Effects of Design Parameters on the Transmitted Torque of a Coaxial Magnetic Gear with Halbach Permanent-Magnet Array

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Abstract: The magnetic gear with Halbach Permanent-Magnet array can offer higher on transmitted torque compare to radially magnetized permanent magnet and also capable of increasing the magnetic field. Then, the study of this paper focuses on the effects of critical design parameters on the transmitted torque. Furthermore, the magnetic field and the steady-state torque characteristic of Halbach type computed by commercial software ANSYS/Maxwell. Under the use of Taguchi method, determined parameters in four levels, and focused on five factors comprise the length of outer and inner rotor iron part, the length of outer and inner rotor permanent magnet, and the length of pole pieces. Analysis result shows the optimum condition, the percentage contribution of the design parameter using the ANOVA test, and the prediction torque was also obtained. Finally, this paper shows the contribution of the outer and inner rotor permanent magnet with 0.35% and 15.53%. The radial length of the pole pieces contributed 3.21%. While the percentage of the outer rotor iron part is 77.18%, and the inner rotor iron part does not significantly affect to the steady-state torque, then it pooled. The estimated torque at optimum condition is 2179.55 Nm.

1 INTRODUCTION

The magnetic gear developed since 1941 (Fau, 1941). At that time, the magnet has two gears, and the rotating axes are parallel to each other. Then, Atallah and Howe (2001) discovered a new magnetic gear type which still being developed until now. The magnetic gear has a low-speed rotor, high-speed rotor, permanent magnets and stationary steel pole-pieces (Atallah and Howe, 2001). Generally, the use of magnetic gear is to replace the functions of mechanical gear. This idea based on the disadvantage of mechanical gear and the advantage of a magnetic gear. Mechanical gear has disadvantages at risk of transmission failure (because of the physical contact between the gears), need periodic maintenance, generates friction and vibration. Moreover, mechanical gear also at risk of overheating. Overheating condition can destruct the structure of the gear, and if the rotation speed is too high, the gear teeth will be melted. In contrast, magnetic gear can be a solution. Magnetic gear has the advantage of transmitting power without physical contact. The other advantages are no vibration and noise, and no maintenance, and its inherent overload protection (Atallah and Howe, 2001; Acharya et al., 2013; Uppalapati et al., 2014).

In the last ten years, industry and institution did research and development about magnetic gear technology. From the research approach, shown in Figure 1 is some publications about magnetic gear accessed from web of science (2018). Those institutions' study not only about the characteristic of magnetic gear, but also about the application of magnetic gear. The researches about magnetic gear characteristics, for example, investigates torque, torque density, eddy current, pole piece shapes, topologies, and noise-vibration. The examples of magnetic gear application are for wind turbine, wave energy conversion, geared-motor, vehicles transmission, and so on. This topic is strongly possible to reach steps for commercial application (Wu et al., 2018; Li, K. et al., 2017; Liu et al., 2014; Li, W. et al., 2017).

The most popular type of magnetic gear is coaxial magnetic gear. Not only more accessible in the manufacturing process, but this type also produces higher transmitted torque than mechanical gear. Using magnetic gear can produce a stable transmitted torque when the rotor rotates at different speeds (Neves and Flores, 2014). Beside coaxial

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type, there are other types which are radial magnetic gear, transverse magnetic gear, worm magnetic gear, planetary magnetic gear, rack and pinion gear, bevel gear, and harmonic gear (Chen et al., 2014; Tlali et al., 2014). Coaxial magnetic gear also has various topologies for example radially magnetized, and Halbach magnetized. Based on previous researches, Halbach permanent-magnet array can offer higher maximum torque. It also has lower torque ripple, lower iron losses and also capable of increasing magnetic field (Choi and Yoo, 2008; Jian et al., 2009; Jian, 2010). It means that for transmitted torque demand, Halbach arrangement is a good choice to be developed. Finally, this study of this paper focuses on the effects of Halbach critical design parameters on the transmitted torque.

