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# DISPLACEMENT MEASURING SENSOR CALIBRATION USING NON-LINEARITY FREE LASER INTERFEROMETER

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**Abstract** − For calibration of displacement measuring sensors with sub-nanometer resolution, a novel calibration system using laser interferometer was developed. It is directly traceably to the Meter and portable due to use of laser coupled by an optical fiber. And also it has a higher accuracy because of nonlinearity free laser interferometer and compact design. The detailed system and one example of calibration are described. Finally a detailed uncertainty budget is described.

**Keywords**: nanosensor, nonlinearity, laser interferometer

## 1. INTRODUCTION

The sensors with nanometer resolution are commonly used to measure the displacement in a variety of measuring instrument such as roundness tester, surface roughness tester and gauge block comparator, and precision stages for lithography. These sensors have nanometer or sub nanometer resolution over a range of a few ten micrometers. The accuracy of these sensors is commonly less than their resolution because of non-linearity, hysteresis, and drift. Traditionally, the calibration of these probes is done by gauge blocks and special physical standards such as roughness standards and roundness magnification standards. These physical standards are not sufficient for calibration with higher accuracy. Furthermore the calibration using the physical standards is usually static. Recently the probe calibration set-up using digital piezo translator was reported.[1,2] It is equipped with a piezo-translator for parallel displacement and a capacitive sensor for measuring the displacement of piezo-translator. The capacitive sensor is calibrated using by a laser with a high-resolution plane mirror interferometer. The system is very compact, but pre-calibration by laser interferometer is required. And also it has a long-term drift deteriorating the accuracy. For this reason, direct calibration systems using the laser interferometer have been developed.[3,4] In these systems, lasers are usually set outside and aligned every time for the calibration.

This paper presents a novel and portable calibration system using the laser interferometer developed at Korea Research Institute of Standards and Science. The system is used for in situ calibrations of the LVDT probes used for roundness and gauge block measurements or nanosensors with high resolution.

## 2. EXPERIMENTAL SYSTEM

The system mainly consists of translator mechanism and displacement measuring interferometer as shown in Fig. 1. The translator consists of single parallel flexure micro-stage and driving mechanism with a low-voltage piezo-translator and differential micrometer head with high resolution. The flexure translator with dimension of 150 x 110 x 100 $mm^3$ was machined by wire cutting machine. The angular errors of pitch and yaw are better than ± 0.1 second over a moving range of 200 micrometers as shown in Fig. 2.

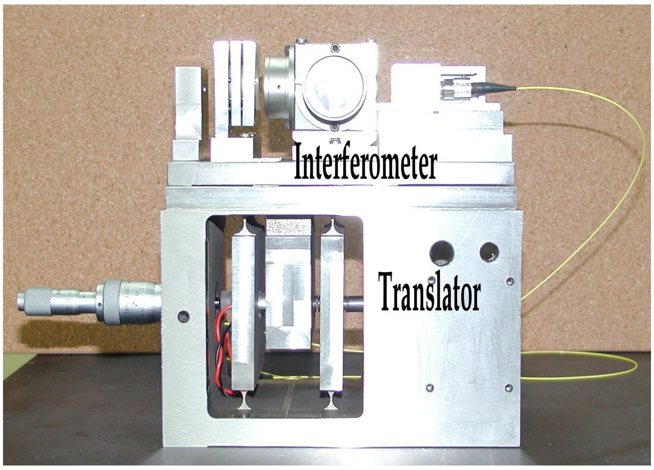

Fig. 1. Single parallel flexure micro-stage with laser interferometer optics.

The schematic diagram of the optical system is shown in Fig. 3. The laser interferometer is set-up on the top of the flexure translator. The measurement principle is based on a homodyne technique using a double-pass differential plane mirror interferometer. The differential plane mirror interferometer is used because of its higher thermal stability and higher resolution. A frequency-stabilized He-Ne laser is used as a light source of interferometer for displacement measurement. The laser beam is coupled by a polarization preserving fiber and directed to the collimating optics. The collimated beam passes the polarizer with its transmission axis inclined at 45 ° to the horizontal plane and directed to the interferometer optics. All optical components except the moving mirror are cemented for thermal and mechanical stability.

