A NEW CAPACITIVE DISPLACEMENT SENSOR WITH HIGH ACCURACY AND LONG RANGE

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ABSTRACT

A new capacitive displacement sensor is designed and fabricated for measurement of a large displacement with very high accuracy. This sensor is a kind of linear encoder with an array of micro electrodes made by micromachining processes. The two patterned electrodes on the sensor substrates are assembled facing each other after being coated with thin dielectric film. Due to the thin dielectric film, it is highly sensitive to displacement but minimizes expected misalignments such as a tilting error. The sensor fabricated as a sample has a grating of electrodes with a width of 100μm, which is coated with a Diamond-Like Carbon(DLC) film 0.8 μm thick. The proposed sensor was tested to conclude that its resolution is 9.07 nanometers for the measuring range of 15 millimeters and that the linearity error is expected to be less than 0.02% throughout the measurable range.

Keywords: Encoder, capacitive displacement sensor, DLC, contact-type, high resolution

INTRODUCTION

When a nano-positioning system is used for an accurate wide-ranged motion task, a precise long- range displacement sensor should be adopted for precise motion control. A capacitive sensor, a Linear Variable Differential Transformer(LVDT), a Position Sensitive Detector(PSD) can detect displacements down to the subnanometer range, but are limited to maximum measuring displacements of a few hundred micrometers [1~4]. Alternatively, a laser interferometer and an optical linear encoder can operate over a wide range but they are not cost-effective due to their complex structure and have poor compatibility because of their large size[5, 6].

On the other hand, the encoder-type capacitive displacement sensor has been presented as a superior sensor capable of high resolution, long range, conciseness [7~11]. It consists of two parallel substrates with scaled conducting bars. In this sensor configuration, horizontal translation of one plate with respect to the other plate while maintaining a constant gap gives rise to periodic variations in capacitance caused by changes in the overlapped area of the bars on the two facing substrates. These capacitive sensors have a theoretical advantage in that they can give both a long sensing range and high resolution by reduction of the pitch size of the series of the bars. If, however, the gap between the two parallel plates is larger than the pitch size of the conducting bars on the sensor, even though the pitch of the bars is very small, the sensor sensitivity is drastically reduced because of a fringe effect around the edge of the bars so the displacement resolution isn't improved. For high resolution with these kinds of sensors, the gap of these sensors should be reduced, but it is difficult to reduce the gap down to tens of micrometers because of the precision limit of the mechanical guide of the sensor. Even if the task of reducing the gap were achieved, the small gap could make it difficult to keep a constant gap between two plates of the sensor

In this paper, we propose a Contact-type Linear Encoder-like Capacitive Displacement Sensor (CLECDiS) for use in nano-positioning systems. It has not only a long sensing range like a traditional encoder-type capacitive sensor, but also high resolution resulting from the small pitch size of the electrode bars and the small gap between its two substrates. Thin dielectric film coated on its electrodes is used as a buffer separating the electrodes of the sensor substrates and keeping a constant small gap size between the substrates. DLC film is adopted as the dielectric material since it minimizes friction and abrasion problems caused by the contact condition of this sensor. Because the proposed sensor is very small and simple, it is easy to adapt this sensor to nano-positioning systems. Also, it has a low-cost fabrication process compared with other displacement sensors with high resolution and accuracy.

DESIGN

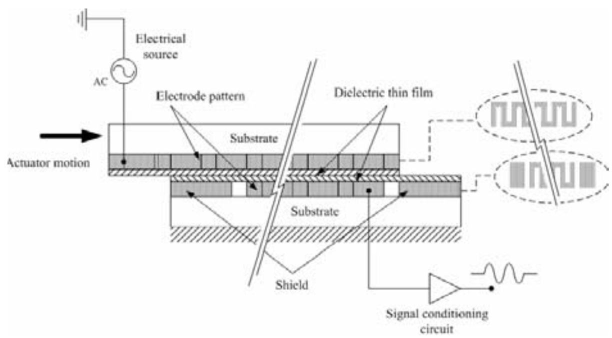

Fig. 1. Basic features of the CLECDiS

Fig. 1 shows a schematic diagram of the CLECDiS. This sensor consists of two parallel plates, each composed of a substrate layer covered with an electrode grating and a thin dielectric film coating. An electric source is supplied to one plate, referred to as the transmitter, and the output signal of the CLECDiS is detected from the other plate, referred to as the receiver. The electrode grating for detecting the signal in the receiver is enclosed by a grounded shield. The electrode grating on each plate is made up a set of regularly spaced parallel bars of uniform size connected in series. This electrode design gives a linear variation in the overlapped area when one plate is moved horizontally. The grounded electrode in the receiver is used to block the influence of stray capacitance and needless electric fields. The dielectric films coated on the transmitter and the receiver should be as thin and uniform as possible. In addition, the films should have a low-abrasion characteristic and a low friction coefficient in order to reduce wear of the film when the plates slide over one another and to improve the dynamic response of the CLECDiS. As the receiver moves in one direction with constant speed, the capacitance value of the CLECDiS changes periodically. A long range displacement can be measured with high accuracy if a double-stage algorithm is adopted: the number of extreme values is used to determine a coarse displacement and the accurate displacement value within the coarse resolution displacement range (half period) can be found by using the value of capacitance.

