Basic study on tactile sensor
by using magnetic suspension

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Abstract

In late years, a study on robotic engineering field is rapid especially in development of humanoid robot. A robot with the controlling of grasp force ability is desirable. Thus, tactile sensor that could detect slipping force is needed and enables in application for the robotic fingertips. In this study, a novel tactile sensor utilizing magnetic attraction force that consequently working between the permanent magnet and magnetic material was proposed. The possibility of magnetic attraction force to perform as magnetic suspension for measuring the slipping force was investigated. The characteristic of permanent magnet was used in realizing a simple structure that enables a freely supportive structure.

Firstly, the sensing principle was studied by finite element method (FEM). The analytical model consist of a full-typed Ni-Fe pole that embedded in a plastic ball with the size of diameter 4mm. A permanent magnet soleplate was placed at gap 0.4mm under the plastic ball. The simulation result showed a good linearity at the range of ±40°. The linear curve could be signified by restorative force expression, \( F = k \theta \). Consequently, the author concludes the performance of magnetic suspension was confirmed. In other respects, the sensitivity characteristic was also inspected by observing the shifting of magnetic field against the rotation angle. 2mT/deg of sensitivity was obtained when on Ni-Fe soleplate at intervals of ±1mm. The sensitivity decreased for permanent magnet soleplate to 0.3mT/deg at intervals of ±0.5mm. Rotation angle \( \theta = 45 \text{°} \) was needed to obtain \( 10N \) of the aim sensitivity. As the \( \theta \) enters the operation range it can be said that the aim sensitivity can be achieved.

A prototype model was fabricated to demonstrate proposed sensing principle experimentally. The experiment results indicate that the magnetic suspension performed well though the order of restorative force is different to analytical result. Furthermore, the Giant Magneto Resistant (GMR) sensor was used to investigate the magnetic field distribution. The experiment result corresponded well to the analytical one. From the above-mentioned result, it is contemplated that the realization of magnetic –typed tactile sensor is possible.
# Contents

Chapter 1 Introduction 1  
1.1 Background of the study 1  
  1.1.1 Human sense of touch 1  
  1.1.2 Tactile sensor 1  
1.2 Objective of this study 2  

Chapter 2 Principle and design concept of tactile sensor 4  
2.1 Principle of tactile sensor 4  
  2.1.2 Selection of sensing principle 4  
  2.1.2 Magnetic principles 4  
2.2 Design concept for magnetic type 6  

Chapter 3 Analytical simulation 8  
3.1 Initial model 8  
  3.1.1 Reviews on principle 8  
  3.1.2 Sensitivity characteristic 9  
3.2 Secondary model 9  
  3.2.1 Reviews on principle 9  
  3.2.2 Magnetic field distribution 11  
  3.2.3 Sensitivity characteristic 12  
  3.2.4 Alignment of GMR sensor 13  

Chapter 4 Experiment 14  
4.1 Fabrication of prototype model 14  
4.2 Torque characteristic measurement 14  
4.3 Magnetic characteristic of GMR sensor 15  
4.4 Magnetic field distribution 17  

Chapter 5 Conclusion 18  

Acknowledgement 19  
References 19  
Achievements 19  
Appendix 20
Chapter 1  Introduction

1.1 Background of the study

1.1.1 Human sense of touch

Human being has 5 senses which are sight, hearing, touch, smell and taste. Each of these senses has their own receptor to detect and make movement. If a robot with a sense like human being can come out, the realization of superior humanoid robot to work together with human being will not be just a dream in future.

In late years, a study on robotic engineering field is rapid especially in development of humanoid robot in contributing spectacularly to the industrialization and modernization worldwide. Many researchers are trying to develop robots which can help human. Nowadays, vision sensor, hearing sensor, and tactile sensor are being developed for robots. However, the development of tactile sensor is late, compared with vision sensor and hearing sensor. The reason of this delay can be said that the structure of the human sense of touch has begun to be elucidated comparatively recent.

The following matters explain how a human being feels the sense of touch. Stimulation information from the outside is received by the receptors that embedded in skin. The information is sent to brain and being recognized as the sense of touch. Human being has several actions handled unconsciously. One of those is “control of grasping force action”. For example, human being can hold a cup fills with water without crushing or dropping it. In fact, the cup is being slip in pettiness in the edge of finger. Human being detects it unconsciously and automatically adjusts the grasp force applied to prevent the cup from falling. In this study, this kind of human ability is called “the minimal grasp force” and it is a huge task to keep such sense to a robot hand.

