Torque Characteristic Analysis of an Axial-gap-type Magnetic Gear developed as a Speed-up-gear

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This paper presents cogging torque reduction methods for an axial-gap magnetic gear utilizing combination of the number of poles with the stationary pole pieces and modifying the pole piece shape. The present study is aimed to develop a magnetic gear, which has a large transmission torque over 360Nm by using the three-dimensional finite element method. The maximum transmission torque of 300Nm was achieved in the prototype gear at 4.4rpm of the low-speed rotor (the gear ratio, Gr = - 13.61).

Index Terms—**Axial-gap magnetic gear, permanent magnet, cogging torque, average torque, finite element method.**

I. Introduction

THE magnetic gears are free form mechanical friction, lubricant, dust, and noise, because they can transmit torque by attraction forces between permanent magnets without contact [1-2]. In this paper, we propose a novel axial-gap-type magnetic gear designed as a speed up gear for applications in micro hydroelectric generation. Axial-gap gears can take the gap widely in comparison with radial-gap types and can be designed compactly in thin structure as an advantage. The axial-gap flux is an attractive alternative as the needed space is limited only along the axial direction [3]. The demerit is that the burden to a bearing becomes larger because the large attraction force is generated between the permanent magnets and the stationary pole pieces.

In recent years, high performance magnetic gears consisting of the permanent magnets have been investigated extensively [4-8] after proposed by Atrallah and Howe [9]. There are many types, however axial-gap types are seldom and their transmission torques are very low. The present study is aimed to develop a magnetic gear, which has a large transmission torque over 360Nm and to make a prototype gear in order to verify the performance experimentally. Application of this gear is a speed up gear for micro hydroelectric generation and it will be connected directly with a generator and a waterwheel in water. Because the installation space (length and outer diameter) is restricted, we have employed axial-gap type in this study. The torque characteristics are numerically analyzed with the three-dimensional finite element method and results are conformed experimentally. In particular, the shape of the stationary pole pieces is discussed to reduce cogging torque effectively.

II. The Axial-gap type Gear Model

The novel axial-gap-type magnetic gear was designed to reduce magnetic attraction force between the permanent magnets and the stationary pole pieces (PPs) as shown in Fig. 1. The low-speed rotor (LSR) is sandwiched between the left and right PPs. As a result, the LSR is free from the force in axial direction, because the forces acting on the both sides of the LSR are in opposite direction.

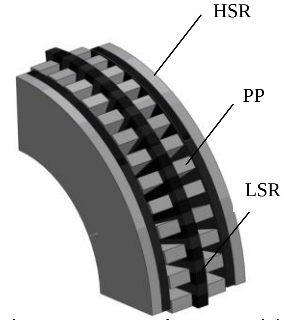

Fig. 1. The axial-gap type magnetic gear model.

Considering limited installation space, the outer diameter of the gear is assumed around 310mm. The number of poles in the high-speed rotor (HSR) is fixed to be 8 in the designing. Because there are two HSRs in the both sides, the output power is doubled. The permanent magnets are assumed as a NdFeB magnet and the magnetic materials of the back yoke of the HSRs and the stationary PPs are assumed as an electrical steel sheet, 50A470.

The gear ratio G_r can be given by

$$G_r = \mp \frac{N_l}{N_h}, \tag{1}$$

where, N_l and N_h are the number of pole pairs in LSR and HSR, respectively. The number of PPs, N_s is defined as

$$N_s = N_l \pm N_h . \tag{2}$$

The double signs in (1) and (2) are in same order. The rotational directions are opposite when the gear ratio is negative.

III. Analyzed Results

The number of PPs and the gear ratio were determined in finding out a suitable combination between N_l and N_s to obtain small cogging torque. In the analysis, we neglected the LSR for simplification because its cogging torque was smaller than one of the HSR when the gear ratio was large. Fig. 2 shows the analyzed model and the flux density distribution (N_s = 55, G_r = - 12.75). Because the number of poles in the HSR was fixed to be 8, the cogging torque became larger when N_s was equal to multiples of 4 and when N_s was an odd number. Then we selected $N_s = 55$ and $N_l = 51$ to make a prototype model in consideration of the magnet size in the LSR that we could process easily.

The cogging torque reduction was investigated numerically by changing the pole piece shape as shown in Fig. 3. Two foots were extended in alternate direction along the rotating direction of the LSR and HSR.

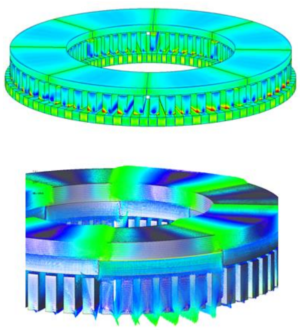

Fig. 2. Magnetic flux density distributions in the half model ($N_s = 55$).

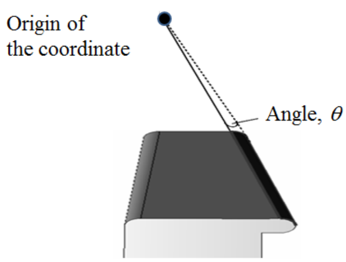

Fig. 3. Definition of foots upper side of PP.

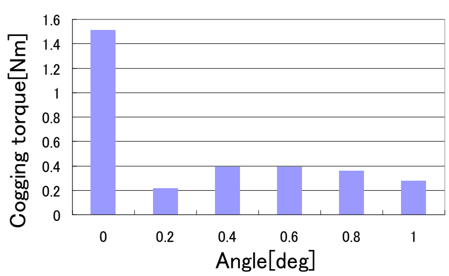

Fig. 4. Maximum cogging torque depending on the foot's angle.

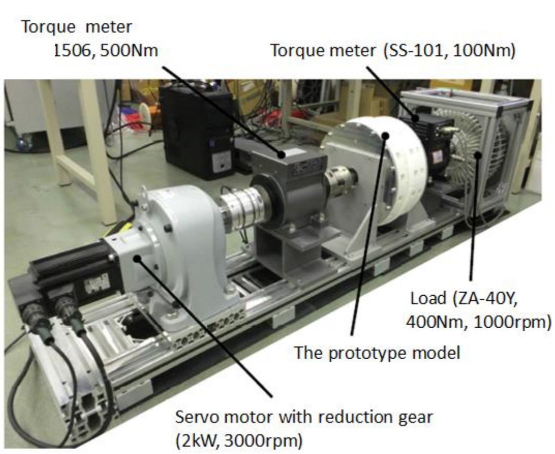

Fig. 5. Experimental setup for the prototype gear.

Fig. 4 shows the maximum cogging torque depending on the foot's angle. As we have expected to change magnetic flux smoothly at the magnetic pole boundaries, the cogging torque was successively reduced in comparison with one of the original model.

IV. Prototype Model

The prototype model was produced form the results obtained in numerical analysis. The nonmagnetic supports for the permanent magnets and the outer frame were made with a 3D printer. Fig. 5 shows the setup for experiment. The maximum transmission torque of 300Nm was achieved at 4.4rpm of LSR (at 60 rpm of HSR: $G_r = -13.61$). Because there is no space for description of the measured results, the detailed results will be shown in the full version of paper.

V. Conclusions

In this paper, the novel axial-gap-type magnetic gear was presented. The large transmission torque over 300Nm was achieved with the double HSR in the prototype gear; however large losses due to eddy currents and bearing frictions were observed and the torque could not reach the designed value over 360Nm. Also the cogging torque reduction method with the extended foots was investigated numerically and the result showed that the proposed method was effective. Optimization of segmented permanent magnet shape of the HSR will be discussed in the full paper.

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