Design of Two-axis Force Sensor for Robot's Finger

Gob-Soon Kim

Abstract: This paper describes the design of a two-axis force sensor for robot's finger. It detects the x-direction force Fx and y-direction force Fy simultaneously. In order to safely grasp an unknown object using the robot's fingers, they should detect the force of gripping direction and the force of gravity direction, and perform the force control using the forces detected. Therefore, the robot's hand should be made by the robot's finger with two-axis force sensor that can detect the x-direction force and y-direction force simultaneously. Thus, in this paper, the two-axis force sensor for robot's finger is designed using several parallel-plate beams. The equations to calculate the strain of the beams according to the force in order to design the sensing element of the force sensor are derived, and these equations are used to design the size of two-axis force sensor sensing element. The reliability of the derived equations is verified by performing a finite element analysis of the sensing element. The strain obtained through this process is compared to that obtained through the theory analysis and a characteristic test of the fabricated sensor. It reveals that the rated strains calculated from the derived equations make a good agreement with the results from the Finite Element Method analysis and from the characteristic test.

Keywords: robot's finger, two-axis force sensor, parallel plate beam, rated strain, interference error

I. Introduction

Robot's gripper has widely being studied today. Maro Ceccarelli et al.[1] made the robot's finger with a force sensor that could only detect the force of grasping direction, and performed the position control and the force control for gripping an unknown object. Daniel Castro et al.[2] made Jaw gripper using one direction force sensor, and had the force control using it. Nkgatho S. Tlale et al.[3] made the intelligent gripper with a contact sensor and a circuits for control it. Carlos M. Valente et al.[4] made three-finger gripper with the vision system which could accurately found the position of a object. And, Obrien DJ et al.[5] fabricated the gripper with the finger that could only detect the force of grasping direction.

The above grippers can unstably grasp an unknown object, because it can carry out the force control of grasping direction but not known for grasping force, as it does not measure the force of gravity direction. In order to stably grasp an unknown object, the finger should detect the force of grasping direction and the force of gravity direction, and perform the force control using the forces detected. Therefore, robot's hand should be composed of the fingers with two-axis force sensor that detects the force of grasping direction and the force of gravity direction. For accurately detecting the forces using two-axis force sensor, it should have smaller interference error.

The precision accuracy of the two-axis force sensor can be estimated by non-linearity, repeatability, and interference error. However, as the interference error is dozens or hundreds of times larger than the other errors, the precision accuracy of the two-axis force sensor is estimated by the interference error.[6]-[8] The interference error can be reduced by accurately locating the strain gauge, through design and strain analyzing the sensing element of the two-axis force sensor.[9]-[12]

In this paper, the two-axis force sensor for robot's finger, which detects the x-direction force Fx and y-direction force Fy, is designed using several parallel-plate beams. The equations to calculate the strain of the beams according to the force in order to design the sensing element of the force sensor are derived, and these equations are used to design the size of two-axis force sensor sensing element. The reliability of the derived equations is verified by performing a finite element analysis of the sensing element. The strain obtained through this process is compared to that obtained through the theory analysis. Also, the strains obtained through the theory analysis are used to determine the attachment location of the strain gauge, and the full bridge circuit is formulated through the selected gauges to calculate the rated strain and interference error. And, the designed sensor is fabricated and is performed the characteristic test. It reveals that the rated strains calculated from the derived equations make a good agreement with the results from the Finite Element Method analysis and the characteristic test.

II. Sensor design

1. Modeling of the sensing element

Fig. 1 shows the robot's hand with two fingers. It consists of two fingers, two links, four motors, a block. The robot's hand with two-axis force sensor that detects x-direction force Fx and y-direction force Fy, which can carry out the position control and the force control, can stably grip an unknown object without the breakage or drop. Fig. 2 shows the finger with two-axis force sensor that can detect x-direction force Fx and y-direction force Fy. As shown in Fig. 2, robot's finger is composed of a two-axis force sensor, a contact plate, a finger frame. The two-axis force sensor consists of four-parallel plate beam (PPB). The sensing element for detecting the force Fy is PPB 1 and PPB 2, the force Fx is PPB 3 and PPB 4. Each PPB is composed of 2-plate beam of the same size, thus, a length of l, width of b, and height of t. And, PPB 1 and PPB 2, PPB 3 and PPB 4 are symmetrical based on the vertical center axis. The contact plate is contacted with an unknown object, and fixed with the center block of the sensor. The finger frame is fixed with both end of the sensor, and transfers the torque from motor to the sensor. The strain on each sensing element is used to design each force sensor. Therefore, it is necessary to analysis the strain of the sensing element.