1.1.2 Tactile Sensor

Tactile sensor became the subject of intense research and development during the 1990s. Tactile sensor is a device, which measures the parameter of a contact between the sensor and an object. An excellent tactile sensor is needed in the fields of robotics industry. There is a range of applications throughout industry for tactile sensor, such as vehicle's anti-lock braking systems (ABS), traction control, robotic grippers and object handling. Furthermore, in recent years tactile sensor is not only required in robotics industry, but also in the fields of medical treatment and welfare. In this area, application to the inspection diagnosis device as sensing technology is expected to treat a flexible subject.

Table 1.1 shows the typical classification of tactile sense. Pressure and slipping force are the main parameters that being measured by tactile sensor. Up to now, there has been extensive research on tactile
sensors, with sensing principles based on

<table>
<thead>
<tr>
<th>Detection contents</th>
<th>Purpose of applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Grasp force control</td>
</tr>
<tr>
<td>Pressure of the finger tip</td>
<td>Measuring the elastic characteristic of the object</td>
</tr>
<tr>
<td>Pressure distribution</td>
<td></td>
</tr>
<tr>
<td>Slipping</td>
<td>Decision and adjustment of the grasp force targeted value</td>
</tr>
<tr>
<td>Displacement and rotation of object in the vertical direction in grasp side</td>
<td>Prevention of the sliding</td>
</tr>
<tr>
<td></td>
<td>Measurement of the surface characteristic</td>
</tr>
</tbody>
</table>

**Table 1.1** Classifications of tactile sense

piezoresistive, capacitive, piezoelectric vibration, and light. Dzung et al \(^{(1)}\) reported a 3-Degree of Freedom (DOF) soft-contact tactile sensor utilizing piezoresistive effect. Motoo Kohei et al \(^{(2)}\) developed a piezoelectric vibration-type tactile sensor using elasticity and viscosity change of sensor structure. These devices detect the contact force between the sensor and an object. Tactile sensors with distributed pressure transducers, have advantages in acquiring surface or the shape’s information of the objects. However, little attempt has been made to feature their functional merits which are still not clear. In addition, they are not equipped with slip sensing function, which is indispensable to dynamic sensing.

On the other hand, a tactile sensor that utilizes light also has been developed. Since a tactile sensor based on this principle requires a charge-coupled device (CCD) camera and image data processing, miniaturization is difficult and the cost is high. At present, conventional tactile sensors are not used for humanoid robots at a practical level.

A tactile sensor with the ability to measure slipping force is important to make dexterous grasping operations of robot hand. If a robot gets possible to recognize sliding, it is believed that the minimal grasp force is enabled by feeding back the sliding information to grasp. Then, it is possible to let a robot hand to treat the object that is easy to slip or breakable.

**1.2 Objective of this study**

The author focus on the idea to enable robot hands to have grasp force control ability, which could measure not only pressure but also slipping force. The following things are the conditions demanded for a tactile sensor \(^{(3)}\).

1. Simple structure
2. Small size and low weight
3. Posses high reliability and sensitivity
4. Densification is possible

In the future, the author concerns to have an array system for tactile sensor. Therefore, simple structure and small size are important keys for the realization. At present, each sensor element of pressure distribute-typed tactile sensor comparatively has complex structure. In this approach, overall structure of tactile sensors becomes complicated and difficult in developing sensor array systems.

In this study, a novel sensing method using magnetic suspension, which enables simple structure and has advantages in self-align suspension was proposed. As a new method for driving the sensor element, the author investigated the possibility of using a magnetic attractive force between a permanent magnet and magnetic material. The author targets to develop a tactile sensor that has sensitivity to measure 1μN of slipping force.
Chapter 2  Principle and design concept of tactile sensor

2.1  Principle of tactile sensor

2.1.1  Selection of sensing principle

Many different principles have been researched and developed. Table 2.1 shows the comparative of sensing principles for tactile sensors. Tactile sensor based-on piezoresistive is excellent in properties of DOF although a suspension is needed to hold sensor elements but their performance deteriorates in the wet environment. Capacitive-typed tactile sensor also has similar advantages to piezoresistive-typed in degree-of-freedom. However, miniaturization is difficult because high precision of suspension structure is necessary. Furthermore, they have disadvantage that is easy to be affected by the humidity. On the other hand, because inductive-type uses a coil for sensing, the simplification structure is not easy.

