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Effect of Stationary Pole Pieces with Bridges on Electromagnetic and Mechanical Performance of a Coaxial Magnetic Gear

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In a coaxial magnetic gear, bridges connecting separate pole pieces are useful for fabrication and also improve mechanical reliability. However, they have a negative influence on electromagnetic performance parameters such as transmission torque and iron loss. This paper investigates the effect of stationary pole pieces connected by bridges on the electromechanical characteristics. The bridge type and thickness are the main parameters influencing the performance of a coaxial magnetic gear. The inner, center, and outer bridge types each show the best performance in terms of different characteristics. However, for any bridge type, an increase in the bridge thickness reduces the overall electromagnetic performance, except for the torque ripple, and improves the overall mechanical performance, including the deformation, von Mises stress, and natural frequency of the stationary part.

Keywords : a coaxial magnetic gear, torque transmission, modal analysis, von mises stress

1. Introduction

Magnetic gears have been proposed by the unique advantage of contactless power transmission compared with mechanical gears. With this benefit, they can limit torque under overloaded conditions and have excellent performance in terms of noise, vibration, and reliability [1]. However, they have been used in a very limited range of applications owing to the poor utilization of a permanent magnet (PM) and thus very low torque per unit volume density. Among the various magnetic gears, the coaxial magnetic gear is considered as a promising candidate to overcome the poor torque density and has been extensively studied for its relatively high performance [2]. It consists of an inner rotor, an outer rotor, and stationary pole pieces in between the rotors.

The stationary pole pieces in the coaxial magnetic gear have an important role in torque transmission by modulating the airgap flux density distribution between the inner and the outer rotors. It also tolerates the shear stress generated by the inner and outer rotors at the facing surfaces of both rotors. In general, the stationary part is molded by epoxy resin with multiple separate pole pieces. This is a disadvantageous structure for manufacturing and for high-torque transmission with a coaxial magnetic gear. Thus, a structure in which pole pieces are connected by bridges has been proposed to compensate for the drawbacks of the conventional structure [1, 3].

This paper investigates the electromagnetic and mechanical performance of a coaxial magnetic gear with bridges at various positions and of various thicknesses. The electromagnetic characteristics include the maximum transmitted torque, torque ripples on both rotors, and iron loss on the stationary part. These are analyzed and compared by using two-dimensional finite element analysis (2D-FEA) and the iron loss model developed by Berotti [4]. The mechanical parameters include deformation, von Mises stress, and natural frequency of the stationary part. These were analyzed by using three-dimensional finite element analysis (3D-FEA).

2. Electromechanical Analysis

2.1. Analysis model

Fig. 1 shows a schematic of the coaxial magnetic gear considered in this paper. The torque is transmitted through stationary ferromagnetic pieces having many separate

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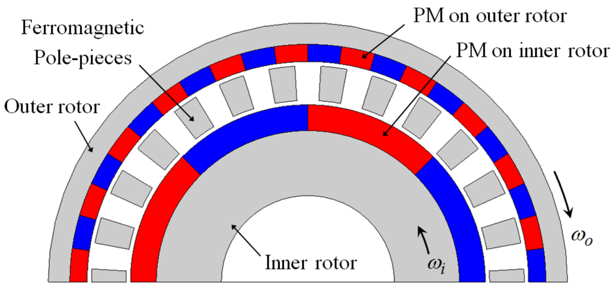


Fig. 1. (Color online) Structure of a coaxial magnetic gear.

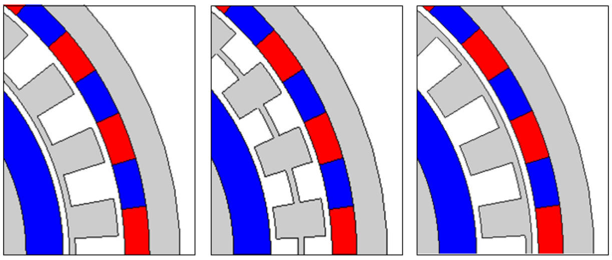
Table 1. Specifications of a coaxial magnetic gear.