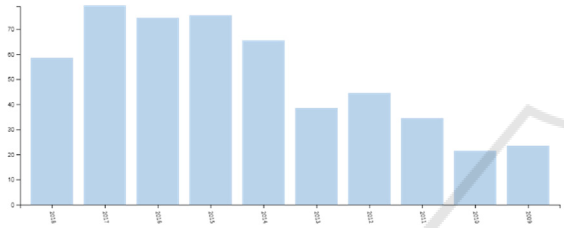


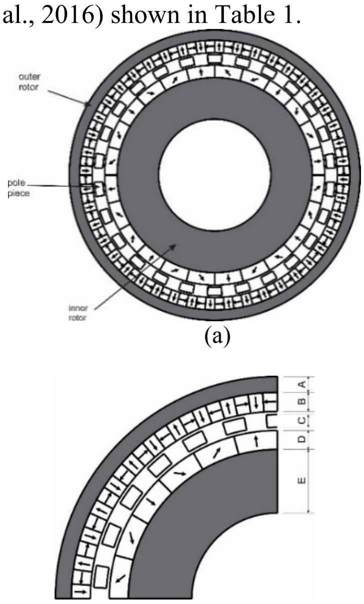
Figure 1: The publication on magnetic gears. (Source: web of science).

1.1 Design Parameters

The Halbach permanent-magnet arrangement used in this paper shown in Figure 2(a). As shown in Figure 2(a), the magnet direction in permanent-magnet arranged by outward-concentrated magnetic field for the inner rotor and inward-concentrated field for the outer rotor.

Figure 2(b) shows the radial length of outer rotor iron part coded as A. B defines radial length of outer rotor permanent magnet. C and D in sequence define radial length of pole piece and radial length of inner rotor permanent magnet. The code E defines radial length of inner rotor iron part. This codes (A, B, C, D, and E) made as factors in this study. Then, these parameters investigated by ANSYS/Maxwell software.

The magnetic gear used in this research has parameters shown in Table 1. This magnetic gear has one input and one output. Under steady-state condition, the simulation of magnetic gear needs to be rotated in a reverse direction between input and output. The input of this simulation is inner rotor, and the output of the simulation is outer rotor. Using 2D ANSYS/Maxwell simulation, set two motion set up to investigate the maximum torque produced by the magnetic gear. The design parameters in this study are identical with the previous research (Mateev et al., 2016) shown in Table 1.



(a)

(b)

Figure 2: (a) Halbach permanent magnet array (b) Critical design parameters.

Table 1: Design parameters of a coaxial magnetic gear mechanism.

Parameter	Value
Number of outer rotor pole pairs (P_o)	26
Number of inner rotor pole pairs (P_i)	4
Number of pole piece (z)	22
Diameter of outer rotor (mm)	140
Diameter of inner rotor (mm)	54
Air-gap length (mm)	1
Radial length of outer rotor iron part (mm)	5
Radial length of outer rotor PM (mm)	6
Radial length of pole piece (mm)	4
Radial length of inner rotor PM (mm)	6
Radial length of inner rotor iron part (mm)	20

Based on Table 1, had been shown the value of parameters. The number of inner rotor pole pairs (p_1), outer rotor pole pairs (p_2) and pole pieces (Ns) defined by (1). The obtaining of pole pair number effected to the gear ratio. The gear ratio of magnetic gear used in this research is 5.5. The number of Gear ratio (Gr) defined by (2). Otherwise, to simulating gear rotation need to consider the rotation speed of the input and output links. The rotational speed of inner rotor (w_1) defined by gear ratio and the rotational speed of outer rotor (w_2) as presented in (3) (Kim et al., 2015).

$$Ns = p_1 + p_2 \quad (1)$$

$$w_1 = -Gr\, w_2 \quad (2)$$

$$w_1 = -Gr\, w_2 \quad (3)$$

During the simulation process using ANSYS/ Maxwell, the material for inner and outer rotor is iron. The material for a permanent magnet is NdFeB35. The material for pole pieces is Steel 1008. The objective of simulation is to gain the transmitted torque in a steady-state condition. Inner rotor and outer rotor rotate in reverse direction with the amount 150 rpm and 27.27 rpm.

2 TAGUCHI METHOD

This research used Taguchi method which the use of this experimental method allows examining under various circumstances (factors). Taguchi Method has three quality characteristics: nominal the best, larger the better and smaller the better. Because of this research investigated transmitted torque with an unlimited number. Therefore the fit characteristic was larger the better characteristic (Taguchi et al. 2005). Based on the previous explanation, the factors for the research variable were factor A, B, C, D, and E. The factors observed in 4 different levels. The used of 5 factors and four levels were demonstrated by Standard Orthogonal Array L16(5^4). These mean there were 16 various experiments with five factors and four levels as shown in Table 2 and Table 3.

The simulation processed based on the various parameters shown in the Table 3. By using the Taguchi Method, the observer could gather the optimum condition, contribution each factor to the result and estimate the result under the optimum conditions. After investigating, the result analyzed using Analysis of Variance (ANOVA), so the final result would be established the percentage contribution of each factor to the transmitted torque (Taguchi et al., 2005; Roy, 1990).

Table 2: Factor and Level.