In consideration of possibility to miniaturize tactile sensor, piezoresistive detection and magnetic type are two principles, which seems to be the most promising. In miniaturization, structure simplicity is required and we develop a free-suspension structure to satisfy the requirement. Compared to piezoresistive principles, magnetic-type is appropriate for this structure due to the attractive force of permanent magnet and promising attractive prospects in future.

In this study, the author take particular note of attractive force that consistently working between permanent magnet and magnetic material. However, the idea of using magnetic force in driving sensor element for tactile sensor is still new and there are some issues to be cleared such as the possibility and device properties. By utilizing the magnetic force characteristic, a tactile sensor that has advantage in self-sensing function is proposed.

Humanoid robots is assumed as indispensable thing for human life in the future. A robot is used not only in the production factory but also at the house in helping chores. In this case, it is essential for those tactile sensors having environmental robustness so that they could perform housework in wet environment such as kitchen.

2.1.2  Magnetic Principles

Fig.2.1 shows the principle of magnetic-typed tactile sensors. The initial structure of tactile sensor consists of a magnetic material covered with plastic ball as the sensor element and a permanent magnet is placed right under the ball (Fig. 2.1.a). Magnetic sensor is also placed next to permanent magnet to detect the changes of magnetic field.

In the static mode, as mentioned in section 2.1.1, attractive force is consistently working between permanent magnet and magnetic material. Magnetic field is
symmetric around the permanent magnet.

**Table 2.1** Comparative chart of sensing principles

<table>
<thead>
<tr>
<th>Principle</th>
<th>DOF</th>
<th>Robustness</th>
<th>Structure</th>
<th>Suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoresistive</td>
<td>1 or 3</td>
<td>□</td>
<td>□</td>
<td>Need</td>
</tr>
<tr>
<td>Capacitive</td>
<td>3</td>
<td>□</td>
<td>□</td>
<td>Need</td>
</tr>
<tr>
<td>Inductive</td>
<td>1</td>
<td>□</td>
<td>□</td>
<td>Need</td>
</tr>
<tr>
<td>Magnetic</td>
<td>2</td>
<td>□</td>
<td>□</td>
<td>Not need</td>
</tr>
</tbody>
</table>

□ : Excellent □ : Good □ : Bad

When the plastic ball received stimulation information from the outside, the coordinate of magnetic pole will shift to the opposite axis due to the rotation of plastic ball and causes the changes of magnetic field distribution (Fig. 2.1b). At this time, restorative force, \( F_1 \) will be generated on the magnet material and make it get back to the original position. This can be characterized as follows.

\[
(1) \quad \text{Where the } k \text{ is the spring coefficient and the } \theta \text{ is the rotate angle. In this study, the author considered spring coefficient as suspension and restorative force as measured slipping force. The magnetic field's difference is transformed into an electrical signal output.}
\]

(a) At the static mode

(b) When externally-applied force
2.2 Design concept for magnetic type

In designing a tactile sensor, simplicity in structure is imperative in order to construct sensors’ array system and miniaturization. In other respects, the author is focusing in the measurement of slipping force in this study, therefore suspension became an important factor. The piezoresistive-typed tactile sensor \(^{(1)}\) consist a frame to hold the sensor element, which is centrally placed. This frame performs a function as suspension and when force is given to the suspension, spring force will be generated. The precision of suspension part is highly required because it is deeply linked to sensor sensitivity and structure.

Conventional tactile sensors \(^{(1)}\) have a frame that causes the overall structure to be complex, which limited the possibility for miniaturization. As a solution, the author proposed a novel structure of tactile sensor with no frame for suspension that make the structure more simple with self-suspension function as the merit.

