Construction of Radial Flux Cycloidal Magnetic Gears with Reduced Permanent Magnet Piece Count Using Consequent Poles

Shima Hasanpour
Dept. of Elec. & Comp. Eng
Texas A&M University
College Station, TX, USA
shimahasanpour@tamu.edu

Matthew Johnson
Dept. of Elec. & Comp. Eng
Texas A&M University
College Station, TX, USA
mjohnson11@tamu.edu

Matthew C. Gardner
Dept. of Elec. & Comp. Eng
University of Texas at Dallas
Richardson, TX, USA
matthew.gardner@utdallas.edu

Bryton Praslicka
Dept. of Elec. & Comp. Eng
Texas A&M University
College Station, TX, USA
bryton.praslicka@tamu.edu

Abas Goodarzi
Magmotor Technologies Inc.
Worcester, MA, USA
abas@magmotor.com

Hamid A. Toliyat
Dept. of Elec. & Comp. Eng
Texas A&M University
College Station, TX, USA
toliyat@tamu.edu

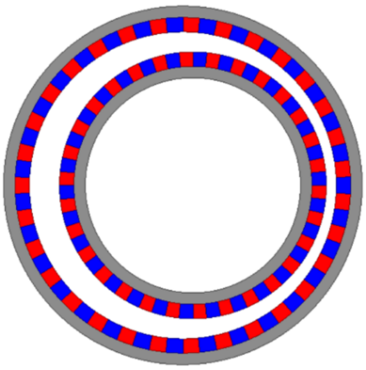
***Abstract*— Cycloidal magnetic gears provide a noncontact alternative to mechanical gears for high gear ratio applications. Most cycloidal magnetic gears in the literature have magnets on the surface of each rotor. However, on a consequent pole rotor, all the magnets are magnetized in the same direction and separated by ferromagnetic teeth. This potentially provides magnet retention and assembly advantages. The consequent pole rotors can take advantage of wider magnets and thinner magnetic air gaps, due to the potential elimination of the magnet retention sleeve. This paper studies the fabrication process and performance of the first cycloidal magnetic gear with a consequent pole rotor. The prototype was built, and its experimentally measured slip torque achieved a 95% match with the 3D FEA simulation model values. The measured ratio of the shafts speeds showed excellent agreement with the ideal 20:1 gear ratio.**

Keywords*— *Consequent pole, cycloidal magnetic gear, finite element analysis (FEA), gear ratio, genetic algorithm, optimization, surface permanent magnet, torque density

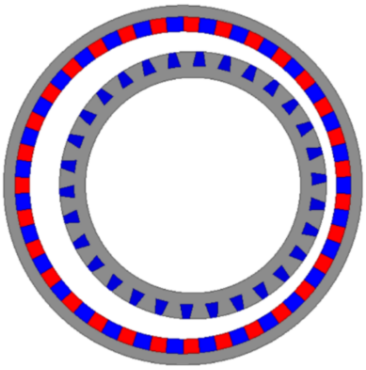
I. Introduction

Magnetic gears are a proposed alternative to mechanical gears [1], which provide a plethora of potential advantages, such as lower acoustic noise and no backlash. These advantages could be critical for space applications [2]-[3], electric aviation [4]-[5], or harvesting renewable energies, such as wind [6]-[8] and wave [9]-[10]. Coaxial magnetic gears (CoMGs) [1], and cycloidal magnetic gears (CyMGs) [2], are among the most promising magnetic gear topologies for achieving high specific torques. CoMGs perform best at a lower gear ratios [11], whereas CyMGs are optimal for higher gear ratios (eg. >16:1) [12].