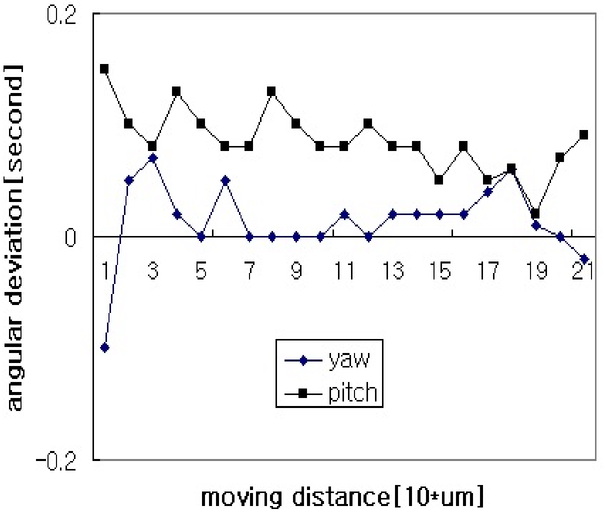

Fig. 2. Angular motion errors of single parallel flexure micro-stage.

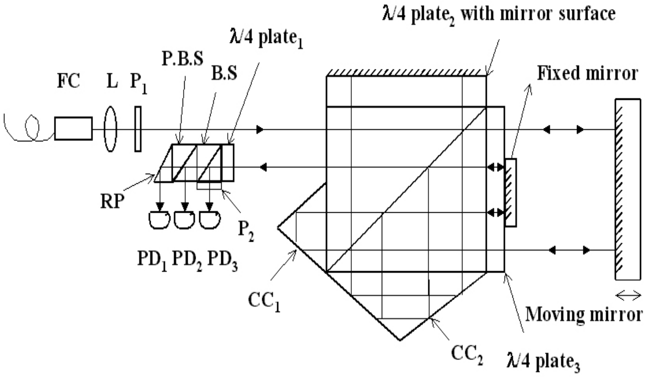

Fig.3. The optical pass arrangement of the laser interferometer unit. FC : fiber connector, P1 and P2 : polarizer, CC1 and CC2 : corner cube prism, B.S : beam splitter, P.B.S : polarizing beam splitter, RP : right angle prism, PD1, PD2 and PD3 : photodiode

The three interference signals, phase shifted by 90 ° with respect with to each other by polarizing optics and quarter-wave plate, are detected by 3 photodiodes. Two of three signals with a phase difference of 90 °are subtracted by differential amplifiers. Therefore two output signals with a phase difference of 90 ° have nearly same amplitude and no DC offset. Then two signals are introduced into A/D converters and counting board at a computer through the signal compensation circuit(see Fig. 4).

Even though the laser interferometer provides the resolution much smaller than sub-nanometer, its accuracy is limited by the nonlinearity. In case the nanosensor is calibrated by the interferometer with nonlinearity error, the accuracy is mainly limited by nonlinearity. In homodyne interferometer, polarization mixing effect, laser power drift, laser beam alignment and imperfection of the electronic circuit are the main error sources of nonlinearity error.[5] By nonlinearity error, offsets of the two signals are not zero and their amplitudes are not equal. And the phase difference of two signals is not 90 °. This causes the Lissajous trajectory of two phase-quadrature signals to be distorted from the ideal circle. In order to reduce the nonlinearity error, careful electronic adjustment are required. In this system, computer calculates the elliptical parameters such as offsets, amplitudes and phase difference from phase quadrature and error signals are fed to the compensation circuit through D/A converters. And also these error terms can be adjusted manually by external potentiometers. However perfect sine and cosine signals can't be obtained.[6] The residual nonlinearity error after compensation circuit can be reduced by software correction using the elliptical fitting technique. Because this method is very time-consuming procedure, it can't be for dynamic probe calibration. For the fast measurement, commercial counter board with interpolating circuit can be used in our system. The position resolution of elliptical fitting technique and electronically interpolating technique are about 0.04 nm and 0.16 nm, respectively.

