ISSN 2347 - 3983

Volume 8. No. 8, August 2020

International Journal of Emerging Trends in Engineering Research

Available Online at http://www.warse.org/IJETER/static/pdf/file/ijeter92882020.pdf

https://doi.org/10.30534/ijeter/2020/92882020

Preliminary Study on Yoke Sizing of Concentric Magnetic Gear

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ABSTRACT

In this paper, torque, torque density, efficiency and efficiency slope of concentric magnetic gear (CMG) at different yoke sizes are evaluated using 2D finite element. Transient analysis when eddy current loss included and excluded are simulated. Efficiency to speed o used in this study is similar to the original gear ratio, 5.5. The change in the yoke size also effect the torque density of the CMG. The finding showed that the change in size at the outer rotor yoke influence the torque and efficiency the most. The smallest outer rotor yoke yields higher torque density of 55% then the average value in this study and slower gear efficiency degradation.

Key words: Magnetic gear; machine design; torque; efficiency; finite element, electromagnetics.

1.INTRODUCTION

Magnetic gear (MG) has been around since late 19th century. Yet, industry still use mechanical gear in many applications.MG has the potential to replace mechanical gear due to its features, such as contactless, lubrication free, minimal noise, low vibration and small magnetic traction system [1]–[5].Latest research apply the concept of flux modulation principle[6]–[8]proposed in 2001 by Atallah to enhance the structure and design [9]–[11] This flux modulation MG is called concentric magnetic gear (CMG). It was demonstrated to produce high torque density with the combination of brushless permanent magnet machine in the range of 10kN.m to 30kN.m comparable to the transverse field machine.

1.1 Working Principle of Concentric Magnetic Gear

Figure 1 shows the structure of CMG[12]. The permanent magnet (PM) is mounted on the inner yoke which act as input rotor. The outer PM is mounted similarly on the outer yoke which act as output rotor. Between the input and output rotor, ferromagnetic pieces are placed. The direction of the flux is from the magnet towards the inner point of the machine for inward pole while opposite direction for outward pole. The magnet pole is placed in alternate way to each other which formed multiple pairs. shown in Figure 2. When the inner rotor rotates, the magnetic field density changed over time at the air gap. The change in the air gap is subjected to the speed of the input rotor. When ferromagnetic pole piece is introduced at the air gap, harmonic is produced at different frequency at the outer side of the pieces. The relation between the magnetic field density frequency and the harmonic frequency is

$$\omega_x = \frac{p_i}{p_i + n_s}\omega_i \tag{1}$$

where ω_h is the harmonic frequency, p_i is the input pole pair, n_s is the number of pole pieces and ω_i is the frequency of the input pole pair. The number of the output pole pair can be determined through equation (2).

$$p_o = p_i + n_s \tag{2}$$

where p_o is the outer pole pair. The torque conversion between output and oinput torque or gear ratio therefore become

$$G_r = \frac{p_o}{p_i} \tag{3}$$

where Gr is the gear ratio.

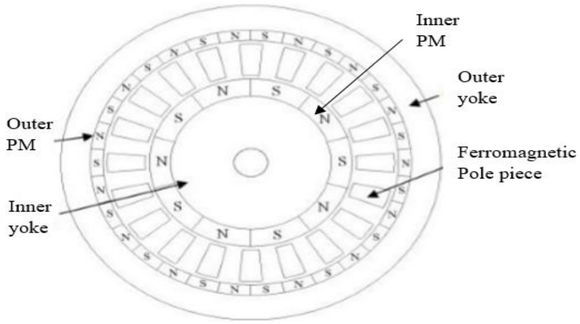


Figure 1:CMG structure

There had been many attempts to optimize CMG through single and multiple objectives [13][14][15][16], material comparison [17], [18] and magnet arrays [19], [20]. However, there are limited research on the basic optimization of torque, torque density, efficiency and slope through yoke sizing study. In order to produce compact, high torque density and efficient CMG, size reduction study should be performed in initial design stage.

In this paper, torque, torque density, efficiency and efficiency slope of CMG at different yoke sizes are evaluated using 2D finite element. Transient analysis when eddy current loss included and excluded are simulated. Efficiency to speed characteristic for each sizes are compared. The CMG gear ratio used in this study is similar to the original gear ratio, 5.5. The change in the yoke size also effect the torque density of the CMG.

2. METHODOLOGY

2.1Structure of CMG in finite element

The reference structure for simulation is shown in Figure 2. The inner rotor consists of 4 pole pairs, outer rotor consists of 26 pole pairs and ferromagnetic pole are 22 pieces. Table 1 shows five dimensions denote as Ref, D1, D2, D3 and D4 of CMG that will be evaluated. Figure 3 illustrated the radius either at inner yoke and outer yoke representing the changes. For this preliminary analysis, the size changes were based on 5mm radius increments or decrement.