The non-uniform air gap of CyMGs modulates the magnetic fields of the permanent magnets (PMs) on the two rotors. Ref. [13] thoroughly explains the operation of CyMGs. Most of the existing CyMG literature [2], [12]-[16] focuses on surface permanent magnet (SPM) CyMGs. Despite exhibiting high torque densities, CyMGs face several challenges. These challenges include large unbalanced magnetic forces, PM retention on the inner rotor (which orbits and rotates simultaneously), and, for high gear ratio designs, fabricating and placing very large numbers of very small PMs. Ref. [17] proposed utilizing a flux shield structure in the large section of the air gap to reduce the unbalanced magnetic forces while also increasing torque density of CyMGs. Ref. [18] addressed the PM retention and fabrication challenges by employing an inner reluctance rotor instead of the SPM rotor, but this resulted in much lower achievable torque densities. However, [19] introduced consequent pole (CP) CyMGs, which could potentially achieve similar or higher torque densities than SPM CyMGs at high gear ratios. CP CyMGs replace half of the PMs on a rotor with teeth, as shown in Fig. 1, and, thus, halve the PM piece count of a rotor, which can simplify the assembly. Additionally, the teeth can be designed to retain the PMs on the inner rotor without the need for a retention sleeve, if the design is such that the PMs are wider at their inner radius than at there outer radius, as on the inner rotor in Fig. 1(b).



(a)



(b)

Fig. 1. Cross-sections of (a) an SPM-SPM CyMG and (b) a CP-SPM CyMG with the inner rotor teeth shaped to retain the PMs.

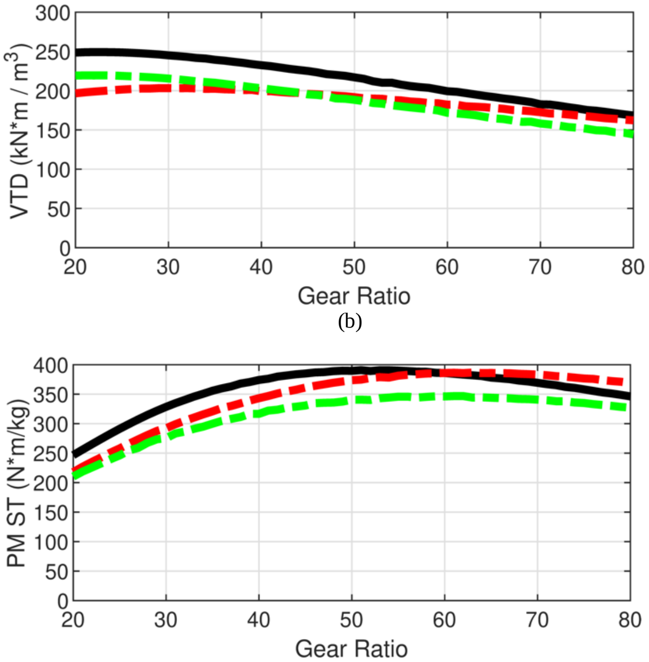
This paper presents the performance of the first CP CyMG prototype and compares it to that of a prototype SPM CyMG with the same gear ratio to validate the simulation results. The prototypes are designed for a gear ratio of 20:1, therefore, this paper continues the studies in [19] and expands the range of gear ratios considered for the genetic algorithm (GA) optimization and uses 2D finite element analysis (FEA) to independently design and optimize SPM CyMGs and CP CyMGs. The measured gear ratio of both prototypes verifies the fundamental operating principles. The slip torque measurement of the CP CyMG prototype is 95% of the slip torque reported by the 3D FEA model, which indicates the accuracy of the model.

II. SIMULATION

Ref. [19] optimized CP CyMGs and SPM CyMGs for maximum permanent magnet specific torque (PM ST) and volumetric torque density (VTD) using a GA with 2D FEA and compared their performance over a broad range of gear ratios, 30:1 to 80:1. However, the gear ratio of 20:1 was chosen for the CP CyMG prototype to enable a comparison with the performance of the prototype with that of an existing independently optimized and fabricated SPM CyMG with a gear ratio of 20:1. Therefore, this study expands the range of gear ratios to 20:1 for the FEA optimization of both topologies, the CP CyMG and SPM CyMG, using the same objectives, method, and parameters value range for the GA reported in [19], which provides a baseline for performance comparison of these two topologies at the gear ratio 20:1.

	SPM-SPM	CP-SPM	CP-SPM
Air Gap (mm)	1	0.75	1
Inner Rotor PM Grip (mm)	N/A	0.25	Any

(a)



(c)

Fig. 2. (a) Legend indicating the different topologies and design scenarios. The maximum (b) VTDs and (c) PM STs achieved for each GA optimization scenario across a range of gear ratios.

