Study on the Basic Characteristics of Magnetic Harmonic Gear with Stackable Structure Using Halbach Array

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The magnetic harmonic gear has been studied because of its high magnet use efficiency. However, the magnetic harmonic gear is difficult to assemble. So, a new type of the magnetic harmonic gear was proposed. This magnetic gear has the stackable structure and is assembled easily. It was confirmed by simulation that the radial magnetic flux was strengthened by alternately arranging the axially magnets with the same poles and the maximum transfer torque and the magnet utilization efficiency improved. Therefore, we make a prototype of the stackable harmonic type magnetic gear using Halbach array and measure and examine torque characteristics.

Keywords: Magnetic gear, Stackable structure, Halbach array, Torque characteristic.

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1. Introduction

Recently the magnetic gears are generally known as a cylindrical type [1-6], a facing type, a harmonic type [7-10] and so on. Previous researches [11-13] studied the stackable harmonic magnetic gears for a high magnet use efficiency, a high transmission torque and easy assembly.

In the harmonic magnetic gear, the input shaft and the output shaft are coaxial. And it has the three rotors which are an inner rotor, a center rotor, and an outer rotor. After here, these are called simply as Inner, Center and Outer respectively. We proposed the new harmonic magnetic gear with stackable structure to improve the torque performance by using the Halbach array. The magnetic flux in the radial direction is improved by arranging the magnets of the axial direction magnetization and the radially magnetization magnet alternately in the same poles. It is confirmed by simulation that the maximum transmission torque and the utilization efficiency of the magnet are improved.

In this paper, we produce the proposed harmonic magnetic gear and study its basic characteristic and compare with the previous one.

2. Structure of new magnetic gear

2.1 Newly Proposed Structure

Fig.1 shows the structure of the magnetic gears used in previous research [11-13]. This gear is stacked an iron part with segment magnets and ring magnets. A high transmission torque was not obtained by this magnet gear. Thus we propose a new harmonic type magnetic gear, which is composed of the following rotor parts with new structure. (Fig.2, 3).

Layer 1: A set of neodymium magnets magnetized in a radial direction is arranged on the circumference. Adjacent magnets are magnetized in opposite directions.

Layer 2: A neodymium magnet magnetized in the axial direction is arranged on the circumference. Similarly, adjacent magnets are magnetized in opposite directions.

Inner: A structure in which Layer 1 and Layer 2 are alternately stacked in a direction in which the magnets each other. By alternately stacking, a Halbach array centered on Layer 1 is formed. This results in a structure that strengthens the radial magnetic flux. (Fig.2)

Center: An assembly of magnetic pole pieces of

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Fig. 1 The past type of magnetic harmonic gear with stackable structure [13].
electromagnetic soft iron which is located between the inner and the outer and has the function of modulating the magnetic flux. (Fig. 3 (b))

Outer: Similar to the inner structure, Layer 1 and Layer 2 are alternately stacked.

In this paper, Inner and Outer are the input and the output respectively in simulation and experiment. Table 1 shows the specifications of the magnetic gears.

### 2.2. Reduction Ratio

The following relationship holds between the numbers of magnetic poles of each rotor and pole pieces in Center in the harmonic magnetic gear.

\[ N_c = N_o \pm N_i \]  

(1)

\[ G_r = \frac{P_o}{P_i} \]  

(2)

where \( P_o \) and \( P_i \) are the number of pole pairs of Outer and Inner, and \( N_c \) is the number of Center pole pieces.

In the magnetic gear produced here, the number of pole pairs are 3 for Inner and 13 for Outer. The number of the magnetic pole pieces of Center is 16. So, the reduction ratio \( G_r \) is \(-13/3 = -4.3\). Since the reduction ratio is negative, Outer rotates in the opposite direction to Inner.

### 2.3 Simulation

To compare the torque and torque density between the past and the proposed structures, we simulate with the same dimension and the same number of pole pair in Table 2, that is same as the past research [13] instead of