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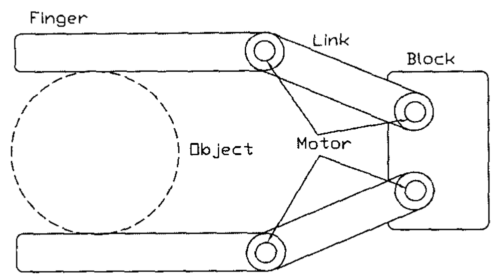

Fig. 1. Robot's hand with two-finger.

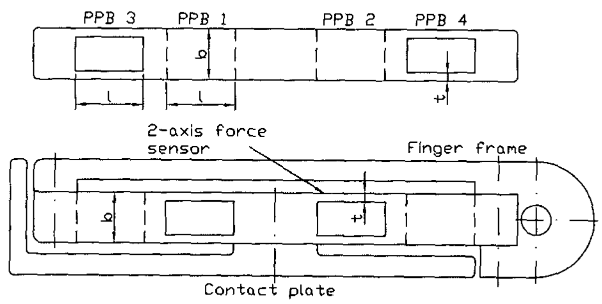

Fig. 2. The sensing element of robot's finger.

2. Theory analysis

Fig. 3 shows the diagram for analyzing the strain of each plate beam when the force Fy is applied to the center of PPB 1 and PPB 2. PPB 1 and PPB 2 are symmetrical based on the center axis of the direction of applied force Fy. The plate beam 1 and beam 2 consisting of PPB 1 are symmetrical based on the horizontal center axis. Also, the plate beam 3 and beam 4 consisting of PPB 2 are symmetrical based on the vertical center axis. Therefore, the equations for analyzing the strain of plate beam 1 can be applied to the plate beam 2, the plate beam 3, and the plate beam 4 respectively, and also, the equations under force Fy can be used to that under force Fx.

In the plate beam 1, as PPB 1 and PPB 2 is composed of four beams which get the same size, the force F_{Fyy} can be expressed as

$$F_{Fyy} = \frac{F_y}{4} \tag{1}$$

where F_{Fyy} is y-direction force applied to plate beam due to force F_y. The moment equilibrium condition at point O, ∑Mo=0, can be written as

$$2M_{Fyz} - F_{Fyy}l = 0 \tag{2}$$

where M_{Fyz} is z-direction moment applied to plate beam due to force F_y. By substituting the equation (1) into (2), the moment M_{Fyz} can be derived as

$$M_{Fyz} = \frac{F_y l}{8} \tag{3}$$

The moment M_x at arbitrary point x leads to

$$M_x = \frac{F_y}{4}(x - \frac{l}{2}) \tag{4}$$

The equations for calculating the strain at the upper surface and lower surface of the plate beam 1 can be derived by substituting the equation (4) into the strain equation $\varepsilon = M_x / EZ_P$. Which can be obtained as

$$\varepsilon_{Fy-U} = \frac{F_y}{4EZ_p}(x - \frac{l}{2}) \tag{5-a}$$

$$\varepsilon_{Fy-L} = \frac{F_y}{4EZ_p}(\frac{l}{2} - x) \tag{5-b}$$

where ε_{Fy-U} is strain produced on the upper surface of plate beam due to force F_y, ε_{Fy-L} is strain produced on the lower surface of plate beam due to force F_y, and E is modulus of longitudinal elasticity, Z_p is polar moment of inertia.

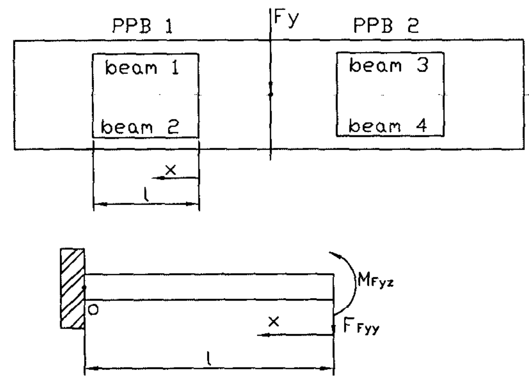

Fig. 3. Free body diagram of plate beams for a precision two-axis force sensor under the force Fy.

3. The sensing element design

The sensing element of two-axis force sensor must be designed so that under forces Fx, Fy the strains output from the full bridge circuit of each force sensor is similar to one another. The design variable is the attachment location taking account into the size of the strain gauge, the rated capacity, rated strain, beam width of b, and beam length of l.

