

Fingertip-size Six-axis Force and Moment Sensor Using Semiconductor Piezoresistance Effect

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ABSTRACT

A compact six-axis force and moment sensor that can be mounted in a fingertip is proposed to enhance the holding function of robots.

Specifically, the sensor system uses the semiconductor piezoresistance effect to detect the six-axis force and moment with a silicon chip (hereafter, “chip”). In addition, a resistive element for temperature compensation is fabricated into the chip to stabilize the temperature characteristics. The structure combines the chip with a metallic stress attenuation mechanism, enabling prevention of the load applied to the sensor from damaging the chip. Accurate sensor characteristics are obtained by integrating the components using anodic bonding and precision integration.

A fingertip-size prototype sensor based on the above concepts realized a rated load of 30 N (moment: 30 Ncm). The output accuracy at the rated load was confirmed to be 2.4 %FS (FS = rated equivalent output), and the temperature characteristics accuracy in the zero load state was confirmed to be 0.19 %FS/°C (0 to 60°C).

1. Introduction

As shown in Fig. 1, six-axis force and moment refers to the forces (F_x , F_y , F_z) and moments (M_x , M_y , M_z) in the three axial directions. It is mainly used for industrial machine applications, and various six-axis force and moment sensor products have been commercialized such as strain gauge, electrostatic capacity, and optical types. All types require precise location of the detecting elements to obtain accurate sensor characteristics, which requires a high level of manufacturing ability, and the manufacturing issues increase further as the size decreases. For example, in case of a strain gauge-type sensor, several to several ten metallic strain gauges need to be affixed to the structure

(flexure element) to which the load is transmitted, and when reducing the size to fingertip size, some physical layouts may not be feasible depending on the number and dimensions of the strain gauges. In consideration of these circumstances, a six-axis force and moment sensor using the semiconductor piezoresistance effect was proposed to help reduce the size to fingertip size.

2. Basic Concepts

Points (1) to (3) below list the basic concepts of the developed sensor.

- (1) The six-axis force and moment detection system using the semiconductor piezoresistance effect⁽¹⁾ enables detailed and accurate placement of compact detecting elements that are a challenge to manufacture using conventional technology. In addition, a resistive element for temperature compensation is fabricated into the chip to stabilize the temperature characteristics.
- (2) The structure combines the chip with a metallic stress attenuation mechanism, enabling prevention of the load applied to the sensor from damaging the chip.
- (3) Accurate sensor characteristics are obtained by integrating the components using anodic bonding⁽²⁾ and precision integration.

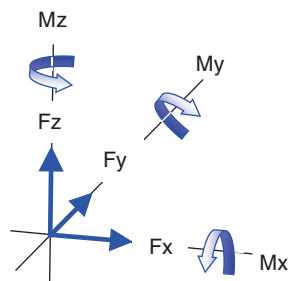


Fig. 1 Six-axis force and moment

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3. Sensor Structure

The sensor structure is described below.

Figure 2(a) shows the external appearance of the sensor. The sensor has a cylindrical shape with a diameter of 13 mm, and grooves machined into the metallic body function as a stress attenuation mechanism. Figure 2(b) shows the internal structure. The chip and the glass are joined by anodic bonding, and the glass and the metallic body are also joined by anodic bonding. In addition, the dotted line in the figure shows an image of the chip deformation when force is applied in the F_z direction. This figure omits the metallic body that corresponds to the bottom half of the sensor and functions as the housing. The shape of this bottom body closely resembles the body for the top half of the sensor, and the structure is integrated by precision integration.

Figure 3 shows an image of chip deformation when a load (F_x in this example) is transmitted to the chip. T-shaped beams are formed on the chip using the MEMS process^{(3), (4)}, and these beams deform to transmit strain to the piezoresistive elements. An additional piezoresistive element is also fabricated in a location other than the T-shaped beams. Strain is not transmitted to this location, so this is used as a resistive element for temperature compensation.

The dimensions and shapes of the sensor components were determined according to knowledge of strength of materials and structural analysis using the finite element