Approximately 1000 single designs at each generation were evaluated over 100 generations for every studied topology. NdFeB 52SH and M15 (29 gauge) were used for the PMs and back irons and CP teeth in all topologies, respectively.

Ref. [19] defines the PM grip parameter for CP CyMGs to evaluate designs where the teeth on the CP rotor can naturally retain the PMs without any retention sleeve required. The PM grip is half of the difference between the length of the chord connecting a PM's corners facing the air gap and length of the chord connecting its corners inside the core [19]. Designs with positive PM grip values can eliminate the need for a PM retention sleeve by naturally holding the PMs in the slots. Two different rotor scenarios were evaluated for the CyMGs with inner CP rotor and outer SPM rotor, 1) a 0.75 mm air gap and a positive 0.25 mm PM grip that eliminates the PM retention sleeve and allows a smaller air gap than the 1 mm air gap baseline and 2) a 1 mm air gap and an unconstrained inner rotor PM grip.

Fig. 2 shows the maximum VTD and PM ST values achieved by each topology. The optimal SPM CyMGs show better performance at lower gear ratios than the optimized CyMGs with a CP rotor as explained in [19]. CP CyMGs replace the PMs with teeth, which will negatively affect the maximum achievable VTD. However, CP CyMGs with 0.75 mm air gap and 0.25 mm PM grip outperform SPM CyMGs in terms of PM ST at higher gear ratios because the effective air gap is lower in addition to more available space for wider arc length PMs on the inner rotor.

III. PROTOTYPE DESIGN

A prototype was fabricated to validate the FEA models for the CP CyMG. Minimizing the fabrication time and cost were

TABLE I. PROTOTYPE'S ACTIVE DESIGN PARAMETER VALUES

<table>
<tr><th>Parameter</th><th>SPM CyMG</th><th>CP CyMG</th></tr>
<tr><td>Inner rotor pole pair count</td><td colspan="2">20</td></tr>
<tr><td>Inner rotor PM piece count</td><td>40</td><td>20</td></tr>
<tr><td>Outer rotor pole pair count</td><td colspan="2">21</td></tr>
<tr><td>Outer rotor PM piece count</td><td colspan="2">42</td></tr>
<tr><td>Outer diameter</td><td colspan="2">81 mm</td></tr>
<tr><td>Outer rotor back iron radial thickness</td><td colspan="2">2.5 mm</td></tr>
<tr><td>Outer rotor PM thickness</td><td colspan="2">2.5 mm</td></tr>
<tr><td>Outer rotor PM outer edge width</td><td colspan="2">4.6 mm</td></tr>
<tr><td>Outer rotor axial length</td><td colspan="2">11.26 mm</td></tr>
<tr><td>Minimum effective air gap thickness</td><td colspan="2">1.5 mm</td></tr>
<tr><td>Axis offset</td><td colspan="2">1.5 mm</td></tr>
<tr><td>Inner rotor PM thickness</td><td>2.5 mm</td><td>2 mm</td></tr>
<tr><td>Inner rotor PM inner edge width</td><td>3.7 mm</td><td>6 mm</td></tr>
<tr><td>Inner rotor back iron radial thickness</td><td>2.5 mm</td><td>3 mm</td></tr>
<tr><td>Inner rotor axial length</td><td>11.26 mm</td><td>10 mm</td></tr>
</table>