| Table 1 Dimensions of the magnetic gear (New proposed type). |
|---------------------------------|--------|--------|
| Outer | Center | Inner |
| No. of pole pair or pole pieces | 13     | 16     | 3     |
| No. of Layer1                   | 5      | -      | 5     |
| No. of magnets for Layer1       | 26×5   | -      | 6×5   |
| Thickness of Layer1 [mm]        | 7      | -      | 7     |
| No. of Layer2                   | 4      | -      | 4     |
| No. of magnets for Layer2       | 26×4   | -      | 6×4   |
| Thickness of Layer2 [mm]        | 5      | -      | 5     |
| No. of center                   | -      | 5      | -     |
| Outside and inside diameter     | φ 120-φ 84 | φ 82-φ 62 | φ 60 |
| Magnet                          | NeoMag: N40, Br:1250-1290mT | - | NeoMag: N40, Br:1250-1290mT |
Table 1. In the simulation, Outer were fixed, and Inner was forcibly rotated from the neutral state at low speed. The maximum transmission torque applied to Outer was measured. The results are shown in Table 3. The maximum transmission torque was 2.5 times and the torque density was expected to be improved 2.2 times. Since a new proposed model have improved properties from this result, a prototype will be manufactured according to the Table 1.

Table 2 Dimension for simulation [13].

<table>
<thead>
<tr>
<th>No. of pole pair or pole pieces</th>
<th>Outer</th>
<th>Center</th>
<th>Inner</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Ring magnets</td>
<td>7</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>No. of iron plates</td>
<td>8</td>
<td>8 X 16</td>
<td>8</td>
</tr>
<tr>
<td>No. of segment magnets</td>
<td>8 X 11</td>
<td>-</td>
<td>8 X 5</td>
</tr>
<tr>
<td>Outside and inside diameter</td>
<td>Φ70- Φ45</td>
<td>Φ43- Φ34</td>
<td>Φ32</td>
</tr>
<tr>
<td>Magnet</td>
<td>NeoMag N40, Br:1250-1290mT</td>
<td>-</td>
<td>NeoMag N40, Br:1250-1290mT</td>
</tr>
</tbody>
</table>

Table 3 Simulation results.

<table>
<thead>
<tr>
<th></th>
<th>The old type</th>
<th>The new type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. transmission torque [Nm]</td>
<td>0.73</td>
<td>1.82</td>
</tr>
<tr>
<td>Volume of magnet [m³]</td>
<td>3.26 X 10⁻⁵</td>
<td>3.61 X 10⁻⁵</td>
</tr>
<tr>
<td>Torque density [Nm/m³]</td>
<td>2.24 X 10⁴</td>
<td>5.05 X 10⁴</td>
</tr>
</tbody>
</table>

3. Experiment

3.1 Experimental device

Fig. 4 shows the experimental set-up. The three phase motor, the input torque detector, the magnetic gear, the output torque detector, and the powder brake are connected in this order. The rotation speed and the torque of the input and the output side are measured with a detector. Inner and Outer are the input and output.

3.2 Stackable structure

Since the produced magnetic gears are the stackable type, experiments are conducted as three types of structure, Structure 1, 2 and 3, in order to verify what kind of difference there is due to the difference in stacking method (Fig. 5). In each structure, the number of layers stacked is expressed as (the number of layers of Layer 1 - the number of layers of Layer 2), e.g. (2-1).

Structure1: A structure in which Layer 1 and Layer 2 are alternately stacked so that both ends are Layer 1.

Structure2: A structure in which Layer 1 and Layer 2 are alternately stacked so that both ends are Layer 2.

Structure3: A structure in which Layer 1 and Layer 2 are stacked alternately so that one end is Layer 1 and the other end is Layer 2.

The magnetic flux concentrates at Layer 1. The Layer 1 of Inner and Outer connects through Center. When Layer 1 is placed at the end of stacks, concentration of magnetic flux in the end layer is less than the case that the Layer 2 is placed at the end.

3.3 Measurement of reduction ratio and torque ratio during rotation

To confirm a work of the produced magnetic gear produced, the reduction ratio and the torque ratio are measured. The rotation speed and the torque of the input shaft and the output shaft are measured. The load conditions by the powder brake are set at no load, 0.7 Nm and 1.0 Nm. In addition, under each load condition, measurement is carried out at 100 rpm intervals from 100 rpm to 1000 rpm. A motor cannot be driven well at 100 rpm and 1.0 Nm. So the data is omitted at that case.

Fig. 6 shows the reduction ratio for all load condition. Fig. 7 and Fig. 8 show the torque ratio under the load of 0.7 Nm and 1.0 Nm. Both the reduction ratio and the torque ratio are close to the theoretical value 13/3 based on the numbers of pole pairs regardless of the number of
Fig. 6 Reduction ratio.

(a) at 0Nm load.

(b) at 0.7Nm load.

(c) at 1.0Nm load.

