Development of a new sensing method for micro/nano displacement measurements based on FBG sensors

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The trend towards miniaturisation in manufacturing has led to a requirement for the technique of micro /nano measurements capable of measuring tiny features on small components. This paper presents the development of a new sensing method for micro/nano displacement measurements based on fiber Bragg grating (FBG) sensors. In this machine, some new ideas are integrated into the design, such as the suspended FBG probe stem, the fiber fused microball tip, and the double-FBG probe structure. Unlike other FBG sensors attached on the surface of cantilevers or embedded in building structures, they are suspended from the probe holder and integrated into the fiber probe stem. The advantage of this technique is the large aspect ratio attainable. Also, utilizing the FBG fiber stem as a probe stem enables the sensor system high strain sensitivity and good linear. The suspended FBG sensor is nested in an ultra precise stainless steel needle to improve its rigid and also reduce the lateral bending error of the FBG fiber stem. To serve the needs of small parts measurements, the fiber fused technique is proposed to form a microball tip on the end of contact fiber probe. Test shows the microball tip diameter can be less than 300 um. Furthermore, a double-FBG probe structure is integrated into the probe to weaken the temperature influence and enhance the measuring accuracy. In this report, the detailed design principle of the FBG-based displacement measuring method and the Bragg wavelength demodulation method is described. It has been proved by preliminary experimental results that the measurement resolution can reach 50nm, using the linear nanopositioner stage with a displacement resolution of 5 nm.

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1. Introduction

In the last few years interest in micro- and nano-technologies has been growing. Many fine components recently fabricated by micro system processes, such as micro-electromechanical systems (MEMS), micro-fluidic chips, inkjet and diesel engine injector nozzles, are in overall dimensions within meso scale[1]. The trend towards miniaturisation in manufacturing has led to a requirement for the technique of micro /nano measurements from microns to tens of nanometers capable of measuring tiny features on small components. Therefore, new concepts and designs of Micro/nano displacement measurements have been proposed. Sensor principles and methods include the scanning probe microscopy(SPM) method, inductive sensor technology, capacitive sensor technology, the laser interference method, grating sensor technology, or strain gauges method [2–9]. In this work, a novel sensing method based on fiber Bragg grating (FBG) sensors, which have advantages of high sensitivity, good repeatability, large measuring range, and good anti-interference, has been produced. In this machine, some new ideas are integrated into the design, such as the suspended FBG probe stem, the fiber fused microball tip, and the double-FBG probe structure.

2. FBG-based sensing system

2.1 Fundamental FBG sensing theory

FBG sensors have been considered as a good alternative transducer for many applications recently. Using a high-precision demodulation system, the resolution can be up to nano strain level. At the same time FBG sensors have good linear relationship in 10,000 micro-strain range. As a sensing way of wavelength encoding the influence of light intensity, joint loss and optical path loss is very low. They are immune to electromagnetic interference and their sizes are small enough to be embedded into the tiny structures without causing any structural damage. FBG sensors have been increasingly studied for a variety of applications such as structure health monitoring, vibration measurement, non-destructive testing, and so forth. In this paper, FBG sensors are used to measure micro/nano displacement signal.

A FBG is composed of periodic changes of the refractive index that are formed by the exposure to an intense UV interference pattern in the core of an optical fiber. If a broadband light is put into the FBG sensor, it reflects the special wavelength component, called the Bragg wavelength. The Bragg condition is expressed as [10]

$$\lambda_B = 2n\,\Lambda \tag{1}$$

Where λ_B is the Bragg wavelength of FBG, n is the effective refractive index of the fiber core and Λ is the grating period. The wavelength, which is determined by the Bragg condition, is reflected at the Bragg grating part, and the other wavelengths pass through it. If we make different Bragg wavelengths along a single strand of optical fiber, strain data can be measured at several points.