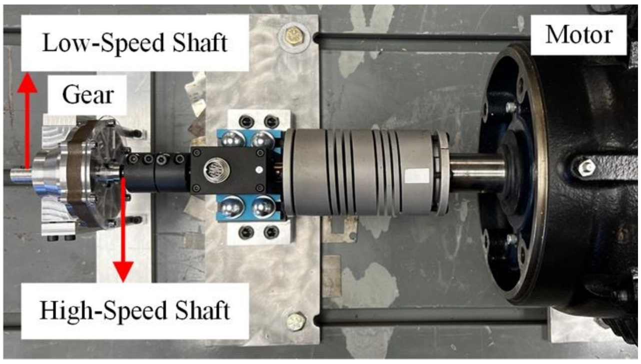
prioritized over maximizing the torque of the CP CyMG prototype. Therefore, the prototype utilized the existing structural parts and the outer rotor from a 20:1 SPM CyMG prototype in addition to off-the-shelf rectangular PMs. Table I summarizes the final prototype design details for the SPM CyMG and the CP CyMG. In the SPM CyMG prototype, NdFeB N52H was used for the PMs and M15 steel was used for the back irons. The CP CyMG prototype used the same outer rotor as the SPM CyMG prototype; however, the PMs and the back iron of the CP CyMG inner rotor were made from NdFeB N50 and 1018 mild steel, respectively, to facilitate rapid fabrication and reduce costs. Fig. 3 shows the inner rotors of the SPM CyMG and CP CyMG and the assembled CP CyMG prototype.

(a)

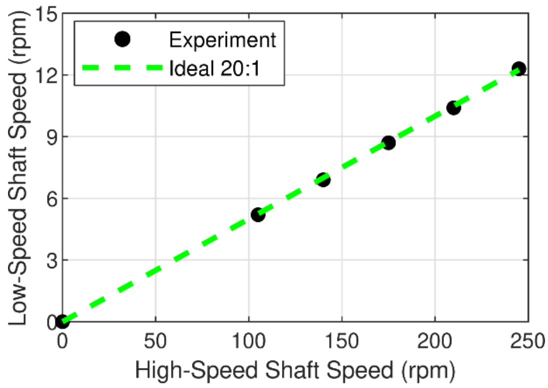
(b)

(c)

Fig. 3. (a) The inner rotor of the SPM CyMG, (b) the inner rotor of the CP CyMG, and (c) the assembled CP CyMG prototype with gear ratio 20:1.



(a)



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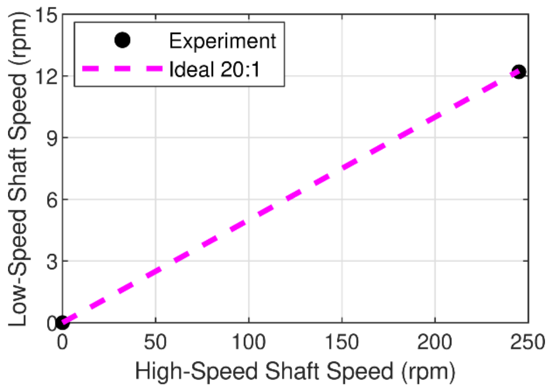


(c)

Fig.4. (a) The test bed for the gear ratio measurement of the prototypes with gear ratio 20:1. Measured high-speed and low-speed shaft speeds compared with the ideal 20:1 gear ratio for the (b) SPM CyMG and (c) CP CyMG prototypes.

IV. Experimental Results

Fig. 4 shows the testbed for the gear ratio measurement of the CP CyMG prototype. To measure the gear ratio, the PM motor shown in Fig. 4(a) was used to drive the high-speed shaft of the SPM and CP CyMG prototypes, while the low-speed shaft was not loaded. The measured rotational speeds of both shafts in the SPM and CP CyMG prototypes agree with the designed gear ratio of 20:1, as shown in Fig. 4 (b) and (c). The gear ratio was only measured for a single input speed (245 rpm) for the CP CyMG prototype because the shaft was damaged during the testing due to misalignment.

Fig. 5 illustrates a different test setup, where the high-speed shaft was kept stationary, while the low-speed shaft was turned to measure the slip torque. Table II presents the

