Portable Calibration System for Displacement Measuring Sensors

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For calibration of displacement measuring sensors, a portable calibration system using a homodyne laser interferometer was developed. The system is directly traceable to the Meter definition. And it is also transportable due to use of a laser source coupled by an optical fiber, so it can be used for calibrating the sensors attached to the length measuring instruments. In general, the accuracy of the laser interferometer with short measuring range is mainly limited by nonlinearity error. In order to reduce nonlinearity error, offsets, amplitudes and phase of the sine and cosine signals from interferometer are manually adjusted and compensated by ellipse fit. Nonlinearity error is reduced to ± 0.15 nm by software-based compensation. On calibrating sensors, the system can be used in a static or a dynamic way. When the system is used statically with measuring time of 2 minutes, the expanded uncertainty at 95 % confidence level is estimated as (1.2 + 2.6 × 10^{-5} L) nm, where L is moving distance in nm.

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1. Introduction

The LVDTs(linear variable differential transformer) and capacitive sensors are commonly used to measure the displacement in a variety of length measuring instruments such as roundness tester, surface roughness tester and gauge block comparator, and precision stages for lithography. These sensors have a resolution of nanometer or sub-nanometer over a measuring range of a few hundred micrometers. The accuracy of these sensors is commonly worse than their resolutions because of nonlinearity, hysteresis and drift. Traditionally, the calibration of these sensors has been done by special physical standards such as gauge blocks, roughness standards and roundness magnification standards because the calibration using these physical standards is very simple and time-saving. However the calibration by physical standards can not provide uncertainty less than nanometer and also the physical standards used as reference should be calibrated for determining the exact values.

Recently the nano-sensor calibration devices using digital piezo-translator(PZT) were reported.[1,2] They are equipped with a PZT for fine displacement and capacitive sensor for measuring the displacement of PZT. The capacitive sensor is calibrated using by a laser interferometer. Since these systems are very compact and portable, they can be used for sensors attached to length measuring instruments. But in these systems, pre-calibration by laser interferometer is required and also they may have the long-term drift deteriorating the accuracy. For this reason, direct calibration systems using the laser interferometers have been developed.[3,4] These systems can calibrate the sensors with accuracy of sub-nanometer, so they can be used to evaluate the nano-sensors. However they are very complicate and huge, so they can not be used for in-situ calibration of the sensors attached to length measuring instruments.

Korea Research Institute of Standards and Science has developed a portable calibration system using the laser interferometer, i.e. the portable sensor calibrator. The frequency stabilized laser source is coupled by a single mode fibre, so the system is compact and also thermal influence from laser head is eliminated. The system can be used for not only performance test of nano-sensors with sub-nanometer resolution but also in-situ calibration of the LVDT probes attached to the length measuring instruments.

2. Experimental system

The system consists of a translator mechanism and a displacement measuring interferometer as shown in Fig. 1. The translator consists of single parallel flexure micro-stage driven by a low-voltage PZT with moving range of 20 μm and a differential micrometer head with resolution of 0.5 μm. The flexure translator with dimension of 150 × 110 × 100 mm was machined by wire cutting machine. The angular errors of pitch and yaw are less than ± 0.1 second over a moving range of 200 micrometers as shown in Fig. 2.

The schematic diagram of the optical system is shown in Fig. 3. The optics of the laser interferometer and the sensor attachment are rigidly fixed to the Invar plate placed on rigid part of the flexure translator, and the moving mirror of the interferometer is fixed to moving part of the flexure translator. The measurement principle is based on a homodyne technique using a plane mirror interferometer. A frequency-stabilized He-Ne laser is used as a light source of interferometer for displacement measurement. The laser beam is coupled by a single mode fiber and directed to a collimating optics. The collimated beam passes the polarizer with its transmission axis inclined at 45 ° to the horizontal plane and is directed to the interferometer optics. All optical components except the moving mirror are cemented for thermal and mechanical stability.

