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미지물체를 잡기 위한 로봇 손가락의 3 축 힘감지센서 설계 및 제작

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Design and fabrication of robot's finger 3-axis force sensor for grasping an unknown object

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ABSTRACT

This paper describes the development of robot's finger 3-axis force sensor that detects the Fx, Fy, and Fz simultaneously for stably grasping an unknown object. 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 detected forces. The 3-axis force sensor that detects the Fx, Fy, and Fz simultaneously should be used for accurately detecting the weight of an unknown object of gravity direction. Thus, in this paper, robot's finger for stably grasping an unknown object is developed. And, the 3-axis force sensor that detects the Fx, Fy, and Fz simultaneously for constructing a robot's finger is newly modeled using several parallel-plate beams, and is fabricated. Also, it is calibrated, and evaluated.

Key Words : Robot's finger, 3-axis force sensor, Parallel plate beam, Rated strain, Interference error, Strain gage

1. Introduction

Robot's gripper has widely being studied today. M. 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. D. Castro, et al.[2] made Jaw gripper using one direction force sensor, and had the force control using it. N. S. Tlale, et al.[3] made the intelligent gripper with a contact sensor and a circuits for control it. The above grippers can not grasp stably an unknown object in the robot's finger, because it does not detect the Fx(x-direction force, the force of grasping direction), Fy(y-direction force), and Fz(z-direction moment) simultaneously. 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 finger should be composed of a 3-axis force sensor that detects the Fx, Fy, and Fz simultaneously. The precision accuracy of a 3-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 3-axis force sensor is estimated by the interference error.[4] The interference error can be reduced by selecting the accurate location of the strain gauge, through design and strain analysis of the sensing element of the 3-axis force sensor.[5]

Thus, in this paper, robot's finger 3-axis force sensor that detects the Fx, Fy, and Fz simultaneously for stably grasping an unknown object is developed. The 3-axis force sensor is modeled using several parallel-plate beams, the equations to calculate the strain on each beam under forces, in order to design the sensing element of the force sensor, is derived. The reliability of the derived equations is verified by calibrating the 3-axis force sensor.

2. Design of robot's finger

2.1 Modeling sensing element of finger

Fig. 1 shows the finger 3-axis force sensor that can detect the Fx, Fy, and Fz simultaneously. As shown in Fig. 1, robot's finger is composed of two 3-axis force sensors, two contact plates, and a finger frame. The 3-axis force sensor consists of five-parallel plate beam (PPB). The sensing elements for detecting the force Fx is PPB 1 and PPB 2, the force Fy is PPB 3 and PPB 4, and the force Fz is PPB5. PPB1, PPB2, PPB3, and PPB4 are composed of 2-plate beam of the same size(thickness is t_1, length is l_1), respectively. And, they are symmetrical based on the vertical center axis. Also, PPB5 is composed of 2-plate beam of the same size(thickness is t_2, length is l_2). 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 on the sensing element through the theory.

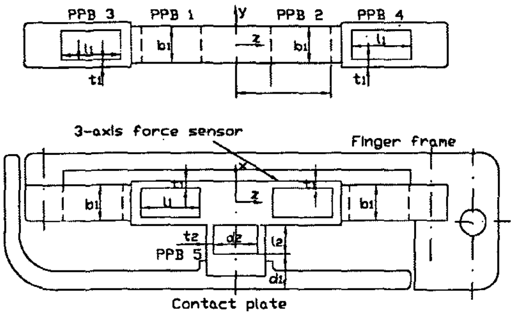

Fig. 1 The sensing element of robot's finger (3-axis force sensor)

2.2 Theory analysis of sensing element

The sensing elements for sensing the Fx is composed of the PPB 1 and PPB 2, the Fy is the PPB 3 and PPB 4, and the Fz is the PPB 5 as shown in 2.2 Modeling sensing element. In order to analysis the strain on PPB 1, PPB 2, PPB 3, and PPB 4, The equations for analyzing the strain of PPB 3 are only derived under the force Fy, because PPB 1, PPB 2, PPB 3, and PPB 4 consist of the two-plate beam with the same size respectively. Also, The equations for analyzing the strain of PPB 5 are derived under the force Fz, Each size of the sensing elements is determined by using the derived equations.

