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MAGNETIC GEARING FOR CENTRIFUGAL PUMPS

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ABSTRACT

This paper presents a novel approach to improving the longevity and efficiency of centrifugal pumps, specifically addressing the challenges posed by cavitation in high-speed pump operations. Flowserve, a prominent U.S. pump manufacturer, currently employs mechanical gearboxes to reduce impeller speeds; however, these systems suffer from significant limitations, including frequent maintenance needs, friction-induced efficiency losses, and potential damage to pump components due to vibrations. In response, we propose the integration of Concentric Magnetic Gears (CMGs) as a viable alternative. CMGs operate by utilizing magnetic flux to connect three rotors, enabling variable gear ratios without physical contact.

CMGs usually consist of three coaxial, hollow cylindrical rotors, or gears of permanent magnets and ferromagnetic metals. The system establishes a gear ratio based on the pairing between the magnets and ferrous metals. The inner and outermost gears, known as the sun and ring gear, respectively, contain magnets of alternating polarities spaced along their lengths. The middle gear, the flux modulator, consists of evenly distributed ferromagnetic poles. This transition to CMGs is anticipated to mitigate friction-related issues, resulting in decreased noise, reduced vibrations, and minimal lubrication requirements. Details include the successful design of a CMG, the structural configuration of the gearbox, comprehensive structural and magnetic analyses, and successful final testing.

This paper is concerned with the improvement of an ongoing magnetic gear system project. This design focused significantly on withstanding centrifugal forces and reducing and understanding eddy current losses within the system.

Keywords: Magnetic Gear, Eddy Currents, Flux Modulator

1. INTRODUCTION

Flowserve, the company sponsoring this project, manufactures industrial centrifugal pumps that require specific gearing or specialized impellers to reduce cavitation in the fluid being pumped. A typical application for these large-scale pumps would be Nuclear Reactor Feedwater pumps. One of these centrifugal pumps can be seen below in Figure 1.

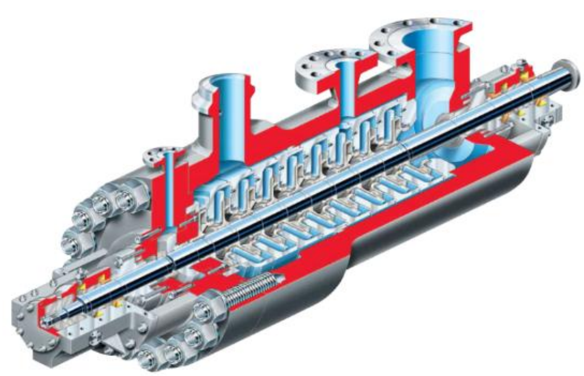

Figure 1 - Flowserve Centrifugal Pump [1]

These pumps often utilize sealed coaxial planetary gear systems to differ impeller speeds across the same axis. These gear reduction systems are typically 95-97% efficient but require lubrication and maintenance to operate. Flowserve is interested in innovative solutions to reduce maintenance-induced downtime of their pump systems and is specifically exploring magnetic gear replacements for their planetary gears. Thus, Flowserve aims to improve the longevity and efficiency of their pumps with concentric magnetic gears (CMGs) and has tasked Team 207 with presenting a working prototype utilizing some of the previous year's manufactured parts alongside many new parts. Flowserve directed the team with four main system-level objectives to ensure the gear is practical for industry applications. First, the gear reduction shall be within the threshold of 3:1 to 2:1 while demonstrating a mechanical efficiency of 95%. Within those guidelines, the gear should be able to transmit at least 6 Nm of torque and shall be able to operate in temperatures up to 400°F. Based on these objectives, the team decided to focus on gear sections with various simulations and calculations to incorporate the previous year's manufactured parts and assess what steps must be taken to meet the requirements.

Description	Objective	Verification
The gear reduction shall be within the threshold of the objective	3:1 - 2:1	Analysis
The gear should demonstrate mechanical efficiency near the objective	95%	Demonstration
The gear should be able to transmit torque matching the objective	~6 N-m	Test
The gear shall be able to operate in temperatures up to the objective	~205° Celsius	Analysis

Figure 2 - System Requirements

The following sections of the report cover all these methods and simulations in Team 207's manufacturing process, results and discussions, and the project's conclusion.

2. MATERIALS AND METHODS

The radial CMG has 3 main components laid out by the previous design team, the inner rotor, or sun gear, the middle rotor, or flux modulator, and outer rotor, or ring gear. These components are analogous to a planetary gearbox using sun, planet, and ring gears. The sun gear is made from a cylindrical piece of low-carbon steel for the backing iron and plated with twelve alternating-pole N50 magnets along the outer face. The ring gear is similar to the sun, with twenty-two magnets of the same magnets plated along the inner face. These are evenly spaced using custom plastic strips. The magnets are held in place using 3M Scotch-weld epoxy adhesive DP240 off-white. These can be seen in Figure 3.