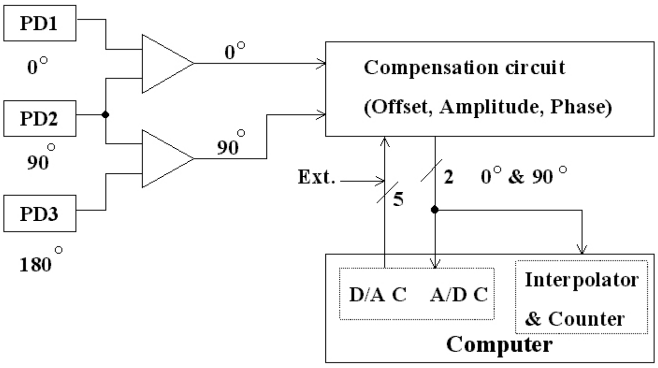

Fig.4. Schematic diagram of electronic circuit for phase angle measurement and nonlinearity error correction.

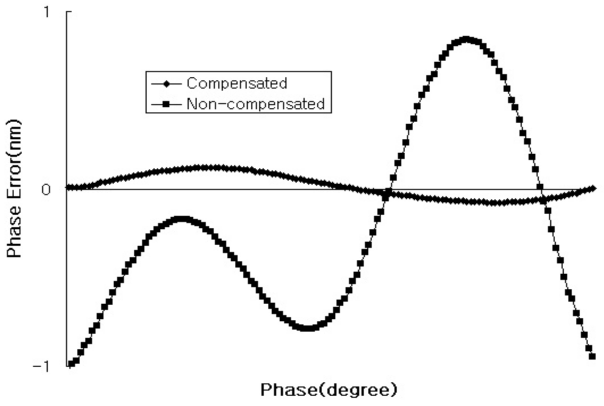

Fig.5. Nonlinearity errors in case of manually adjustment of the compensation circuit (non-compensated) and software correction by elliptical fitting (compensated).

Even if the system can be operated without compensation circuit, the signal optimization by compensation circuit is able to reduce the error in post-processing of software-based elliptical fit or electronic interpolation. Table 1 shows an example of the ellipse parameters of the phase-quadrature signals before and after compensation circuit. As shown in table 1, by the electronic compensation circuit, amplitudes become nearly same and offsets and phase errors are considerably reduced. However , for dynamic calibration, the electronic compensation of the nonlinearity is required. By the electronic compensation, the nonlinearity error can be reduced to 0.3 nm.

Table 1 Ellipse parameters of phase-quadrature signals collected without and with electronic compensation.

| | Amplitude (Sin, V) | Amplitude (Cos, V) | Offset (Sin, V) | Offset (Cos, V) | Phase error δ(°) |
|---|---|---|---|---|---|
| Without | 5.262 | 4.860 | 0.045 | -0.142 | 1.987 |
| With | 5.026 | 4.961 | - 0.011 | 0.022 | 0.102 |

An example of the nonlinearity errors is shown in Fig. 5. This is result of manually adjustment of the compensation circuit (non-compensated) and software correction by elliptical fitting (compensated). From Fig. 5, We can figure out that nonlinearity error has the two-cycle periodicity because offset error and amplitude error are nearly same. This periodicity of nonlinearity depends on optical alignment and electronic adjustment. However nonlinearity error can be reduced to ± 0.15 nm by software-based compensation.

## 3. SENSOR CALIBRATION AND UNCERTAINTY EVALUATION

The interferometer was compared with a capacitance gauge. With moving the stage smoothly using the PZT, the signals from laser interferometer and capacitance gauge were read through the analog to digital converters of DAQ board. The difference between the displacement calculated from laser interferometer and output voltage from the capacitance gauge (dot line) is plotted in Fig. 6. The periodic sinusoidal modulation, which mainly comes from the nonlinearity of homodyne interferometer, is obtained from phase calculation of the manually compensated signals without software-based correction. The slowly varying signal with high frequency noise (solid line) is obtained from phase calculation of the compensated signals with software-based correction. This figure shows that periodic sinusoidal modulation is completely removed. And also we can figure out that this slowly varying line mainly comes from the nonlinearity of capacitance gauge. In this experiment, we can't find the residual nonlinearity error of the laser interferometer. It indicates that the non-linearity error of the homodyne interferometer is nearly compensated by new phase encoding electronics and software-based correction and less than noise of the capacitance gauge. In this case, the peak to peak of the periodic error after compensation electronics is about 2.0 nm. The residual error of the capacitance gauge is about 0.7 nm over measuring range of 850 nm. However nonlinearity error of the capacitance gauge can be reduced by polynomial fit. In the figure, the high frequency noise is mainly caused by instabilities of the system such as the noise of the capacitance gauge, air turbulence and vibration.