Factor	Level 1	Level 2	Level 3	Level 4
A	5	10	15	20
B	6	4	7	5
C	4	7	5	6
D	6	5	4	7
E	20	15	10	5

Table 3: Orthogonal Array.

	A	B	C	D	E
1	5	6	4	6	20
2	5	4	7	5	15
3	5	7	5	4	10
4	5	5	6	7	5
5	10	6	7	4	5
6	10	4	4	7	10
7	10	7	6	6	15
8	10	5	5	5	20
9	15	6	5	7	15
10	15	4	6	4	20
11	15	7	4	5	5
12	15	5	7	6	10
13	20	6	6	5	10
14	20	4	5	6	5
15	20	7	7	7	20
16	20	5	4	4	15

3 RESULT AND DISCUSSION

Using ANSYS/Maxwell software obtain magnetos tatic field and transmitted torque. The magnetostatic field will be useful for future research assistant tool in optimizing magnetic gear design (Wu, 2015). It is related to increasing its field based on pole piece shapes as well as permanent magnet arrangement. Figure 3 presents the magnetostatic field in angle 45^0 from 16 experiments. Magnetostatic field presented in the same color scale which can be compared to another experiment from the color.

Moreover, the value of the steady-state transmitted torque shown in Table 4. This value then shows the ability of every single magnetic gear experiments to transmit power and torque. The table also shows the signal to noise which measures the sensitivity and external influencing factors, not under control.

Based on Table 4, the transmitted torque in optimum condition attains 2150.76 Nm which came from experiment 4. The factors value in experiment 4 were level 1 for A factor and level 4 for another factor. The lowest transmitted torque found in experiment 16 which only 989.62 Nm. The factors value in experiment 16 were level 4 for A and B factor, level 1 for C factor, level 3 for D factor and level 2 for E factor.

