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Analysis of Torque Characteristics according to Non-uniform Air Gaps of Coaxial Magnetic Gear

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Recently, studies on magnetic gears have been actively conducted. Magnetic gears can replace mechanical gears as they can perform noncontact power transfer, thereby minimizing loss and damage from friction. A magnetic gear has two rotors with different numbers of poles because of its structural characteristics. For a rotor with a relatively lower number of poles, large torque ripples occur owing to the increase in the permeance variation within the air gaps. Other electric equipment studies conducted thus far have primarily changed the shape of iron core to reduce torque ripples. However, since the magnetic gear has two air gaps, it is necessary to identify the relationship between the two gaps and the ripple before changing the shape of the iron core. In this paper, factors that affect torque ripple are classified and analyzed by examining the magnetic flux density of two air gaps, to propose an air gap structure that benefits the design of magnetic gears.

Keywords : magnetic gear, two air gap, torque ripple, harmonic analysis, air gap flux density, ripple factor

1. Introduction

The attractive force between an iron core and a permanent magnet is well known as the cause of cogging torque and torque ripple in electrical equipment. In electric motor design, a large number of methods for the reduction in ripple by changing the teeth shape have been proposed [1-3]. For similar instruments that use iron core and permanent magnets, those methods can be easily applied for ripple mitigation. A magnetic gear which is one of the most interested electric equipment today can replace the mechanical gear, as it can minimize the loss or damage from friction by performing noncontact power transfer [4-6]. The magnetic gear is also an equipment that uses permanent magnetic and iron core. Magnetic gears can ameliorate torque ripple by changing the structure of the pole piece that is composed of iron. The mitigation of torque ripple by changing the shape of the pole pieces is based on the principle of modulating the waveform of the air gap magnetic flux density. As a magnetic gear has two air gaps unlike an electric motor, the analysis of the flux density impact due to such change on each air gap should be first conducted. Herein, the factors that affect the output and the factors that affect the ripples are separated through the analysis of the air gap flux density of the magnetic gear. Subsequently, the impact degree of the length of the two air gaps on each factor is analyzed, to propose design guidelines that can provide a reference for the reduction in ripple through the change in the pole piece shape.

2. Magnetic Gear

A magnetic gear generally refers to a power transfer equipment that uses a permanent magnet. As power is transferred through the magnetic force of the permanent magnet, it does not cause a direct contact unlike a mechanical gear [7]. Therefore, it can minimize the heat generated from friction, as well as the damages or destructions. Its maintenance is convenient, as it does not require a lubricating oil [8]. Studies regarding using a rotor with two axes e.g., mechanical gears have been conducted in the mid or late 1990's; however, the methods proposed were not widely used despite many advantages of noncontact power transfer, owing to their

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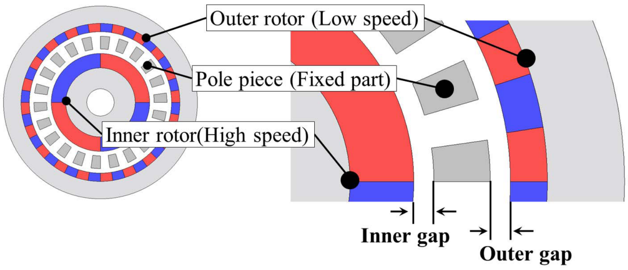
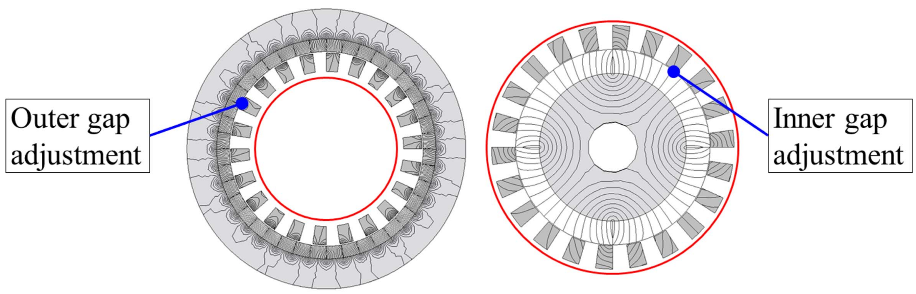


Fig. 1. (Color online) Coaxial magnetic gear.