Quantity	Value
Outer radius of outer rotor [mm]	60
Inner radius of outer rotor [mm]	55
Outer radius of stator pole pieces [mm]	50
Inner radius of stator pole pieces [mm]	42
Outer radius of inner rotor [mm]	35
Outer rotor magnet thickness [mm]	4
Inner rotor magnet thickness [mm]	6
Stack length of stationary pole pieces [mm]	60

poles. Let p be the number of pole pairs of the inner rotor, and n_s be the number of stationary pole pieces. Then, the gear ratio is expressed as

$$G = \frac{n_s - p}{p} \tag{1}$$

For the basic analysis model, p and n_s are set as 4 and 26, respectively, resulting in a gear ratio of 5.5:1; the other important dimensions are listed in Table 1. For connecting the separate pole pieces in the basic analysis model, there are three ways to apply bridges, as shown in Fig. 2. The bridge types are classified on the basis of their position: inner, center, and outer parts between the separate pole pieces.



(a) (b) (c)

Fig. 2. (Color online) Structure of stationary pole pieces with different bridge types: (a) inner bridge, (b) center bridge, and (c) outer bridge.

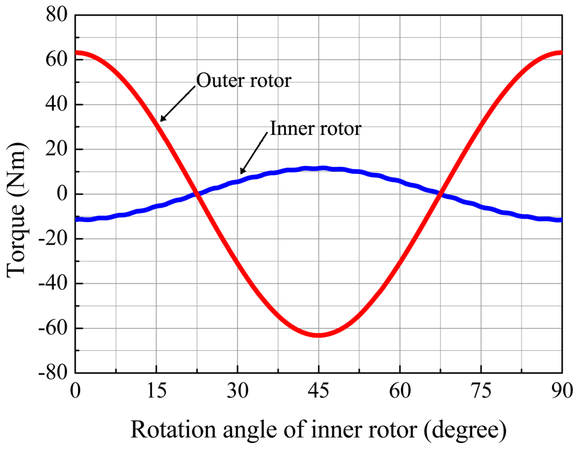


Fig. 3. (Color online) Comparison of torque for the inner and outer rotor.

2.2. Electromagnetic analysis

In the coaxial magnetic gear, the airgap flux density distribution is an important factor influencing the maximum transmitted torque. However, the bridges tend to interrupt modulation of the airgap flux density owing to considerable flux leakage, which is caused by closing of the magnetic paths through the bridges. The flux leakage generated by the bridges eventually reduces the maximum torque on both rotors and causes additional iron losses on the stationary part. The torque exerted on both rotors can be calculated by 2D-FEA with the commercial software package FLUX 2D. Fig. 3 shows the variations in the torque on both rotors when the outer rotor is fixed and the inner rotor rotates. The values of the maximum torque on the inner and outer rotors are –11.49 N·m and 63.22 N·m, respectively. When the torque is transmitted from the inner rotor (high-speed side) to the outer rotor (low-speed side), the latter rotates in the reverse direction to that of

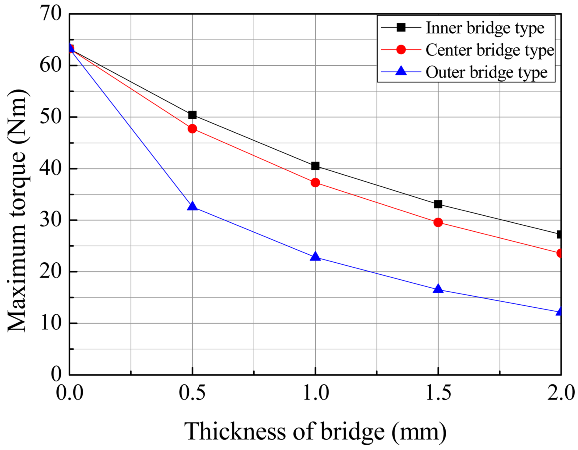


Fig. 4. (Color online) Maximum torque on the outer rotor for various bridge thicknesses.

the inner rotor, as shown in Fig. 1. Thus, the stationary pole pieces experience a clockwise torque of 11.49 N·m and a counterclockwise torque of 63.22 N·m on their inside and outside surfaces, respectively.

Fig. 4 compares the variation in the maximum torque on the outer rotor according to the position and thickness of the bridges. The thickness is increased from 0 to 2 mm. When the thickness of the bridges is increased from 0 to 0.5 mm, the maximum torque is decreased by 20%, 26%, and 48% for inner, center, and outer bridge types, respectively. With a further increase in the bridge thickness, the maximum torque is consistently diminished by up to 57%, 63%, and 89%, respectively. However, the gear ratio of the coaxial configuration is constant regardless of the bridge type. From the analysis, it is apparent that outer bridges afford significantly worse results in terms of the maximum torque compared with the other two bridge types. It is also reasonable that the thickness of the bridges should be as low as possible to increase the maximum torque in the coaxial magnetic gear by reducing leakage flux though the bridges.