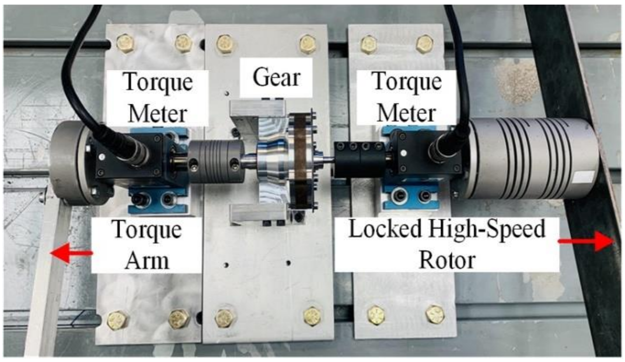


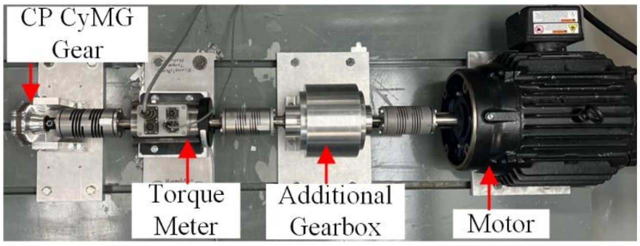
Fig. 5. The test setup for the slip torque measurement of the CP CyMG and SPM CyMG with gear ratio 20:1.

TABLE II. EXPERIMENTALLY MEASURED SLIP TORQUE

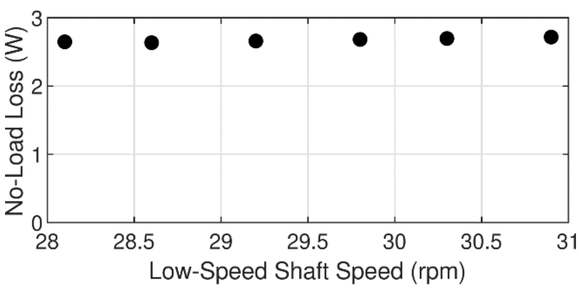
Measurement	SPM CyMG		CP CyMG	
	3D FEA	Experiment	3D FEA	Experiment
Slip Torque	5.36 Nm	5.1 Nm	3.55 Nm	3.4 Nm
Specific Torque		9.7 Nm/kg		6.5 Nm/kg

experimental slip torque measurements for the SPM CyMG and CP CyMG prototypes. The results in Table II demonstrate that the experimentally measured slip torque for each prototype is about 95% of the slip torque value predicted by a 3D FEA model, indicating good agreement between the simulated and experimental results.

Fig. 6(a) shows the test bed for measuring the CP CyMG prototype's no-load losses, where an additional gearbox was used to step up the speed of the CP CyMG's low-speed shaft. The torque and speed of the low-speed shaft were measured at different operating speeds to calculate the no-load losses. Fig. 6(b) shows the no-load losses for a range of low-speed shaft operating speeds. The average no-load losses for multiple low-speed shaft operating speeds ranging between 28 and 31 rpm was 2.6 W. The experiment was limited to a maximum of 620 rpm on the high-speed shaft because of mechanical and structural considerations. The minimum speed of 28.1 rpm on the low-speed shaft (562 rpm on the high-speed shaft) was imposed by the test bed motor drive's low speed limitations and the gear ratio of the additional gearbox. The CP CyMG prototype's maximum operating power with the low-speed shaft rotating at 30 rpm is 10.7 W (based on its slip torque of 3.4 Nm), while its no-load losses are about 25% of this maximum power. As in [2], the prototype used sleeve bearings for the pins, which contributes to high frictional losses. Additionally, solid steel was used for the back irons, which increases eddy current losses. Using needle bearings for the pins and laminated back irons would likely reduce losses significantly, as efficiencies as high as 94% were reported in [14] for a SPM CyMG.



(a)



(b)

Fig. 6. (a) The test bed for the CP CyMG prototype no load losses measurement and (b) the CP CyMG prototype's measured no-load losses.

V. Conclusion

This paper presented the fabrication details and performance of the first consequent pole cycloidal magnetic gear (CP CyMG) prototype, which had a gear ratio of 20:1. The prototype used the outer rotor of an existing surface permanent magnet cycloidal magnetic gear (SPM CyMG) with the gear ratio of 20:1 to reduce the fabrication costs and the time. The speed ratios of both prototypes were measured and agreed very well with the ideal gear ratio, which verified the fundamental operating principles of the proposed topology. Also, the experimental slip torque values of both prototypes agree well with the slip torque values predicted by a 3D FEA simulation. The no-load losses of the CP CyMG prototype are about 25% of its maximum power, which is due to employing solid steel for the back irons rather than a laminated core, and high frictional losses in the sleeve bearings used for the pins.