poor torque density and transfer efficiency [9, 10]. Subsequently, in 2001, Atalleh *et al.* suggested a coaxial magnetic gear with significantly improved transfer efficiency for the first time [4]. Currently, many studies are conducted on coaxial magnetic gears. A coaxial magnetic gear has a shape as demonstrated in Fig. 1. It is composed of three parts—inner rotor (4 poles), pole piece (24 poles), and outer rotor (40 poles). Because of its characteristics that enable each part to rotate separately, a magnetic gear has two air gaps: inner gap and outer gap. In magnetic gear studies conducted thus far, the length of the two gaps were calculated from the perspective of manufacturing precision and output decision; therefore, the same length was applied to the two air gaps. However, there is no reason to apply the same length for both air gaps in all cases. In some electric equipment studies on the amelioration of torque ripple, the length of the gap changes partially by peeling the edge of the pole piece or inserting an arc to the side of the pole piece. Therefore, the impact degree of the length variation of the two air gaps on the characteristics of the magnetic gear needs to be more clearly identified.

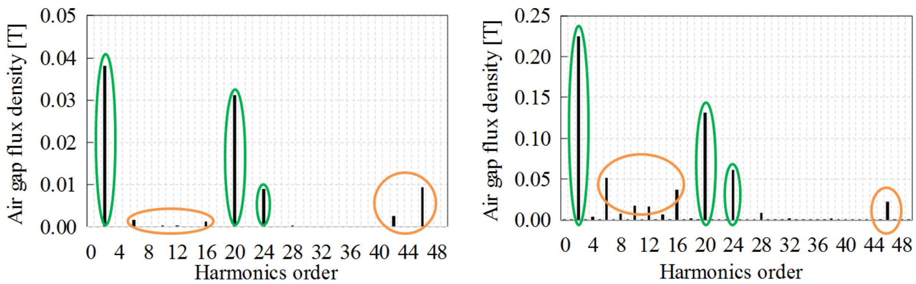
3. Analysis of Major Characteristics of Magnetic Gear

The pole piece of a magnetic gear modulates the magnetic flux from the permanent magnet of each rotor and transfers it. In detail, the magnetic flux generated from the inner rotor is modulated and transferred to the outer rotor, and the magnetic flux generated from the outer rotor is modulated and transferred to the inner rotor. The model shown in Fig. 2 was developed to distinguish the modulated magnetic flux for analysis. (a) is a model for the analysis of the magnetic flux of the inner gap with the outer rotor and pole piece only. (b) is a model for the analysis of the magnetic flux of the outer gap with the inner rotor and pole piece only. The harmonic analysis result of the air gap flux density is displayed in Fig. 3. In the Fig. 3(a), the 20th harmonic is generated from the 40 poles on the outer rotor, and the 24th harmonic is generated from the 24 pole pieces. The 2nd harmonic which synchronizes with the 4 poles on the inner rotor is that the



(a) Inner gap flux density model (b) Outer gap flux density model

Fig. 2. (Color online) Air gap flux density model.



(a) Inner gap flux harmonics (b) Outer gap flux harmonics

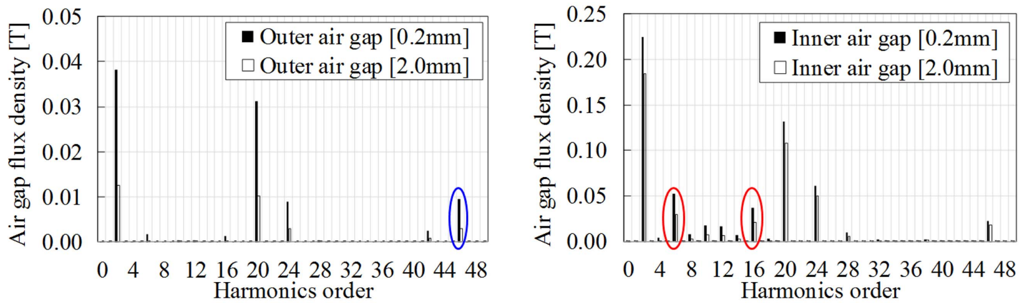
Fig. 3. (Color online) Air gap flux harmonics.

magnetic flux of 40 poles on the outer rotor is modulated through the pole piece. In the Fig. 3(b), the 2nd harmonic is generated from the 4 poles on the inner rotor, and the 24th harmonic is generated from the 24 pole pieces. The 20th harmonic which synchronizes with the 40 poles on the outer rotor is that the magnetic flux of 4 poles on the inner rotor is modulated through the pole piece. The abovementioned 2nd, 20th, and 24th harmonics are factors for the output transfer; therefore, it can be seen that the other harmonics including the 6th, 16th, and 46th function as torque ripple.

