Experimental Tests and Efficiency Improvement of Surface Permanent Magnet Magnetic Gear

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Magnetic gears offer several advantages against conventional mechanical gears such as easy maintenance, low vibration and acoustic noise, and high reliability. For the practical application of magnetic gears, experimental studies on gear characteristics that consider real manufacturing constraints should be performed. This paper presents the loss analysis, experimental tests, and performance improvement of a surface permanent magnet (SPM) magnetic gear. The torque characteristic and the efficiency of the SPM magnetic gear were calculated using finite element analysis (FEA). Experiments were performed on a trial magnetic gear. The FEA and experimental results demonstrated the improved efficiency of the trial gear. The maximum efficiency of the improved gear was over 96%.

Keywords: magnetic gear, loss analysis, experimental tests, finite element analysis (FEA), eddy current loss

1. Introduction

Mechanical gears are widely used in low-speed large-torque applications, such as wind-power generation and hydropower generation systems. However, they have several problems including vibration, acoustic noise, and maintenance concerns due to mechanical contacts. In addition, the mechanical gears require lubricant to reduce friction and ensuing heat generation.

Magnetic gears can transmit torque without mechanical contact. Therefore, they have low vibration and acoustic noise, easy maintenance, and no lubricant against conventional mechanical gears. Various types of magnetic gears have been introduced in previous papers^{(1)–(3)}. Among them, a planetary type magnetic gear⁽⁴⁾ has attracted interest recently.

Figure 1 shows a basic structure of the planetary type magnetic gear. It consists of an inner and outer rotors with surface-mounted permanent magnet (SPM) and ferromagnetic stationary parts which are called pole pieces. It works as a gear by modulating the magnet fluxes due to the pole pieces. Transmission torque density of the planetary type magnetic gear is higher than the other types because all the magnets of the inner and outer rotors contribute to generate and transmit torque⁽⁵⁾⁽⁶⁾.

For practical application of the magnetic gears, experimental studies on characteristics of the gear taking into account of real manufacturing constraints should be clarified. In this paper, first, the torque characteristics, core loss, and eddy current loss in permanent magnets of the magnetic gear are calculated by three-dimensional finite element analysis (3D-

Fig. 1. Structure and specifications of SPM magnetic gear

FEA). Next, no-load and load test results of a trial SPM magnetic gear are indicated and compared to the ones obtained from 3D-FEA. Finally, based on the FEA and experimental results, an efficiency-improved trial magnetic gear is demonstrated. The maximum efficiency of the improved gear achieves up to over 96%.

2. Characteristics Analysis of Magnetic Gear

2.1 Torque Characteristics Figure 1 shows the structure and specifications of the SPM magnetic gear used in the consideration. The inner and outer rotors have permanent magnets on their surfaces. The pole-pairs of the inner

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and outer rotors are 3 and 31, respectively. Hence, the gear ratio is 10.333 determined by the ratio of the inner and outer pole-pairs⁽⁵⁾. The pole pieces are placed between the inner and outer rotors. The number of the pole pieces is 34 given by the sum of the numbers of the inner and outer pole-pairs. The material of the permanent magnet is sintered Nd-Fe-B of which the remanence B_r is 1.25 T and the coercivity H_c is 975 kA/m, respectively. Core material of the pole pieces and the rotor back yokes are non-oriented silicon steel.

Figure 2 shows the FEA model of the magnetic gear. The number of elements is 427,023. Leakage flux in an axial direction have to be considered by 3D-FEA since the structure of the magnetic gear is flat. The FEA model is a half model in the axial direction considering axial symmetry. The axial length of the air area to consider the leakage flux is two times

as much as the magnetic gear area.

Figure 3 shows the transmission torque characteristic calculated by 3D-FEA. The internal phase angle represents the difference between d -axes of the inner and outer rotors. It is understood that the maximum transmission torque is obtained when an internal phase angle is 90 degrees in the same manner as conventional synchronous machines. The maximum torque of the inner and outer rotors are 1.24 N·m and 12.5 N·m, respectively.

Figure 4 shows the torque waveforms at the maximum output point when the inner and outer rotors rotate with constant speeds of 3,000 r/min. and 290 r/min., respectively. It is clear that the torque ripple of the magnetic gear is very small.