In order to realize this structure, the author suggests a tactile sensor that utilizes magnetic suspension, which is performed by permanent magnet. Five models are proposed as sensor structure to study the possibility of suggested magnetically driven mechanism. As shown in Fig.2.2, a tactile sensor, which consist a diameter 5.5mm magnetic material as sensor element covered with plastic ball to prevent oxidization is developed. A pole type permanent magnet: \(0.4 \times 0.8 \text{ (mm)}\) is placed right under the ball. The size is decided on the easy-to-fabricate reason. This model is set as the initial model and promising a high magnetic attractive force property due to the small surface in contact between the magnetic material and permanent magnet.

Another four models also suggested considering the performance of permanent magnet when set as soleplate (Fig. 2.3). Fig. 2.3 (a) and (b) have a half pole and full pole, respectively. The following two structures were used to get the optimized structure. In structure 1, the permanent magnet soleplate and the Ni-Fe pole was used.
In structure 2, the vise versa was used. These models promising the enhancement of magnetic adsorption rate between the soleplate and the pole. Further study on each models will be discuss in chapter 3 and define as the secondary model.

There is a possibility that a tactile sensor will slip off when a force that bigger than slipping forces is given to it. As a practical matter, a roller guide is required to prevent the tactile sensor from moving further than the operation range. Even now, e.g. a devise to increase the fractional force is done by arrange hard rubber around the sensor.
Chapter 3 Analytical simulation

3.1 Initial model

3.1.1 Reviews on principle

Finite Element Method (FEM) was used to analyze the proposed sensing concept. As mentioned in section 2.2.1, this tactile sensor utilizes the magnetic attraction force between the permanent magnet and ferromagnetic material. In general, magnetic attractive force, \( F_2 \) is denoted as follows if magnetic field, \( H \) from magnet is enough to saturate the magnetic material.

\[
F_2 = \frac{1}{2} \mu_0 M_s H^2
\]

Where, \( M_s \) is the saturation induction of ferromagnetic material.

Fe was chose as the magnetic material because Fe has high saturation magnetic flux density, relatively high permeability and easy to work. Fig.2.2 shows the initial analytical model. Analysis condition are characterized as follows.

Permeability of Fe: 300
Permeability of air: 1
Permeability of permanent magnet: 1
Saturation flux density: 2.2T
Gap between Fe and permanent magnet: 0.8mm

Size of permanent magnet:

\[0.4 \times 0.8 \text{ (mm)}\]

Firstly, the prerequisite value of coercive force is required in order to generate 1\( \mu \)N of restorative force of magnetic material when tactile sensor changed at a minute rotation angle. The coercive force of permanent magnet is set up as parameter and relation with the restorative force was studied. In this simulation, the \( B-H \) curve was approximated by linear curve with the permeability of permanent magnet as 1 and the relation can be express by follows,

\[ B = \mu H \]

The operating characteristic is showed in Fig.3.1. As the author analyzed shape by fixation, the magnetic flux density is in proportion to coercive force. The intensity of permanent magnet is related to coercive force and shape.

Fig.3.2 shows the simulation results. From the results, when minute rotation angle is set to 1 degree, the author concluded that 200kA/m of coercive force is needed to generate 1\( \mu \)N of restorative force. This value is used in all the analysis.

The restorative force characteristic is investigated to confirm the sensing principle with this result. The restorative force of magnetic material on the rotation angle was investigated. The range was \( \pm 180 \) degrees. As shown in Fig. 3.3, at the
range of ±10 degrees the restorative force can be signified by \( F = k \theta \) and present a good linearity. The spring coefficient, \( k \) is 1.25N/deg. 12.57µN was obtained for a rotary angle of -10 degrees. This result indicates that the restorative force of magnetic material is proportional to rotation angle and the operation of magnetic suspension is confirmed.

![B-H curve](image)

**Fig.3.1** B-H curve i.e Hc:Coercive force

![B-H curve](image)

**Fig.3.2** The relation of the coercive force against restorative force

![Graph](image)

**Fig.3.3** Restorative force characteristic of initial model

3.1.2 Sensitivity characteristic

The sensitivity characteristic was also studied. Fig.3.4 shows the simulation result. However, the change of magnetic field distribution was not seen from the result. The narrowness of the operation range resulted in the concentration of magnetic flux and thus, high sensitivity is impossible with this structure.