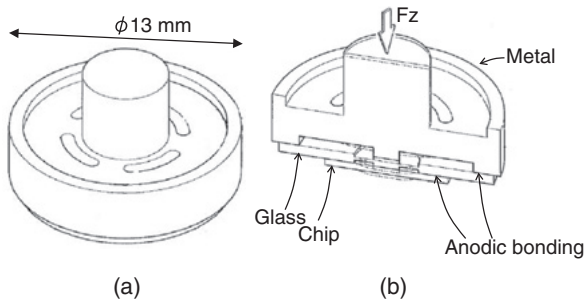


Fig. 2 Oblique perspective view of sensor

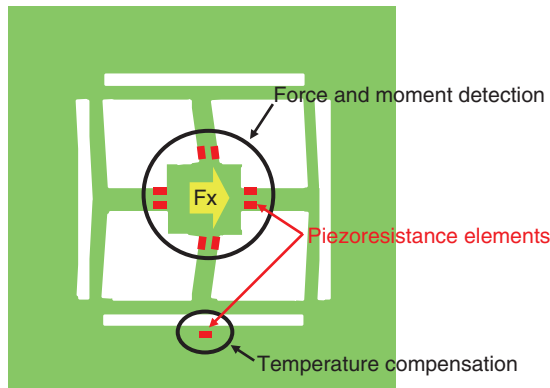


Fig. 3 Image of chip deformation

method, with the design goals of fingertip size ($\phi 13$ mm) and the rated load (force: 30 N, moment: 30 Ncm).

4. Six-axis Force and Moment Calculation Method

The chip of this sensor has eight piezoresistive elements fabricated into the T-shaped beams, and strain generated according to the load can be detected by these piezoresistive elements. The detected strain is converted to the six-axis force and moment as follows. First, a known load was applied to each axis separately, the change in resistance of the eight elements (R1 to R8) was measured, and the components of the matrix $[A]$ in Eq. (1) were obtained beforehand. Then, when an unknown load is input, calculations are performed using the inverse matrix $[A]^{-1}$ shown in Eq. (2).

$$\begin{bmatrix} R1 \\ R2 \\ R3 \\ R4 \\ R5 \\ R6 \\ R7 \\ R8 \end{bmatrix} = \begin{bmatrix} A_{11} & & & & & & & A_{81} \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ A_{81} & & & & & & & A_{86} \end{bmatrix} \begin{bmatrix} Fx \\ Fy \\ Fz \\ Mx \\ My \\ Mz \end{bmatrix} \quad (1)$$

$$[F, M] = [A]^{-1} [R] \quad (2)$$

In addition, temperature compensation can also be performed using the calculation method shown in Fig. 4. Specifically, the output when the temperature is varied between 0 and 60°C in the zero load state is measured beforehand to obtain the correlation with the temperature compensation resistor. Temperature compensation can then be performed in an environment of unknown temperature by subtracting the load detection resistor output obtained from the correlation with the temperature compensation resistor output.

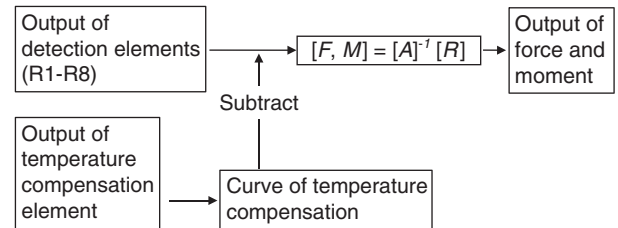


Fig. 4 Block diagram of force and moment detection

5. Evaluation of Characteristics Using a Prototype

5.1. Load Application Characteristics

A prototype sensor was made and the output accuracy was evaluated by applying loads in a constant room

temperature environment. This paper shows an excerpt of the results when applying F_x and M_x .

Figure 5 shows the output results when force equivalent to the rated load ($F_x: \pm 30$ N) is applied. As shown in this graph, it was confirmed that only F_x is detected, and other loads are almost not detected. Figure 6 shows the offset (error) from the line obtained by linear approximation using the least-squares method, for the output characteristics shown in Fig. 5. The M_z output exhibited the largest offset of 0.4 Ncm relative to the F_x load of 30 N, so the output accuracy for F_x application was confirmed to be 1.4 %FS (FS = rated equivalent output).

Figures 7 and 8 show the output data for the moment ($M_x: \pm 30$ Ncm). Here, the F_z output exhibited the largest offset of 0.7 N, so the output accuracy for M_x application was confirmed to be 2.4 %FS.

The output accuracy when the other loads (F_y , F_z , M_y , M_z) not shown in this paper are applied was confirmed

to be higher than the results for M_x application described above. Therefore, the output accuracy of this sensor at the rated load is thought to be 2.4 %FS.

5.2. Temperature Characteristics

The output accuracy when the temperature is varied between 0 and 60°C was evaluated with the sensor in the zero load state. Figure 9 shows the relationship between the load detection resistors (R1 to R8) and the temperature compensation resistor. Note that the change in resistance is measured as a voltage, so the graph shows the voltage output. This relationship was substituted into the calculation method shown in Fig. 4 to evaluate the accuracy after temperature compensation.

Figure 10 shows the results after temperature compensation of the sensor output when the temperature is varied between 0 and 60°C. An offset of 3.4 N occurred in the F_z output, which is equivalent to 11.3% of the rated load (30 N). Therefore, the temperature characteristics accuracy of the developed sensor within the measurement temperature range is thought to be 0.19 %FS/°C.