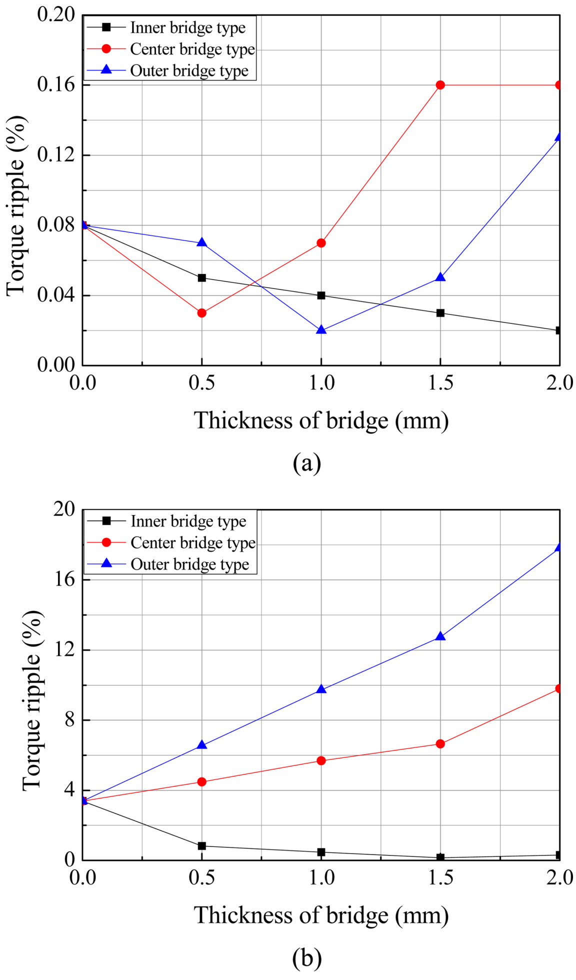


Fig. 5. (Color online) Torque ripple ratio for various bridge thicknesses on (a) outer rotor and (b) inner rotor.

Fig. 5 shows the changes in the torque ripple on both rotors according to the bridge type and thickness. The torque ripple is defined as the ratio of the peak-to-peak value to the average for the maximum torque when the rotors rotate at the maximum torque angle. With the center and outer bridge types, the peak-to-peak value of the torque is practically constant; however, the average torque decreases with an increase in the bridge thickness, as shown in Fig. 4. Thus, the torque ripple tends to increase with the bridge thickness. In contrast, with the inner bridge type, the peak-to-peak torque decreases at a higher rate than the decline in the average torque with an increase in the bridges thickness. Thus, in this case, the torque ripples on both rotors are gradually reduced with an increase in the bridge thickness.

In order to analyze the iron loss on the stationary part with the bridges, the iron loss model developed by Berotti was used [4]. In the frequency domain, the specific iron loss can be separated into hysteresis loss P_h, classical eddy current loss P_c, and excess loss P_e as follows:

$$P_{loss} = P_h + P_c + P_e = k_h f B_m^{\alpha} + k_c f^2 B_m^2 + k_e f^{1.5} B_m^{1.5} \quad (2)$$

where f and B_m are the frequency and maximum magnetic flux density, respectively. Coefficients k_h, k_c, k_e, and α are determined from the measured data at a certain frequency. Fig. 6 compares the iron losses according to the position and thickness of the bridges when the inner rotor rotates at 1100 rpm. An increase in the bridge thickness from 0 mm to 0.5 mm caused a rapid increase in the iron loss to 218%, 171%, and 193% for the inner, center, and outer bridge types, respectively. Thus, an increase in the thickness of the bridges tends to cause an increase in the iron loss on the stationary part. Under the same frequency