2.2 Iron Loss Calculation Method

The iron loss W_{iron} can be calculated by the Steinmetz's equation as follows:

$$W_{iron} = A_h f B_m^2 + A_e f^2 B_m^2, \dots \dots \dots (1)$$

where the frequency of the flux is f , the maximum flux density is B_m , the hysteresis and eddy current loss coefficients are A_h and A_e , respectively. A_h and A_e of the non-oriented silicon steel used in the magnetic gear are 2.2×10^{-2} and 7.1×10^{-5} , respectively.

The flux waveforms in pole pieces and rotor yokes include harmonic components. Thus, in this paper, it assumes that the iron loss can be obtained from the sum of iron losses of each harmonic component. Consequently, Eq. (1) can be written as follows:

$$W_{iron} = \sum_{k=1}^n (A_h k f B_m^2 + A_e (k f)^2 B_m^2). \dots \dots \dots (2)$$

The frequency of the flux in each pole piece f_s is expressed as follows:

$$f_s = p_h n_h = p_l n_l, \dots \dots \dots (3)$$

where the pole-pairs of the inner and outer rotors are p_h and p_l , respectively. The rotational speeds per second of the inner and outer rotors are n_h and n_l , respectively. Thus, the frequency of the flux in each pole piece is 150 Hz when the inner rotor rotates at 3,000 r/min.

The fluxes in the inner and outer rotors are varied by the slot of the pole pieces in the same manner as the conventional SPM motors. Therefore, the frequencies of the flux in the inner and outer rotors f_h and f_l are expressed as follows:

$$f_k = n_s n_k \quad (k = h, l), \dots \dots \dots (4)$$

where the number of the pole pieces is n_s . Thus, the frequencies of the flux in the inner and outer yokes are 1,700 Hz and 165 Hz, respectively, when the inner rotor rotates at 3,000 r/min.

2.3 Eddy Current Loss in Permanent Magnet

The flux in the air gap of the magnetic gear is included harmonic components since the inner and outer rotors have the different pole-pairs and rotational speeds. Thus, eddy currents are induced in the sintered Nd-Fe-B magnets on the two rotors.

The basic equation of electromagnetic field analysis considering the eddy current is given as follows⁽⁷⁾:

$$\text{rot}(\nu \text{rot} \mathbf{A}) = \mathbf{J}_0 - \sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \text{grad} \phi \right), \dots \dots \dots (5)$$

Fig. 2. 3D-FEA model of the magnetic gear

Fig. 3. Calculated transmission torque characteristic

Fig. 4. Torque waveforms at the maximum output point

where the vector potential and the scalar potential are $\mathbf{A}$ and ϕ , respectively. The magnetic reluctivity is ν , the forced current density is J_0 , and the electrical conductivity is σ .

In general, the eddy currents are induced on a surface of the rotor magnets due to the skin effect. The skin depth d is given by

$$d = \frac{1}{\sqrt{\sigma f \mu_0 \mu_r \pi}}, \dots \dots \dots (6)$$

where the magnetic permeability of vacuum is μ_0 and the relative permeability of conductor is μ_r . The frequencies of the flux in the inner and outer rotors are given by Eq. (4). The μ_r and σ of the sintered Nd-Fe-B magnet used in the magnetic gear are 1.037 and 6.67×10^5 S/m, respectively. Thus, the skin depths of the inner and outer magnets are 14.7 mm and 47.1 mm, respectively. The radial and axial lengths of the inner and outer magnets are short enough in comparison with the skin depths. Therefore, the whole permanent magnets in the FEA model are divided into fine meshes since there is a possibility that the eddy currents are induced in the whole magnets.

Figure 5 shows the eddy current loss density distribution of the rotor magnets calculated by the 3D-FEA. It is understood that the eddy currents are induced in the whole outer magnets and on the surface of the inner magnets.