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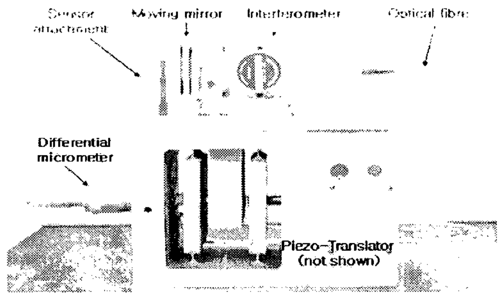

Fig. 1 Photograph of a portable sensor calibrator

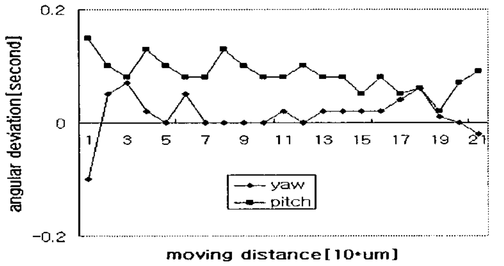

Fig. 2 Angular motion errors of a single parallel flexure micro-stage

Three interference signals(S_1, S_{90} and S_{180}) with a phase shift of 90 ° from one to the other are detected by 3 photodiodes. The signals of S_1 and S_{180} are subtracted from S_{90} to remove the DC offset. Two output signals(sine and cosine, phase-quadrature signals) have nearly equal amplitude, zero DC offset and a phase difference of 90 °. However they are not perfect sine and cosine due to nonlinearity of the laser interferometer. So we introduced a nonlinearity compensation system. The gain and offset of two phase-quadrature signals are manually adjusted by potentiometers to get equal amplitude and zero DC offset. And also they are phase adjusted to get the phase difference of 90 °. The corrected signals are introduced into the up/down counter and the A/D converters respectively.(see Fig. 4)

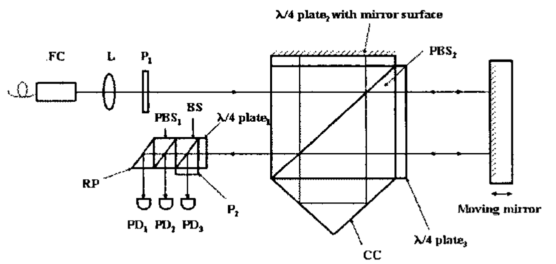

Fig. 3 Optical pass arrangement of a laser interferometer unit. FC : fiber connector, P1 and P2 : polarizer, CC : corner cube prism, B.S : beam splitter, P.B.S : polarizing beam splitter, RP : right angle prism, PD1, PD2 and PD3 : photodiode

Even though the laser interferometer provides the resolution much better than sub-nanometer, its accuracy is limited by the 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.[5,6] Due to the nonlinearity error, offsets of the two signals are not zero and their amplitudes are not equal. The phase difference between 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 optical alignment and electronic adjustment are usually required. In this system, computer calculates the ellipse parameters such as offsets, amplitudes and phase difference, and the ellipse parameters are adjusted by optical alignment and potentiometers of the compensation circuit. However the perfect sine and cosine signals can not be obtained by optical and electronic adjustments. The residual nonlinearity of two phase-quadrature signals from compensation circuit can be reduced by software-based correction using the ellipse fit technique.[5-7] Since this method is very time-consuming procedure, it is not suitable for dynamic calibration. For the fast measurement and easy transportation, the compact interpolator and counter circuit,[8] which can be interfaced with notebook PC, can be also used in our system.

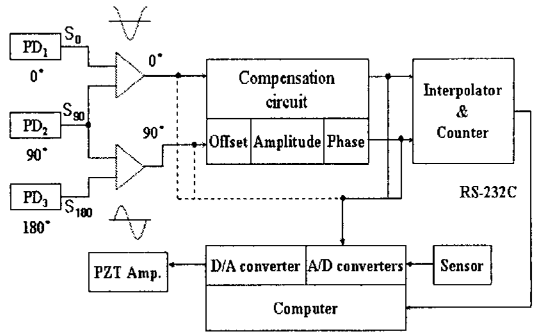

Fig. 4 Schematic diagram of electronic circuit for phase angle measurement and nonlinearity correction

3. Performance test and sensor calibration

3.1 Performance test

Table 1 shows an example of the elliptical parameters of the phase-quadrature signals before and after compensation circuit. As shown in table 1, by fine adjustment of the electronic compensation circuit, amplitudes become nearly same and offsets and phase errors were considerably reduced and the residual nonlinearity of ± 0.3 nm was measured. Another example of the nonlinearity is shown in Fig. 5. This is result of hardware-based correction by compensation circuit (non-compensated) and software-based correction by ellipse fit (compensated). Here careful adjustment of the compensation circuit was not done in order to evaluate the performance of software-based correction. From Fig. 5, we can figure out that nonlinearity has the two-cycle periodicity. The first order term, which results from non zero offset, is the dominant part. However nonlinearity error can be reduced to ± 0.15 nm by software-based correction.