Fig. 7 Torque ratio at 0.7Nm load.

Fig. 8 Torque ratio at 1.0Nm load.

(a) Structure 1.

(b) Structure 2.

(c) Structure 3.

Fig. 9 Maximum transmission torque.
stacks, the rotation speed, and the load conditions. Therefore, it is confirmed that the proposed magnetic gear works well according to the designed gear ratio.

### 3.4 Measure maximum transmission torque

When the magnetic torque exceeds a certain level, the magnetic gear causes a step-out. At a step-out each maximum transmission torque is measured with the Structures 1 to 3. At first, the transmission torque is measured when the output shaft is fixed and the input shaft was rotated manually. Next, the input rotation speed is set at intervals of 50 rpm from 100 rpm to 300 rpm and of 100 rpm from 300 rpm to 1000 rpm. The load by powder brake is increased until a step-out occurs. When a step-out occurs, the torque is measured as the maximum torque. Fig.9 shows that the maximum transmission torques for Structure 1, Structure 2, and Structure 3 are 8.10, 5.62, and 7.13 [Nm] respectively. From Fig.9, it seems that the maximum transmission torque can be gradually adjusted by the number of layers regardless of the difference in structure. To consider the most efficient stacking method, three structures are compared. The center is the role of direct connection between Inner and Outer. The number of Layer 1 is same as the number of a stack of Center. So Fig.10 are compared on the condition that the same number of Layer 1 for each structure. The torque is larger in Structure 2 and Structure 3, where the amount of magnets in these two structure are larger than that in Structure 1.

Next, the torque density is compared among Structure 1, Structure 2, and Structure 3. Fig.11 (a) shows Structure 1 and Structure 2. Fig.11 (b) compares Structure 1 and Structure 3. Comparison are done under the condition that the number of Layer 1 are same for each structure. From Fig.11, we can see that the torque density of structure 1 is larger under all conditions. Therefore, it be revealed that Structure 1 is the most efficient stacking method.

The torque density decreases as the number of stacked layer increases. Because the magnets of Layer 2 don’t directly relate to the transmission torque, the rate of the increase of the magnet volume is larger than the increase of the strength of the magnetic flux by the Halbach array. So the torque density is considered to decrease.

The proposed magnetic gears have more magnets than the ones we have studied, even though the number of layers is the same. So, in order to examine the proposed magnetic gears have more magnets than the
Table 4 Comparison of torque densities.

<table>
<thead>
<tr>
<th>Torque Density Characteristic</th>
<th>Old type model</th>
<th>New type model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. transmission torque [Nm]</td>
<td>2.72</td>
<td>8.63</td>
</tr>
<tr>
<td>Volume of magnet [m$^3$]</td>
<td>$5.09 \times 10^{-5}$</td>
<td>$7.24 \times 10^{-5}$</td>
</tr>
<tr>
<td>Torque density [Nm/m$^3$]</td>
<td>$5.34 \times 10^4$</td>
<td>$11.9 \times 10^4$</td>
</tr>
</tbody>
</table>

ones we have studied, even though the number of layers is the same. Therefore, in order to examine the use efficiency of the magnet, we want to compare them by the torque density divided by the volume of the magnet using the maximum transmission torque. Since the dimensions of both prototypes are different, a simple comparison cannot be done. So, in the simulation, we compare the various characteristics for the same dimension in Table 1. Also we rotate Inner with the Center fixed, but the maximum transmitted torque measured the torque applied to Outer.

As shown in Table 4, the torque density of the previous magnetic gear model is $5.34 \times 10^4$ [Nm/m$^3$], and the new magnetic gear model is $11.9 \times 10^4$ [Nm/m$^3$]. The torque density is improved in the new proposed magnetic gear. As the number of stacked layers increases, the torque density will converge to a constant value irrespective of the structure.

4. Conclusion

In this research, we propose and produce a stackable harmonic type magnetic gear having a new structure. For the proposed new magnetic gear, the results as measuring the torque characteristics are as follows:

(1) In all the stack conditions, the prototype magnetic gear is able to transmit the rotational motion and torque normally.

(2) Maximum transmission torque reach 8.10 [Nm].

(3) The most efficient stack method is Structure 1 in which both ends are Layer 1.

(4) The torque density of the proposed gear with a new structure is improved.

(5) As the number of stacked layers is increased, the torque density decreased.

The torque properties are improved in the proposed magnetic gear. The optimization of gear dimensions are needed for a future work.

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References


