DESIGN AND CALIBRATION OF A SUB-NM RESOLUTION DIFFERENTIAL CAPACITIVE POSITION SENSOR

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Abstract:

This paper introduces the design and calibration of a capacitive position sensor used for measuring the mechanical deflection of a beam with sub-nanometer resolution. It is known that the most accurate and SI traceable method for displacement measurement is the laser interferometry. However, in our application we need to know not only the displacement of the object under measurement but also its distance to a reference origin. To measure the distance with a common two-beam interferometer, in which the measured displacement is proportional to the number of fringes counted, one needs to move the object from the reference origin to the desired position and continuously track the readout of the laser interferometer. To meet this need, we have developed a capacitive position sensor dedicated to this application. The capacitive sensor consists of three planar electrodes, i.e. two stationary electrodes and one movable electrode attached to the beam under measurement. The position sensing is based on differential capacitance detection and realized by a capacitive-inductive bridge circuit. We present the design and working principle of this sensing circuit. The performance of the capacitive position sensor was evaluated by calibrating it against a laser interferometer. The calibration also supplies the lack of SI traceability of the capacitive sensor. The calibration results show that the capacitive position sensor is able to measure position with sub-nanometer resolution. The sensing coefficient of the capacitive position sensor was found to be (14.0 ± 0.1) mV/nm.

Keywords: Capacitive position sensing, Optical interferometer, Displacement calibration, Capacitance bridge

1. INTRODUCTION

Laser interferometry is used in dimensional measurements for applications where the SI traceability and high accuracy are requested. Among all types of optical interferometers, the two-beam interferometer is one of the most common types, in which the measured displacement is proportional to the number of fringes counted. To measure the distance with this type of interferometer, one needs to track the displacement readouts of the interferometer and integrate them to obtain the distance information. In our application, we need to know gap distances between three planar electrodes that used to generate precise electrostatic forces [1]. Although other type of interferometer, for example a Fabry-Perot interferometer [2, 3], may be used for our application, however it requires a more complicated optical setup. To meet this need, we developed a capacitive position sensor that uses the planar electrodes as sensing electrodes and measures the gap distances between them. We also calibrated the capacitive position sensor against a laser interferometer system, in order to compensate the sensor's lack of SI traceability. In the following sections, we present the design and working principle of the capacitive position sensor, and the experimental setup and results of the displacement calibration.

2. DESIGN AND WORKING PRINCIPLE

The three planar electrodes are arranged as the configuration shown in figure 1. The top and bottom electrodes are stationary and fixed to a rigid metal housing. The middle electrode is movable and mechanically connected to the beam, which is a rectilinear guiding stage (represented by two springs). The electrodes are made of aluminum alloy, whose surfaces are fine polished and coated with a thin layer of gold. The nominal gap distance d and area are 0.5 mm and 1178.1 mm^2, respectively. All electrodes are electrically insulated with the metal housing. Two capacitors C_1, C_2 each having gap distances d_1 and d_2 are formed. When the middle electrode is displaced from the center position ($d_1=d_2=d$) by z, an imbalance in the capacitance value C_1, C_2 is created. The relation between the imbalance capacitance defined as $\Delta C=C_1-C_2$ and the off-center displacement z can be derived using the model of parallel-plate capacitor, in which the capacitance C_0 is expressed by the medium permittivity ε, electrode area A and gap distance d between electrodes as

$$C_0 = \frac{\varepsilon A}{d}; \tag{1}$$

and the differential capacitance is derived to be

$$\Delta C = C_1 - C_2 \cong \frac{2C_0}{d} z, \tag{2}$$

which is linearly proportional to displacement z for $z/d \ll 1$. Hence, the displacement z can be measured by detecting the ΔC. The differential capacitance ΔC is detected by a resonant capacitance bridge circuit and a lock-in amplifier. Figure 2 shows the schematic of differential capacitance sensing circuit. The bridge consists of the capacitors C_1, C_2 and a radio frequency (RF) transformer T_{rf}. An RF detection signal $V_d \sin \omega_d t$ of amplitude V_d = 0.5 V and frequency ω_d = 2π·100 kHz is applied to the middle electrode via a fine wire.

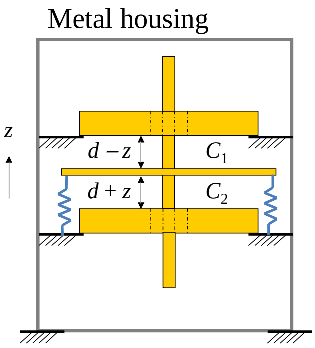


Fig. 1: Capacitor consisting of three planar electrodes.