3.2 Secondary model

3.2.1 Reviews on principle

Two models were used to get high sensitivity as shown in Fig. 2.3. A pole was
embedded into plastic ball and a plate type permanent magnet was used instead of permanent magnet pole. The size of plate and plastic ball are, and 4mm, respectively. The gap between plastic ball and plate is 0.4mm. The former model has a half-sized pole and the latter model has a sized pole. The gap between plastic ball and permanent magnet was changed from original 0.8 mm to 0.4 mm. Compared to the initial model, a smaller size of tactile sensor is suggested to increase the adsorption rate of the magnetic field. A Ni-Fe alloyed metal was chose because has higher permeability in substitution for Fe. High permeability material is desirable to enhance the magnetic attractive force in relatively low field.

In these models, magnetic flux from permanent magnet is supposed does not concentrate to soft magnetic material. The following two conditions was used in analysis. Analytical conditions were as mentioned below.

Permeability of Ni-Fe: 1000
Permeability of permanent magnet: 1
Permeability of air : 1
Coercive force of permanent magnet ‘200kA/m

Condition 1:
- Permanent magnet as soleplate
- Ni-Fe as soleplate

Condition 2:
- Permanent magnet as soleplate
- Ni-Fe as pole

The restorative force characteristic was studied on the secondary models. The contact between the rotational angle and restorative force was examined. was set as rotation angle of the plastic ball. From the results as shown in fig.3.5 indicates that in the both condition can obtained a good linearity at the degrees of operation range. Comparatively larger operation range was obtained than initial model. The linear curve could be signified by restorative force equation as mentioned in chapter 2 and the author conclude that magnetic suspension was performed well.

Table 3.1 shows the spring coefficient for each model and conditions, respectively. Model 1 is the half-typed pole model and model 2 is the full-typed pole model. This table indicates that model 1 has bigger spring coefficient value in comparison with model 2. A small spring coefficient is preferable for tactile sensors to perform a minute force in operation. In this case, half-typed pole model with permanent
magnet as soleplate has the less of value than other models and conditions

Table 3.1  Spring coefficient of each model

| Condition 1: Ni-Fe as soleplate | Model 1 | 0.639 |
| Condition 2: Permanent magnet as soleplate | Model 1 | 0.215 |
| Condition 1: Ni-Fe as soleplate | Model 2 | 0.215 |
| Condition 2: Permanent magnet as soleplate | Model 2 | 0.068 |

![Image](image-url)

Fig.3.5 Restorative force characteristic of improved model i.e. PM1 is permanent magnet for model 1, PM2 is permanent magnet for model 2.

For the magnetic suspension of the model (the permanent magnet soleplate and full-typed Ni-Fe pole) used in this research, was obtained. From the analytical simulation result, the model gets linear within the range of ±40 degrees and can be shown by \( F = k\phi \). By substituting the aim sensitivity, \( F = 1\mu N \) and \( k = 0.22\mu N/\text{deg} \) into the expression, rotation angle, \( \phi \), will be obtained. As the obtained rotation angle enters the operation range, it can be said that the aim sensitivity can be achieved.

3.2.3 Magnetic Field Distribution

The z-axis of magnetic field distribution was investigated to evaluate the sensitivity characteristic on the tactile sensors. When tactile sensor is rotating to an angle, the magnetic field would shift due to the rotation. At 0.1mm above the plate and range of distance i.e. the entire length of soleplate, the changing of magnetic field was observed. The static state was set as criteria parameter i.e. 0 mm and rotational angle was ±60 degrees. The shift of magnetic field was showed in Fig.3.6 and 3.7. The full-typed pole model was only studied in this section considering the easiness of fabrication process.

Fig.3.6 indicates that magnetic field became bigger and converged in the edge of permanent magnet soleplate. At the central part of tactile sensor, the magnetic field center was shifted along the rotational angle. In comparison with permanent magnet soleplate, Ni-Fe soleplate shows the same tendency which magnetic field only shifted at the central part (Fig. 3.7). The shifting range of magnetic field contribution for
Ni-Fe soleplate is larger compared with permanent magnet soleplate.

