Development of Micro Capacitive Inclination Sensor

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Keywords: Inclination Sensor, Electric capacity, Surface tensity, MEMS

1. Introduction

Recently, there has been increased demand for smaller and higher-performance sensors incorporated in a variety of electronic devices, in order to both upgrade them and save resources. More specifically, there is an increased need for small inclination sensors that have linear analog outputs used to control the positions of mechanical parts. We have focused our attention on the reported capacitive inclination sensors using dielectric oil. These have the advantage of easily providing linear analog outputs with respect to inclination. Because they have no parts that cause friction and wear, it is possible to improve reliability. Although they are commercially available, their electrodes have a much larger size—24 mm diameter and 1.5 mm thickness—than the small acceleration and pressure sensors in practical use. Capacitive inclination sensors using dielectric oil may be used in a wider range of applications if their volumes can be reduced by a factor of several hundred, and if the reduced sensors can achieve almost the same performance as conventional sensors. Because they use liquid to detect inclination, however, finding a solution to the scale effect problem is an important task for miniaturization and development. This paper reports the development of a micro-capacitive inclination sensor.

2. Principle and Design

Figure 1 shows the basic principle of this inclination sensor. This micro inclination sensor is designed to detect inclination with changes in capacitance of the dielectric oil.

We developed the use of the target of the sensor as size 5 mm × 5 mm × 5 mm, resolution 0.5 deg, detection Range ±45 deg, response speed 0.5 sec/deg. To manufacture a sensor within a cube of 5 mm, to reduce the diameter of the common electrode to 4.0 mm or less. When manufacturing such a small sensor, it is strongly affected by the surface tension of oil because of the scale effect. To verify whether or not it is possible to manufacture an inclination sensor within the cube of 5 mm, we carried out an experiment. As a result, it was confirmed to be able to solve these problems by setting up the Slit and pseudo channel shown in Figure 2.

3. Conclusion

The change in the oil liquid side was determined using image processing. As a result, it has been understood that resolution is 0.1deg or less and its response speed was 0.79 sec/deg. The sensor was made and evaluated from the above-mentioned result. As a result of evaluating the outputs of this sensor, a linear and analog output from −10~+10mV between −45~+45 deg has been obtained. It is possible to further improve these characteristics with optimization of the sensor structure.

![Fig. 1. Principle of an inclination sensor](image1)

![Fig. 2. Simulation model of slit and pseudo channel type micro inclination sensor](image2)
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A micro capacitive inclination sensor was developed by using micro machining techniques. Electrodes of the sensor are 40 \( \mu \)m in a gap and 12 mm² in area. The sensor detects difference of capacitance, which varies with movement of silicone oil accompanying with inclination of the sensor, but there is a problem of surface tension caused by the narrow gap of the electrodes. In order to solve the problem, novel structures of the sensor for injection of the oil into micro channels and retaining a horizontal plane of the oil were devised. As a result, downsizing of the sensor was realized.

Keywords : Inclination Sensor, Electric capacity, Surface tension, MEMS

1. Introduction

Recently, there has been increased demand for smaller and higher-performance sensors incorporated in a variety of electronic devices, in order to both upgrade them and save resources. More specifically, there is an increased need for small inclination sensors that have linear analog outputs used to control the positions of mechanical parts[1]. Some researchers have reported inclination sensors using electrically conductive liquid[2]; others have reported inclination sensors using acceleration sensors manufactured by MEMS technologies[3][5]. We have focused our attention on the reported capacitive inclination sensors using dielectric oil[6]. These have the advantage of easily providing linear analog outputs with respect to inclination. Because they have no parts that cause friction and wear, it is possible to improve reliability. Although they are commercially available, their electrodes have a much larger size—24 mm diameter and 1.5 mm thickness—than the small acceleration and pressure sensors in practical use. Capacitive inclination sensors using dielectric oil may be used in a wider range of applications if their volumes can be reduced by a factor of several hundred, and if the reduced sensors can achieve almost the same performance as conventional sensors. Because they use liquid to detect inclination, however, finding a solution to the scale effect problem is an important task for miniaturization and development. This paper reports the development of a micro-capacitive inclination sensor.