In order to design the sensing element, the rated capacity of forces Fx and Fy was determined at 100 N. The rated strain was determined at approximately 1000 $\mu m/m$, the attachment location of the strain gauge was determined at 2.5 mm from each end under forces Fx and Fy in the length direction of the beam. The central line following the length of the beam was determined as the attachment location in the width direction of the beam. The size of sensor could be calculated by substituting the determined values into the strain equation (5-a), (5-b). The results were shown that the beam with, b was 12 mm, the beam length, l was 16 mm, and the beam height, t was 1.98 mm. Aluminum 2024-T351, which is the most widely used material for small capacity force sensor sensing elements, was used as material for the sensing element.

III. Finite element analysis and strain distribution

1. Finite element analysis

In order to confirm the strain calculated through the theory analysis, the finite element analysis was performed on the sensing element of the force sensor under force Fy. The finite element analysis uses ANSYS, which is commercial finite element analysis software to calculate the strain on the beam in two dimensions. The analysis was hypothesized to be in a plan-stress state, and a 4 nodes element was used as the finite element. The material property is the modulus of longitudinal elasticity that is the constant value of the aluminum, thus 70 GPa, and the poison's is 0.3. The mesh was in 0.5 mm intervals in the length direction of the beam, and the height was divided into four parts. In the finite element analysis, force Fy, 8.3333 N/mm, which is the force per unit width of the beam, was applied in each y-direction.

An enhanced version of the force sensor sensing element's deformed shape was shown under force Fy in Fig. 4. As hypothesized in the theory analysis, the deformed shape of the sensing element showed a right and left symmetry when force was applied.

Fig. 4. Finite element mesh and deformed shape of beams for Fx, Fy force sensor under the force Fx or Fy.

2. Strain distribution

Fig. 5 shows the strain distribution generated from the above surface and the below surface plate beam 1 when force Fy=100 N is applied. Both the theory analysis value and finite element increase and decrease linearly, with an absolute value strain, centering on the 8 mm point, which is the center of both ends of the beam. The theory analysis value and finite element analysis value coincide within a 1.0 % range in all areas excluding the 1 mm point from both ends of the beam. The finite element analysis value decreases at both ends because the end effect of the connecting point between the beam and the rigid body and the numerical error appear synthetically.

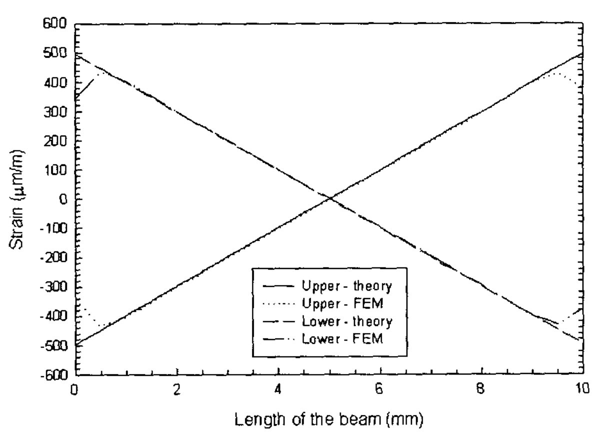

Fig. 5. Strain distribution on beam 1 under force Fx of 200 N.

IV. Manufacture of the sensor

The attachment location of the strain gages for Fx sensor were selected by S1~S4, and the strain gages for Fy sensor were selected by S5~S8 as shown in Fig. 6. In order to make the 2-axis force sensor, the strain gages were attached at the selected attachment location using a M-bond 200 made in Micro-Measurement Company. The full bridge circuit for each sensor was constructed using strain gages S1(T1), S2(C1), S3(T2), S4(C2) for Fx sensor and S5(T1), S6(C1), S7(T2), S8(C2) for Fy sensor, as shown in Fig. 7. The strain gage was manufactured in Micro-Measurement Company. The constant of the gage(gage factor) is 2.08; length 1.52 mm; width 2.54 mm.

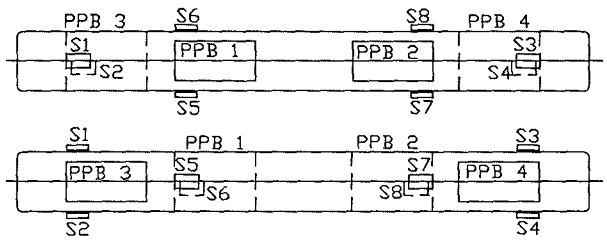

Fig. 6. Location of strain gages.