Fig.3.6 Magnetic field distribution of permanent magnet soleplate

Fig.3.7 Magnetic field distribution of Ni-Fe soleplate

From this result, the author concludes that improved model indicates better magnetic field contribution comparing to initial model. Furthermore, the magnetic field was altered against the rotation angle and sensitivity characteristic can be evaluated.

3.2.4 Sensitivity characteristic

The sensitivity characteristic on improved model is evaluated using the analytical results from section 3.1.4. In this study, the author intends to detect flux variation with a Hall sensor. The z-axis of magnetic field distribution was studied because Hall sensor could only detect unidirectional magnetic field. Fig. 3.8 shows the schematic diagram of the evaluation method and the explanation was as follows.

The author assumed that to arrange Hall sensor in two places i.e. sensor 1 and sensor 2. The differential of magnetic field is calculated in this interval when the tactile sensors were turned by 10 degrees from 0 to 60 degrees. Sensitivity is calculated from the linear part of graph from Fig. 3.9.

When permanent magnet is set as soleplate, $0.3 \text{mT/deg}$ of sensitivity at a range of $\pm0.5 \text{mm}$ distance from standard state was obtained. On the other hand, the sensitivity is $2\text{mT/deg}$ for Ni-Fe soleplate at the range of $\pm1 \text{mm}$ distance. From this result, Ni-Fe soleplate indicates higher sensitivity in comparison with the permanent magnet soleplate.

The author adopted Hall sensor as magnetic sensor for a gap 0.8 mm in the first place for initial model. Hall sensor has higher sensitivity compared to others magnetic sensor in measuring the magnetic fields’ differences. However, the author find difficulty to obtain high sensitivity for
initial model as discussed in section 3.1.2 and, thus to narrow the gap from 0.4mm to 0.8mm in enhancement the adsorption rate of the magnetic field.

Though superb sensitivity could be gained with Hall sensor, the author understood that it is difficult to realize a Hall sensor for gap 0.4mm. Therefore, Giant Magneto Resistance (GMR) sensor, which is thinner than Hall sensor as substitute was proposed.

GMR sensor assume to place at 0.1mm above permanent magnet soleplate. The magnetic field distribution was observed from the center point by every distance due to the rotation. The analyze results was showed in Fig. 3.10.

From this figure, the highest magnetic sensitivity was obtained at distance from the center point. The sensitivity is $0.31 mT/deg$. GMR sensor should be aligning at this point in order to detect the shift of magnetic field. The same sensitivity was provided in smaller space in comparison with Hall sensor.

**Fig.3.8** Schematic diagram of evaluation method

**Fig.3.9** Sensitivity characteristic of improved model

**Fig.3.10** GMR sensor alignment

### 3.2.5 Alignment of GMR sensor

Relative to Hall sensor, which only detects unidirectional magnetic field, a GMR sensor responds to all direction of the magnetic field. Therefore, the alignment of GMR sensor has to be studied. In this case, the author study only for permanent magnet soleplate based on inspecting improved model by experiment.
Chapter 4  Experiment

4.1 Fabrication of prototype model

A prototype model was fabricated to demonstrate the proposed principle by experiment. The improved model (b) as mentioned in chapter 3 was fabricated. A cyclic ball with the size of diameter 5.5 mm was drilled through its center. Drilling was done by using laser cutter and the core diameter is 1.2 mm. Fe pole was embedded to the core. A piece of permanent magnet plate was placed right under the cyclic ball. A blue plastic as the roller guide was covered the cyclic ball. Fig.4.1.a shows the naked structure of the fabricated sample and Fig. 4.1.b shows the completed prototype model.

4.2 Torque characteristic measurement

The contact between rotation angle and the torque force was investigated to study the operation of the magnetic suspension. Voice coil motor (VCM) is a particular type of motor that is designed to provide linear motion. The VCM that being used in this experiment generates a relation of force against applied current. Model in Fig.4.1.b was used in the experiment.

A bend string attached from the free edge of Fe pole to VCM stage as shown in Fig. 4.2. Then, a position of VCM was fixed and set the position as default. The string was strained by moving the movable stage to a distance. The movement changed the angle of tactile sensor. The current value that needed till displacement return to the default was measured. Torque force was calculated from the necessary electric current. Gauss meter measured the coercive force of permanent magnet. The value is equivalent as used in the simulation that is 216kA/m.
experimental setup
In the initial experiment, a linear curve with nearly 20 degrees slipped off from the origin was obtained. The causation of this error is the misalignment of experiment device. The string that linked to the VCM has to be parallel but the experiment device has an angle from the beginning. The experiment device was improved by designing a better device and performed new experiment.