2. Principle

As shown in Figure 1 (a) and (b), a capacitive inclination sensor have a circular common electrode and two semicircular opposing electrodes to form two capacitors. The sensor cavity is half filled with oil. Even when the inclination sensor is tilted, as shown in

\[ \Delta C = \frac{\varepsilon_{\text{oil}} - \varepsilon_{\text{air}}}{d} \times \frac{S}{4} \times \frac{\theta}{90} \] ..............................(1)

Equation (1) expresses the proportional relationship between capacitance change \( \Delta C \) and inclination angle \( \theta \). It is possible to detect it as an amount of the voltage change by converting the amount of the capacitance change in impedance, and amplifying the differential motion. It is possible, therefore, to provide an inclination sensor that has a linear analog output with respect to inclination.

3. Design

3.1 Target Specifications To develop a general-purpose inclination sensor, we investigated the required range and resolution of detection in the automotive, home electric-appliance,
medical, and information technology fields where inclination sensors can be applied. Our investigation reveals that many applications require a detection range of ±45 deg or more, and a resolution of 1 deg or less. Marketed capacitive inclination sensors are several hundred times larger than pressure and acceleration sensors manufactured by the micro electro mechanical systems (MEMS) technology. Almost all small inclination sensors provide only ON/OFF outputs. From these investigation results, we determined target specifications as shown Table 1. This specification satisfies the performance demanded with a general industrial equipment.

3.2 Design To manufacture a sensor within a 5 mm cube, to reduce the diameter of the common electrode to 4.0 mm or less. In an existing sensor, a capacitive inclination sensor was designed so that when the sensor is tilted to 0.5 deg, the capacitance change \( \Delta C \) is 5.26 fF. If the common electrode has a diameter of 4.0 mm, and if the desired capacitance is equivalent to that of the existing sensor, it is necessary to set the distance between the electrodes to 40 \( \mu \)m or less according to Equation (1).

When manufacturing such a small sensor, it is strongly affected by the surface tension of oil because of the scale effect. It is anticipated, therefore, that because of the surface tension, the oil surface will not be horizontal as shown in Figure 2. When tilted, the sensor does not have symmetrical capacitance changes at the two semicircular opposing electrodes. Such a phenomenon could cause the sensor to deviate from the design.

To verify whether or not it is possible to manufacture an inclination sensor within the 5 mm cube, we carried out an experiment.

4. Verification Experiment

4.1 Simulation Model Manufacturing Method We manufactured a simulation model in order to verify whether or not an inclination sensor could operate with a common electrode whose diameter is 4.0 mm, and the distance between the electrodes is 40 \( \mu \)m or less.

A substrate of Si and a plate of Pyrex glass were used to manufacture the simulation model. Figure 3 shows the manufacturing process. Using deep reactive ion etch (DeepRIE), the Si substrate was processed first, to produce a cavity of 4 mm in diameter and 40 \( \mu \)m in depth. Next, the processed Si substrate was joined by anodic bonding to the Pyrex glass plate that had an oil injection hole. Once it was half filled with oil (KF96-2: Shin-Etsu Chemical Co., Ltd.) using a syringe, the injection hole was sealed by epoxy cement.

4.2 Surface Tension Effect Observed Figure 4 (a) shows the pattern of the manufactured simulation model. Figure 4 (b) shows the manufactured simulation model half filled with oil.

With this simulation model, we verified that despite the inclination, the liquid level of oil was kept the horizontal, even when the oil was placed in such a small space that had an electrode diameter of 4 mm and a distance of 40 \( \mu \)m between the electrodes. However, we observed the oil surface greatly deformed along the walls by surface tension, as expected. When tilted with the oil surface deformed, the sensor does not have symmetrical capacitance changes \( \Delta C \) at the two semicircular opposing electrodes, and cannot provide linear output with respect to inclination.

We have devised a method of providing a slit structure in the oil fill part. By establishing several slits in the oil fill parts, the
surface of oil is transformed in each slit. As a result, it is possible to reduce the deformation of oil surfaces due to surface tension. We manufactured a simulation model in order to verify whether or not this method can eliminate the effect of surface tension.