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

	Amplitude (volt)	Offset (volt)	Phase error (degree)	Nonlinearity (nm)
Without	5.26 (sin) 4.86 (cos)	0.05 (sin) -0.15 (cos)	1.99	2.4
With	5.02 (sin) 4.96 (cos)	-0.01 (sin) 0.02 (cos)	0.10	0.3

The portable sensor calibrator was compared with a capacitive sensor. With moving the stage smoothly using the PZT, the readouts of laser interferometer and capacitive sensor were recorded simultaneously with short sampling time to avoid the long-term drift. The difference between two readouts is depicted in Fig. 6, showing the nonlinearities of the laser interferometer and the capacitive sensor. The line with periodic sinusoidal modulation, which mainly comes from the nonlinearity of homodyne interferometer, is a result measured without software-based correction. The line with slowly varying signal is a result measured with software-based correction.

This figure indicates that the non-linearity (about ± 1.0 nm) of the homodyne interferometer is mostly compensated by software-based correction. This slowly varying signal mainly comes from the nonlinearity of capacitive sensor. The nonlinearity of the capacitive sensor is about 0.7 nm over measuring range of 850 nm.

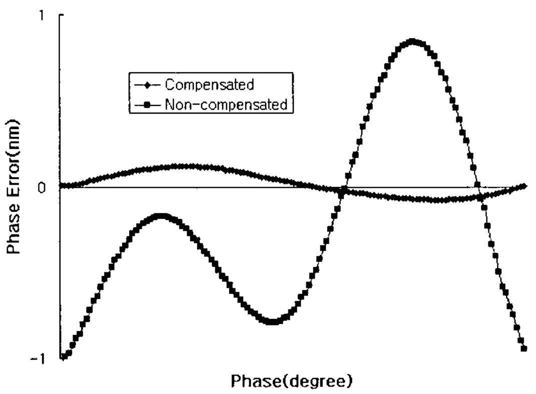

Fig. 5 Nonlinearity errors in case of manually adjustment of the compensation circuit (non-compensated) and software-based correction by ellipse fit (compensated)

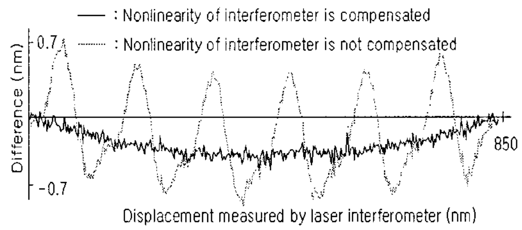

Fig. 6 Difference of the measurement between the laser interferometer and the capacitive sensor

3.2 LVDT calibration

The LVDTs are widely used in displacement measurement, especially in gauge block comparator, roughness tester and roundness tester. It has high resolution and long measuring range. Usually LVDTs are calibrated by several gauge blocks. The calibration of LVDT using gauge block takes too much time and is not accurate because of manual operation and uncertainty of gauge blocks. In this experiment, the LVDT with resolution of 0.01 μmwas calibrated with portable sensor calibrator. With moving the stage smoothly using the PZT, the readouts from counter and LVDT were recorded through serial interface and A/D converter, respectively. The nonlinearity of the LVDT is 0.1 μm over measuring range of 10 μm. The nonlinearity of the LVDT can be reduced by polynomial fit. The residual nonlinearity after 5^{th} polynomial fit is less than 0.01 μm which is equivalent to resolution of the LVDT.

3.3 Roundness tester calibration

The roundness tester is usually calibrated by a magnification standard or gauge block. This calibration provides only magnification accuracy over 1 or 2 measuring ranges. The magnification accuracy and linearity of the roundness tester were statically calibrated over all measuring ranges, while the spindle of the roundness tester was not rotated. The portable sensor calibrator was placed on roundness tester like a specimen for roundness measurement, and the probe was contacted with the moving mirror of the calibrator. For displacement of the moving mirror, both differential micrometer head and PZT were used. The result is shown in table 2. The gain of the amplifier was adjusted at the magnification of 2,000. The maximum deviations of magnification and nonlinearity are 0.85 % and 1.2 %, respectively.

