TECHNICAL DIGEST OF THE 9TH SENSOR SYMPOSIUM, 1990. pp. 245 ~ 248

Flat-Type Six-Axial Force-Sensor

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A flat-type force sensor that be able to detect 6-axial force has been developed. A Si substrate, forming piezo-resistors is bonded on a flat-type strain generative body with full flexibility to each axis. Piezo-resistors are assembled as bridge circuits so that no interference occurs at each of the outputs. Its detection principle and characteristics are dealt with in this paper, and make sure that it satisfies the basic performance of a force sensor.

1. Introduction

As more and more robots are being used recently in the industries, robots with higher-performance force sensors are being desired. Conventional force sensors are formed by sticking metallic strain gauges on the strain generative body of a cubical design.

Despite the fact that force is the most primitive component, conventional force sensors may not necessarily be considered to be satisfactory in terms of performance and price.

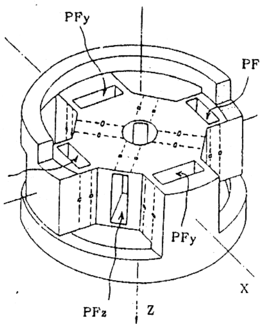
The flat-type 6-axial force sensor that has been developed this time, has piezo-resistors to detect the 6-axial forces of 3-components of force (F_X, F_Y, F_Z) in the respective direction of X-, Y-, Z-axis and the 3-components of moment (M_X, M_Y, M_Z) around each axis. Piezo-resistors are integrated on a single crystal Si substrate using semi-conductor technology, and the Si substrate is sticked on a surface of the flat-type strain generative body. The principle of detecting strain utilizes the piezoresistive effect that resistivity of diffused layers changes with the strain. As a consequence, the new sensors are characterized by their small size, high sensitivity and low cost.

2. Comparision between conventional sensor and newly developed sensor.

As shown in Fig.1, Conventional force sensors(1) are formed by sticking metallic strain gauges on each side of the starin generative body of cubical configuration. The principle of detecting force and moment is based on the detection of force by sticking strain gauges on the side perpendicular to the direction in which the force is acting, and by converting changes of resistance due to mechanical deformation into electric signals by the bridge circuit. Therefore the structure of the conventional force sensor is very complicated, and the sensitivity is very low just because of metallic gauge.

The newly developed flat-type 6-axial force sensor, as shown in Fig.3 and 4, is formed, by integrating p-type piezo-resistors on the n-Si substrate and by bonding it to the surface of the strain generative body.

Strains produced by forces and moments on the strain generative body are detected by converting the change of piezo-resistors into electric signal by the bridge circuit. Diaphragm is formed in such way that the center of the surface of the strain generative body is freely



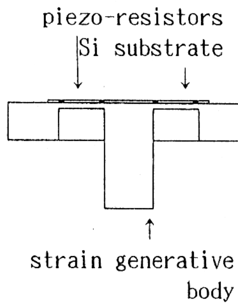


Fig.1 Conventional force sensor(1)

Fig.2 Flat type triaxial force sensor(3)

moved in the direction of X-, Y-, Z- axis, In addition, the upper plane of the strain generative body is made to be flat so that Si substrate can directly be bonded to it. The newly developed 6-axial force sensors have several advantages over the conventional sensors because of use of semiconductor technology. On the contrary, they are inferior to conventional sensors with metallic strain gauges in respect to the temperature drift because of the same reason. But, the temperature drift of the newly developed force sensor is compensated by conventional methods(2) used in pressure sensors.