SIMULATION

With most traditional encoder-like capacitive displacement sensors, it is difficult to predict the actual capacitance of the sensors because the fringe effect is generally ignored [9, 12]. Relations of the pitch size of the electrode bars and the gap size of these sensors should be carefully considered to minimize nonlinearity caused by the fringe effect. Since a change in the sensor capacitance results from variation of the electric field between the electrodes in the sensor, one can simulate the nonlinearity of an encoder-like capacitive displacement sensor by Finite Elements Analysis(FEA) software for analysis of an electric field. For this, the reduced model of the CLECDiS was defined and analyzed by the FEA software, Maxwell®. The reduced model consisted of a transmitter with 11 electrode bars and a receiver with 5 electrode bars enclosed by a ground electrode. Electrical effects of the dielectric substrates in the sensor were ignored and the medium between the transmitter and the receiver was considered to be air. The size of every electrode bar in the reduced model was 0.001mm (thickness) × 1mm (width) × 12.2mm (length) and the pitch size of the series of bars was twice the width of the bars.

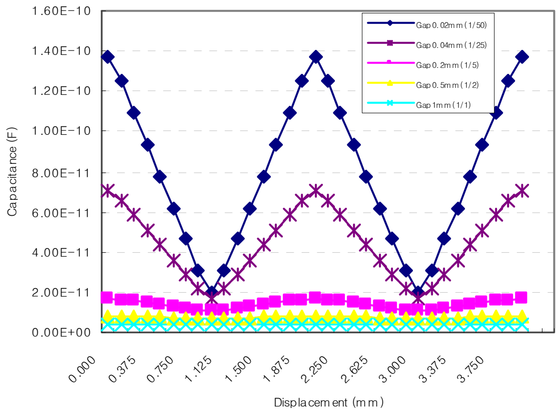

Fig. 2. Capacitance traces of the simulation model at various gap sizes

Fig. 2 shows the capacitance trace of the reduced model at various sizes of the gap between the transducer and receiver when the transmitter moves 4 mm. The capacitance in this simulation result changes with a period of 2mm, the same as the pitch size of the electrodes in the model. As the gap size of the sensor plates becomes larger, approaching the width of the electrode bar, the sensitivity of the model decreases rapidly. When ratio of gap size to electrode bar width is 0.02, sensitivity is 2360 times more than when the ratio is 1. The reason why the sensitivity of the sensor model changes nonlinearly is the fringe effect at the edge of the electrode bars in the sensor. There are some encoder-like capacitive displacement sensors in which the gap is similar to the width of the electrode bars on the sensors so that a phase change in the readout of the sensor is linearized[7, 8], but these sensors have restricted resolution and accuracy because of problems related with low sensitivity and misalignment of the sensors. These simulation results verify that the gap size is very important for a high resolution and accuracy. Consequently, the proposed CLECDiS can obtain high resolution and accuracy by the contact method using a very thin and uniform buffer layer.

FABRICATION

The CLECDiS was fabricated by micromachining technology. A 170-nanometer-thick gold electrode was deposited on a glass wafer and patterned by use of the photo lithography process. The spatial period of electrode bars on the CLECDiS was 200 micrometers. Hence, the period of capacitance variation should be 200 micrometers. Fig. 3 shows two couples of the CLECDiS module cut from a glass wafer. The size of the receiver and the transmitter are 34 mm by 32 mm and 42 mm by 24 mm, respectively. These CLECDiS samples can measure displacements up to 15mm in range.

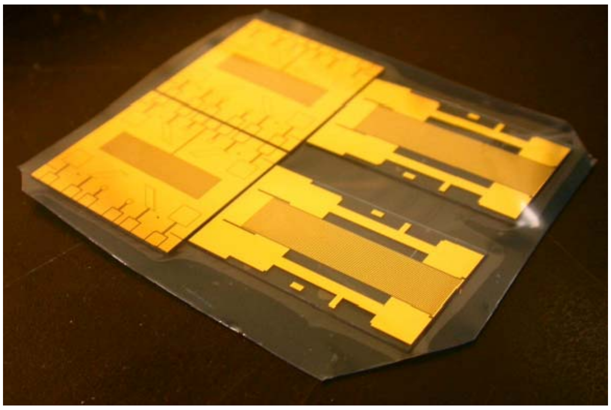

Fig. 3. Two couples of the CLECDiS modules (the transmitter and the receiver) fabricated by micromachining technology

