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# Capacitive Force Sensor

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## Abstract

In this paper, the sensitivity, linearity and temperature drift characteristics of various capacitive force sensors are evaluated and compared using new experimental methods. In particular, two designs were employed to reduce temperature drift. Both types of sensor use high-sensitivity Al coated PET film, and their externals are miniaturized. The first has a layered design consisting of two dielectric substances with different temperature characteristics. The prototype of this design had a temperature drift of only 0.1% of the sensor's capacity in the 20-80 ℃ range. The second type uses both a dummy sensor and an active sensor with the same characteristics. The temperature drift of the prototype was one-fifth the temperature drift of a single sensor.

## 1. Introduction

Most conventional force sensors use strain guages and piezoelectric elements. The sensitivity, linearity and temperature drift of these sensors have been studied in [1]-[3]. Recently, considerable research has been devoted to optical force sensing techniques [4]-[11]. However, optical techniques have major drawbacks in that the need for a light source makes them expensive and difficult to miniaturize. On the other hand, relatively little attentiion has focused on capacitive force sensors. The advantage of capacitive force sensors is their simple construction, which allows them to be miniaturized and built at a low cost. Furthermore, when resonance circuits are used, the force can be converted into a digital signal. In this paper, we investigate the sensitivity, linearity and the temperature drift characteristics of two types of capacitive force sensor, and present improved methods for measuring sensitivity and temperature drift.

## 2. Basic Mechanism of Capacitive Force Sensor

The basic mechanism of a capacitive force sensor is illustrated in Fig.1. The capacitance of the sensor is given by

$$C_0 = \varepsilon \cdot \varepsilon_0 \cdot S / t_0 \qquad (1)$$

where S is the area of the electrode, $t_0$ is the distance between electrodes, $\varepsilon$ is the dielectric rate in a vacuum and $\varepsilon_0$ is the dielectric rate of the dielectric substance. When a force F in the normal direction acts on the electrode, the change in the distance $\Delta t$ between electrodes results in a change of capacitance $\Delta C$, given by

$$C_0 + \Delta C = \varepsilon \cdot \varepsilon_0 \cdot S / (t_0 - \Delta t) \qquad (2)$$

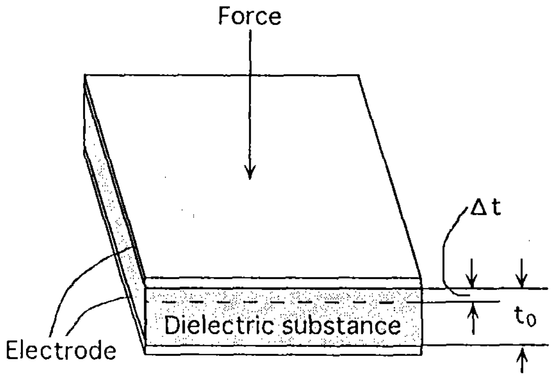

Fig. 1 Basic Mechanism of Sensor.

The strain can be derived from (1) and (2).

$$\Delta t / t_0 = \Delta C / (C_0 + \Delta C) \quad (3)$$

When $C_0 >> \Delta C$,

$$t_0 / \Delta t = C_0 / \Delta C \quad (4)$$

$$F = k \cdot \Delta t / t_0 \quad (5)$$

where k is the elasticity of the dielectric substance. Eqs. (4) and (5) yeild

$$\Delta C = C_0 \cdot F / k \quad (6)$$

Therefore, the sensitivity of the sensor is proportional to the capacitance $C_0$ and inversely proportional to the elasticity k.

## 3. Experimental Setup

Fig.2 shows the experimental setup used to examine the characteristics of the capacitive force sensors. The sensor was placed between the standard load meter on the table of a NC machining center and a press rod fixed to the tool chuck of the spindle head. Because the position of the press rod was controlled by the NC apparatus, the displacement of the sensor could be accurately controlled. The displacement, force and change in capacitance were measured simultaneously by an LCR meter (frequency:10 kHz) and recorded. The displacements of the press rod and the standard load meter could be disregarded because they were far smaller than that of the sensor.

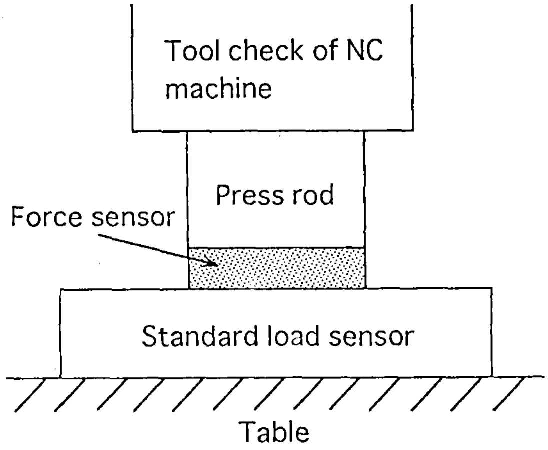

Fig. 2 Experimental Setup for Measuring Sensitivity.