4. Analysis of Impact from Adjustment of Air Gap Length

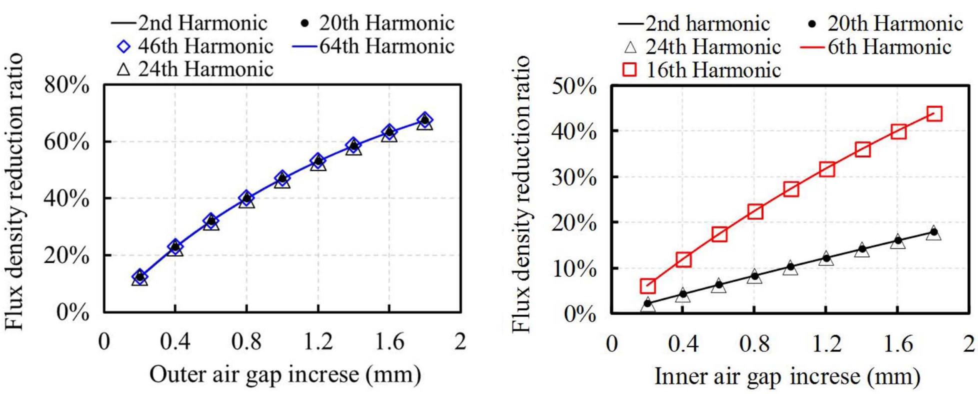
The following are the conditions required to analyze the impact of the change in the length of the two air gaps of a magnetic gear on the factors of the output transfer and the factors that cause the torque ripples. A pole piece is a structure that functions as a baseline, which fixates the shape, size, and location. The thickness of the permanent magnetic in the R-axis side is fixed, as the size of the permanent magnet affects the intensity of the magnetic force. Therefore, the air gap distances between the pole piece and rotors were adjusted by modifying the diameter of each rotor. The air gap flux densities of the model with an air gap length of 0.2 mm and the model with an air gap length of 2.0 mm were analyzed. The result of the analysis is demonstrated in Fig. 4. As shown in the graph, the magnetic flux density decreases following the increase in the air gap length. However, the degree of magnetic flux decrease differs for each air gap. As displayed in Fig. 4(a), the 2nd, 20th, and 24th harmonics that are the factors of the output transfer decrease by more than 60 %, from 0.038 T to 0.012 T, 0.03 T to 0.01 T, and 0.009 T to 0.003 T, respectively, following the adjustment of the outer gap. Meanwhile, as shown in Fig. 4(b), the 2nd, 20th, and 24th harmonics show less decrease by 18 %, from 0.22 T to 0.18 T, 0.13 T to 0.11 T, and 0.06 T to 0.05 T, respectively, following the adjustment of the inner gap.

For a detailed analysis of the factors that cause the torque ripples, the degree of air gap flux density decrease following the change in the air gap length is presented for each factor. The two factors other than the three output transfer factors have the largest value among the torque ripple factors. As demonstrated in Fig. 5(a), the decrease rate for all the torque ripple factors is high when the outer air gap is adjusted, and the inclination gradually decreases



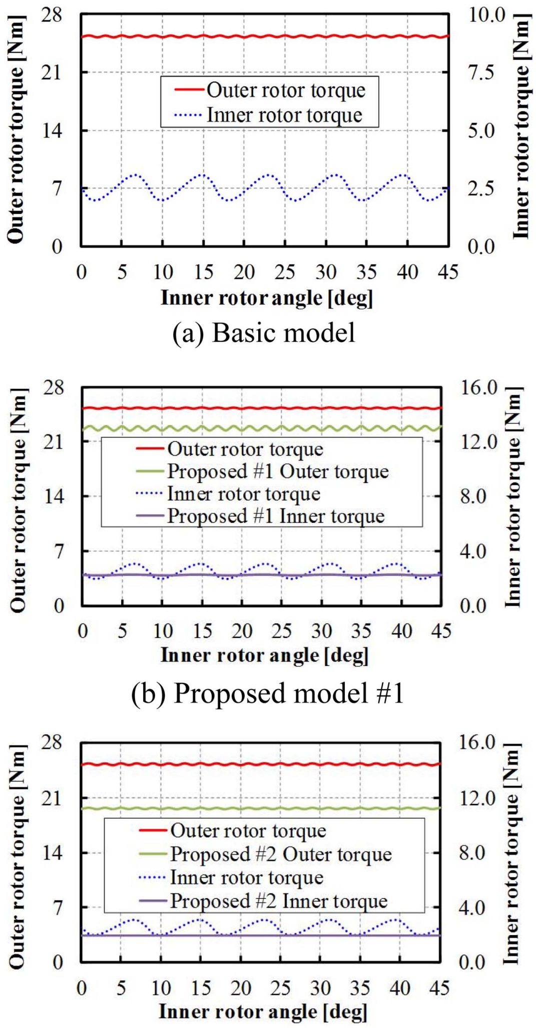
(a) Inner gap flux density (b) Outer gap flux density

