Capacitive sensor for micropositioning in two dimensions

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A compact sensor for measuring position in two dimensions has been developed. The device, operating on the principle that the capacitance of parallel plate electrodes depends on their mutual area of overlap, is compatible with high magnetic fields and cryogenic temperatures. A resolution of approximately 1.2 μm has been achieved and is limited by the electronics used. The position reproducibility, which is limited by drift of the positioner used to test the sensor, has been measured to be better than 3 μm. © *1998 American Institute of Physics.* [S0034-6748(98)02901-3]

I. INTRODUCTION

The need for high resolution positioning is being driven in part by the recent interest in scanning probe microscopies.[1] Steppers, such as inertial translators[2] and inchworms,[3] are popular choices for positioners since they combine submicron resolution with virtually unlimited range. Several factors may affect the reproducibility of these devices. Steppers commonly employ piezoelectric actuators which exhibit hysteresis, creep, and temperature sensitivity. Load variations can also affect reproducibility since the strain of piezoelectric elements depends on load. For inertial translators, step size depends on frictional forces and therefore on the conditions of surfaces in contact.[4,5] Although step size variation is often reported, reproducibility is sufficient for many applications.[5,6] Severe environments can further compromise performance. The reduction in piezoelectric strain coefficients at cryogenic temperatures leads to significant reduction of step sizes. Therefore, more steps are needed to move a given distance, and a larger error is likely. Lack of reproducibility can be a significant disadvantage in certain scanning probe experiments. Since the dimension of a scanned area is small, typically on the order of $10 \times 10\ \mu\mathrm{m}^2$, it may be difficult to return a probe to a particular spot after an excursion of several millimeters. A position sensor can eliminate this problem. In fact, commercial micropositioners typically require position feedback to operate reproducibly.[3]

The development of the sensor described in this article was motivated by the desire to do scanning probe microscopy at croygenic temperatures in the confined space of a high magnetic field solenoid. Commercial sensors appear to have shortcomings for this application. Linear variable displacement transducers (LVDTs), available in miniature sizes as small as 10 mm in length,[7] rely on the inductive behavior of a permeable core and so should not be expected to perform reliably in strong magnetic fields. Position sensing detectors (PSDs)[8] use PIN junctions to precisely measure the position of a light beam but generally fail to work below about 30 K due to carrier freeze out in the doped regions. Commercial capactive sensors[9] have excellent resolution and are, in principle, compatible with high fields and low temperatures. They tend, however, to be bulky on the order of centimeters. Furthermore, one sensor is needed for each dimension. Our capacitive sensor is compact, measures position in two dimensions, and is expected to function at low temperatures and high magnetic fields.

II. DESIGN

The sensor consists of planar metallic electrodes separated by a small gap. The top electrode, designed to act as a sample holder, is attached to a micropositioning device to move it above the stationary bottom electrode which is divided into four equally sized and electrically isolated quadrants. If edge effects are neglected, the capacitance of each top electrode-quadrant pair (denoted C_1, C_2, C_3, and C_4) should be proportional to the respective overlap area [see Fig. 1(a)].[10] A signal approximately proportional to the difference in capacitance between two adjacent quadrants is measured by the circuit shown in Fig. 1(b). A transformer is used to apply voltages, of equal magnitude V and frequency ω but 180° out of phase, to two adjacent quadrants while the remaining quadrants are grounded. If the active quadrants are i and j, the signal is ideally given by

$$V_{ij} = \omega V (C_i - C_j) R, \tag{1}$$

where R is the resistor of Fig. 1(b). By means of a switch, signals from perpendicular quadrant pairs (V_{21} and V_{41}) are measured. According to the overlap area model of capacitance,

$$V_{21} \propto C_2 - C_1 = -2\epsilon_0 \frac{x(y+d/2)}{z}, \tag{2}$$

$$V_{41} \propto C_4 - C_1 = -2\epsilon_0 \frac{y(x+d/2)}{z}, \tag{3}$$

where d is the length of top electrode (10 mm), ϵ_0 is the permittivity of free space, z is the gap between electrodes, and the origin is placed at the center of upper electrode. Equations (2) and (3) provide a map between voltage measurements and the top electrode position.