## 4. Results and Discussion

### 4.1 Sensitivity.

To investigate the performance of capacitive force sensors, two sensors A and B were constructed. Sensor A is shown in Fig.1. The size of the electrode was 22×30mm, the dielectric substance was silicon rubber of 2mm thickness, and the capacitance was 22pF. The response of sensor A (force versus change in capacitance and force versus displacement) is shown in Figs.3 and 4. The change in capacitance clearly increases with both force and displacement, but not in a linear fashion.

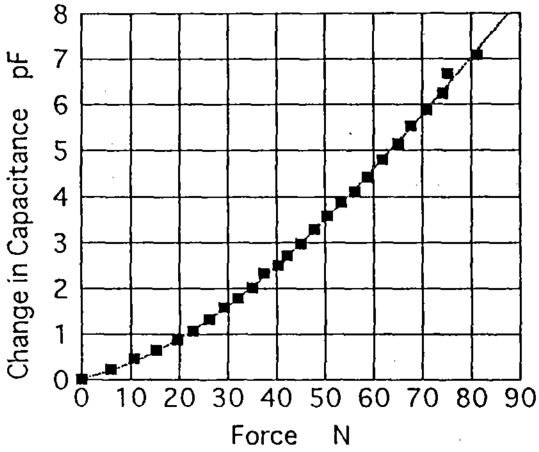

Fig. 3 Relationship between Force and Change in Capacitance.

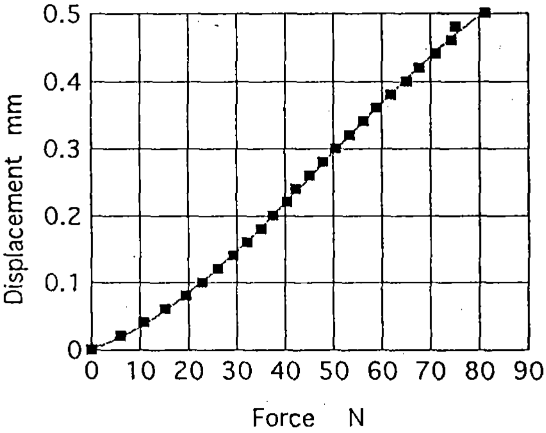

Fig. 4 Relationship between Force and Displacement.

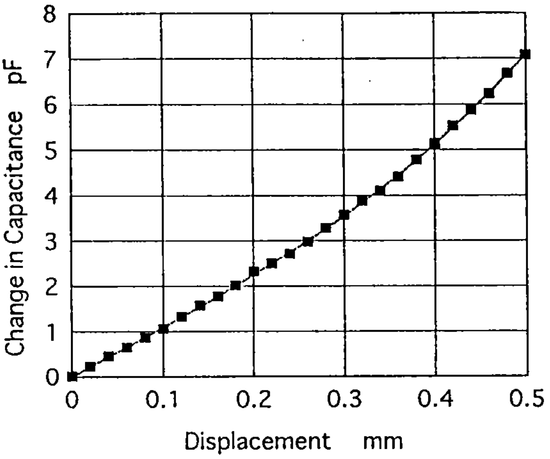

Fig. 5 Relationship between Displacement and Change in Capacitance.

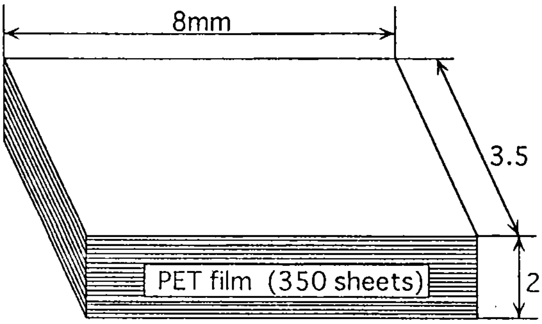

Fig. 6 Structure of Laminate Type Sensor.