Figure 5 (a) shows the pattern of the simulation model manufactured. Figure 5 (b) shows the manufactured simulation model half filled with oil. By inserting slits in the oil fill part, the oil surfaces became symmetrical and the effect of oil surface tension effect was reduced.

4.3 Oil Flow Observed  Although the provision of slits could reduce the effect of surface tension, the slits caused a problem in that oil did not reach the central part of the sensor. When the sensor is half filled with oil, oil spreads rapidly into the slits through surface tension; therefore, oil will not reach the central part of the sensor. Such a phenomenon not only forms an extra non-oil space in the central part of the sensor, but also causes the sensor to become less sensitive.

We studied a structure that enabled oil to reach the central part of the sensor. We investigated the oil flow ease into slits and the opened part of the slit structure, and the dependency of the ease of oil flow on the structure. To evaluate the oil flow ease to enter, the pattern of Figure 6 was made. The flow ease of oil to enter was classified into three: Oil entered completely, Oil entered on the way, and Oil did not enter at all. The oil flow ease evaluated applying the point respectively. That is, oil enters easily by the point high. Figure 7 shows the oil flow ease, and the dependency of the oil flow ease on the aperture ratio of the slit structure. The aperture ratio is a ratio of the pitch of columns to the column diameter. Investigation reveals that the oil flow ease depends on the aperture ratio. To enable oil to reach the central part of the sensor, it is necessary to maximize the aperture ratio. There was a problem that oil was not able to be injected into the central part by the difference of the injection pressure of oil even if aperture was expanded.

To solve this problem, we devised an oil channel that guided oil to the central part of the sensor. The only problem was that disturbance of the oil flow by the oil channel disabled the sensor. We placed several columns to form a pseudo channel that did not disturb oil flow when the sensor was tilted. Figure 8 (a) shows the pattern of the pseudo channel. We manufactured this simulation model and carried out the experiment.

When the simulation model was half filled with oil, we observed oil flowing through the pseudo channel into the central part before the oil spread into the slits in the oil fill part. Figure 8 (b) shows the shape of oil at inclination.

![Fig. 5. Simulation model of slit type micro inclination sensor](image)

![Fig. 6. Evaluation pattern of the oil flow ease](image)

![Fig. 7. Relation between index of oil flow ease and aperture ratio](image)

![Fig. 8. Simulation model of slit and pseudo channel type micro inclination sensor](image)

![Fig. 9. Shape of oil at inclination](image)
4.4 Operation Check  With this simulation model, we carried out an inclination experiment. Figure 9 shows the tilted simulation model. Figure 9 reveals that even when the sensor is tilted, the liquid level of oil was kept the horizontal. The change in the oil liquid side was determined using image processing. As a result, it has been understood that resolution is 0.1deg or less. This resolution satisfied demand for a target specification of 0.5 deg, and was equivalent to that of the existing inclination sensor. The simulation model had impeccable performance. The above-mentioned results produced a reasonable prospect that we could manufacture an inclination sensor that had a linear analog output with respect to inclination.

5. Structure Optimization

5.1 A Study of Structure Using the Experimental Design From the results of the verification experiments, we obtained guidelines on manufacturing a sensor that had the slit structure and the pseudo channel. In the verification experiments, however, the quality of oil filling varied depending on the simulation model. Response speed did not satisfy demand for the target specifications.

Using the Taguchi method, we evaluated the effects of structural parameters on the quality of oil filling and on response speed.

Eight factors were selected as structural parameters that might have an effect on the quality of oil filling and on response speed. Table 2 lists the values of the structural parameters used in the experiments.

