Optimized Design, Analysis of High Gear Ratio Magnetic Gear for High Speed and High power

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In this paper, we proposed a non-contact magnetic gear model with a halbach array of 81kW and 60krpm for high speed and high power applications. The optimization model was proposed using orthogonal array and the response surface methodology, and was selected considering torque, torque ripple and power density. The feature of this paper is the division of axial permanent magnet to reduce eddy current loss. Also, the characteristics of the optimization model are analyzed through 2-D and 3-D finite element analysis. When each permanent magnet was divided into 8 segment, the eddy current loss was reduced by about 76%. The structural deformation and stress of the pole piece component were confirmed by the forced vibration analysis considering the electric force mapping on each pole piece.

Index Terms— Magnetic gears, Optimization, Response surface methodology, Finite element analysis.

I. INTRODUCTION

PROPULSION system such as aircraft engines and torpedoes require high speed and high power reducer of highly reliable. Traditional mechanical gears have problems such as friction, vibration. Also high speed mechanical gears are difficult to manufacture and maintain, so high speed non-contact magnetic gears are proposed to resolve these problems. Magnetic gears have the following advantages over the mechanical gearboxes: minimum acoustic noise, reduction of maintenance cost, improved reliability, overload protection and physical isolation between input and output shafts [1]-[3]. However, magnetic gears have a disadvantage which permanent magnets (PMs) cause high eddy current loss because of high electrical frequency at high speed. There is radial and axial division of PMs as a method to reduce eddy current loss.

In this paper, we proposed a halbach array model for high power and high speed non-contact magnetic gear of 81 kW and 60krpm. In halbach array, the magnetic field on one side is strong and the magnetic field on the other side is weak. The magnetic field of this array is stronger than the conventional SPM magnet array [4]-[5]. Optimization was performed statistics methodology such as orthogonal array, main effect analysis by analysis of means (ANOM) and response surface methodology (RSM). Torque, torque ripple, and specific power were considered to improve performance. In addition, the eddy current loss was analyzed and compared by 3-D finite element analysis (FEA) according to the increase of the axial division of PMs.

II. OPTIMIZED DESIGN OF MAGNETIC GEAR

As shown in Fig. 1, the magnetic gear consists of an inner rotor (inner PM and inner back yoke), an outer rotor (outer PM and outer back yoke), pole pieces and double air gaps. The input rotation speed of the inner rotor is 60krpm and the outer rotor rotation speed is 6krpm. The gear ratio is 10:1 and axial stack length is 70mm. If the axial stack length is increased, the pole piece structure becomes structurally unstable.

![Fig. 1. Structure of halbach magnetic gear (axial length 70mm).](image)

Therefore, an appropriate stack length must be considered. Also PM ratio is the ratio of the PM in the rotor. As the PM ratio increases, a large amount of heat was generated by magnetic flux saturation. To choose the appropriate PM ratio is important factor, so as design variable for optimization must be considered.

TABLE I

<table>
<thead>
<tr>
<th>Design variables</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Inner rotor thickness</td>
<td>33</td>
<td>35</td>
<td>37</td>
</tr>
<tr>
<td>2 Inner PM ratio</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>3 Outer PM ratio</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>4 Pole piece thickness</td>
<td>15</td>
<td>16</td>
<td>17</td>
</tr>
</tbody>
</table>

Since the inner rotor is high speed, the linear velocity of inner rotor must be considered due to the structural limitation of the used rotor materials. In this model, constraint condition of the linear velocity was set to 0.75 mach (255m/s) or less. CFRP (carbon fiber reinforced plastic) material was applied to the surface of inner rotor to protect PMs that have always been compressed. Permanent magnets are better and stable when compressed.

In order to analyze the least number of combinations, L18 mixed orthogonal array as the sampling method was used to get the approximation results. In screening, the sensitive design variable was selected by the main effect of ANOM and RSM analysis by statistics methodology such as ANOM and RSM.
was performed for the detailed optimization with effective design variables. The optimization process is shown in Fig. 2.

Fig. 3. Result of optimal solution and overlaid contour plot.

III. 3D MAGNETIC FIELD ANALYSIS CONSIDERING LOSSES

Table II shows the characteristics of magnetic gears according to the number of axial divisions of PMs. To analyze the loss, iron loss and PM loss should be identified using a 3-D FEA, and PM was divided into 8 segments to reduce eddy current loss. In case of 8 segments, eddy current loss and core loss occurred 2.96kW and 0.71kW respectively. The eddy current loss decreased by about 76% when compared with 1 segment. The efficiency was about 95.85% by loss analysis.

TABLE II

<table>
<thead>
<tr>
<th>Inner(Outer) torque(Nm)</th>
<th>1 segment</th>
<th>8 segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power(kW)</td>
<td>15.6(137.30)</td>
<td>13.75(134.97)</td>
</tr>
<tr>
<td>Efficiency(%)</td>
<td>86.27</td>
<td>84.81</td>
</tr>
<tr>
<td>Iron loss(kW)</td>
<td>1.76</td>
<td>12.50</td>
</tr>
<tr>
<td>Eddy current loss(kW)</td>
<td>0.76</td>
<td>0.71</td>
</tr>
<tr>
<td>Total loss(kW)</td>
<td>13.26</td>
<td>3.67</td>
</tr>
</tbody>
</table>

Fig. 4 shows the direction of the eddy current loss for each PM. Fig. 4 (a) shows that by the law of amperes, an eddy current loss occurred in a perpendicular to the direction of the magnetization in circumference direction. Fig. 4 (b) can be confirm that eddy current loss occurred perpendicular to the direction of the magnetization in a radial direction.

IV. FORCED VIBRATION AND STRESS ANALYSIS

Generally, pole piece has a laminated structure, so its structural stability is very weak. Therefore, the forced vibration analysis of magnetic gear is essential to check structural stability. Since proposed model operates at high speeds, forced vibration analysis of pole piece structure is also considered as well as magnetic analysis.

Fig. 5. Forced vibration result of optimal model

V. CONCLUSION

We have successfully optimized for the 81kW, 60krpm model using statistical methodology such as ANOM and RSM. To increase the torque and specific power, a halbach array was applied and the PM was divided into 8 segments in the axial direction to direct the eddy current loss. Magnetic field analysis considering losses and mechanical performance analysis was conducted. The eddy current loss was reduced about 76% by dividing PMs. Also structural stability of the pole piece structure was confirmed by forced vibration analysis.

REFERENCES