Figure 3 - Ring Gear & Sun Gear

The short comings of the previous team's flux modulator design relied too heavily on epoxy to bind the ferromagnetic poles to the plastic spacers together, without much mechanical support. Although their design restricted movement of the poles radially inward towards the sun gear by the nature of the endcap design, the poles were free to move radially outwards toward the ring gear. This caused the modulator to become out-of-round from the magnetic forces on the poles and contact the magnets. A significant focus has been placed on the development of the Flux Modulator. Taking into account the existing Sun and Ring gears, the Flux Modulator has been engineered to optimize performance within the bounds of manufacturing capabilities and design constraints. Figure 4 illustrates the re-designed modulator.

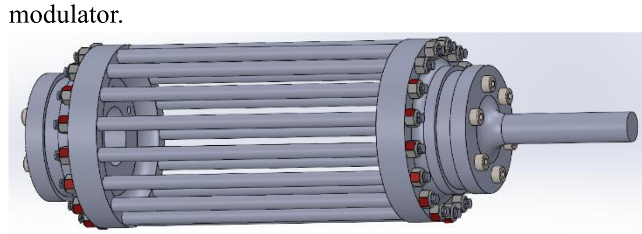

Figure 4 - Flux Modulator

This design incorporates 17 circular modulator poles as structural elements within a cage-like Flux Modulator configuration that surrounds the Sun Gear. The modulator poles are made from 6 mm diameter 1018 cold-drawn steel and have a total length of 167 mm. There is a reduction in diameter to 4 mm for 20 mm of threaded length on either side of the pole. Electrical Steel, also known as silicon steel which is iron with 1.5-5% silicon, would provide superior magnetic performance compared to carbon steel. However, sourcing material from manufacturers capable of producing these specific dimensions proved challenging.

On each side of the modulator, new endcaps were designed with through holes for the flux modulator poles to pass through and be tightened using washers and nuts. Recessed pockets on the inner face accommodate an inner bearing to support the input shaft, and an outer bearing face for the outer bearing to support the modulator itself. Two plates are secured to the faces of the endcaps using screws to restrict the inner and outer bearing from moving axially. One of these plates features a shaft that serves as the output shaft of the gearbox, directly linked to the flux modulator. Both the endcaps and plates are constructed from 6061-T6 aluminum for weight reduction and aluminum’s non-ferrous properties.

New end caps for the ring gear were designed to accommodate the new flux modulator endcaps and were also made from 6061-T6. The completed model can be seen in Figure 5 with the sun gear is denoted in blue, the flux modulator in red, and the ring gear in grey.

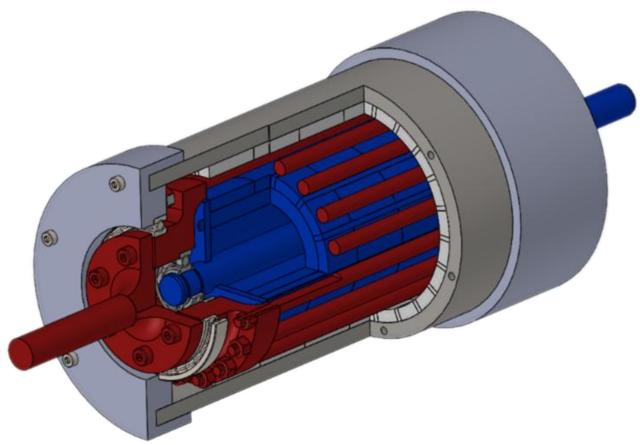

Figure 5 - CAD cutaway of complete CMG

Due to the nature of the CMG’s ratios, one component must be held stationary. The sun gear and flux modulator were chosen to be the input and output, while the ring gear was held stationary.

Output/Input	Sun Gear	Ring Gear	Flux Modulator
Sun Gear $P_s = 6$	1:1	6:11	6:17
Ring Gear $P_r = 11$	11:6	1:1	11:17
Flux Modulator $N = 17$	17:6	17:11	1:1

Figure 6 - Table of capable gear ratios

As per Figure 6, keeping the ring gear stationary creates a 17:6 ratio (2.83:1) when the sun gear and flux modulator are free spinning. This was done to meet requirements but also avoid spinning the hefty ring gear or cantilevering any rotors.

Table 1: CMG characteristics

Components	**Parameters**		
	Pole Pairs	*Inner diameter*	*Outer diameter*
Ring gear	11	78.74	101.6
Flux Modulator	17	64	77
Sun gear	6	38.10	61.47
	Grade	*Thickness*	*Length (total)*
Magnets	N50	5	123.37
	Length	*Diameter*	*Weight*
Total gear size	*198.8*	110	6.7

All dimensions in mm, weight in kg.

3. 2D magnetic simulation

Initial objectives specified that the CMG must produce a calibrated output torque of no less than 6 Nm. Meeting this threshold necessitates a detailed examination of design parameters, with particular attention to the integration of ferromagnetic poles. Due to their significance in both structural and magnetic aspects of the device, optimizing these poles is essential. The magnetic torque output was evaluated using FEMM, a two-dimensional magnetic solver developed for electric motor analysis. A CAD model of the CMG was imported into FEMM to calculate magnetic flux distributions across the design's cross-section as shown in Figure 7. When combined with MATLAB, FEMM enables the computation of magnetic torques across different rotor configurations using Lua scripting.