III. RESULTS

To test the sensor, the upper electrode was glued to a flat surface mounted to an xyz translational stage.[11] Directly be-

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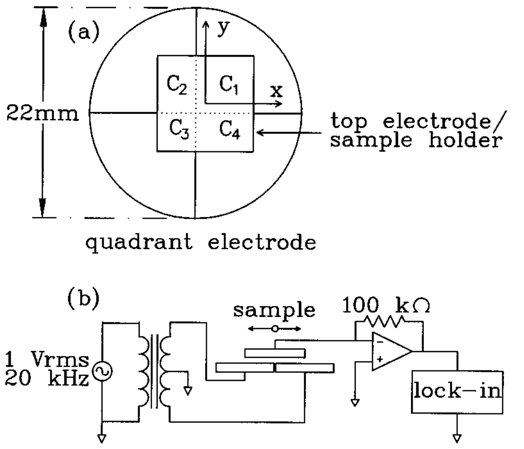

FIG. 1. Schematic of the two dimensional capacitive position sensor. (a) The top electrode moves in the xy plane changing the capacitance it forms with each quadrant. (b) The circuit measures the difference in capacitance between the top electrode and two adjacent quadrants.

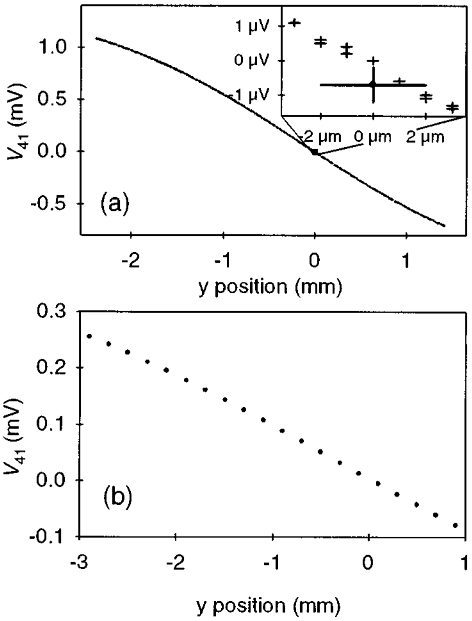

FIG. 2. Response of the sensor to changes in y position. (a) Data is taken in 20 μm steps with $z = 430\ \mu$m. The single point in the inset with a large horizontal bar (uncertainty in the coarse positioner) and a large vertical bar (signal drift) corresponds to the signal after moving away more than a millimeter and returning to the original position. The inset also shows data taken in 1 μm steps. Horizontal bars represent uncertainty in the fine positioner of the micrometer stage used for translation of the top electrode while vertical bars represent noise in the signal. (b) Response of the sensor with $z = 1.3$ mm. Since different x positions were used, the plots do not scale inversely with z.

low the upper electrode, the quadrant electrode was glued to a flat surface mounted to the stationary block of the translational stage. The translational stage was actuated by three differential micrometers. The uncertainties in the coarse and fine scales were ±2 and ±0.2 μm, respectively. The gap between electrodes could be varied to approximately 1.3 mm. Using a lock-in amplifier with a time constant of 500 ms, signals as large as 1 mV were measured with a noise of ±0.2 μV and a drift of 1 μV on the time scale of hours. Similar noise figures were obtained when the sensor was disconnected from the operational amplifier,[12] suggesting that the principal noise source was the operational amplifier. Using an optical microscope, the translation stage was observed to drift approximately 3 μm in the horizontal plane from a set position. The observed signal drifts of the sensor are consistent with the magnitude and time interval of this motion.

Figure 2(a) shows the response of V_{41} to changes in the y position of the top electrode with $z = 430\ \mu$m. Contrary to Eq. (3), the curve in Fig. 2(a) is sublinear. Similar curves of V_{21} versus x position are superlinear using the same gap between electrodes. Deviations from linearity[13] were primarily caused by the coupling of horizontal and vertical motions of the translational stage which was measured to be about 70 μm. The effects of this coupling are greatly reduced when the gap is increased to roughly 1.3 mm as shown in Fig. 2(b). Although the detailed behavior of these curves is of interest, it is the reproducibility of data that is critical. Each point on the main curve in Fig. 2(a) could be reproduced, even after days, within the combined uncertainty of the coarse positioner and the signal drift. This is exemplified by one point, identifiable by its large error bars, in the figure inset which represents the signal measured upon returning to an original position after a translation of roughly 1 mm. The large horizontal and vertical error bars depict the uncertainty in the coarse positioner and the signal drift, respectively. Points with error bars representing the uncertainty of the fine positioner (horizontal) and signal noise (vertical) are also shown in the inset. The voltages were measured twice for each position, and the top electrode was always moved several microns between the first and second measurements. The inset data are always found to reproduce within the uncertainties.