2.2 Simulation configuration

JMAG Designer 16 is used as the simulator. As shown in Table 1, the dimension changes only made at inner yoke inner side and outer yoke outer side. The reason is to avoid redrawing other parts if changes are made at other places. At inner yoke inner side, 2 additional radiuses are considered likewise at outer yoke outer side. The permanent magnets at the inner and outer rotor are NEOMAX-35AH, the magnetic material at the inner yoke, outer yoke and pole piece are NSSMC 35H210. Transient analysis is configured and run for ¼ of full rotation. Initially loss was neglected to evaluate the maximum power and torque of each dimension. Then, eddy current loss at the magnets were included and simulated at 4 different speed pairs. The rotors speed settings are shown in Table 2.

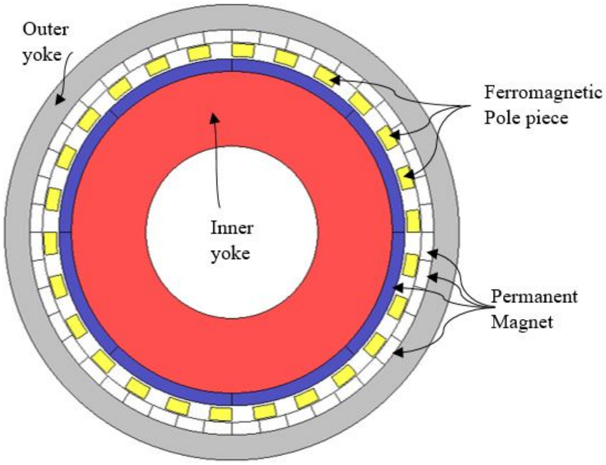


Figure 2:CMG structure for simulation

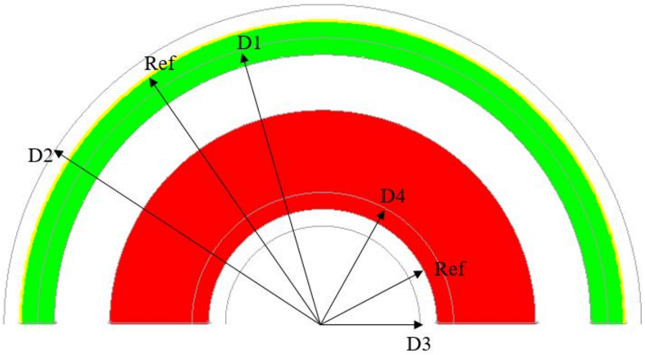


Figure 3: Illustration showing the size modification in either inner or outer yoke

Table 1: Dimensions of CMG under evaluation

Parts	Ref.	D1	D2	D3	D4
Inner yoke radius at inside (mm)	34	34	34	29	39
Inner yoke radius at outside (mm)	63.5				
Outer yoke radius at inside (mm)	80				
Outer yoke radius at outside (mm)	90	85	95	90	90
Inner pole pair radius (mm)	68.5mm				
Axial length (mm)	30mm				
Inner magnet arc	45^o				
Pole piece arc	6.923^o				
Outer magnet arc	8.18^o				
Inner magnet width (mm)	5mm				
Outer magnet width (mm)	5mm				
Inner air gap width (mm)	1mm				

Outer air gap width (mm)	0.5mm

Table 2. Rotor speed setting

	Speed (rpm)				
Rotor	Without loss	Eddy current loss included			
Inner	1000	1000	2000	3000	4000
Outer	181.8	181.8	363.6	545.4	727.2

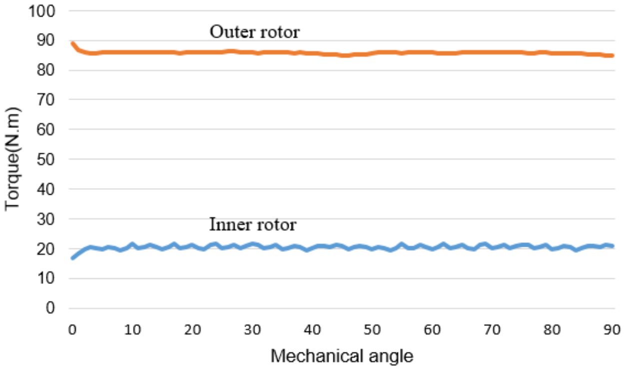
Torque waveform at inner rotor and outer rotor can be captured from this simulation. Integral average can be determine from the torque waveform. Gear efficiency can be calculated through equation (4)

