Influence of Soft Magnetic Material on the Force of Attraction and Repulsion between Magnets

Sho NAKAJIMA\textsuperscript{*1}, Manabu HIASHIMA\textsuperscript{*1}, Kunihisa TASHIRO\textsuperscript{*1}, Hiroyuki WAKIWAKA\textsuperscript{*1}

Many researchers and engineers to date have been researching applications for permanent magnets. Examples of a device in line with that research are a vibration sensor and a limit switch. These devices use a repulsion magnetic field with permanent magnets and this magnetic force is an important parameter in permanent magnets. When the poles between the two magnets are the same, this force is repulsive and when they are opposite, this force is attractive. It was confirmed in recent years that when two magnets are placed close together and arranged facing each other with a magnetic material on one of their sides, the repulsion force changes to an attractive force at the boundary point. The purpose of this paper is to measure the resultant force when the two magnets are placed close to one another under the above mentioned conditions. We also compared measured values to calculated values, and considered the validity of FEM analysis about calculation of magnetic force.

Keywords: permanent magnet, attractive force, repulsion force, soft magnetic material.

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1. Introduction

Many researchers and engineers to date have been researching applications for permanent magnets. Examples of a device in line with that research are a vibration sensor and a limit switch. The attractive and repulsive force is one of the important parameters of a permanent magnet. It is a confirmed phenomenon that when two magnets are placed close together and arranged facing each other with a magnetic material on one of their sides, the repulsion force changes to an attractive force at the boundary point [1]. We used a finite element method (FEM) to measure the magnet force of this phenomenon. Also we compared measured values with calculated value, and considered the validity of the FEM analysis about calculation of magnetic force. These contents are useful to make progress of bi-stable actuator etc.

2. The principle

2.1 Configuration of Magnetic Path Including Permanent Magnet

The formula of magnetic force is as shown in Eq. (1) when the magnet flux density is $B$, cross sectional area is $S$ and permeability of vacuum is $\mu_0$ [2]. When we think about a closed magnetic path like Fig. 1 (a), we can calculate attractive force and repulsion force using the permeance method but when the gap value $\delta$ is too large and we think about an opened magnetic path like in Fig. 1 (b), it is difficult to calculate these forces using this method [3]. In this paper, we calculate the forces in an opened magnetic path like Fig. 1 (b) with an FEM analysis.

$$F = \frac{B^2 S}{2\mu_0} \quad [\text{N}] \quad (1)$$

2.2 The Attractive Force and Repulsion Force between Magnets

When the two magnets having equal value magnetic forces are placed together, we think about attractive force and repulsion force. They are arranged so that their poles are the same. The length of the gap between them is $\delta$. When a soft magnetic material is not present

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Correspondence: S. NAKAJIMA, Department of Engineering, Shinshu University, 4-17-1 Wakasato, Nagano, Nagano 380-8553, Japan
email: hwaki01@shinshu-u.ac.jp
\textsuperscript{*1}Shinshu University
like in Fig. 2 (a), a repulsion force is generated between the magnets, and magnetic flux flow is like in Fig. 2 (a). Also when the soft magnetic material between magnets is too short like in Fig. 2 (b), only a repulsion force is generated. But when the length of soft magnetic material between magnets is a specific value like in Fig. 2 (c), an attractive force is generated between the two magnets.

3. An Experimental Method

3.1 Attractive Force and Repulsion Force Measurement Method between Magnets

Table 1 shows the specifications of the permanent magnet used, Fig. 3 shows the measurement model and Fig. 4 shows the magnetic force measurement method. The two magnets and the soft magnetic material’s forms are round with diameters of 10 mm. Both magnets have the same value for surface magnetic flux density and the soft magnetic material used is S45C. We measured the magnetic force between the soft magnetic material with a neodymium magnet B using an X stage and a load cell. When magnet B got closer to the other one used in the X stage, we measured the magnetic force on the load cell. Also we measured the length of the gap $\delta_g$ when the attractive force and repulsion force were inverted. We repeated the same experiment with the length of the soft magnetic material $l$ as 0, 1, 2, 3, 6, 30 mm and using neodymium magnets and ferrite magnets.

3.2 Attractive Force and Repulsion Force Analysis Method between Magnets

We performed our analysis of the attractive and repulsive force using software named JMAG-Designer Ver.11 to analyse the transient magnetic fields.

We performed our analysis using one-quarter model of Fig. 3. We analysed the resultant magnetic force when the length $l$ of the soft magnetic material was changed and the magnets used were either neodymium or ferrite. Also we estimated the length of the gap $\delta_g$ when the attractive force and repulsion force were inverted. When analysing the analysis of transient magnetic fields, it is necessary to prepare the gap $\delta_g$ between magnet B and the soft magnetic material [4]. For that the value of the first gap was 0.2 mm.