The Bragg wavelength is a function of the refractive index of the fiber core and the grating period. If the grating is exposed to external perturbation, such as strain and temperature, the Bragg wavelength is changed. By measuring the wavelength change accurately, the physical properties can be measured. The shift of a Bragg wavelength due to strain and temperature can be expressed as[11]

$$\Delta\lambda_B = \lambda_B\left[(\alpha_\Lambda + \alpha_n)\Delta T + (1 - p_e)\varepsilon\right] \tag{2}$$

$$p_e = \left(\frac{n_{eff}{}^2}{2}\right)\left[p_{12} - \nu\left(p_{11} + p_{12}\right)\right] \tag{3}$$

where α_Λ is the coefficient of thermal expansion, α_n is the thermo-optic coefficient, and p_e is the strain-optic coefficient of an optical fiber. In Eq. (3), ν is the Poisson's ratio, and p_{11} and p_{12} are the components of the strain-optic tensor. A germanosilicate glass generally has a strain-optic coefficient of 0.22. Using above equations with the assumption of no temperature change, we can measure the strain from the wavelength shift as

$$\varepsilon = \frac{1}{1 - p_e}\cdot\frac{\Delta\lambda_B}{\lambda_B} \tag{4}$$

The displacement results can be obtained through the demodulation of FBG wavelength shift. The tunable PZT-actuated matched FBG-based filter demodulation method is used in the system. The tunable matched FBG-based filter is formed by connecting a matched FBG with the same properties as the sensing FBG onto a PZT. The reflection spectrum of FBG sensors enters the matched FBG through the coupler, and then is reflected into the detector through the coupler and the matched FBG. When a drive voltage is applied to the PZT, the matched FBG is stretched by the PZT and hence the Bragg wavelength of the matched FBG is tuned due to the applied strain. The wavelength shift of the sensing FBG is traced automatically by using a closed-loop control system, as shown in Figure 1. The signal output from this control loop gives a voltage change corresponding to the wavelength change of the matched FBG, which is equal to the wavelength shift of the sensing FBG. But the measurement range and accuracy of this method are mainly constrained by the characteristics of the PZT used.

2.2 System configuration

The schematic diagram of micro/nano displacement measurement system is shown in Figure 1. Unlike other FBG sensors attached on surface of the cantilever beam or embedded in building structures, the FBG sensors are suspended from the probe holder and integrated into the fiber probe stem. FBG sensors are sensitive to the change of the axial strain, instead of the lateral strain. Therefore, this suspended structure of the probe is designed to convert micro-displacement to micro-strain of the FBG sensor, whose advantage is the large aspect ratio attainable (10mm deep for a 500um diameter hole). Also, utilizing the FBG fiber stem as a probe stem enables the sensor system high strain sensitivity and good linear. The suspended FBG sensor is nested in an ultra precise stainless steel needle to improve its rigid and also reduce error due to the slight lateral bending on the FBG fiber stem.

In addition, an idea of the double-FBG probe structure is integrated into the probe to weaken the temperature influence and enhance the measuring accuracy. Because of the temperature-sensitive intrinsically of FBG sensors, temperature and axial strain along the fiber stem can directly affect the Bragg wavelength, while the FBG itself can not distinguish the respective contributions of temperature and strain. In the dynamic strain detection, filtering methods can reduce the effect of temperature. However, in Quasi-static or static strain detection, ambient temperature change will lead to measurement error. In this instrument, a double-FBG sensing structure was designed, in which one FBG senses micro-displacement and temperature, the other FBG detects temperature only. It can be considered approximately that two FBG sensors lie in the same temperature field. Through the subsequent data processing, error caused by temperature can be real-time compensated.

In the demodulation system, using only one matched fiber Bragg grating to demodulate two FBG sensing signals simultaneously, the additional errors caused by differences in optical devices and the Optical path can be reduced.

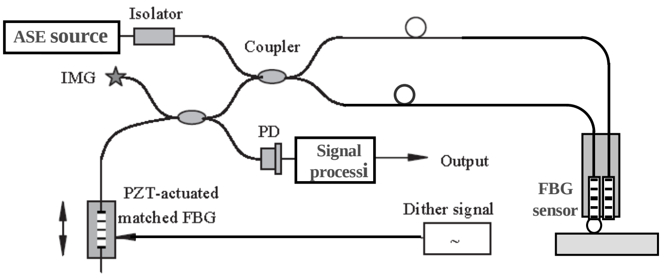

Fig. 1 Schematic diagram of FBG-based displacement measurement system

To serve the needs of small parts and holes measurement, the fiber fused technique[12] is proposed for the FBG fiber to form a probe microball tip which touches the surface being measured.