Fig. 4. (Color online) Air gap flux density by gap length adjustment.



(a) Inner gap flux density (b) Outer gap flux density

Fig. 5. (Color online) Flux density reduction ratio by air gap length.



(a) Basic model

(b) Proposed model #1

(c) Proposed model #2

Fig. 6. (Color online) Torque waveform of basic and proposed model.

following the increase in the air gap length. When the inner air gap is adjusted as in Fig. 5(b), the decrease rate of the torque ripple factors rises following the increase in the air gap length. The factors of output transfer change as well, but the degree of change is approximately 30 % when compared to Fig. 5(a), indicating that the effect of the amelioration of ripple in consideration of the output decrease is significant when the inner air gap is adjusted.

The abovementioned results were combined and applied to the basic model with a 0.4 mm length for the two air gaps, as presented in Fig. 6 and Table 1. The basic model is a 10:1 magnetic gear with 2.5-Nm inner torque, 25-Nm outer torque, 44 % inner ripple, and 1 % outer ripple. To minimize the output reduction due to the air gap length, the outer air gap was reduced to 0.2 mm and the inner gap was increased to 2 mm to mitigate the inner ripple, as in Proposed #1. Consequently, the inner ripple was ameliorated by 95 %, while the output reduction was minor at approximately 10 %. However, the outer ripple increased by more than twofold, following the decrease in the outer gap length. In Proposed #2, the length of the outer gap was the same and only the length of the inner gap increased to 2 mm, to mitigate the inner ripple. The result shows approximately 20 % in output reduction, and is higher compared to Proposed #1; however, the inner ripple was ameliorated by 95 % while the outer ripple remained the same.

5. Conclusion

This paper proposed the design guidelines that can reduce ripples by changing the shape of a pole piece, based on the analysis of the impact of the length of the two air gaps of a magnetic gear on each of the output and ripple factors. The factors that affect the output and torque ripples were separated through the analysis of the harmonic waves of the air gap flux density, and the characteristics of their change following the variation in the length of air gaps were examined. The result demonstrated that the outer air gap is sensitive to the increase or decrease in the output and ripple, while the inner air gap is more sensitive to the increase or decrease in ripples than to the output. Generally, since a magnetic gear designs with a larger number of poles in its outer rotor, variation of the permeance within the outer air gap maintains a consistent level. Therefore, it is advantageous for low ripple design. Similarly, adjustment of outer air gap has only little influence on the change in outer ripple which is basically low and it just caused a severe output reduction. Meanwhile, the inner ripple is likely to occur high since the number of poles in the inner rotor is designed to be low. This study confirmed that the adjustment of the inner air gap yields a more significant ripple reduction effect, considering the degree of the output reduction. Therefore, it can be applied to the improvement in ripple separately, or for its application through the change in the pole piece.

Table 1. Result.

No.	Inner air gap	Outer air gap	Inner torque	Outer torque	Inner ripple	Outer ripple
#1	2 mm	0.2 mm	2.27 Nm	22.34 Nm	2.07 %	3.12 %
#2		0.4 mm	1.98 Nm	19.77 Nm	2.34 %	0.94 %

In addition, because the inner rotor rotates at a high speed, a shatter-proof structure such as a sleeve is essential at 10,000 rpm or a higher speed, to prevent scattering of permanent magnet. Therefore, the effect of lengthening the inner air gap suggested herein will be useful not only for the reduction of ripple, but also for the design of structures appropriate for sleeve applications.

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