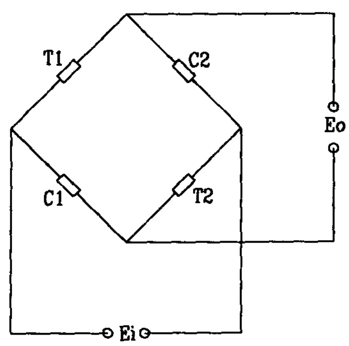

Fig. 7. Full bridge circuit.

V. Results and considerations

In order to evaluate the rated strain and interference error, the two-axis force sensor was tested by the Force/Moment Calibration Machine. [13] The expanded relative uncertainty of the machine is less than 0.1 %. Output signals from each sensor was measured using a strain indicator [SYSTEM 4000, maker : Micro-Measurement]. Each sensor was tested three times by the machine and the value from each sensor was averaged, respectively.

The strain and interference strain of each attachment location of the force sensor strain gauge is used to calculate the rated strain and interference error of each force sensor through equation (6).

$$\varepsilon = \varepsilon_{T1} - \varepsilon_{C1} + \varepsilon_{T2} - \varepsilon_{C2} \quad (6)$$

where, ε is the strain calculated from the full bridge circuit, ε_{T1} is the strain of tension strain gage T_1, ε_{T2} is the strain of tension strain gage T_2, ε_{C1} is the strain of compression strain gage C_1, ε_{C2} is the strain of compression strain gage

C_2. The full bridge circuit is shown in Fig. 7.

Table 1 shows the rated strain and the interference error of each sensor from the theoretical analysis, FEM analysis and the characteristic test. The rated strain value of Fx sensor and Fy sensor from the theory analysis was 1004 $\mu m/m$, that from the finite element analysis was 996 $\mu m/m$, and that from the characteristic test of Fx sensor was 990 $\mu m/m$ and of Fy sensor was 992 $\mu m/m$. As a result of comparing the finite element analysis based on the theory analysis, the rated strain error was found to be within 0.8 %, and result of comparing the characteristic test based on the theory analysis, the rated strain error of Fx was found to be within 1.39 % and the rated strain error of Fy was found to be within 1.20 %. Also, the interference error that greatly affect on the precision accuracy of two-axis force sensor was found to be 0 %, when the finite element analysis was compared based on the theory analysis. And the interference error of Fx sensor was found to be 0.9 % and Fy sensor was found to be 0.6 %, when the characteristic test was compared based on the theory analysis. This error may be generated due to the processing error of the sensing element and the attachment error of the strain gages. The interference errors of the sensor in study are reduced compared to the other that have come out, which is about 3 %[14].

Table 1. Rated strain and interference error of each sensor.

Force sensor	Analysis	Rated strain ($\mu m/m$)	Interference error (%)
Fx sensor	Theory	1004	0
	FEM	996	0
	Test	990	0.9
Fy sensor	Theory	1004	0
	FEM	996	0
	Test	992	0.6

Therefore, equations (5-a) and (5-b) derived in this paper are judged to be useful in the rated strain and the natural frequency for designing two-axis force sensor modeled. It is thought that the two-axis force sensor can be used for a robot's finger, and it can be used for gripping an unknown object in the industry and home usefully.

VI. Conclusion

In this paper, the two-axis force sensor for robot's finger, which detects the x-direction force Fx and y-direction force Fy, was designed using several parallel-plate beams. The equations to calculate the strain of the beams according to the force in order to design the sensing element of the force sensor were derived, and these equations were used to design the size of two-axis force sensor sensing element. The reliability of the derived equations was verified by performing the finite element analysis of the sensing element and the characteristic test of the fabricated sensor. The results are as follows.

As a result of comparing the finite element analysis and the characteristic test based on the theory analysis, the rated strain error was found to be within 1.39 %. Also, the interference error that greatly affect on the precision accuracy of two-axis force sensor was found to be 0.9 %, when the finite element analysis and the characteristic test was compared based on the theory analysis. The interference errors of the sensor in study are reduced compared to the other that have come out, which is about 3 %.

Therefore, equations (5-a) and (5-b) derived in this paper are judged to be useful in the rated strain and the natural frequency for designing two-axis force sensor modeled. It is thought that the two-axis force sensor can be used for a robot's finger, and it can be used for gripping an unknown object in the industry and home usefully.

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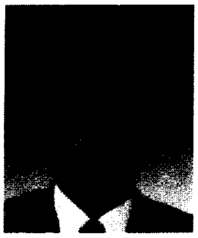

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