In the retrial experiment, a linear curve via the origin in the operation range of 0 to 10 degrees was obtained as shown in Fig. 4.3. From this result, the linear curve could be signify by restorative force equation, \( F = k \theta \), and the spring coefficient, \( k \) is \( 1.52 \) mN/deg. The objective of this experiment was to observe the performance of the magnetic suspension and the tendency. The existence of \( k \) value from linearity in the experiment results shows that magnetic suspension is confirmed experimentally. Rotation angle, \( \Theta \) was derived from the following equation.

\[
\Theta = \arctan \left( \frac{y}{x} \right) = \arctan \left( \frac{r}{r_0} \right)
\]

(4)

Where, \( x \) denotes the displacement and \( r \) denotes the radius of the sphere.

Experiment result is corresponded well with the analytical one, though the order of restorative force is different. The reason might be the size difference between the analytical model and the fabricated prototype. The diameter of the pole in analytical and fabricated prototype was respectively \( 3.4 \) mm and \( 1.2 \) m. The fabricated model has relatively larger surface area, thus bigger adsorption of the magnetic field was generated towards the permanent magnet soleplate.

**Fig.4.3 Torque characteristic by experiment**

### 4.3 Magnetic characteristic of GMR sensor

As discussed before in section 3.2.4, a thin magnetic sensor is required. Therefore, the GMR sensor that composed by thin magnetic multilayer was adopted (Fig.4.4). GMR sensor used in this study was provided by Panasonic Electronic Device Co. Japan. They fabricated a meander shape GMR element. The size of line width, entire length, and width are 10 µm, 140 µm, and 115 µm, respectively (Fig.4.5). At first, the magnetic characteristic of this sensor was evaluated by experiment because the properties are not clear yet. The characteristic was measured using the following steps.

First, the measurement circuit was set as shown in Fig. 4.6. The magnetic field intensity was controlled using a measurement system consisting a function generator and Helmholtz coil. A fixed
resistance, \( R_1 \) working as the reference input was connected to this system to measure applied current i.e. \( V_{in} \). 10 kHz of alternate current (A.C) and 0.6V of direct current (D.C) were applied, respectively. Those values were fixed. The voltage of reference input and GMR element were measured using oscilloscope. Finally, the voltage of GMR sensor i.e. \( V_{out} \) was measured against the reference input.

In this experimental, the sensitivity property of Helmholtz coil is characterized as \( 1.70 \mu A \). Applied current was calculated from the \( V_{in} \) and the magnetic field intensity was derived using the above-mentioned characteristic. Oe i.e. oersted is CGS Gauss Unit for magnetic field.

![Gross structure of GMR sensor](image1)

**Fig.4.4** Gross structure of GMR sensor

![The size of GMR sensor element](image2)

**Fig.4.5** The size of GMR sensor element

The initial resistance of GMR element, \( R_0 \) is \( 240.2 \Omega \). A resistance change is provided as a change of the voltage by diverting an electric current to this GMR element. Fig.4.7 shows that the output voltage of the GMR element is proportional to the applied magnetic field. From the linear curve, the sensitivity of this GMR sensor is i.e. when 1 A/m of magnetic field is applied to the GMR element, 0.131 mV of output voltage will be generated.
4.4 Magnetic field distribution

The magnetic field distribution of proposed tactile sensor was also demonstrated by experiment. The experiment device was built as shown in Fig.4.8. Above-mentioned GMR sensor was used for measuring the magnetic field intensity.

The GMR sensor was fixed at certain position and set as criteria parameter. The sample was placed right under the GMR sensor and GMR sensor terminal was connected to the oscilloscope. 0.6 V of D.C was applied. The sample was moved by using the movable micro stage by 1mm at an interval of \( \pm 0.01 \text{mm} \). The dial indicator with 0.01mm resolution was used to measure the displacement. Finally, the voltage of GMR sensor i.e. \( V_{out} \) was measured against the displacement.