5.2 Quality of Oil Filling To determine the dominant structural parameters for the oil filling quality, we measured the oil filling length after the oil was injected to the sensor. Figure 10 shows the result of converted the measured distance into Signal-Noise (S/N) ratio. The S/N ratio was obtained by using Equation (2) from the measurement result. Figure 10 shows the result. Control factor D, the pitch of oil spreading columns, was the structural parameter that had the strongest effect on the quality of oil filling. As the ratio of the column pitch to the column diameter changed from 1.2 to 3.0, the quality of oil filling changed by 4 dB. The smaller the pitch ratio, the higher the quality of oil filling. As other structural parameters changed, the quality of oil filling changed by 1 dB or so. It was found, therefore, that other structural parameters did not have a strong effect on the quality of oil filling.

\[
S / N = -10 \log \left( \frac{1}{n} \sum (y_i^2) \right) \]  
\[ n: \text{Number of samples} \]  
\[ y_i: \text{Each measurement result} \]  

Fig. 10. Evaluation of oil filling

5.3 Response Speed To determine the structural parameters that had a strong effect on response speed, we evaluated the response speed when the sensor was tilted to 45 deg. The S/N ratio was obtained by using Equation (3) from the measurement result.

\[
S / N = -10 \log \left( \frac{1}{n} \sum y_i^2 \right) \]  
\[ n: \text{Number of samples} \]  
\[ y_i: \text{Each measurement result} \]  

Figure 11 shows the result. Control factor B, the dielectric oil viscosity, was the structural parameter that had the strongest effect on the response speed of the oil. As the dielectric oil viscosity changed from 0.65 mm²/sec to 10 mm²/sec, the speed of moving dielectric oil changed by 20 dB when the sensor was tilted. The lower the viscosity, the higher the response speed.

Control factor D, the pitch of the oil spreading columns, was the structural parameter that had the second strongest effect on response speed, although it also had a strong effect on the quality of oil filling. As the ratio of the column pitch to the column diameter changed from 1.2 to 3.0, the speed of the moving dielectric oil changed by 4 dB. The larger the ratio of the pitch to the column diameter, the higher the response speed. This was the opposite effect to the effect of the pitch-to-diameter ratio on the quality of oil filling. As other structural parameters changed, response speed changed by 2 dB or so. It was clarified, therefore, that other structural parameters did not have a strong effect on

![Table 2. Structural parameters](image)

![Diagram](image)
response speed.

6. Manufacture of the Inclination Sensor

From the results of structure optimization, we successfully extracted two structural parameters that had the strongest effect on the performance of the inclination sensor. The first structural parameter was the pitch of oil spreading columns. There was a trade-off between its effect on the quality of oil filling and its effect on response speed. The second structural parameter was the oil viscosity, which had a strong influence on response speed. We manufactured a micro capacitive inclination sensor based on these results. Because the quality of oil filling had priority, we set the pitch of the oil spreading columns to 1.2. Although a lower viscosity of oil filling was desired, it was difficult to control the quantity of volatile oil when the sensor was half filled with oil. We decided to use oil that had the lowest viscosity of 2 mm²/sec unless volatility was a problem when the sensor was half filled with oil.

Figure 12 shows a photograph of the sensor actually manufactured. Figure 13 shows the relationship between the inclination angle and output voltage of this sensor. When tilted from $-45 \sim +45$ deg, the sensor was able to detect the variation from $-10 \sim +10$ mV. The sensor had a measured response speed of 0.79 sec/deg.

7. Conclusion

We successfully developed a micro capacitive inclination sensor with a linear analog output. The main features of this inclination sensor are a slit structure that can reduce the effect of surface tension, and the pseudo channel. Using the Taguchi method, we successfully obtained guidelines on an optimized design regarding the structural parameters of the devised inclination sensor. An inclination sensor was manufactured based on the study of simulation models, and then evaluated. It was verified that when tilted from $-45 \sim +45$ deg, the sensor has an analog voltage output with respect to inclination. The sensor has a response speed of 0.79 sec/deg. The voltage changes by about 2V when 45deg is changed in the design. However, the result is an output of 1/200. As for the main cause, it is possible that the distance between the electrodes has changed because of the bonding film used for the substrate bonding. The response speed of the sensor does not yet reach the target specification. It is expected, however, that it will be possible to improve response speed by optimizing the structural parameters, including the permittivity of oil. We are planning to continue optimizing the structure toward developing an inclination sensor that satisfies demand for the target specifications.

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References


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