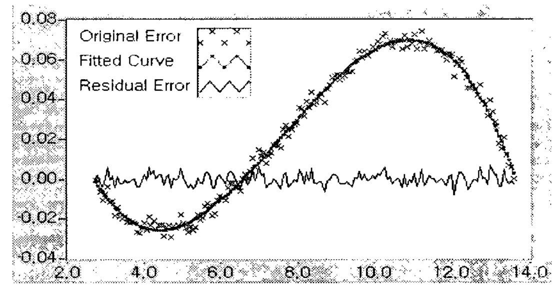

Fig. 7 Calibration result of the LVDT)

Table 2 Calibration result of a roundness tester

Item \ Magnification	100	200	500	1,000	2,000	3,000	10,000	20,000
Deviation of Magnification (%)	0.2	0.33	0.17	0.15	0.1	0.76	0.85	0.73
Nonlinearity (%)	0.4	0.4	0.3	0.3	0.4	0.7	0.9	1.2

4. Uncertainty evaluation

The uncertainty of the calibration system is estimated from considering components of laser interferometer and mechanical system. The uncertainty from sensor was not considered. The uncertainty budget for the static measurement is shown in table 3. Laser frequency uncertainty depends on center frequency calibration and instability of the laser source. It is usually less than 1×10^{-8}. The uncertainty of refractive index of air is due to calibration uncertainty of sensors for measurement of temperature, pressure and humidity, and it can usually be measured with accuracy of better than within 1×10^{-7}. The sensors to be calibrated can be easily aligned with Abbe's offset less than 0.8 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's error is about 0.4 nm. The measuring direction of the sensor should be parallel to the laser beam. Its angular deviation is usually less than 5×10^{-3} radian and causes the cosine error of 1.3×10^{-5}. The nonlinearity error of the laser interferometer is compensated by both electronic circuit and software-based elliptical fit. The residual nonlinearity is less than ± 0.15 nm. 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 causes dead path error. It depends on distance between reference mirror and moving mirror and change in the refractive index of air during measurement. In order to reduce the thermal and mechanical instability, all optical components are cemented at Invar plate. However asymmetric thermal expansion makes the change of the optical path length between reference beam and measurement beam. It is very difficult to evaluate the dead path error and the thermal and mechanical instability exactly, because they usually depend on measuring time and environmental conditions. So the uncertainty by these factors was estimated by long term stability. After the moving part of the micro-translator was rigidly fixed at Invar plate, the change in displacement measured by the laser interferometer was recorded. It usually takes less than 2 minutes to calibrate the sensors, so the drift for 2 minutes was estimated. When the system is used statically, the expanded uncertainty at 95 % confidence level is estimated as $(1.2 + 2.6 \times 10^{-5} L)$ nm, where L is moving distance in nm. This is given for moving range of 200 μm and measuring time of 2 minutes.

5. Conclusion

We developed the calibration system for displacement measuring sensors with high resolution. The system consists of the micro-translation stage with normal measuring range of 200 μm and the homodyne laser interferometer. The laser beam is coupled to the interferometer by the optical fiber and the structure is compact, so this system can be used for calibrating the sensors attached to the length measuring instruments. The measurement of nonlinearity of the laser interferometer has shown a nonlinearity of ± 0.3 nm when only manual hardware adjustment of gain, offset and phase was used, ± 0.15 nm when software-based correction was used. When the system is used statically, the expanded uncertainty at 95 % confidence level is estimated as $(1.2 + 2.6 \times 10^{-5}\ L)$ nm, where L is moving distance in nm. The system can be used in a dynamic way. However the weight of the moving part of the micro-translator must be reduced for dynamic mode which requires the fast response time.

Table 3 Uncertainty budget of the calibration system, when is used statically with measuring time of 2 minutes

Sources of uncertainty	Standard Uncertainty
Laser frequency	1×10^{-8}
Refractive index of air	1×10^{-7}
Abbe's error	0.4 nm
Cosine error	1.3×10^{-5}
Nonlinearity of interferometer	0.15 nm
Drift(dead path error, thermal and mechanical instabilities)	0.4 nm
Combined standard uncertainty	$(0.6 + 1.3 \times 10^{-5}\ L)$ nm, L: nm
Expanded uncertainty (k=2)	$(1.2 + 2.6 \times 10^{-5}\ L.)$nm, L: nm

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