Fig.4.9 shows the experimental results. This figure indicates that the linear magnetic field altered against the displacement was obtained without saturation or hysteresis. This characteristic is appropriate in adapting to the differential sensor alignment as shown before. From this result, the author conclude that obtained distribution curve correspond approximately to the analytical result.
Chapter 5  Conclusion

In this study, a novel method for driving a tactile sensor by using the magnetic suspension that consistently working between a permanent magnet and magnetic material was proposed. This sensor was developed in application for measuring the slipping force. A simple structure of tactile sensor, which enables the miniaturization in the future was suggested. The author targeted to measure 1µN of slipping force.

At first, FEM was used to investigate the best structure and sensor characteristic for tactile sensor. From the analytical result, a permanent magnet with 200 kA/m of coercive force was needed to generate 1µN of restorative force, which considered as measured slipping force in this study. The tactile sensor's structure consist of a plastic ball with the size of diameter 4mm with embedded full-typed Ni-Fe pole. A permanent soleplate was placed at gap 0.4mm from the plastic ball. The sensing principle was confirmed with this model and restorative force, \( F = k\theta \) could be signify at the range of \( \pm 10 \) degrees. The spring coefficient, \( k = 0.22 \text{ N/deg} \) was obtained. By substituting the aim sensitivity, \( F = 1 \mu N \) and above-mentioned \( k \) into the restorative force equation, rotation angle, \( \theta = 45.5 \text{ deg} \) will be obtained. As the obtained \( \theta \) enters the operation range it can be said that the aim sensitivity can be achieved.

The sensitivity characteristic was studied also. When permanent magnet was set as soleplate, \( 0.2 \text{ mT/deg} \) of sensitivity was obtained at \( \pm 0.5 \text{ mm} \) distance. On the other hand, Ni-Fe soleplate showed \( 2 \text{ mT/deg} \) of sensitivity at the range of \( \pm 1 \text{ mm} \). However, the realization of Hall sensor at gap 0.4mm is difficult and a thinner GMR sensor was chose as sensor detector for the solution to this issue. In comparison with Hall sensor, same sensitivity was provided for permanent magnet soleplate in smaller space i.e. \( \pm 0.4 \text{ mm} \).

A prototype model was fabricated to investigate the principle by experimental. From the experimental results, the author concluded that magnetic suspension performed well because a linear curve via the origin was obtained for 0 to 10 degrees of operation range. Experimental result is corresponded well with the analytical result, though the order of restorative force is different.

The magnetic field distribution was studied by experiment using the GMR sensor A linear curve of magnetic field change against the displacement was obtained without saturation or hysteresis.

From the above-mentioned analytical and experimental results, the author concluded that the realization of novel tactile sensor that utilizes magnetic suspension is possible.
Acknowledgement

The author extends her grateful to Professor Yasuhiro Koshimoto for advices on the progress for this study and to Dr. Hirofumi Han for the helpful comments. We also appreciated the cooperation from Mr. Kiyotami Shiraga in helping to manufacture the components of our experimental device. Financial support from Panasonic Electronic Devices Co. is gratefully acknowledged. The author also feels strong gratitude towards the entire smart sensing lab’s member for pleasant student life. Lastly, the author sent her feeling of thankfulness to Mr. Mohd Ashraf Ismail and Mrs. Azavitra Zainal for the moral support that gave the author tremendous strength.

References
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Achievements
Appendix

A.1 B-H curve of Fe
The following figure and table indicates the B-H curve characteristic for Fe which being used in the analytical simulation. Magnetic Field is saturated at 2.2T.

<table>
<thead>
<tr>
<th>H (kA/m)</th>
<th>B (T)</th>
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<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
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<tr>
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<td>1.13</td>
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<tr>
<td>6</td>
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</tr>
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<td>8.5</td>
<td>2.1</td>
</tr>
<tr>
<td>12</td>
<td>2.2</td>
</tr>
</tbody>
</table>

A.2 Magnetic Flux Line using FEM
Permanent magnet as soleplate for model (b)

(a) Rotation angle is 20°

(b) At the static mode

(c) Rotation angle is 20°
Ni-Fe soleplate as soleplate for model (b)

(a) Rotation angle is $20^\circ$

(b) At the static mode

(c) Rotation angle is $20^\circ$