

## **Design and Analysis of a Column Type Multi-Component Force/Moment Sensor**

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### **Abstract**

A sensing element of column type was devised as a multi-component force/moment sensor by attaching strain gages. The ratio of length over diameter ( $L/D$ ) for the sensing element was designed analytically and verified by finite element analysis. The fabricated sensor was evaluated by using a deadweight force/moment calibration machine within Korea Research Institute of Standards and Science(KRISS). The interference errors between force and moment components were minimized by addition and subtraction processes of signals obtained from strain gages. Finally the calibration showed that the interference error of  $F_x$  component was less than 7.3 % FS, and in case of other components, 5.0 % FS.

### **1. Introduction**

Recently some simple and precise multi-component force/moment sensors have been needed for controlling of robots, machine tools, and also for monitoring of structural health. However, from the standpoints of the cost and shape, it is not efficient to use the high cost commercial sensor in a direct way while some parts of structure such as column and square types can be used efficiently and economically as a sensing element for measuring the force and moment components.

Ono and Hatamura [1] developed a multi-component load cell of two parallel plates type to improve the sensitivity. Hatamura *et al.*[2] also devised a small size multi-component load cell which was consist of the radial plate type for measurement of moment components and the parallel type for force components. In addition, Ju *et al.*[3] suggested a sensing element of binocular type for stable strain distribution and easy fabrication, and Kang *et al.* [4] evaluated binocular type six-component load cell by using

experimental technique. Kim *et al.* [5] developed a three-component load cell by using parallel plate structure. However, these multi-component force/moment sensors have some difficulties in performing the design and fabrication of sensing element and reducing the interference error. Additionally, the stiffness of total system such as robots and machine can be decreased due to attachment of multi-component sensor with low stiffness. Therefore, the purpose of this paper is to design a stain gage-based force/moment sensor with a sensing element of column type and evaluate the multi-component sensor using a six-component force/moment calibration machine.

## 2. Multi-component Force/Moment Sensor of Column Type

### 2.1 Design and Fabrication

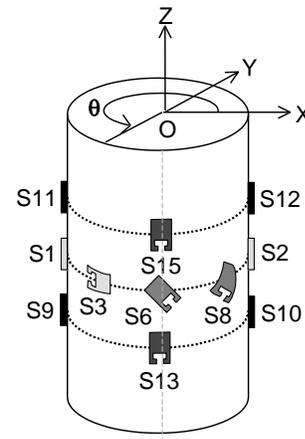
Figure 1 shows a sensing element of column type for measuring three forces ( $F_x$ ,  $F_y$ ,  $F_z$ ) and three moments ( $M_x$ ,  $M_y$ ,  $M_z$ ) using strain gages. And Figure 2 shows the position of strain gages for measurement of six components.

In case of  $F_z$  component, the full bridge circuit as shown in Figure 2 was arranged by using four strain gages (S1 ~S4). Here S1 and S2 strain gages are subjected to tensile loading while S3 and S4 are subjected to compressive loading. Therefore, the strain and the ratio of output voltage ( $E_o$ ) to supply voltage ( $E_i$ ) can be expressed by

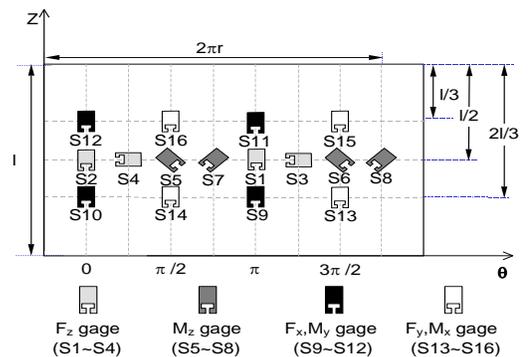
$$\varepsilon = \varepsilon_{S1} = \varepsilon_{S2} = \frac{4F_z}{\pi D^2 E}, \quad (1)$$

$$\varepsilon_{S3} = \varepsilon_{S4} = -\nu \varepsilon_{S1}, \quad (2)$$

$$\frac{E_o}{E_i} \Big|_{F_z} = \frac{(1+\nu)K\varepsilon}{2 - \{(1-\nu)K\varepsilon\}} \approx \frac{1.3K\varepsilon}{2}, \quad (3)$$



**Figure 1.** A sensing element of column type for measuring three forces and three moments using strain gages.



**Figure 2.** Position of strain gages for the measurement of six components.

where  $E$  for Young's modulus,  $\nu$  for Poisson's ratio, and  $K$  being gage factor of strain gage.

Being subjected to only  $F_z$  ( $= 200$  kN), the multi-component sensor was designed to obtain the ratio of output voltage to supply voltage, 2 mV/V. Additionally the ratio of length ( $L$ ) over diameter ( $D$ ) for the sensing element was designed as almost 2.0 to decrease the ending effect [6, 7]. Finally the diameter and length of the sensing element were determined as 28.1 mm, 56.2 mm, respectively.