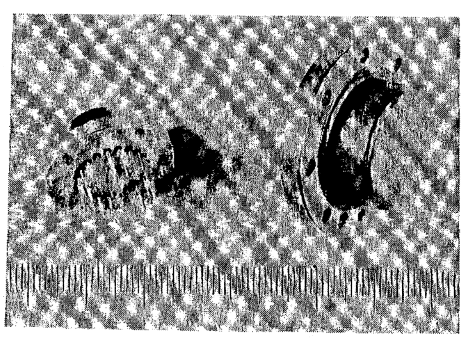


Fig.3 Flat-type triaxial (at the left) & six-axial force sensor(at the right)

3. Principle of Detection

Flat-type triaxial force sensors(3) are already suggested. The structure of the strain generative body is shown in Fig.2. When detecting the triaxial force (M_X, M_Y, F_Z), the diaphragm is only moved in the

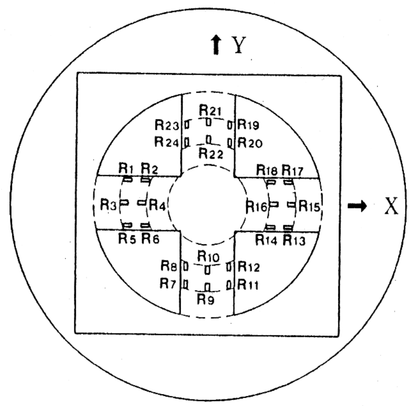
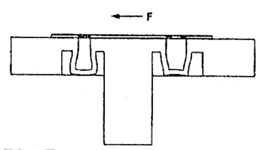


Fig.4 Top view of 6-axial force sensor



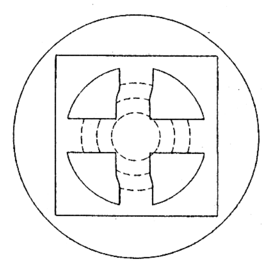


Fig.5
(a):Cross sectional structure in case of F_X (or F_Y)

(b):Top view of strain generative body in case of F_Z

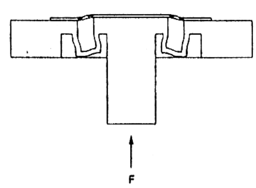
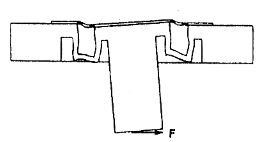


Fig.6 Cross sectional structure in case of F_Z



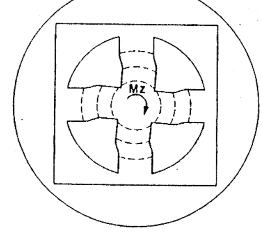


Fig.7 Cross sectional structure in case of M_X (or M_Y)

Fig.8 Top view of strain generative body in case of M_Z

direction of Z-axis, while in detecting six-axial force (F_x, F_Y, F_z, M_x, M_Y, M_z) the center of of the strain generative body surface can freely be deformed in directions of X-, Y-, Z-axis. Fig.3 shows the triaxial force sensor at the left and the newly developed 6-axial force sensor at the right. The Si substrare grooved by anisorotopics etching is bonded on the upper surface of strain generative body. A total of 48 piezo-resistors are formed at 24 places on beams shown in Fig.4.

The deformation of strain generative body is shown in
Fig.5 in case where the force F_x (or F_Y) works in the direction of X-axis (or Y-axis);
Fig.6 in case where the force F_z works in the direction of Z-axis;
Fig.7 in case where the moment M_x (or M_Y) works around X-axis (or Y-axis);
and Fig.8 in case where the moment M_z works around Z-axis.

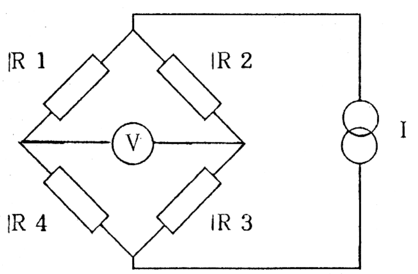


Fig.9 Circuit diagram of force sensor

	IR 1	IR 2	IR 3	IR 4
VF_x	R20+R23	R19+R24	R7 +R12	R8 +R11
VF_Y	R1 +R6	R2 +R5	R14+R17	R13+R18
VF_z	R3 +R15	R4 +R16	R3 +R15	R4 +R16
VM_x	R10+R21	R9 +R22	R10+R21	R9 +R22
VM_Y	R3 +R16	R4 +R15	R3 +R16	R4 +R15
VM_z	R5 +R17	R1 +R13	R11+R23	R7 +R19

Table 2 Composition of bridge circuits

A Table 1 shows the change of resistance formed on the Si substrare due to the force and moment shown in Fig.5 to 8. In this table, "+" indicates an increase, "−" indicates a decrease, and "0" indicates no change in piezo-resistors at respective positions (R1 ~ R24). Here, given that each piezo-resistors are equal and the change of resistance due to strains are all equal, the output without interference to the other axes can be obtained by forming these piezo-resistors into bridge circuits as shown Fig.9 and by assembling the resistors positioned in R_1 through R_{24} as shown in Table.2.

