha}]$, theory analysis shows that propagation constant β in the core of fiber and the constant in the cladding of fiber meets:

$$\Delta\beta \quad \beta_{m\ 1} - \beta_m = (\frac{g}{g+2})^{1/2} \bullet \frac{2\sqrt{\Delta}}{a}(\frac{m}{M})^{\frac{g-2}{g+2}} \tag{6}$$

In formula (6): ’a’ is radius of the core of the fiber. ‘g’ means a parameter which is about the refractive index distribution of the fiber. ’m’ is the mode. ‘M’ is the sum of the mode. $\Delta = \left[n^2(0) - n^2(a)\right]/2n^2(0)$ n(0)is the index of refraction of the core. n(a) is the index of refraction at the location where the radius is a.

The best tooth spacing of best structure of the micro-bending tooth (Λ) meet:

$$\Lambda_o = \frac{2\pi}{\Delta\beta} = \left(1+\frac{2}{g}\right)^{\frac{1}{2}} \frac{\pi a}{\sqrt{\Delta}} \left(\frac{M}{m}\right)^{\frac{g-2}{g+2}} \tag{7}$$

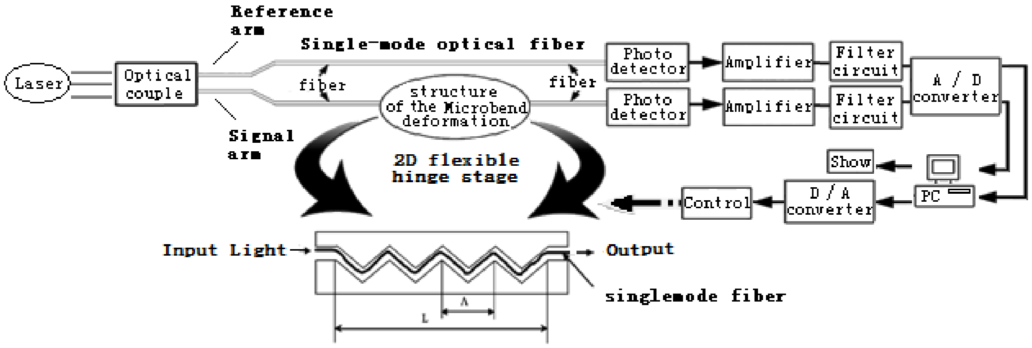

Fig.3. Optical detecting system schematic

Shown in fig.3, the light generated by He-Ne laser is coupled into Y type (1:1 single-mode) optical fiber with optical coupler. Before the modulation, optical signal in the signal arm is basically the same as the one in reference arm. After being modulated by micro-bending structure, the signal arm will produce optical loss. Displacement information reflected by the optical loss can be detected by the photoelectric detector. And the information will be processed and converted by a series of circuit. Then Labview software will be used to control DAQ to complete the signal acquisition. Meanwhile, the further processing filter will be completed in the computer. And what's more the reference arm data will be subtracted by the signal arm data. So that the noise made by Source of instability and the same environment at the scene will be largely ruled out. Finally, signal indication and feedback control can be achieved.

3. EXPERIMENT AND RESULTS

3.1 Experimental curve

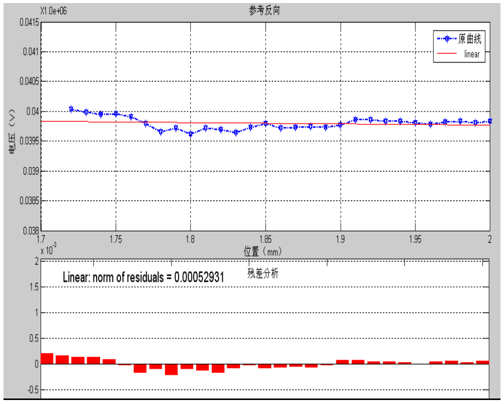

Fig.4. Micro-bending structure reference arm

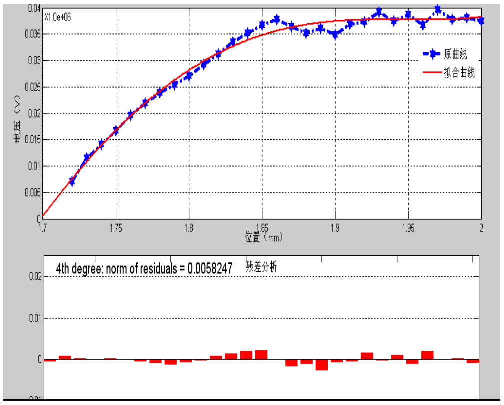

Fig.5. Micro-bending structure signal arm

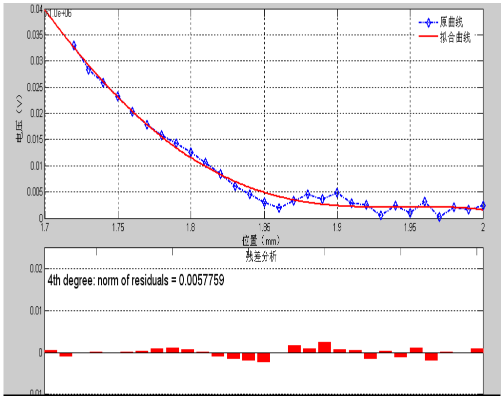

Fig.6. Signal curve after subtracting

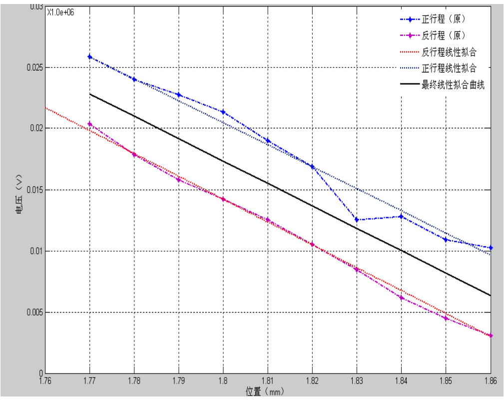

Fig.7. Linear part

Those above are the data derived through experiments using the micro-bending tooth Λ=3.50mm, and the acquisition of the experiment data is completed by the DAQ controlled by Labview software. The fitting curve of the signal data is shown as figure4~figure7, of which figure 6 is obtained after subtraction operation.

3.2 Analysis of data

Signal arm: Residual standard deviation: s =0.0079266
Correlation coefficient: R^2 = 0.9699 F Statistics = 144.8380 P=0.0000<0.05
The signal after subtracting:
Residual standard deviation: s=0.0063342
Correlation coefficient: $R^{2=}$ 0.9839 F Statistics= 658.3662 P=0.0000<0.05
The linear range of data analysis:
Residual standard deviation: s=5.3432e-004 Correlation coefficient: $R^{2=}$0.9806
Sensitivity: S=202.825mV/nm Range of measure: 0~50μm
Non-lineate error: δ_L=7.7% Hysteresis error: δ_H=8.6%

4. CONCLUSION

According to the analysis above, we know that optical fiber displacement sensor has capacity of strong anti-jamming good bending properties and flexible forms of space layout. The two-dimensional flexible hinge stage integrated with the optical fiber displacement sensor is not only compact, but also can improve the accuracy and stability of the stage significantly. The sensitivity of detection can reach 203mv/nm, which meet the demand of micro-driving test stage.

5. ACKNOWLEDGEMENT

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