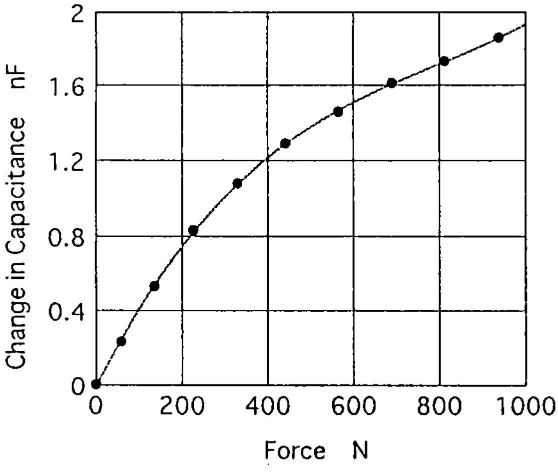

Fig.7 Sensitivity of Laminate Type Sensors.

The elastic constant of sensor A is about 160 N/mm, and the maximum strain of approximately 0.23 is reached at a force of 80 N. Fig.5 shows the relationship between the change in capacitance and the displacement. It is clear that the change in capacitance is locally nearly proportional the displacement. The non-linearity of the relationship between force and change in capacitance stems from the elastic deformation characteristic of sensor A. The sensitivity of sensor A is insufficient.

Figure 6 shows sensor B, which was constructed with a stacked Al coadet PET (Polyethylene terephtalate) film of thickness 5$\mu$m. Sensor B is considerably smaller than sensor A at 3.5×8.0×2mm in width. Its capacitance is 33$\mu$F, roughly 1000 times that of sensor A. Fig.7 shows the sensitivity of sensor B. The change in capacitance is locally proportional to the force, and the maximum change in capacitance is about 30 times that of sensor A. The elastic constant of sensor B was 10000 N/mm, and the maximum strain was 0.05 at a force of 800 N. The variance between the sensitivity curves of sensors A and B stems from differences in the deformation characteristics of their dielectrics substances.

### 4.2 Temperature Drift

The most serious drawback of capacitive force sensors is their temperature drift. Fig. 8 shows the temperature drift of two laminate type B sensors, referred to as B1 and B2, in the 25-85℃ range. As the temperature rises, a gap in capacitance of nearly 1.0 nF appears between the two sensors. Though this gap amounts to only 1% of the maximum capacitance of the sensors, it represents 80 N on the sensitivity curve of Fig.7.

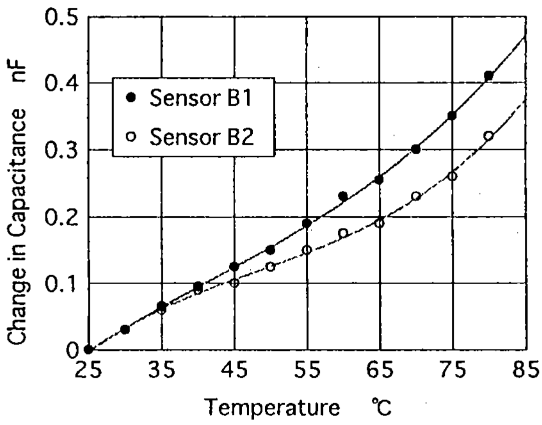

Fig.8 Temperature Drift in Laminate Type Sensors.

This analysis motivated the construction of a new sensor system, composed of an active sensor to which force is applied and a dummy sensor which is used to compensate for the temperature drift. The temperature drift in this sensor system is the difference between the temperatures of sensors B1 and sensor B2. The sensor system has the characteristic shown in Fig.7, and a temperature drift of 0.1nF.

A second approach to decreasing the temperature drift was tried. Figure 9 shows sensor C, composed of two kinds of dielectric substances with different dielectric rate to temperature relationships. Sensor C was placed in a thermostatic chamber and its temperature was varied from 20 to 100 ℃. The resulting temperature drift characteristic is shown in Fig.10. The temperature drift of sensor C in the 20-80 ℃ range was 0.1% of the sensor's capacitance. However, because the dielectric rate of the PET increased with temperature while that of the silicon rubber decreased, there was a compensatory effect which kept the drift stable within that temperature range.

### 4.3 Response Curve

One approach to improving the linearity of the sensor's response is to improve its elasticity rate. On this hypothesis, sensor D was constructed with the dielectric substance of mica. The characteristic value of sensor D was measured by LCR meter. The elastic constant was $10^5$ N/mm, and the maximum strain was 0.005 at a force of 8000 N. The sensor's rigidity was 10 times that of sensor B; however, its sensitivity dropped to by a factor of 10.