The full bridge circuit for  $M_z$  loading was composed of four strain gages attached to the inclination of  $\pm 45$  degrees from the  $z$  direction. Here S5 and S6 strain gages are subjected to compressive loading, S7 and S8 being subjected to tensile loading. On the other hand, the capacity of  $M_z$  depends on the dimension of sensing element based on  $F_z$  and the voltage output of  $M_z$ . The strain and output can be represented by

$$\varepsilon_{S7} = -\varepsilon_{S5} = \varepsilon_{45^\circ} = \frac{\gamma}{2} = \frac{8M_z}{\pi D^3 G}, \quad (4)$$

$$\left. \frac{E_o}{E_i} \right|_{M_z} = K\varepsilon, \quad (5)$$

where  $\gamma$  is shear strain,  $D$  for diameter, and  $G$  being shear modulus.

Figure 3 shows the sensing element subjected to  $F_x$  and  $M_y$  loadings. The measurement of each loading is performed by the half bridge circuit, which is composed of two strain gages. Here S10 and S12 strain gages are subjected to compressive loading, S9 and S10 being subjected to tensile loading when the sensing element is subjected to  $F_x$  and  $M_y$  loadings. The corresponding strain for  $F_x$  loading can be obtained as

$$\varepsilon_{S9} = -\varepsilon_{S10} = \frac{32z_2 F_x}{\pi D^3 E}, \quad (6)$$

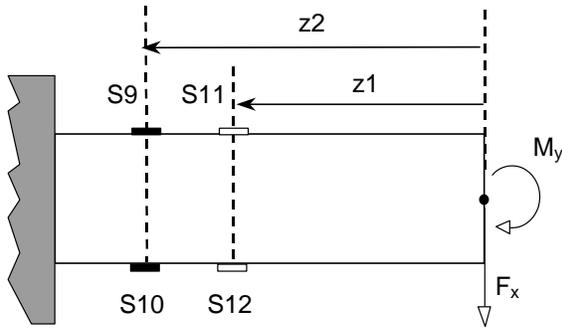
$$\varepsilon_{S11} = -\varepsilon_{S12} = \frac{32z_1 F_x}{\pi D^3 E}. \quad (7)$$

For  $M_y$  loading,

$$\varepsilon_{S9} = \varepsilon_{S11} = -\varepsilon_{S10} = -\varepsilon_{S12} = \frac{32M_y}{\pi D^3 E}, \quad (8)$$

and the corresponding outputs can be obtained by

$$\left. \frac{E_o}{E_i} \right|_{F_x} = \left. \frac{E_o}{E_i} \right|_{M_y} = \frac{K\varepsilon}{2\{1 - (K\varepsilon)^2\}} \approx \frac{K\varepsilon}{2}. \quad (9)$$



**Figure 3.** Sensing element subjected to  $F_x$  and  $M_y$  loadings.

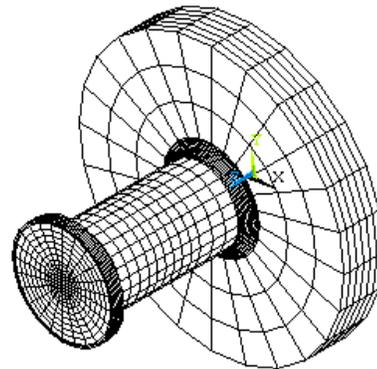
Finally, the capacity of other components based on the  $F_z$  loading were also designed to obtain the ratio of output voltage to supply voltage, 2 mV/V using equations (4) to (9). Table 1 shows the designed capacity of sensing element and the outputs of bridge circuits obtained from equations (1) to (9). Here  $S_{cir.1}$ ,  $S_{cir.2}$ ,  $S_{cir.3}$ ,  $S_{cir.4}$ ,  $S_{cir.5}$  and  $S_{cir.6}$  are the bridge circuits for  $F_x$ ,  $F_y$ ,  $F_z$ ,  $M_x$ ,  $M_y$ , and  $M_z$  loadings, respectively.