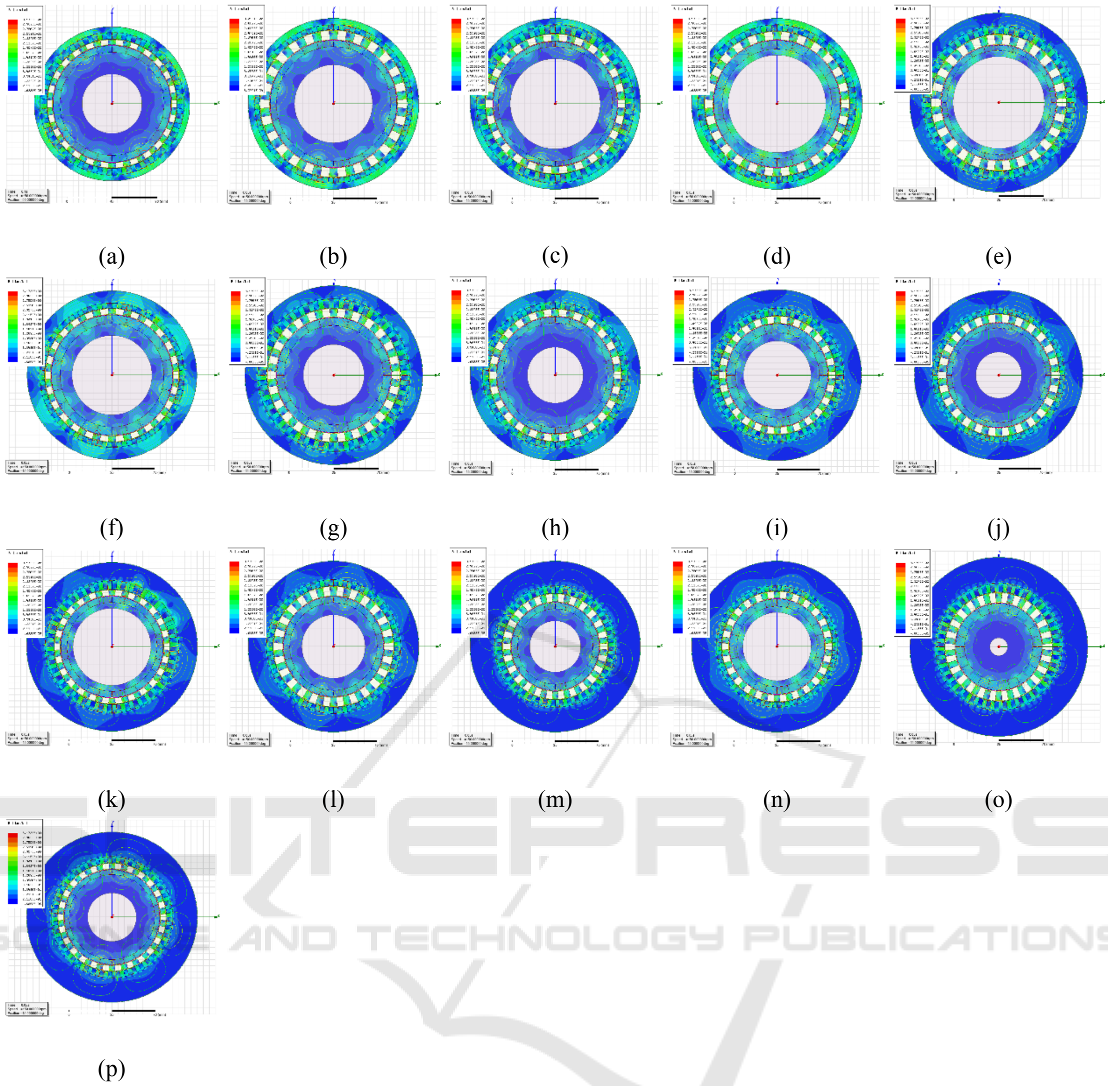


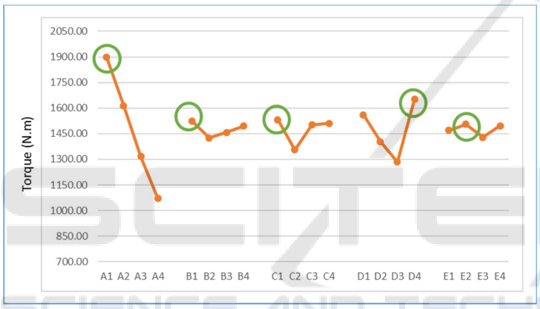
Figure 3: Magnetostatic Field Analysis in (a) Experiment 1, (b) Experiment 2, (c) Experiment 3, (d) Experiment 4, (e) Experiment 5, (f) Experiment 6, (g) Experiment 7, (h) Experiment 8, (i) Experiment 9, (j) Experiment 10, (k) Experiment 11, (l) Experiment 12, (m) Experiment 13, (n) Experiment 14, (o) Experiment 15, (p) Experiment 16.

After got the data shown in Table 4, the data were analyzed to perceive the average performance of the main effect on S/N and transmitted torque. Because this research used higher the better characteristic, so, based on Figure 4 can be concluded that the optimum level by radial length of outer rotor iron part is level 1. The optimum level by radial length of outer rotor permanent magnet is level 1. The radial length of pole pieces can affect strongly in level 1. On the other hand, radial length of inner rotor permanent magnet and inner rotor iron part can perform better in level 4 and level 2.

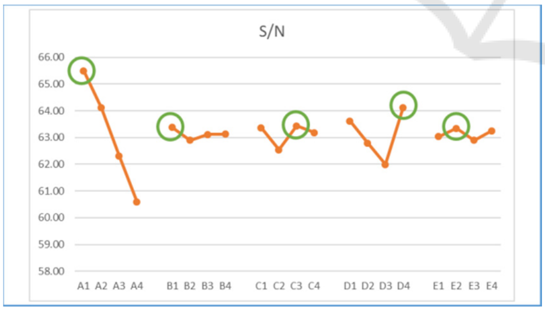
Furthermore, the effects of research variable analyzed using ANOVA down to percentage contribution. The radial length of outer rotor iron part factor has the highest percentage contribution that is 77.92% followed by radial length of inner rotor permanent magnet with 16.28%. Radial length of outer rotor permanent magnet and radial length of pole piece factors consecutively with 1.10% and 3.95%, while radial length of inner rotor iron part factor affecting not significantly in the amount of 0.75%. Because it is under 1%, so this factor needs to be pooled. Table 5 shows the result of ANOVA analysis. The description symbols mentioned in Table 5 are degree of freedom (f), Sum of Squares (S), Variance (V), Variance Ratio (F), and Percentage Contribution (P) in percent (%).

Table 4: The result of transmitted torque.