2.4 Estimated Efficiency of Magnetic Gear The efficiency of the magnetic gear is calculated by using the torque and losses obtained above. The efficiency η is expressed as follows:

$$\eta = \frac{P_{out}}{P_{out} + W_{iron} + W_{eddy}} \times 100 \quad (\%), \dots \dots \dots (7)$$

where the iron loss of the pole pieces and the rotor yokes is W_{iron} , the eddy current loss of the magnets is W_{eddy} , and the mechanical output of the magnetic gear is P_{out} , which is

Fig. 5. Eddy current loss density distribution in permanent magnets

Table 1. Calculated losses and efficiency

	Inner rotor (Input)	Outer rotor (Output)
Rotational speed	3,000 r/min.	290 r/min.
Torque	1.22 N·m	12.5 N·m
Power	391 W	379 W
PMs eddy current loss	3.3 W	2.0 W
Iron cores iron loss	In 0 W, Pp 2.0 W, Out 4.6 W	
Total loss	11.9 W	
Efficiency	97.0 %	

given by

$$P_{out} = \omega_l \tau_l, \dots \dots \dots (8)$$

where the angular velocity and the average torque of the outer rotor are ω_l and τ_l , respectively. On the other hand, mechanical loss and eddy current loss in housing described in Sect. 3.3 are neglected.

Table 1 shows the calculated losses and efficiency of the magnetic gear. It is understood that the magnetic gear has high efficiency of 97%.

3. Experimental Test Results

On the basis of the above results, a trial SPM magnetic gear was manufactured. The structure of the magnetic gear has almost the same specifications shown in Fig. 1, but the stack length of the pole pieces is changed from 10 mm to 16 mm as shown in Fig. 6 in order to sandwich the individual 34 pole pieces between the aluminum housing with high proceeding accuracy.

Figure 7 shows the general view of the experimental setup. The trial magnetic gear operates as a reduction gear on this system. The rotational speed of the inner rotor is regulated an arbitrary speed by the servomotor. The load torque is controlled by the hysteresis brake.

3.1 No-load Test Figure 8 shows the input rotational speed versus output rotational speed at no load. It is understood from the figure that the ratio of the inner and outer rotor speeds is 1 : 10.333 as desired, and that the measured and calculated values are in good agreement.

3.2 Load Test Figure 9 shows the torque and speed behavior when the load torque is gradually increased and the inner and outer rotors rotate at constant speeds of 300 r/min. and 29 r/min., respectively. The figures indicate that the trial gear can transmit the required speed and torque of the ratio of 10.333 up to the maximum torque. However, the gear

Fig. 6. Expanded view the magnetic gear on the r - z plane

Fig. 7. General view of experimental setup

Fig. 8. Input and output speeds characteristics

(a) Rotational speed behavior

(b) Torque behavior

Fig. 9. Rotational speed and torque behaviors with load torque

loses synchronism when the load torque exceeds the maximum torque. It is understood that the magnetic gear has essentially overload protection function which the mechanical gear does not have. On the other hand, the maximum torque of 9.40 N·m has the difference with the one of 12.5 N·m obtained from 3D-FEA shown in Fig. 3.

The reason for the difference between the calculated and measured torques is the difference of the stack length of the pole pieces. The stack length of the pole pieces of the trial magnetic gear is 16 mm while the ones of the inner and outer rotors are 10 mm as shown in Fig. 6.

Figure 10 shows the flux density distribution on the r - θ and r - z planes around pole pieces when their stack length is 16 mm. Figure 10(a) shows that there is almost no leakage flux in radial direction around the outer rotor core. On the other hand, Fig. 10(b) indicates that the flux leaks to air around the pole pieces in the axial direction. Therefore, the effective flux which contributes to generate torque is reduced.

Figure 11 shows the stack length of the pole pieces versus the maximum transmission torque of the magnetic gear when the stack lengths of the inner and outer rotors are 10 mm each.

 (a) On the r - θ plane

 (b) On the r - z plane

Fig. 10. Flux density distribution around pole pieces

Fig. 11. Relationship between stack length of pole pieces and transmission torque

It is clear that the torque of the magnetic gear is maximized when the stack length of the pole pieces is 10 mm as the same stack length of the rotors. The maximum torque when the stack length of the pole pieces is 16 mm is calculated as 9.47 N·m, which almost agree well with the measured maximum torque of 9.40 N·m shown in Fig. 9.