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BIOGRAPHIES

Shima Hasanpour (S’ 18) received the B.S. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 2018, and the M.S. degree in electrical engineering from Texas A&M University, College Station, TX, USA, in 2021. She is currently pursuing the Ph.D. degree in electrical engineering while working with the Advanced Electric Machines and Power Electronics Laboratory, Texas A&M University. Her research interests include the optimal design and control of electric machines, magnetic gears, and magnetically geared machines.

Matthew Johnson (S’ 13, M’17) received the B.S. and Ph.D. degrees in electrical engineering from Texas A&M University, College Station, TX, USA, in 2011 and 2017, respectively. Matthew worked in the medium voltage drives research and development group at Toshiba International Corporation from 2016 to 2018 and then as an engineer at the DEVCOM Army Research Laboratory from 2018 to 2022. Matthew is currently the Chief Technology Officer of FluxWorks LLC, a startup working to commercialize magnetic gearing technology. Matthew is also an Adjunct Professor in the Department of Electrical and Computer Engineering at Texas A&M University. His research interests include the modeling, design, and analysis of electromechanical, magnetomechanical, and electrical energy conversion systems, as well as general multi-physics modeling and optimization of devices and systems.

Matthew C. Gardner (S’ 15, M’ 19) received the B.S. degree from Baylor University, Waco, TX, USA, in 2014, and the Ph.D. degree from Texas A&M University, College Station, TX, USA, in 2019, both in electrical engineering. In August 2020, he joined the University of Texas at Dallas, where he is an Assistant Professor. His research interests include optimal design and control of magnetic gears and electric machines.

Bryton Praslicka (S’ 20, M' 23) earned his B.S. and Ph.D. both in electrical engineering from Texas A&M University, College Station, Texas in 2019 and 2023, respectively. His research interests include the multi-physics optimization of electric machines, magnetic gears, and magnetically geared machines. He currently serves as Founder and Chief Executive Officer of FluxWorks, a Texas-based startup company commercializing magnetic gears and magnetic gear accessories. In 2022 he was awarded The McFerrin Center for Entrepreneurship Future Texas Business Legend Award in Honor of James Galloway, ‘29, and in 2023 he was awarded the Texas A&M University Association of Former Students Distinguished Graduate Student Award for Excellence in Research.

Abas Goodarzi (S’81, M’86, SM’97) received the B.S, degree from California State University, Sacramento 1981, the M.S. and Ph.D. degree from University of Missouri-Columbia in 1983 and 1986 respectively. In 1986 he joined the Department of Electrical and Computer Engineering, Cal State San Francisco, and in 1989 he joined Hughes Aircraft and Technical Director for General Motors EV1 program. Dr. Goodarzi is a 40-years veteran in the electric, hybrid, and fuel cell industries. He is the founder and CEO of Magmotor and prior his roles at Magmotor, Dr. Goodarzi was founder and CEO of US Hybrid. He is a registered professional engineer since 1985 and has many papers and awards to his name, including Hughes achievement awards, IEEE-PELS award for his contribution to Electric drives for Medium and Heavy duty vehicles industry, Plenary speaker for APEC and co-authored the textbook "Electric Powertrain: Energy Systems, Power Electronics, and Drives for Hybrid, Electric, and Fuel Cell Vehicles", published in 2018 and recently translated into other languages including Mandarin that is used at universities around the world.”

Hamid A. Toliyat (S’87, M’91, SM’96, F’08) received the B.S. degree from Sharif University of Technology, Tehran, Iran, in 1982, the M.S. degree from West Virginia University, Morgantown, WV, USA, in 1986, and the Ph.D. degree from University of Wisconsin at Madison, Madison, WI, USA, in 1991, all in electrical engineering. In March 1994, he joined the Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX, USA, where he is currently the Raytheon Endowed Professor of electrical engineering. Dr. Toliyat has many articles and awards to his name, including the Nikola Tesla Field Award.