**Table 1.** Interference error voltage for the designed capacity of sensing element.

Load	Output voltage ( $\mu V/V$ )					
	$S_{cir.1}$	$S_{cir.2}$	$S_{cir.3}$	$S_{cir.4}$	$S_{cir.5}$	$S_{cir.6}$
$F_x(24.4 \text{ kN})$	2000	0	0	0	1000	0
$F_y(24.4 \text{ kN})$	0	2000	0	1000	0	0
$F_z(200 \text{ kN})$	0	0	2000	0	0	0
$M_x(913.9 \text{ Nm})$	0	-2000	0	-2000	0	0
$M_y(913.9 \text{ Nm})$	2000	0	0	0	2000	0
$M_z(696.3 \text{ Nm})$	0	0	0	0	0	2000

## 2.2. Finite Element Analysis

The finite element analysis using ANSYS ver.5.7 was carried out to evaluate the safety of sensing element subjected to multi-component loading. Figure 4 shows the finite element mesh of eight nodes. The bottom part of sensing element was fixed, and the part between column and plate was rounded to reduce the stress concentration. The material used is SNCM8 steel, which has Young's modulus of 210 GPa, Poisson's ratio 0.3. When the sensing element is subjected to the designed loadings simultaneously, the maximum Von-mises stress showed 1.97 GPa at notch, which was more than the allowable stress of the material(1.4 GPa). Therefore, the capacity of forces( $F_x$ ,  $F_y$ ,  $F_z$ ) and moments( $M_x$ ,  $M_y$ ,  $M_z$ ) for sensing element were redesigned as 6.1 kN, 6.1 kN, 50 kN and 228.5 Nm, 228.5 Nm, 174.1 Nm, respectively.



**Figure 4.** Finite element mesh of sensing element.

## 2.3. Method for Reduction of Interference Error

When the sensing element is subjected to  $F_x$  or  $M_y$  loading,  $S_{cir.1}$  and  $S_{cir.5}$  bridge circuits occur the output due to interference effect each other. However, the interference error of force and moment components can be removed by using equations (6) to (8). In case of  $F_x$  or  $M_y$  loading as shown in Figure 3, the relation of outputs between  $S_{cir.1}$  and  $S_{cir.5}$  bridge circuits can be represented by

$$\frac{E_o}{E_i} \Big|_{M_y}^{S_{cir.1}} = \frac{E_o}{E_i} \Big|_{F_x}^{S_{cir.1}} + \frac{E_o}{E_i} \Big|_{M_y}^{S_{cir.1}}, \quad (10)$$

$$\frac{E_o}{E_i} \Big|_{F_x}^{S_{cir.5}} = \frac{E_o}{E_i} \Big|_{F_x}^{S_{cir.5}} + \frac{E_o}{E_i} \Big|_{M_y}^{S_{cir.5}}, \quad (11)$$

$$\frac{E_o}{E_i} \Big|_{F_x}^{S_{cir.1}} = \beta \frac{E_o}{E_i} \Big|_{F_x}^{S_{cir.5}}, \quad (12)$$

$$\frac{E_o}{E_i} \Big|_{M_y}^{S_{cir.1}} = \frac{E_o}{E_i} \Big|_{M_y}^{S_{cir.5}}, \quad (13)$$

where  $\beta$  is  $z_2$  over  $z_1$ . Thus, each output can be obtained as

$$\frac{E_o}{E_i} \Big|_{F_x} = \frac{\beta}{\beta-1} \left( \frac{E_o}{E_i} \Big|_{F_x}^{S_{cir.1}} - \frac{E_o}{E_i} \Big|_{M_y}^{S_{cir.5}} \right), \quad (14)$$

$$\frac{E_o}{E_i} \Big|_{M_y} = \frac{1}{\beta-1} \left( \beta \frac{E_o}{E_i} \Big|_{F_x}^{S_{cir.5}} - \frac{E_o}{E_i} \Big|_{M_y}^{S_{cir.1}} \right). \quad (15)$$

In a similar way, each output for  $F_y$ ,  $M_x$  loadings can be decoupled as

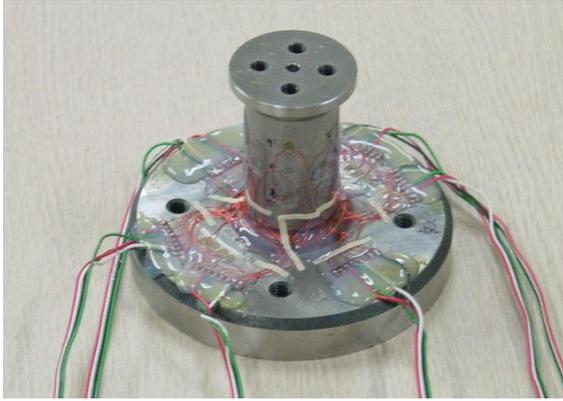
$$\frac{E_o}{E_i} \Big|_{F_y} = \frac{\beta}{\beta-1} \left( \frac{E_o}{E_i} \Big|_{F_y}^{S_{cir.2}} - \frac{E_o}{E_i} \Big|_{M_x}^{S_{cir.4}} \right), \quad (16)$$

$$\frac{E_o}{E_i} \Big|_{M_x} = -\frac{1}{\beta-1} \left( \beta \frac{E_o}{E_i} \Big|_{F_y}^{S_{cir.4}} - \frac{E_o}{E_i} \Big|_{M_x}^{S_{cir.2}} \right). \quad (17)$$

## 2.4. Fabrication and Experiment

Figure 5 shows the fabricated multi-component force/moment sensor. The supporting and loading parts were drilled to fix using bolt. The sensor was fabricated with tolerance  $\pm 0.02$  mm. The sixteen strain gages were used for two full bridge circuits and four half bridge circuits. The strain gage of MM-N2A-06-SO71P (Measurement Co., USA) was used, and it has 1.57mm gage length, 2.12 gage factor, 350 $\Omega$  resistance.