4. Output Characteristics

The output characteristics of the newly developed flat-type 6-axial force sensor is shown in Table 3. The values shown in the table are normalized by the VF_x output

	Piezo-Resistor																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
F_x	+	+	+	+	+	+	+	−	0	0	−	+	−	−	−	−	−	−	−	+	0	0	+	−
F_Y	−	+	0	0	+	−	+	+	+	+	+	+	+	−	0	0	−	+	−	−	−	−	−	−
F_z	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+
M_x	0	0	0	0	0	0	−	+	−	+	−	+	0	0	0	0	0	0	+	−	+	−	+	−
M_Y	+	−	+	−	+	−	0	0	0	0	0	0	−	+	−	+	−	+	0	0	0	0	0	0
M_z	−	+	0	0	+	−	−	+	0	0	+	−	−	+	0	0	+	−	−	+	0	0	+	−

+: $+\Delta R$, −: $-\Delta R$, 0: no change

Table 1 Change of piezo-resistors formed in each position to the force, and by VM_X output to the moment. Table 3 is called 6x6 compliant matrix, and the elements other than the diagonal elements are interference elements.

$$\begin{bmatrix} F_X \\ F_Y \\ F_Z \\ M_X \\ M_Y \\ M_Z \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix}^{-1} \begin{bmatrix} VF_X \\ VF_Y \\ VF_Z \\ VM_X \\ VM_Y \\ VM_Z \end{bmatrix}$$

As this type of sensor is superior in the linearity and hysteresis, the output of 6-axial force without interference can be obtained by calculating the product the inverse compliant matrix and the output voltage of the sensors.

	Force and Moment					
	F_X	F_Y	F_Z	M_X	M_Y	M_Z
VF_X	100.0	-8.2	4.6	8.5	-23.8	-6.3
VF_Y	-5.3	112.2	3.8	-25.8	4.9	-5.8
VF_Z	-4.8	-5.1	171.1	-5.7	-9.5	8.8
VM_X	-19.6	7.5	5.7	100.0	3.7	7.1
VM_Y	8.5	-20.7	6.9	4.6	95.3	7.9
VM_Z	-2.9	-3.8	-3.9	4.7	4.1	140.2

Table 3 Output characteristics of force sensor

5. Temperature Drift

The temperature drift of the force sensor are determined by
a temperature drift of offset and
a temperature drift of sensitivity
like a pressure sensor. The typical temperature drift obtained when the newly developed force sensor is excited with a constant current is shown in Table 4. It is apparent from this table that the temperature drift of F_Z output (VF_Z) is larger than other outputs. This is because, due to the difference between a thermal expansion coefficient of single crystal Si substrate and that of strain generative body materials, the change of temperature produce strain in the direction of Z-axis. Therefore it seems that F_Z output (VF_Z) is influenced by the temperature. In addition, as the other bridge circuits are formed to be insensitive to strains in the direction of Z-axis, the other output variation due to the change of temperature is small.

	Temp. drift of offset	Temp. drift of sensitivity
$VF_{X,Y}$ $VM_{X,Y,Z}$	0.30	0.03
VF_Z	0.70	0.05

Table 4 Temperature drift (%FS／℃)

6. Conclusion

In conclusion, it may be said that the performance of flat-type 6-axial force sensor formed by using semi-conductor technology is quite satisfactory.

Despite the fact that the force is the most primitive physical component, there had been no appropriate sensor to measure it with ease. It is expected that this sensor will be more improved in its performance and will be utilized in the field of robotics and measureing instruments by making the most of the excellent features of this flat-type 6-axial force sensor.

Reference

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