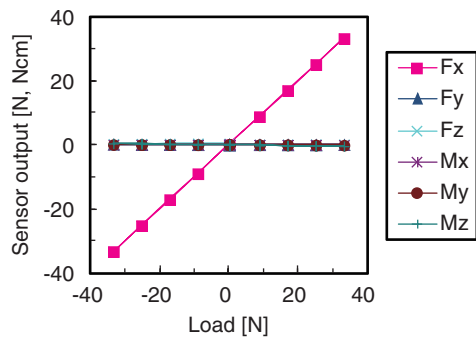


Fig. 5 Characteristic of load impression (F_x)

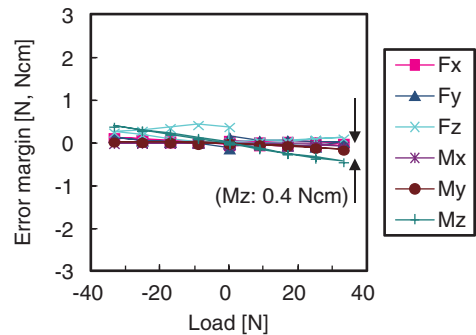


Fig. 6 Detection error margin of load impression

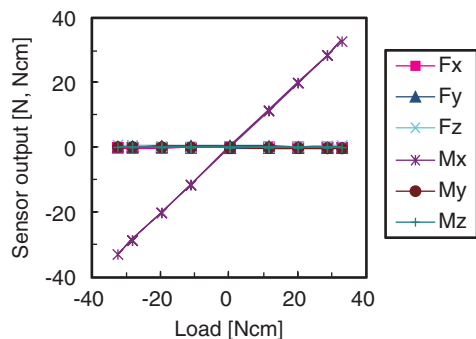


Fig. 7 Characteristic of load impression (M_x)

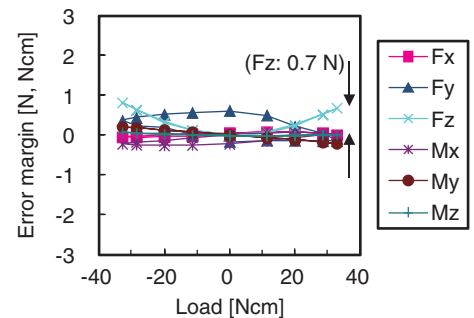


Fig. 8 Detection error margin of load impression

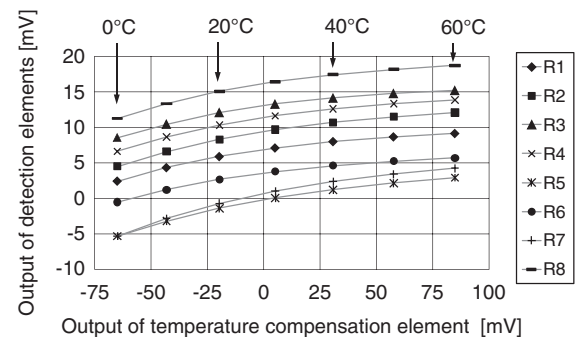


Fig. 9 Curve of temperature compensation

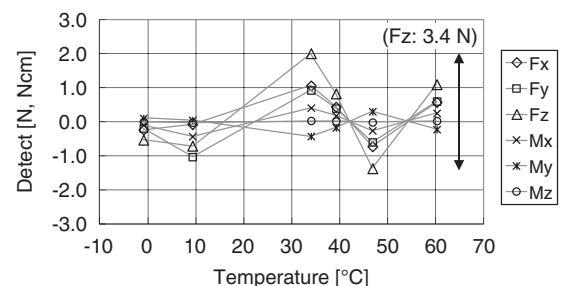


Fig. 10 Sensor output (after temperature compensation)

Table 1 Sensor characteristic results

Diameter		13 mm
Load range	Force	30 N
	Moment	30 Ncm
Accuracy	Load	2.4 %FS
	Unload 0 – 60 °C	0.19 %FS/°C

6. Conclusion

Table 1 shows the characteristics of the prototype sensor. This shows that a fingertip-size sensor capable of providing accurate output was realized.

A compact six-axis force and moment sensor is needed to enhance the holding function of a robot's fingertips, and the basic sensor concept proposed in this paper is thought to be an effective means of achieving this goal.

Furthermore, this sensor uses semiconductor technology, so in addition to a compact size and high accuracy, the power consumption can be reduced by increasing the resistance of the piezoresistive elements. It is expected that mass-productivity can also be increased by manufacture using a semiconductor process that does not require special skills.

References

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