<table>
<thead>
<tr>
<th>Item</th>
<th>Neodymium magnet</th>
<th>Ferrite magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coercive force [kA/m]</td>
<td>960</td>
<td>270</td>
</tr>
<tr>
<td>Maximum energy product [kJ/m$^3$]</td>
<td>313</td>
<td>30</td>
</tr>
<tr>
<td>Surface magnetic flux density [mT]</td>
<td>420</td>
<td>110</td>
</tr>
<tr>
<td>Diameter [mm]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Length</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

(a) Without soft magnetic material

(b) With a short soft magnetic material that is too short

(c) With a long soft magnetic material between magnets having a specific one value

Fig. 2. Magnetic flux flow between magnets.

Fig. 3. Measurement model (unit: mm).

Soft magnetic material (S45C)

Magnet A

Magnet B

Retainer (SUS304)

X stage (IKO:PK566-A)

Load cell

(TEAC-TL-PFR)

Portable Multi Logger (Omron:ZR-RX7)

Digital indicator (TEAC:TD-510)

Neodymium magnet A

Neodymium magnet B

Fig. 4. Magnetic force measurement method.
4. Results and Landscape

4.1 Results

Fig. 5 (a) shows the magnetic flux flow when an attractive force occurred while Fig. 5 (b) shows magnetic flux flow when a repulsion force occurred during analysis. In Figs. 5 (a) and 5 (b), we confirmed the flow of the magnetic flux when each force occurred.

Fig. 6 shows a comparison of magnetic force-gap characteristics (using neodymium magnets), Fig. 7 shows comparison of magnetic force-gap characteristics (using ferrite magnets) and Table 3 shows the gap length when the attractive force inverted into a repulsion force. In Figs. 6 and 7, a positive magnetic force was defined as an attractive force and a negative one was repulsive. When the length $l$ was longer than 1 mm and the value of $\delta_g$ was as the shorter, we predicted that the attractive force and repulsion force would invert. Next, we observed the value of $\delta_g$ when this phenomenon occurred. In Table 3 the value of $\delta_g$ was smaller when the length of $l$ ($\geq$ 2 mm) was as the shorter. Also the value of $\delta_g$ when this phenomenon occurred was more dependent on the length of $l$ than on the magnetic force of the magnets. However when the length $l$ was shorter than 1 mm, only a repulsion force was observed. As a result, in order for the attractive force and repulsion force to invert, the minimum length of $l$ is between 1~2 mm.

Next, we compared the measured value with the calculated values of the magnet forces. In the results, the error between the measured value and the calculated value was smaller when the length of $l$ was either 0 mm or longer than 6 mm. Consequently, we estimated the appropriateness of the calculated value when $l$ was 0 mm or longer than 6 mm. There is a case where error was larger when $l$ was between 1 mm and 3 mm (specifically using neodymium magnets).

4.1 Landscape

In the results, we estimated the appropriateness of the calculated value in the case with neodymium magnets where the error was larger when $l$ was between 1 mm and 3 mm. It is necessary to improve our measured and analysis terms. In the future, we would measure magnetic force and normalize magnetic force dependent on the magnet’s size.

5. Conclusion

(1) When the length of the soft magnetic material was longer than 1 mm and the value of the gap was as the shorter, we predicted that the attractive force and repulsion force would invert. Also the value of gap when this phenomenon occurred was much more dependent on the length of that material than on the magnetic force of the magnets. When the length of soft magnetic material was shorter than 1 mm, only repulsion force was observed. In order for the attractive and repulsion forces to invert, the minimum length needs to be between 1~2 mm.

(2) We compared the measured value with the calculated values of the magnet forces. In the results, an error of between the measured value and the calculated value was smaller when the length of the soft magnetic material was 0 mm and longer than 6 mm. However error was larger when the length of that material was between 1 and 3 mm. It is necessity to improve our measured and analysis terms. In the future, we would measure magnetic force and normalize magnetic force dependent on the magnet’s size.
Table 3  Length of gap when attractive force inverted to repulsion force

<table>
<thead>
<tr>
<th>Length l [mm]</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neodymium magnet</td>
<td>Ferrite magnet</td>
</tr>
<tr>
<td>30</td>
<td>6.0</td>
<td>5.6</td>
</tr>
<tr>
<td>6</td>
<td>1.6</td>
<td>1.5</td>
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<tr>
<td>3</td>
<td>0.76</td>
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<tr>
<td>2</td>
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<tr>
<td>1</td>
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<td>---</td>
</tr>
<tr>
<td>0</td>
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<td>---</td>
</tr>
</tbody>
</table>

Fig. 6. Comparison of magnetic force-gap characteristics (Neodymium magnet)

Fig. 7. Comparison of magnetic force-gap characteristics (Ferrite magnet).

References