On the other hand, because of capacity of tester machine, the experiments for  $F_x$ ,  $F_y$  and  $F_z$  loadings were performed with 3 kN, 3 kN and 50 kN, respectively, and the three-component of moment being 45 Nm.



**Figure 5.** The fabricated multi-component sensor of column type.

### 3. Result and Discussion

Table 2 shows the output voltages of bridge circuits using equations (14) to (17) when the sensing element was subjected to each component loading. Here  $S_{F_x}$ ,  $F_y$ ,  $F_z$  are for the output voltages of each force component, and  $S_{M_x}$ ,  $M_y$ ,  $M_z$  being each moment component. Table 3 represents the designed capacity of the sensing element calculated linearly from Table 2.

Meanwhile, Figure 6 represents the interference error based on the output of each component. Here the interference error of  $F_x$  component showed the large value 7.3 % FS/FS while other components was less than 5.0 % FS/FS. Compared with other commercial multi-component sensor, this interference error represented the large value.

**Table 2.** Output voltage of sensing element subjected to the experimental loading ( $F_{x,y,z}$ : kN,  $M_{x,y,z}$ : Nm).

Load	Output voltage ( $\mu V/V$ )					
	$S_{F_x}$	$S_{F_y}$	$S_{F_z}$	$S_{M_x}$	$S_{M_y}$	$S_{M_z}$
$F_x(3)$	250.3	-5.7	-1.7	18.2	11.3	-5.1
$F_y(3)$	6.1	259.7	0.2	5.0	12.0	5.4
$F_z(50)$	-2.8	0.3	526.8	5.8	-11.0	2.4
$M_x(45)$	-1.8	-3.9	0.4	100.9	-3.0	-1.2
$M_y(45)$	0.3	-1.9	-0.2	-0.9	102.8	3.8
$M_z(45)$	-2.1	3.1	1.1	-2.7	1.9	133.4

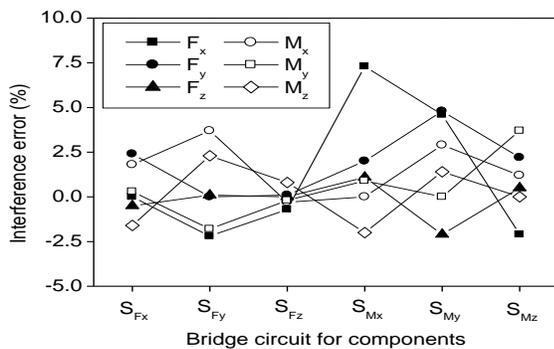
**Table 3.** Output voltage of sensing element of the designed capacity ( $F_{x,y,z}$ : kN,  $M_{x,y,z}$ : Nm).

Load	Output voltage ( $\mu V/V$ )					
	$S_{F_x}$	$S_{F_y}$	$S_{F_z}$	$S_{M_x}$	$S_{M_y}$	$S_{M_z}$
$F_x(6.1)$	519.0	-11.7	-3.5	37.6	23.8	-10.6
$F_y(6.1)$	12.6	538.4	0.4	10.3	25.0	11.1
$F_z(50)$	-2.8	0.3	526.8	5.8	-11.0	2.4
$M_x(228.5)$	-9.2	-19.8	1.8	512.2	-15.0	-6.1
$M_y(228.5)$	1.6	-9.6	-1.2	-4.5	522.0	19.1
$M_z(174.1)$	-8.2	12.1	4.2	-10.3	7.3	516.1

However, from the standpoints of the cost and shape, it is found that the column-type structure can be used efficiently as a sensing element.

### 4. Conclusion

The sensing element of column type based on strain gages has been used successfully to measure multi-component force/ moment. The conclusions are as follows:



**Figure 6.** Interference error for output voltage of multi-component sensor obtained from experiment

1) The interference error between forces and moments can be reduced by position of optimal strain gage, composition of bridge circuit.

2) The interference error of  $F_x$  component was 7.3 % FS/FS, and other components being less than 5.0 % FS/FS.

3) The sensing element of column type could be used efficiently and economically as a sensing element for measuring the force and moment components.

## 5. References

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