As implied earlier, two measurements are needed to define the position of the top electrode in two dimensions. V_{21} and V_{41} were measured in steps of 200 μm over a 9 mm^2 grid with an approximate gap between electrodes of 430 μm. The data were interpolated to make the contour plot shown in Fig. 3(a). The x and y coordinates have been defined such that the origin of the contour plot roughly corresponds to the intersection of the two 0 mV contour lines. The contour lines section the plot area into cells that are approximately rectangular and that vary in size according to position. The largest of these cells formed by contours separated by, 0.2 μV defines a linear resolution of 1.2 μm. Figure 3(b) shows the predicted contour plot based on Eqs. (2) and (3) with a proportionality constant estimated from experimental parameters. Considering the aforementioned coupling of horizontal and vertical motions of the translational stage and other possible nonlinearities,[13] the agreement between plots is quite good. Ultimately, the differences between the model and the data are unimportant for our application. It is most important that the plot in Fig. 3(a) provides a reproducible map between signal and position.

In conclusion, we have built and tested the sensor with sufficient resolution and reproducibility to make possible the repositioning of a scanning probe to a specific spot in a hori-

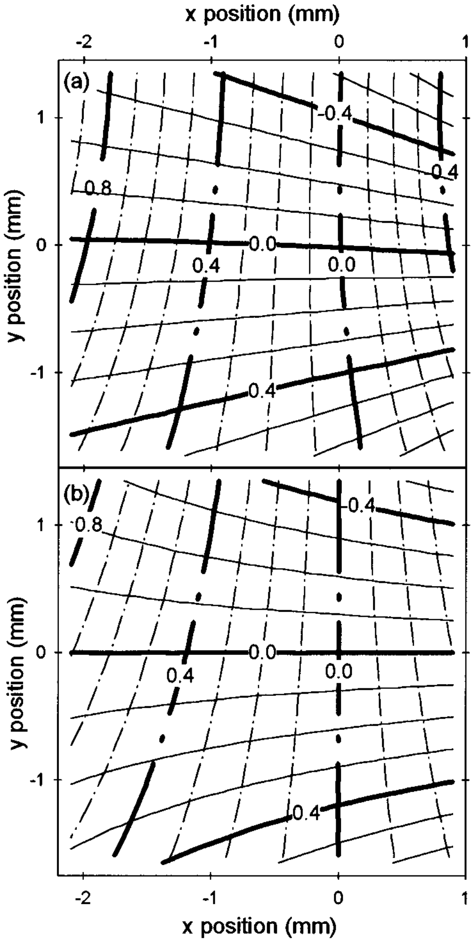

FIG. 3. Contour plots of the signals V_{21} (broken lines) and V_{41} (solid lines) in millivolts for (a) actual data and (b) predictions based on the overlap area model of top electrode-quadrant capacitances.

zontal plane to within microns over a range of millimeters. It is sufficiently compact to fit inside the bore of a high field solenoid and should be operable at cryogenic temperatures and in high magnetic fields. We stress that the sensor's resolution of 1.2 μm is limited by electronics[12] and that 3 μm may be a considerable overestimate of the irreproducibility due to drift in the measuring device.[11]

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[9] ''Capacitive Sensors,'' brochure, Physik Instrumente (PI), GmbH & Co., Polytec-Platz 5-7, 76337 Waldbronn, Germany (unpublished).

[10] A similar design which uses two split capacitor electrodes, a rotor, and a stator, to measure angular displacement is found in Randall D. Peters, Rev. Sci. Instrum. **63**, 3989 (1992). See also Randall D. Peters, *ibid.* **64**, 2256 (1993) and references therein.

[11] Microblock HS, 17AMB 201/LMD, MellesGriot, Irvine, California 92614 (unpublished).

[12] OP-27, Analog Devices, One Technology Way, Norwood, MA 02062-9106 (unpublished).

[13] There are various other potential sources of nonlinearities. When considered separately, the following causes have their corresponding effects: stray capacitance can affect the zero position, misalignment between the upper electrode, the quadrant axes, and the translational stage in the *xy* plane introduce quadratic terms, tilting of the quadrant electrode *out of parallel* with the *xy* plane of the upper electrode introduce cubic terms. When combined with coupled horizontal-vertical motion of the translation stage, effects may be quite complex.