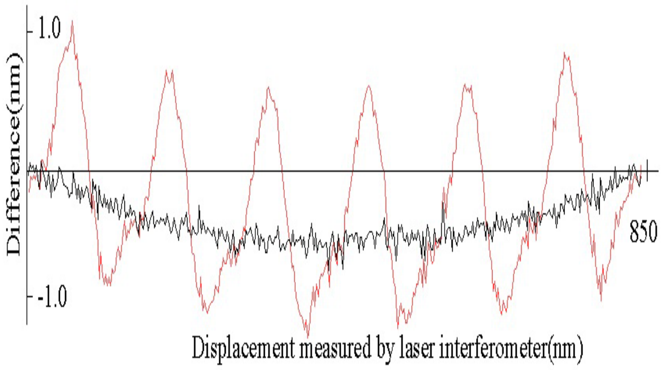

Fig. 6. Difference of the measurement between the laser interferometer and the capacitance gauge.

The uncertainty of the calibration system is estimated from considering components due to laser interferometer and mechanical system. Here, we don't consider the uncertainty from sensor to be calibrated. The result for the static measurement is shown in Table 2. Laser frequency uncertainty depends on center frequency calibration and instability of the laser source. It is usually less than $5 \times 10^{-9}$. Refractive index uncertainty is due to calibration uncertainty of sensors of temperature, pressure and humidity, which is within $1 \times 10^{-7}$. Usually sensor to be calibrated can be easily aligned with Abbe offset less than 1 mm and the angular motion errors of the micro-translator over 200 μm moving range are less than ± 0.1 second. Therefore uncertainty from Abbe error is about 0.4 nm. The laser beam is aligned horizontally using the position sensitive detector and its deviation from horizontal and vertical reference line is about 5 μm over 1 mm moving range of the micro-translator. It makes the uncertainty of $1.3 \times 10^{-5}$. The variation of optical path length by the change in the refractive index of air in the uncompensated path between reference mirror and moving mirror cause dead path error. It depends on distance between reference mirror and moving mirror and measuring time which causes the change in refractive index of air. The uncertainty from uncompensated dead path error is less than 0.2 nm. The nonlinearity error of the laser interferometer is compensated by both electronic circuit and software. The residual nonlinearity error is less than ± 0.15 nm. In order to reduce the thermal and mechanical instability, all optical components are cemented. However unsymmetric thermal expansion makes the change of the optical path length between reference beam and measurement beam. This estimated uncertainty is about 0.2 nm.

When the system is used statically, the expanded uncertainty is estimated as 1.04 nm + 2.6 x $10^{-5}$ L. This is given for moving range of 200 µm and measuring time of 2 minutes.

Table 2 Uncertainty budget of the calibration system, when is used statically.

| Sources of uncertainty | Uncertainty |
|---|---|
| Laser frequency | 5 x $10^{-9}$ |
| Refractive index of air | 1 x $10^{-7}$ |
| Abbe error | 0.4 nm |
| Cosine error | 1.3 x $10^{-5}$ |
| Dead path error | 0.2 nm |
| Nonlinearity of interferometer | 0.15 nm |
| Thermal Drift | 0.2 nm |
| Expanded uncertainty (k=2) | 1.04 nm + 2.6 x $10^{-5}$ L |

## 4. CONCLUSIONS

We developed the set-up for calibration of displacement measuring sensors with nanometer or sub-nanometer resolution. The system consists of micro-translation stage with normal measuring range of 200 µm and nonlinearity free laser interferometer with a single frequency. The system can be used in a static and dynamic way. The preliminary test shows that the system can calibrate the sensor with accuracy of nanometer.

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