$$G_{E\,ff} = \frac{\tau_i \omega_i}{\tau_o \omega_o} \tag{4}$$

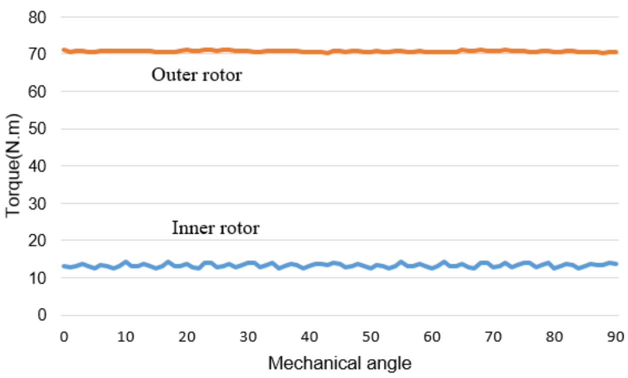
where τ_i and τ_o is the inner rotor torque and outer rotor torque, $\omega_i$and $\omega_o$is the inner rotor speed and outer rotor speed.

3.RESULT

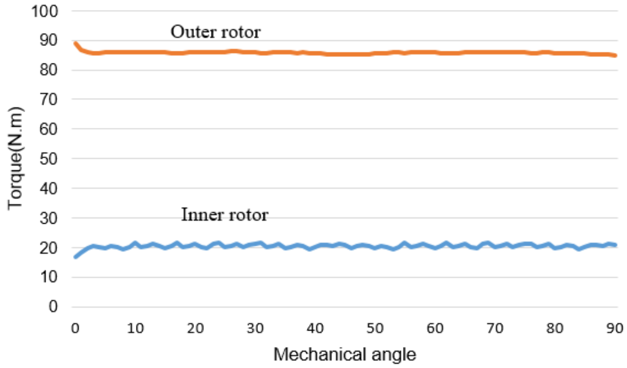
The torque waveforms with in five different size Ref, D1,D2, D3 and D4 are shown in Figure 4 (a)-(e).



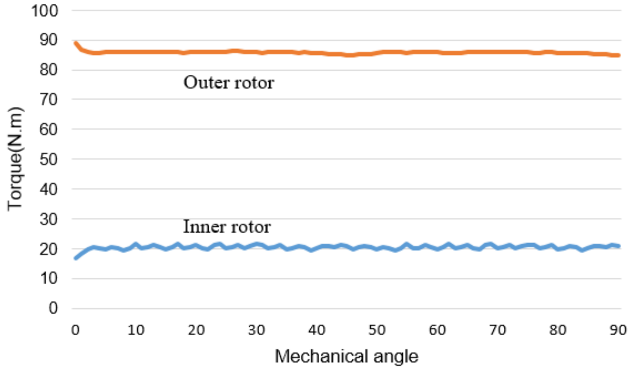
(a) Torque waveform in Ref.



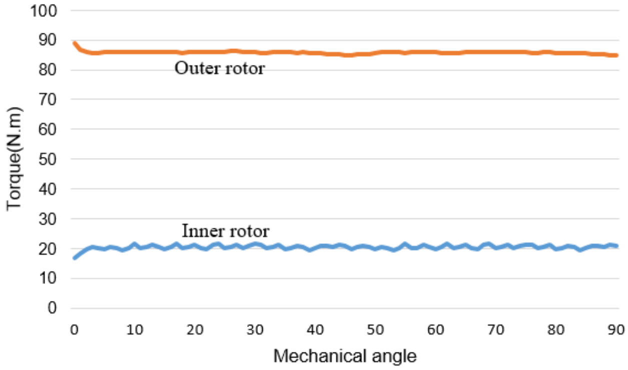
(b) Torque waveform in D1



(c) Torque waveform in D2



(d) Torque waveform in D3



(e) Torque waveform in D4

Figure 4: Torque waveforms of five sizes of inner yoke or outer yoke.

Initial observation showed that no significant difference in waveform except for in D1 where the inner and outer rotor torque were slightly lower. Torque at inner rotor in D1 is about 30% lower than the average of inner rotor torque in all yoke size. Torque at outer rotor in D1 is 14% lower than the average of the outer rotor torque in all yoke size. The difference in value could be due to the saturation build up at the smaller area of outer rotor yoke. However, in D2, when the larger outer yoke size is used, the torque did not increase because the flux density source is generated only from permanent magnet in magnetic gear. This outcome may be different if larger permanent magnet volume is use. Table 2 summarized the average torque in all the sizes and yoke sizes from the JMAG tools.