3.3 Measured Efficiency Figure 12 shows the input and output powers, and efficiency of the trial magnetic gear when a load torque is 8.0 N·m. The mechanical losses are included. The figure indicates that the trial magnetic gear has high efficiency in low-speed region. The efficiency of the trial gear is about 55% when the inner rotor rotates at 3,000 r/min., and the maximum efficiency of the gear is about 85% at 200 r/min. The efficiency of the trial gear is lower than the calculated value obtained from FEA shown in Table 1. In order to discuss the reason, the no-load loss is indicated below.

Fig. 12. Input and output powers, and efficiency of trial magnetic gear

Fig. 13. Mechanical input of trial magnetic gear at no-load

Fig. 14. Expanded view of trial magnetic gear on the r - z plane

Figure 13 shows the mechanical input of the trial magnetic gear at no load. It is understood that the no-load input power obtained from the trial tests is significantly larger than the one obtained from 3D-FEA, and that the no-load input power increases exponentially when the inner rotor speed is increasing. The main cause is the eddy current loss of the aluminum housings to hold the pole pieces and outer rotor.

Figure 14 shows the expanded view of the trial magnetic gear on the r - z plane. The pole pieces and outer rotor are held by the aluminum housings. Therefore, as shown in Fig. 10, the leakage flux passes through the aluminums, and then the eddy current is induced in the aluminums.

The eddy current loss of the aluminum housings of the trial magnetic gear is estimated by 3D-FEA. The electrical conductivity of the aluminum is 3.76×10^7 S/m. Figure 15 shows the eddy current density distribution of one side of the housing to hold the pole pieces. The figure indicates that the eddy currents are induced the surface of the aluminum housing.

Fig. 15. Eddy current loss density distribution in aluminums

Fig. 16. Mechanical input of trial magnetic gear at no-load. (Including eddy current loss in the aluminums.)

Figure 16 shows the mechanical input of the trial magnetic gear at no-load obtained from measurement and the 3D-FEA considering the eddy current loss in the aluminum housings. It is clear that the no-load input power obtained from 3D-FEA is in good agreement with the one obtained from the measurements. Then it is main cause that the efficiency degradation obtained from the measurement in comparison with the calculation. Therefore, to improve the efficiency, it is necessary to reduce the eddy current in the aluminum housings.

3.4 Efficiency Improvement

To reduce the eddy current in the aluminum housings, one approach is to keep more distance between the housings and the rotors. However, the torque is decreased as shown in Fig. 11. Therefore, in this paper, the aluminum housings are replaced with Bakelite ones, the Bakelite is one of the synthetic resins, namely, non-conducting and non-magnetic material.

Figure 17 shows the expanded view of the improved trial magnetic gear on the r - z plane. It is understood that the aluminums are replaced Bakelite.

Figure 18 shows the pole pieces of the improved trial magnetic gear. The figure indicates that all the support parts are made of Bakelite.

Figure 19 shows the comparison of the efficiency of the initial and improved trial magnetic gears when a load torque is 8.0 N·m. The mechanical losses are included. It is clear that the efficiency of the trial magnetic gear employing the Bakelite is improved in comparison with the one using the aluminums as supporters. The efficiency of the improved mag-

Fig. 17. Expanded view of improved trial magnetic gear on the r - z plane

Fig. 18. Pole pieces of improved trial magnetic gear

Fig. 19. Comparison of efficiency of trial magnetic gears

netic gear is 83% when the inner rotor rotates at 3,000 r/min. The efficiency of the improved gear is lower than the calculated value shown in Table 1 due to the mechanical loss. The maximum efficiency of the improved gear achieves up to 96% at 200 r/min.

4. Conclusions

This paper described the performance analysis of the trial magnetic gear and the efficiency improvement.

It was clear that the maximum torque of the magnetic gear strongly depend on the stack length of the pole pieces, and the optimum length of the pole pieces is equal to the stack length of the inner and outer rotors.

The maximum efficiency of the initial magnetic gear was about 85% at 200 r/min. It was indicated that the eddy

current loss in the aluminum is dominant in comparison with the other losses. By replacing the aluminum housings with the Bakelite ones, the efficiency of the improved trial magnetic gear achieved up to over 96%.

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