Based on micro-EDM machining principle and the optical melting principle, the probe ball is prepared. Using the fiber welding machine the glass fiber melts rapidly after it absorbs energy of the EDM discharge. Because of the surface tension influence, the melting part of the fiber gradually forms ball shape, and then the tiny spheres is obtained at the end of FBG fiber. The images of the optical micro-ball are presented in figure 2. The corresponding measurement results are listed in table 1. Test shows probe microball tip diameter of less than 300um.

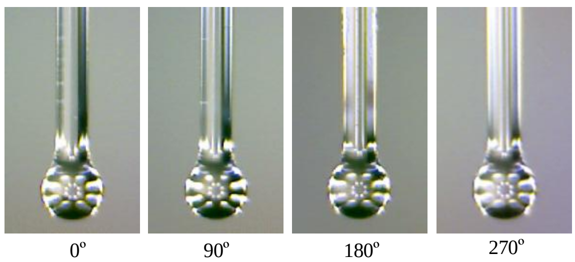

Fig. 2 Images of the optical micro-ball

Angle	0°	90°	180°	270°
diameter	235.6	234.0	236.4	234.8

Table. 1 Measurement results of the optical micro-ball diameter

When the probe tip contacts the surface being measured, the suspended FBG fiber stem and the fiber fused microball tip all deform, thereby in the FBG sensor axial compression occurs, and thus the sensor signals output.

3. Characteristics of Piezoelectric Ceramics

In principle of tunable PZT-actuated matched FBG demodulation, the match FBG is stretched by the piezoelectric ceramics. The final displacement measurement results are obtained indirectly by the displacement of the piezoelectric ceramic. That is, the accuracy of the system depends on the displacement accuracy of the piezoelectric ceramic. In addition, although the piezoelectric ceramic has the advantages of high-resolution, small-size, fast-response, etc., its inherent behaviors of hysteresis, creep and nonlinear seriously affect its application.

In this design the driving voltage of the piezoelectric ceramic is the triangular wave voltage. Only the rising segment is used in measurement, so hysteresis has little effect. Meanwhile the DC-Offset voltage of the triangular wave is very small, about 40mV, to minimize the influence of creep. In order to solve nonlinear problems, the displacement calibration is mad on the condition of the driving voltage of fixed frequency and fixed amplitude.

The displacement of piezoelectric ceramic is Calibrated using Renishaw XL-80 laser measurement system, presented in Figure 3. The linear measurement accuracy is ± 0.5 ppm. The frequency of reading is 50 kHz. The maximum linear measurement speed is up to 4 m/s. The linear resolution is still up to 1 nm even at maximum speed. The measured displacement of piezoelectric ceramic is displayed in Figure 4.

The fitting Method of the 8-order generalized polynomial is used to fit the data in the rising curve of the measured displacement. The results in Figure 5 show that when displacements are less than 0.0025mm and more than 0.03375mm the fitting error is less than 80nm. On the contrary, in the middle wide range from 0.0025mm to0.03375mm the fitting error is less than 20nm. Therefore, in the actual measurement, FBG sensors are set to work in the scanning range of 0.005 to 0.03mm.