Table 2: Summary of average torque without loss in all size

	Torque (N.m)		Volume (cm^3)	
Yoke size	Inner rotor	Outer rotor	Inner yoke	Outer yoke
Ref	20.54	85.8	0.27	0.16
D1	13.34	70.77	0.27	0.08
D2	20.55	85.8	0.27	0.25
D3	20.54	85.8	0.30	0.16
D4	20.54	85.8	0.24	0.16
Average	19.10	82.79		

Torque density can be calculated as follows

$$T_D = \frac{\tau}{v} \tag{5}$$

where TD is the torque density, τ is the average torqueand v is the volume. In order to focus on the torque density due to yoke size change, permanent magnet volume is proposed to be excluded from the total volume either in inner rotor or outer rotor. The calculate torque density for each yoke size is shown in Table 3. The torque density in D1 is 30% lower at the inner rotor but 58% higher at the output rotor compare to other yoke size.

Table 3: Torque density for inner and outer rotor when permanent magnet is excluded from the volume.

Yoke size	Torque density (kNm/m^3)	
	Inner rotor	Outer rotor
Ref	75.79	536.25
D1	49.23	909.64
D2	75.83	347.37
D3	68.24	536.25
D4	86.67	536.25
Average	71.15	573.15

Gear efficiency calculated from equation (4) were plotted against the speed in Figure 5. This graph showed that D1 yield higher efficiency then other yoke sizes. Ref, D2, D3 and D4 produce almost similar efficiency. Table 4 showed all the efficiency values in constructing the graph. Assuming that the graph to be linear, the slope can be calculated by dividing y values with the x values. D1 slope is around 10% lower than the average slope of the efficiency graph.

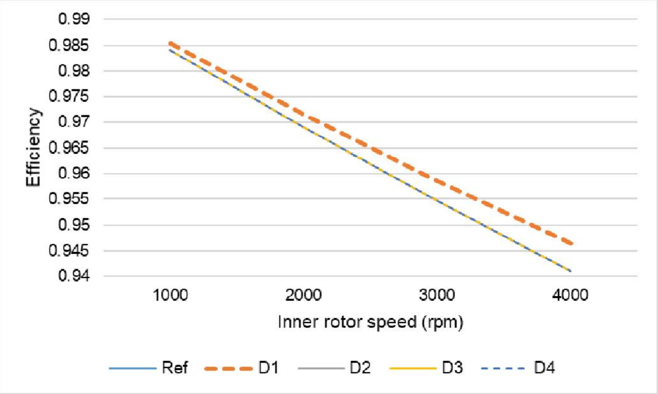


Figure 5: Efficiency versus inner rotor speed in five yoke sizes

Table 4: Gear efficiency values taken from four speed setting

Rotor Speed (rpm)	Ref	D1	D2	D3	D4
1000/181	0.9842	0.9854	0.9842	0.9842	0.9842
2000/363	0.9690	0.9715	0.9690	0.9690	0.9690
3000/545	0.9547	0.9586	0.9547	0.9547	0.9547
4000/727	0.9410	0.9465	0.9410	0.9410	0.9410
Slope (10^{-5})	1.44	1.30	1.44	1.44	1.44

4. RESULT DISCUSSION

D1 inner rotor and outer rotor torque is 30% and 14% lower than the average torque value in this study. However, D1 yield 58% higher torque density at outer rotor. The smaller radius of outer yoke had caused flux leakage and reduce magnetic flux density in the area. This case does not mean that D2 at bigger radius would produce higher torque. The optimal torque with this setup is already reach at Ref size. Hence, increasing the size does not increase the torque generated.

The gear efficiency in D1 is higher because of the magnetic field density at this yoke size is smaller than its' counterpart. Eddy current loss is proportional to the magnetic field density, hence the loss produced is lesser in D1. The reduced change in yoke volume in D1 is greater than the reduced change in torque value. Therefore, the torque density in D1 yield higher value compared to other yoke sizes.

5. CONCLUSION

In this paper, magnetic gear is constructed with five different yoke sizes, referred as Ref, D1, D2, D3 and D4. The size modification only applies either at inner yoke or outer yoke only. The study is meant to evaluate the torque performance and efficiency when different yoke size is applied to the machine. 2D finite element software JMAG Designer version 16 was used in transient mode for evaluating torque when loss is excluded. Then, the analysis is expanded at different speed setting for the case where eddy current loss is included. Based on the result obtained from no loss study, there were around 20N.m and 85N.m at inner and outer rotor, except in D1 which is slightly lower. Likewise, the result from the eddy current loss inclusion study showed that gear efficiency produces better result in D1 and the slope show slower efficiency degradation compared to other yoke size. The gear efficiency degradation in D1 is also much slower because it indirectly influenced by the smaller flux density in D1. In conclusion, the parts which contributes the biggest change in torque and efficiency is outer yoke. Further study is ongoing at much smaller yoke size and higher speed setting.

ACKNOWLEDGMENT

The authors would like to thank the Ministry of Higher Education Malaysia, UniversitiTun Hussein Onn Malaysia (UTHM) under Research Fund E15501, Research Management Centre, UTHMand UniversitiTeknikal Malaysia Melaka (UTeM).

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