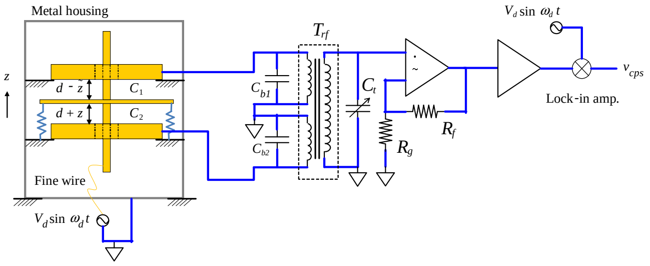


Fig. 2: Schematic of differential capacitance sensing circuit.

The RF detection signal propagates to the circuit ground via two loops each of which contains C_1 or C_2, respectively. Any capacitance imbalance between C_1 and C_2 produces a voltage output at the secondary winding of the RF transformer T_{rf}. To increase the signal to noise ratio, a trimmer capacitor C_t is connected to the secondary winding to form an LC resonant circuit. The output of the LC resonant circuit is buffered by an OP amp, then amplified by another AC gain stage, and finally demodulated by a lock-in amplifier. The output of the lock-in amplifier v_{cps} is proportional to the off-center displacement z.

3. DISPLACEMENT CALIBRATION WITH LASER INTERFEROMETER SYSTEM

The capacitive position sensor was calibrated against a laser interferometer system. The displacement resolution of the laser interferometer system is about 5 nm. We use electrostatic forces to move the middle electrode by about ± 4 µm. The electrostatic force was generated by applying two audio frequency, high voltage signals to the two stationary electrodes. The displacement of the middle electrode was measured by both the capacitive position sensor and the laser interferometer system. Figure 3 shows the data acquired in the calibration measurement. To reduce the effect from noises such as vibration, drift, acoustic noise, etc, v_{cps} and z_{itf} were averaged in each step to obtain corresponding mean values. From the averaged v_{cps} and z_{itf}, the sensitivity coefficient of the capacitive position sensor was found by linear fit. One of the fitting results is shown in figure 4. The residual errors (denoted as re in Fig.4) were all below 5 nm. The uncertainty of this linear fit was found to be 2.9 nm. The slope of this fitting curve was found to be (71.4 ± 0.24) nm/V, corresponding to a sensitivity of (14.0 ± 0.05) mV/nm of the capacitive position sensor. We statistically combined all sensitivity coefficients given in each linear fit and obtained a sensitivity coefficient of (14.0 ± 0.1) mV/nm.

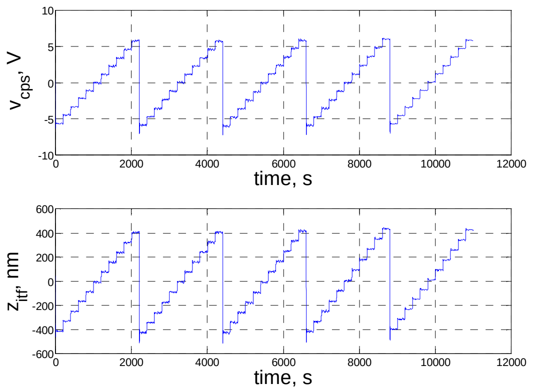
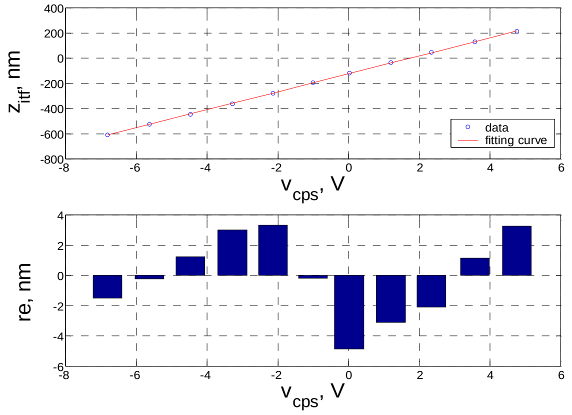


Fig. 3: Displacement of the middle electrode measured by both the capacitive position sensor and the laser interferometer system.



4. RESULTS AND DISCUSSION

A capacitive position sensor dedicated for measuring the deflection of the mechanical beam was built and characterized with the laser interferometer system. The sensor is capable of measuring the off-center displacement of the middle electrode. The resolution of the sensor is limited by the thermal noise of the capacitive-inductive bridge which was expected to be below far below 50 pm. Assuming the resolution is dominated by the resolution of an analog-to-digital converter used in the data acquisition system, a sub-nanometer displacement resolution is achievable with the sensor.

ACKNOWLEDGEMENTS

This work is supported by the Bureau of Standards, Metrology and Inspection (BSMI), Taiwan, R.O.C.

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