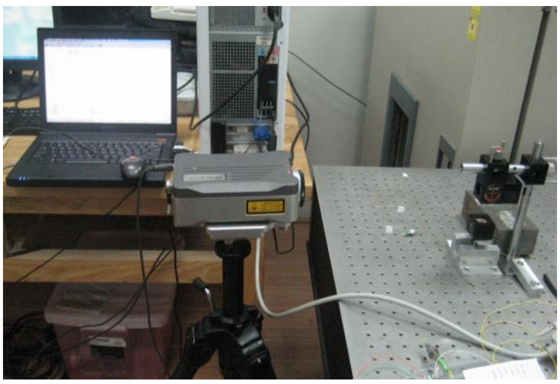

Fig. 3 Experimental system of PZT non-linear displacement calibration

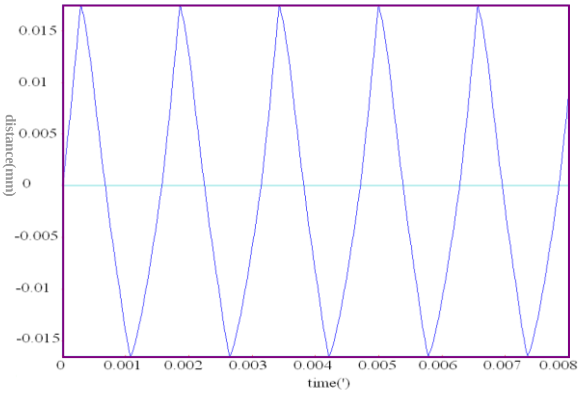

Fig. 4 Measured displacement curve of piezoelectric ceramics

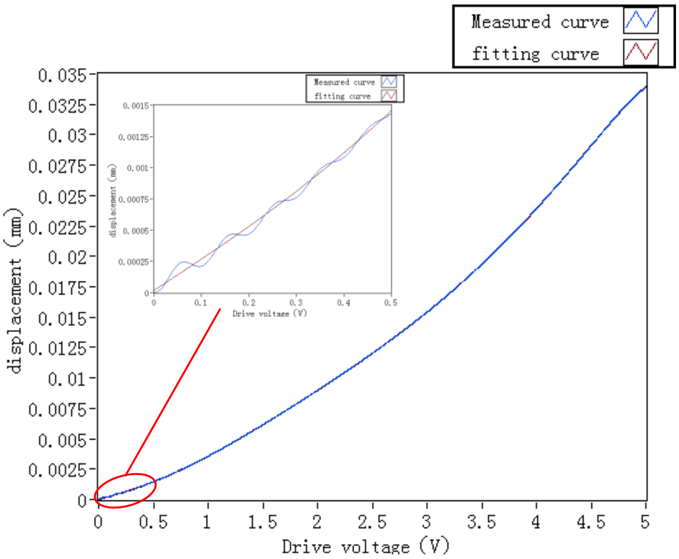

Fig. 5 Fitted curve and measured curve of piezoelectric ceramics

4. Experimental tests

To evaluate the sensitivity and the resolution of the FBG probe, experiments were performed by the linear nanopositioner stage with a displacement resolution of 5 nm. The probe was fixed on the linear nanopositioner stage, and was driven to contact the workpiece surface. A photograph of the probe configuration test system and the probe is shown in figure 6 and figure 7 respectively. Light of wavelength 1550 nm was launched from a broadband ASE source to the Bragg grating sensor integrated probe. The position of workpiece and probe spherical tip can be viewed on-line using a microscope for easy measurements. The displacement of the probe was controlled precisely by the controller driving voltage. The tests were performed Continuously within ±4μm displacement range of the probe according to the PZT driving characteristics o f the linear nanopositioner stage.

Before the probe system is applied for displacement measurements, the stability was observed, which verified the operational reliability of the system. All the experimental data indicated that the stability of the measurement system was better than 1mV and one of stability experimental data is illustrated in figure 8.

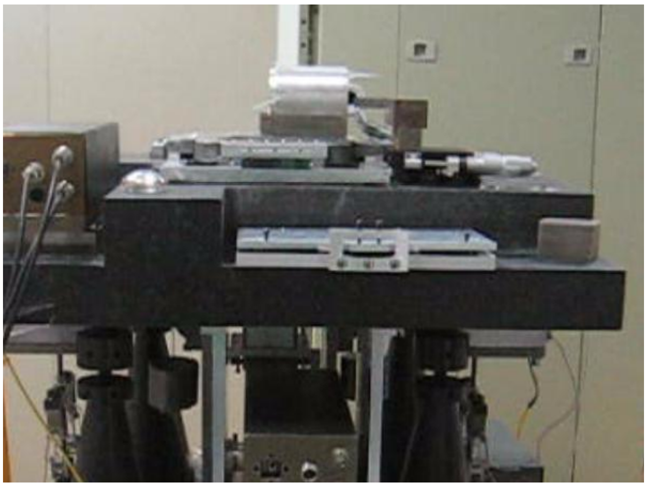

Fig. 6 Performance test system of the FBG-based sensing system

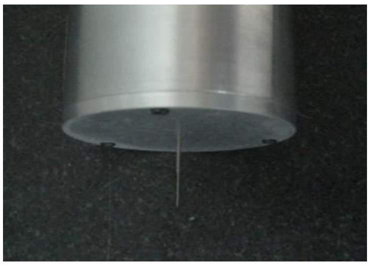

Fig. 7 Images of the FBG-based probe

The resolution of the contact probe is the minimum detectable compression displacement of the probe produced by the instrument used in the tests. Figure 9 shows the actual output voltage values corresponding to the linear nanopositioner stage displacement of 50nm, 100nm, 200nm and 500nm successively, after the probe has contacted the workpiece. The best resolution from the test result achieved so far is 50 nm. After contact, the output signal varied almost linearly with increased nanopositioner stage displacement, shown in figure 10. The sensitivity of the probe approximately equal to the slope of the data set (23.25mV/um).