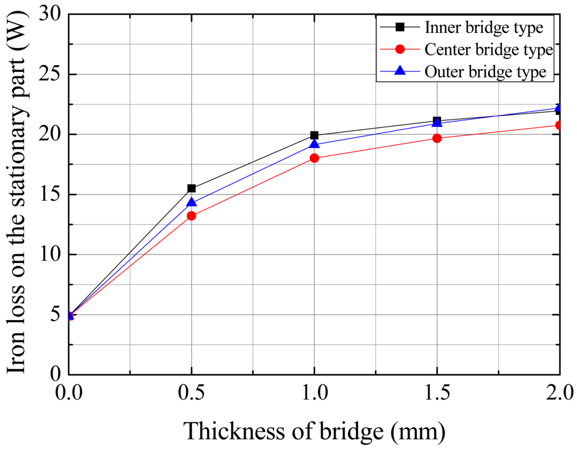
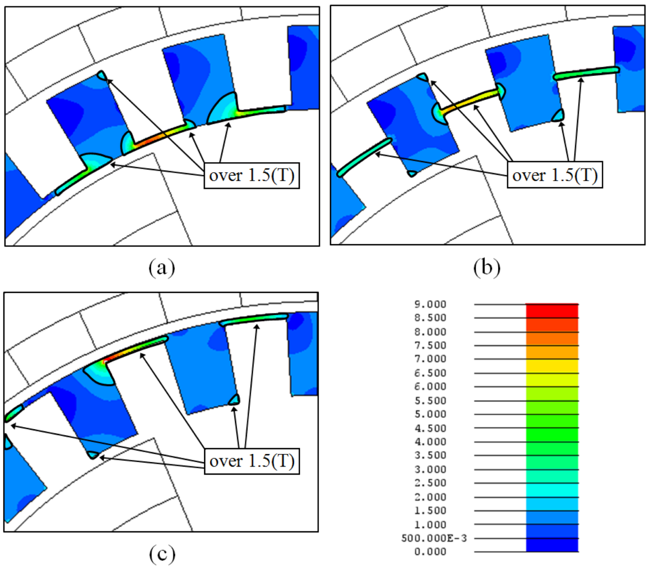


Fig. 6. (Color online) Comparison of iron loss on the stationary part for various bridge thicknesses.



(a) (b) (c)

Fig. 7. (Color online) Flux density distribution on the stationary part with different bridge types: (a) inner bridge, (b) center bridge, and (c) outer bridge.

conditions, the iron loss depends on the peak magnetic flux density and volume of the analysis model.

For 0.5-mm-thick bridges, the volumes of the stationary parts differ by only 1% among bridge types. Thus, the peak flux density is the dominant factor influencing the iron loss. Fig. 7 shows the flux density distribution on the stationary part for 0.5-mm-thick bridges. In the center bridge type, the bridge experiences somewhat low magnetic flux density, which is caused by the relatively low iron loss.

2.3 Mechanical analysis

The separate pole pieces are useful for relatively high torque transmission with a coaxial magnetic gear. However, this configuration is difficult to manufacture and mechanically weak against the shear stress generated by the rotors. In order to overcome these problems, bridges are used to connect the pole pieces. To investigate the mechanical effects of the bridges, structural analysis and modal analysis for the stationary parts with the bridges were carried out using the commercial software package ANSYS. The separate pole pieces were fixed by epoxy resin. Table 2 lists the material properties of the epoxy resin and steel for the pole pieces and bridges.

Table 2. Material properties of steel and epoxy resin.

Quantity	Steel	Epoxy resin
Young's modulus [GPa]	200	3.5
Poisson's Ratio	0.3	0.34

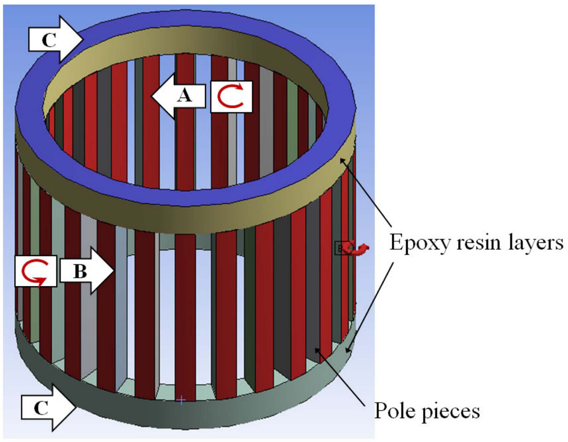


Fig. 8. (Color online) Boundary conditions for structural analysis.

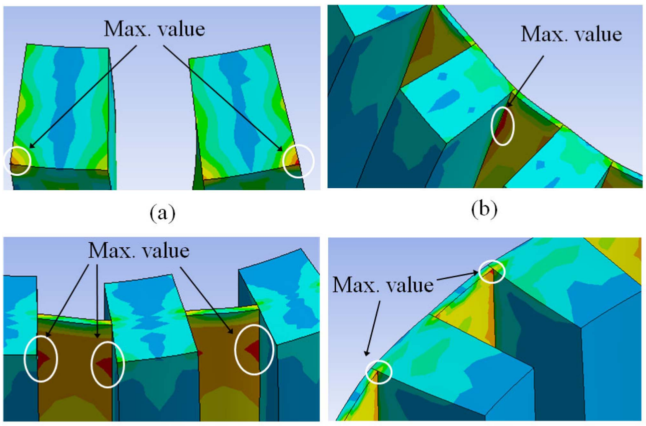
Table 3. Maximum deformation and von Mises stress for different bridge positions and thicknesses.