2.2.1 Under the applied force Fy

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

The moment M_z at arbitrary point z leads to

$$M_z = \frac{F_y}{4}(z - \frac{l}{2}) \tag{1}$$

The equations ε_{Fy-U} and ε_{Fy-L} 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 $\varepsilon = M_z / EZ_P$. Which can be obtained as

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

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

Where, E is modulus of longitudinal elasticity, Z_p is polar moment of inertia.

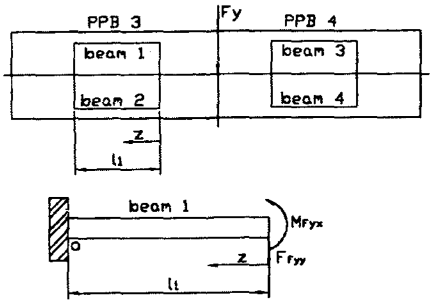

Fig. 2 Free body diagram of plate beams for a 3-axis force sensor under the force Fy

2.2.2 Under the moment Fz

Fig. 3 shows the diagram for analyzing the strain on each plate beam under the force Fz. The plate beam 5 and beam 6 consisting of PPB 5 are symmetrical based on the horizontal center axis. Therefore, the equations for analyzing the strain on plate beam 5 can be applied to the plate beam 6.

The moment M_x at arbitrary point x leads to

$$M_x = \frac{F_z}{4}(x - \frac{l_2}{2}) \tag{3}$$

The equations ε_{Fz-U} and ε_{Fz-L} for calculating the strain on the upper surface and lower surface of the plate beam 5 can be derived by substituting the above equations into the banding strain equation and the compression strain. Which can be obtained as

$$\varepsilon_{Fz-U} = \frac{F_z}{2EZ_p}(x - \frac{l_2}{2}) + \frac{F_z}{A_2Ed_5}\left(\frac{l_2}{2} + d_4\right) \qquad (4\text{-a})$$

$$\varepsilon_{Fz-L} = -\frac{F_z}{2EZ_p}(x - \frac{l_2}{2}) - \frac{F_z}{A_2Ed_5}\left(\frac{l_2}{2} + d_4\right) \qquad (4\text{-b})$$

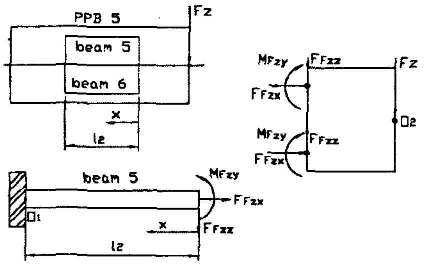

Fig. 3 Free body diagram of plate beams for a 3-axis force sensor under the force Fz

2.3 Sensing element design

The variables for designing the each sensing element is the attaching location taking account into the size of the strain gauge, the rated capacity, rated strain, beam width b_1 and b_2, beam length l_1 and l_2, beam thickness t_1 and t_2, the x-direction length from the contact plate to the end the end of beam, d_1, the x-direction length between two beams of PPB 5 d_2.

In order to design the sensing element, the rated capacity of Fx sensor, Fy sensor, and Fz sensor was determined at 100 N respectively. The rated strain of Fx sensor, Fy sensor, and Fy sensor was approximately determined at 1000 $\mu m/m$. And, the attaching location of the strain gauge for Fx sensor, Fy sensor, and Fz sensor was determined at 2 mm from each end point of beams in the length direction of the beam and at the central line in the width direction of the beam.

The size of sensor was calculated by substituting the determined values into the strain equation (2-a), (2-b), (4-a) and (4-b). It showed that the width of beam b_1 and b_2 were 16 mm, the length of beam l_1 was 12 mm, l_2 was 10 mm, the thickness of beam t_1 was 1.46 mm, t_2 was 1.79 mm, d_1 was 10 mm, d_2 was 24 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.

3. Results and Considerations

Fig. 4 shows the attaching locations of the strain gauges for each sensor. The strain gages, S1~S4 were selected as the strain gauges for Fx sensor, S5~S8 for Fy sensor, and S9~S12 for Fz sensor. In order to calculate the rated strain and interference error on the strain gages' location of each sensor, the equation (5) is usually used.

$$\varepsilon = \varepsilon_{T1} - \varepsilon_{C1} + \varepsilon_{T2} - \varepsilon_{C2} \qquad (5)$$

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. 5.