The gap size of most traditional encoder-like capacitive displacement sensors is several tens of micrometers because of critical precision of the mechanical guidance joined to the sensors. As the gap size of the CLECDiS is determined by the thickness of the buffer film, the gap size of the CLECDiS can be much smaller. If a spin coater, a Chemical Vapor Deposition (CVD) system, or a sputtering system is used for coating dielectric buffer film on the electrodes of the CLECDiS, the gap size of the CLECDiS probably can be reduced down to tens of nanometers as long as the buffer film is not damaged. Friction and abrasion problems of the buffer film should be sufficiently considered since the CLECDiS adopts the contact method. In order to minimize the errors resulting from these problems, we applied a DLC film as the dielectric buffer layer. Since the DLC is an amorphous carbon film, like a diamond with high hardness, low friction, and wear-resistance[13], it is suitable for the buffer layer of the CLECDiS. The DLC which was here had a hardness(H) of 11 GPa[14], the friction coefficient of about 0.05~0.07[15]. The DLC film was coated on the electrodes of the sensor plates by Radio Frequency Plasma Assisted CVD(rf_PACVD) process. Thickness of the DLC was controlled by process time and bias voltage driving the target plate in the CVD chamber. The DLC film of these tests was determined to be 800 nm thick.

EXPERIMENTS

To effectively test the characteristics of the CLECDiS sample, it was necessary to ensure that the two sensor plates remained in contact during the sliding motion, and that the moving direction coincided with the sensing direction of the sensor. The test bench for CLECDiS consisted of a spring guide and two tilting stages. The spring guide helps to maintain contact between the two facing plates while the tilting stage was used to align the sensor properly. The receiver was actuated by a commercial positioning system, Newport M-562 and CMA25-CCCL. The velocity of the positioning system was held at 0.1 mm/s by Newport ESP300. The capacitance was measured using an impedance analyzer (Agilent, 4294A).

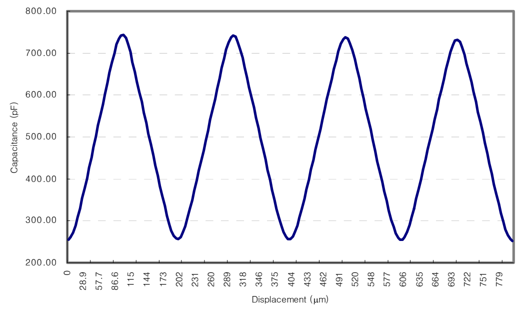

Fig. 4. The measured capacitance of the CLECDiS with DLC film

Fig.4 shows the capacitance trance of the CLECDiS when the positioning system moved to 800μm. It changes with the spacing-period of the electrode bars on the CLECDiS. A high sensitivity of 4.89 pF/μm was obtained. The displacement resolution of the fabricated CLECDiS is expected to be 9.07nm based on the S/N ratio of the impedance analyzer used for measurement in the experiments.

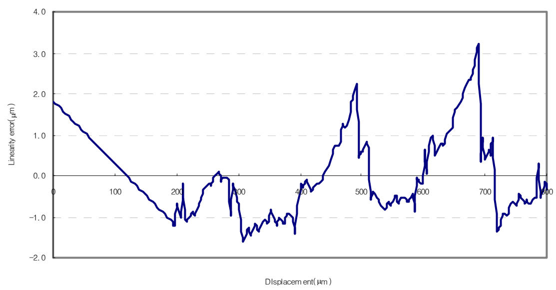

Fig. 5. the linearity error of the CLECDiS in Fig. 4.

Even if a small gap size between the transmitter and the receiver can improve linearity around the average capacitance of the CLECDiS, linearization should be sufficiently considered at extreme values of the sensor capacitance because of large nonlinearity around the extreme points. In this paper, all ranges of measured capacitances can be linearized by using two look-up tables which were made considering the displacement-capacitance and displacement-capacitance velocity relations. Fig. 5 is the linearity error of data in Fig. 4. The CLECDiS obtained a linearity error of less than 0.4% in the measured range of 800μm. Since the measured error is bounded and all sensing ranges are 15mm, a linearity error of the CLECDiS is expected to be less than 0.02% in this range.

CONCLUSION

A contact-type linear encoder-like capacitive displacement sensor (CLECDiS) is proposed for measurement of a long-range displacement with high accuracy. Since the electrodes are separated with a thin dielectric layer in the proposed sensor, the CLECDiS can easily achieve gap control between the facing electrodes, thus maximizing the sensitivity of the sensor itself. A DLC as the buffer layer was adopted for reduction of Friction and abrasion. Since the gap between the electrodes can be maintained in a sub-micrometer range in the CLECDiS, its gap size can be considerably reduced. The CLECDiS fabricated by micromachining proves that it can achieve a resolution of 9.07 nanometers and a linearity error of less 0.02% in all measurable ranges. The proposed sensor is suitable for use in nano-positioning systems because it is small and simple and has high resolution and accuracy over a long range.

Acknowledgments

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