		Max. deformation (μm)	Max. von Mises stress (Mpa)
No bridge type		3.17	2.90
Inner bridge type	0.5 mm	2.52	5.04
	1.0 mm	2.36	3.56
	1.5 mm	2.27	2.72
	2.0 mm	2.22	2.29
Center bridge type	0.5 mm	2.41	4.80
	1.0 mm	2.26	3.45
	1.5 mm	2.19	2.64
	2.0 mm	2.14	2.58
Outer bridge type	0.5 mm	2.38	5.07
	1.0 mm	2.24	4.03
	1.5 mm	2.18	2.57
	2.0 mm	2.14	2.61

In the structural analysis, the maximum deformation and von Mises stress were calculated under the boundary conditions shown in Fig. 8. The three boundary conditions employed are as follows:

- A-surfaces: clockwise torque generated on the inside of pole pieces, 11.49 N·m;
- B-surfaces: counterclockwise torque generated on the outside of pole pieces, 63.22 N·m;
- C- surfaces: fixed support on top and bottom surfaces of the stationary part

The mechanical failure of the stationary part can be analyzed on the basis of the von Mises stress [5]. It is an equivalent stress derived from the principal stresses, and mechanical failure occurs when the maximum von Mises stress exceeds the yield stress of the material. Table 3 compares the maximum deformation and von Mises stress



(a) (b) (c) (d)

Fig. 9. (Color online) Distribution of von Mises stress: (a) no bridge, (b) inner bridge, (c) center bridge, and (d) outer bridge.

Table 4. Results of modal analysis for different bridge positions and thicknesses.

		1st (Hz)	2nd (Hz)	3rd (Hz)
No bridge type		1410.7	1745.8	3168.5
Inner bridge type	0.5 mm	1064.4	1679.6	2846.4
	1.0 mm	1080.1	1739.3	2936.8
	1.5 mm	1082.0	1781.0	2962.8
	2.0 mm	1083.2	1813.0	2989.6
Center bridge type	0.5 mm	1450.1	1735.2	3232.4
	1.0 mm	1495.0	1781.4	3342.1
	1.5 mm	1555.4	1901.5	3496.6
	2.0 mm	1628.5	2090.9	3685.2
Outer bridge type	0.5 mm	1655.2	2500.8	3702.2
	1.0 mm	1672.0	2532.6	3753.9
	1.5 mm	1682.7	2541.8	3801.4
	2.0 mm	1699.0	2565.6	3859.7

on the stationary part. With an increase in the bridge thickness from 0 to 0.5 mm, the maximum deformation decreased by 24%, 21%, and 25%; however, the maximum von Mises stress increased by 74%, 66%, and 75% for the inner, center, and outer bridge types, respectively. The maximum von Mises stress is generated on the joint between the pole pieces and bridges, as shown in Fig. 9, and is decreased by an increase in the bridge thickness. In all cases, the maximum von Mises stress had considerable margin from the yield stress of steel which has a typical value of 250 Mpa. In terms of deformation, the lowest value was obtained in the outer bridge type, and it decreased with an increase in the bridge thickness.

Table 4 compares the natural frequency of the stationary parts, as obtained by the modal analysis. With a change in thickness from 0 to 0.5 mm, the first natural frequency decreased by 25% for the inner bridge type, while it increased by 3% and 17% for the center and outer bridge types, respectively. The natural frequency for all the bridge types gradually increased with the bridge thickness. From the mechanical analysis, it is found that bridges reduce the deformation on the stationary part for all bridge types, even though thin bridges cause increased maximum von Mises stress on the joints of the pole pieces and bridges. In particular, the outer bridge type shows the best mechanical performance among the three bridge types tested herein.

3. Conclusion

This study investigates the effects of the stationary parts connected by bridges on the electromechanical performance of a coaxial magnetic gear. The position and thickness of the bridges are the main parameters influencing the performance. The inner bridge type has the best performance in terms of the maximum torque and torque ripple; however, it produces large iron losses compared with the other two bridge types. The outer bridge type shows the worst electromagnetic characteristics; however, it has the best mechanical performance in terms of deformation and natural frequency. In addition, the center bridge type provides good performances in terms of iron loss and von Mises stress. In any bridge type, however, an increase in the bridge thickness reduces the overall electromagnetic performance, except the torque ripple, and improves the overall mechanical performance.

Acknowledgments

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