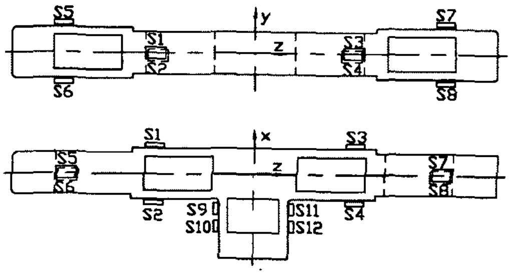

Fig. 4 Attaching location of strain gages

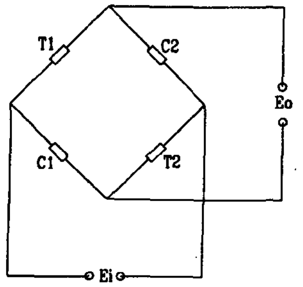

Fig. 5 Full bridge circuit

In order to manufacture the 3-axis force sensor, the attaching location of the strain gauge for Fx sensor, Fy sensor, and Fz sensor was determined at 2 mm from each end point of beams in the length direction of the beam and at the central line in the width direction of the beam. The strain gages were attached at the selected attachment location as shown in Fig. 4 using a M-bond 200 made in Micro-Measurement Company. The full bridge circuit for each sensor was constructed using strain gages S1(C1), S2(T1), S3(C2), S4(T2) for Fx sensor, S5(C1), S6(T1), S7(C2), S8(T2) for Fy sensor, and S9(T1), S10(C1), S11(T2), S12(C2) for Fz sensor as shown in Fig. 8. The strain gage maker is Micro-Measurement Company. The constant of the strain gage (gage factor) is 2.08; length 1.52 mm; width 2.54 mm.

The fabricated 3-axis force sensor was calibrated using the 6-component force/moment sensor calibration machine. Table 1 shows the rated strain and the interference error of each sensor. The rated strain value of each sensor (Fx sensor, Fy sensor, and Fz sensor) from the theory analysis was 1000 $\mu m/m$, that of Fx sensor, Fy sensor, and that of Fx sensor, Fy sensor, and Fz sensor from the experiment was 961 $\mu m/m$, 1055 $\mu m/m$, and 1048 $\mu m/m$ respectively.

As a result of comparing the experiment based on the theory analysis, the rated strain error of Fx sensor was found to be within 3.9 %, Fy sensor 5.5 %, and Fz sensor 4.8 %.

The interference error that greatly affect on the precision accuracy of the 3-axis force sensor was found to be 0 % at the theory analysis. The interference error of the Fx, Fy, and Fz force sensor was found to be 0.7 %, 0.6 %, and 0.3 % at the experiment respectively. This is because of the error of attaching location of strain gage, the error of the testing, the cutting error of sensing element of sensor, and so on.

As a result, derived equations, (2-a), (2-b), (4-a) and (4-b) are judged to be useful in the rated strain for designing the modeled 3-axis force sensor. Also, the interference error of the 3-axis force sensor fabricated in experiment was within 0.7 %, confirming satisfactory results in the force sensor manufacturing process for the robot's finger.

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

Force Sensor	Analysis	Rated strain ($\mu m/m$)	Interference error (%)
Fx sensor	Theory	1000	0
	Exper.	961	0.7
Fy sensor	Theory	1000	0
	Exper.	1055	0.6
Fz sensor	Theory	1000	0
	Exper.	1048	0.3

4. Conclusion

This paper describes the development of robot's finger 3-axis force sensor that detects the Fx, Fy, and Fz simultaneously for stably grasping an unknown object. The 3-axis force sensor was modeled by five-PPB, and fabricated. As a result of comparing the experiment based on the theory analysis, the rated strain error of the 3-axis force sensor was found to be within 5.5 %.

The interference error that greatly affect on the precision accuracy of the 3-axis force sensor was found to be 0 % at the theory analysis. The interference error of the 3-axis force sensor was found to be 0.7 % at the experiment. As a result, derived equations, (2-a), (2-b), (4-a) and (4-b) are judged to be useful in the rated strain for designing the modeled 3-axis force sensor. Also, the interference error of the fabricated 3-axis force sensor in experiment was within 0.7 %, confirming satisfactory results in the force sensor manufacturing process for the robot's finger. It is thought that the developed robot's finger the 3-axis force sensor can stably grasp an unknown object, with any controller. In future research, the controller for robot's hand will be fabricated.

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