Because the responsiveness of the LCR meter was low, a better method was needed to measure the sensor's response. Fig. 11 shows a circuit which was built for this purpose. Cx denotes the capacitance of the sensor, given by

$$C_x = - e_0 \ C_s / e_i \qquad (7)$$

where ei is the voltage of carrier wave(10 Hz). When $C_s$ and $e_i$ are made constant in (7), $e_0$ is proportional to $C_x$. The carrier wave modulated with the sensor signal was converted into a DC signal by the sample hold circuit. However, attempts to measure the response of sensor D using the measurement circuit were not successful because the noise exceeded the signal. To reduce the noise caused by electromagnetic induction, the

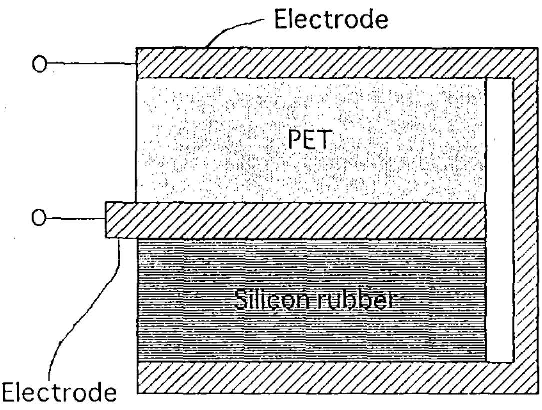

Fig. 9 Structure of Low Drift Sensor.

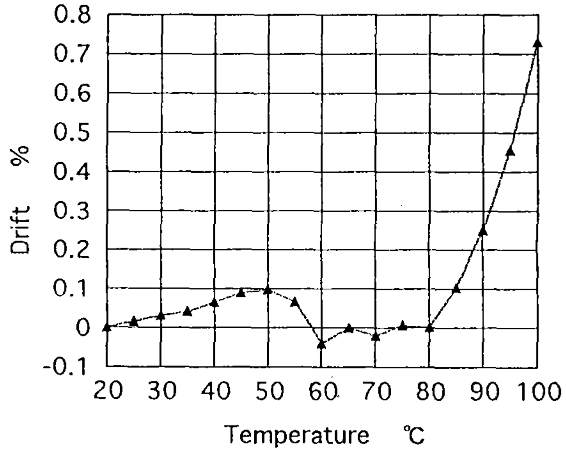

Fig.10 Temperature Drift in Developed Sensor.

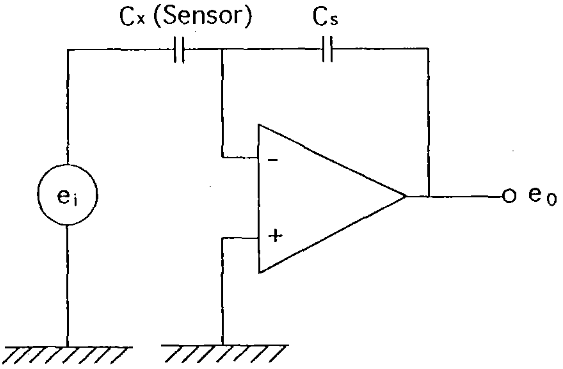

Fig. 11 Measurement Circuit.

Table 1 Characteristics of sensors.

| Type of Sensor | Dielectric Substance | Characteristics | k (N/mm) | $\Delta C/C_0$ |
|---|---|---|---|---|
| A | Silicon Rubber | Simple | 80 | 0.23 (80N) |
| B | PET | High Sensitivity | $10^4$ | 0.05 (800N) |
| C | PET+ Silicon Rubber | Low Drift | | |
| D | Mica | Dynamic Response | $10^5$ | 0.005 (800N) |

sensor needed to be shielded. The circuit was sensitive to noise because it did not have a leveling system.

A dielectric substance with a high elasticity rate would help to improve the sensor's response. On the other hand, because sensitivity is inversely proportional to elasticity rate, the measurement circuit would be forced to measure smaller rates of change in capacitance. Thus, the instrumentation circuit should be improved to fit the requirements of a high rigidity sensor.

## 5. Conclusion

Table I shows the characteristics of various sensors which were developed to study methods for improving the sensitivity, temperature drift and response of capacitive force sensors. The sensor which was constructed by depositing Al coated PET film had the highest sensitivity and the most miniaturization. Two designs were employed to improve the temperature drift. The first consisted of two dielectric substances having different temperature characteristics. The temperature drift in the 20-80 ℃ range was decreased to 0.1% of the sensor's capacity. The second design consisted of a an active sensor and a dummy sensor of the same characteristic which was used to compensate for temperature drift. The temperature drift of this sensor system became one-fifth that of the individual sensors. Dielectric substances with a high elasticity rate were used in an attempt to improve the sensor's response. However, because sensitivity was in inverse proportion to the elasticity rate, the measurement circuit could measure only a small rate of change in capacitance. The authors concluded that the instrumentation circuit should be improved in the insufficiency only by improving the rigidity of the sensor to improve its response.

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