5. Conclusions

This paper presents the development of a novel FBG-based sensing system for micro/nano displacement measurements. The FBG sensors are suspended from the probe holder and integrated into the fiber probe stem to sensing displacement. The fiber fused technique is proposed to form a microball tip on the end of contact fiber probe to serve the needs of small parts and holes measurement. Test shows the microball tip diameter can be less than 300 um. The probe prototype testing has shown a preliminary resolution of 50 nm and sensitivity of 23.25mV/um. This resolution has potential to be further improved with probe modifications and stricter temperature control. Further study and experiments will be performed to investigate the repeatability, the uncertainty, dynamic response, system optimization and correction.

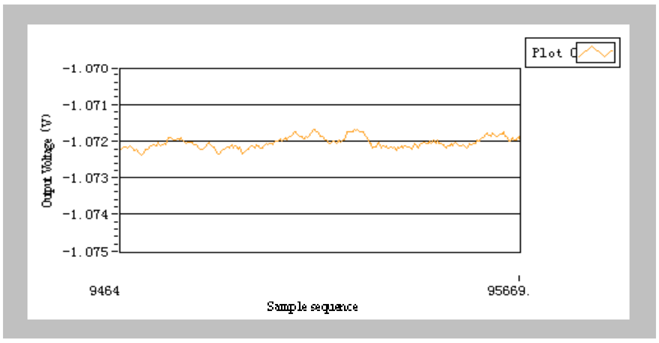

Fig.8 Stability experimental data of the FBG-based sensing system

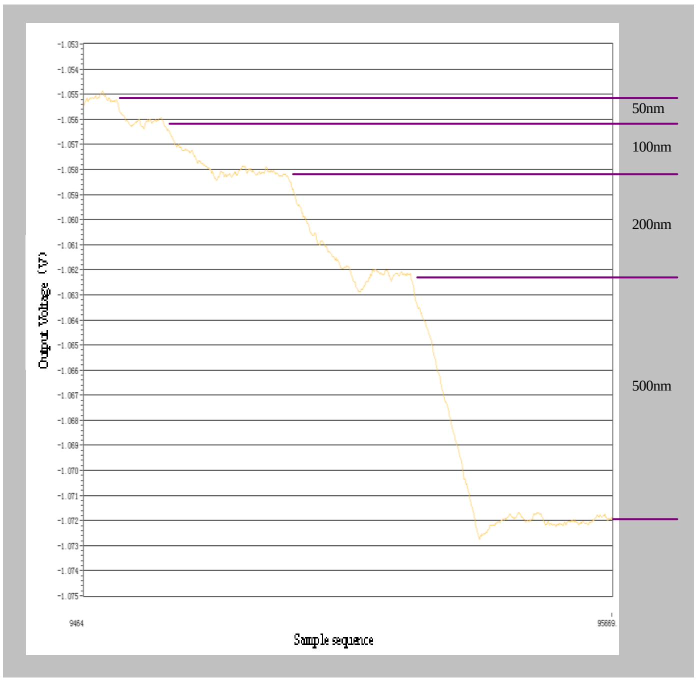

Fig. 9 Actual output voltage values of the sensing system corresponding to the nanopositioner stage displacement of 50nm, 100nm, 200nm and 500nm successively

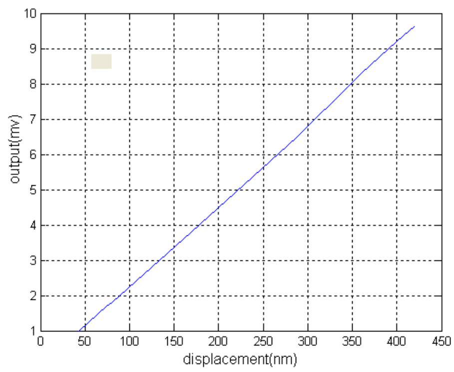

Fig. 10 Part of strain sensitivity results with curve fitting

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