	A	B	C	D	E	Maximum Torque	S/N
1	5	6	4	6	20	2081.7311	66.3685
2	5	4	7	5	15	1687.6924	64.5459
3	5	7	5	4	10	1667.5242	64.4414
4	5	5	6	7	5	2150.7576	66.6518
5	10	6	7	4	5	1373.1758	62.7545
6	10	4	4	7	10	1751.7327	64.8694
7	10	7	6	6	15	1747.7003	64.8493
8	10	5	5	5	20	1580.9525	63.9784
9	15	6	5	7	15	1599.5511	64.0800
10	15	4	6	4	20	1106.7157	60.8807
11	15	7	4	5	5	1307.2708	62.3273
12	15	5	7	6	10	1255.7313	61.9779
13	20	6	6	5	10	1037.6316	60.3209
14	20	4	5	6	5	1156.4207	61.2623
15	20	7	7	7	20	1106.7295	60.8808
16	20	5	4	4	15	989.6207	59.9094



(a)



(b)

Figure 4: Plots of factors main effect.

After pooled, the percentage contribution turned to 77.18% for outer rotor iron part. The contribution value was 0.35% for outer rotor permanent magnet and 3.21% for pole pieces. Moreover, 15.53% contribution was given by radial length of inner rotor permanent magnet. Hence, the other contribution (error) contributes 3.73%. Pooled ANOVA table is shown in Table 6.

Table 5: ANOVA table.

Factors	**f**	**S**	**V**	**F**	**P**
A	3	1535851.226	511950.41		77.92
B	3	21706.963	7235.6543		1.10
C	3	77895.350	25965.12		3.95
D	3	320800.948	106933.65		16.28
E	3	14718.848	4906.28		0.75
All other/ error	0	0	0		
Total	15	1970973.335			100

Table 6: Pooled ANOVA table.

Fac-tors	f	S	V	F	P
A	3	1535851.23	511950.41	104.4	77.18
B	3	21706.96	7235.65	1.5	0.35
C	3	77895.35	25965.12	5.3	3.21
D	3	320800.95	106933.65	21.8	15.53
E	(3)	14718.85	Pooled		
All other/ error	3	14718.85	4906.28		3.73
Total	15	1970973.34			100

Furthermore, to estimate the transmitted torque under the optimum conditions, the data from Figure 3 used for the simulation. Every highest effect calculated as parameters then obtained transmitted torque with 2179.55 Nm This value had to be confirmed with the simulation and obtained 2261.40 Nm transmitted torque. The magnetostatic field of this optimum condition shown in Figure 5, and Figure 6 shows the transmitted torque graphic.

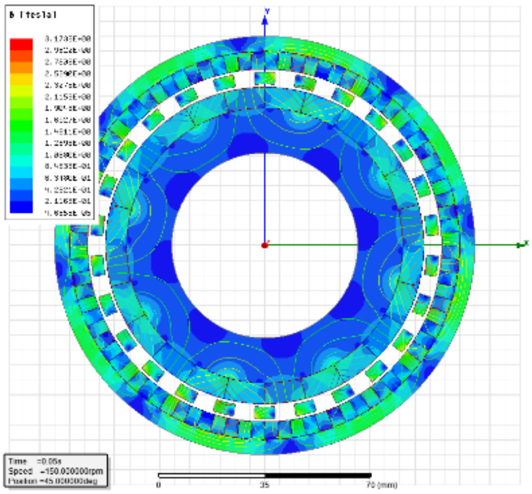


Figure 5: Magnetostatic Field in Optimum Condition.

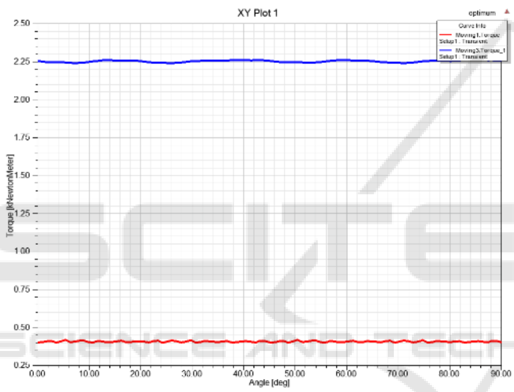


Figure 6: Steady-State Torque in Optimum Condition.

4 CONCLUSIONS

In the case of this research, the effects of critical design parameter to the magnetostatic field and transmitted torque had been obtained. By using Taguchi method, the transmitted torque in optimum condition, percentage contribution of research variable (factors) and estimate torque in optimum condition had been presented. This research will be a useful assistant to design coaxial magnetic gear with transmitted torque demand by considering the radial length of the critical design parameter. The best parameters in this research are 5mm for radial length of outer rotor iron part, 6mm for radial length of outer rotor permanent magnet, and 4mm for radial length of pole pieces. Furthermore, the radial length of inner rotor permanent magnet and inner rotor iron part are 7mm and 15mm. Future work on this study will investigate the effects to the flux density, iron losses, torque ripple and efficiency of coaxial magnetic gear and solve the problem about manufacturing Halbach magnetized type.

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