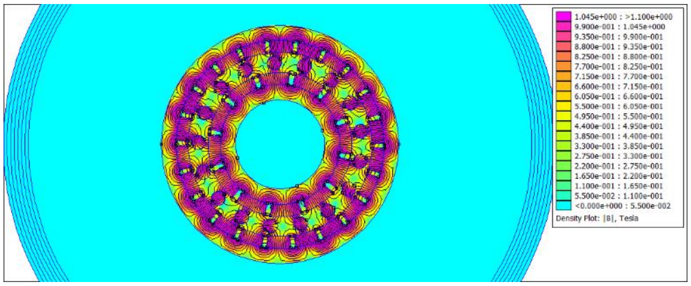

Figure 7 - Magnetic flux simulation of cross-section using FEMM

Circular geometries were selected for the modulator poles rather than the conventional warped isosceles trapezoidal shape from the previous design team to simplify the construction of the redesigned modulator. Although this change results in a theoretical reduction in a CMG's maximum torque output by approximately 3%, it concurrently decreases the torque ripple (66.8% for the inner rotor and 62% for the outer rotor). It's Eddy-current loss, which also affects gear efficiency, was also lower in the circular design compared to the conventional design [2]. The analysis focused on determining the optimal diameter of the ferromagnetic poles. To this end, simulations were conducted to assess the CMG's torque output over a range of modulator pole diameters. The CAD model's cross-section was imported into FEMM, where the ring gear and modulator remained fixed while the sun gear was rotated from 0° to 30° in 0.5° increments to evaluate the breakaway torque. Pole diameters between 3 mm and 6 mm were considered, with 6 mm identified as the maximum allowable diameter to maintain a mechanical clearance or air gap of 1 mm between the poles and surrounding magnets. Figure 8 shows the largest torque peak associated with 6 mm poles, with a peak simulated torque of 34.5 Nm.

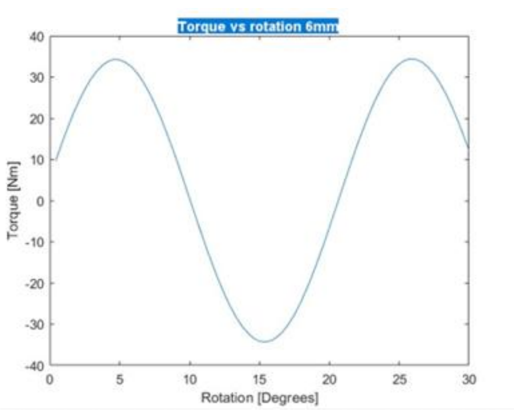

Figure 8 – Fluctuation of Torque based on Rotation

The analysis indicated a linear relationship between pole diameter and torque output, as illustrated in Figure 9. A 6 mm diameter was therefore determined to offer the best trade-off between torque performance, structural integrity, and mechanical clearance. This relationship provides a foundation for scaling the CMG design to meet a broader range of performance requirements.

It should be noted that only 2D simulations were made and not 3D, due to the expensive licenses associated with those programs. Because FEMM can only do a cross-section view, this neglects the magnetic flux leakage around the ends of the poles. This has been shown in other research to drastically lower performance [3]. Ideal modulator topologies wrap the ends of the poles around to the ends of the magnet pole pairs and terminate into the back iron which allows for a higher static torque density and lower torque ripple, but this was not implemented as it would be excessively difficult to assemble in a radial CMG.

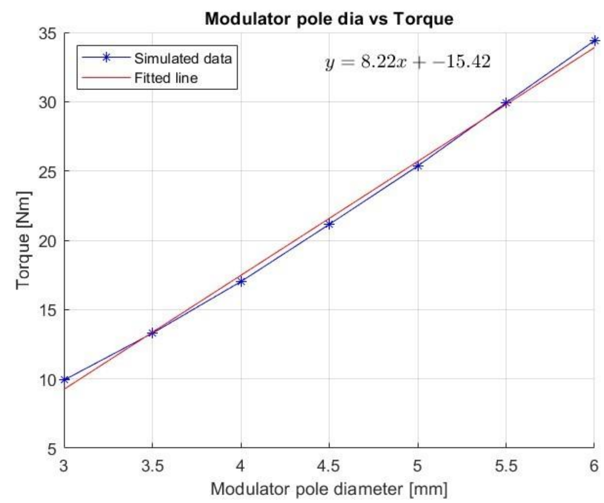

Figure 9 – Pole Size Impact on Torque Output

4. FEA simulation

The previous design of the flux modulator experienced structural failure under load; therefore, it is critical that the current design does not encounter the same issue. Ansys FEA software was utilized to conduct the necessary mechanical failure analyses on the flux modulator. The problem was decomposed into various potential causes of failure. The prior design failed primarily due to centrifugal loading. Additionally, thermal loading and magnetic torque loading were identified as important factors to consider. An angular velocity of 1200 RPM, 35 Nm of torque between the endcaps, and thermal loading of 208 degrees Celsius (400 degrees Fahrenheit, the maximum operating temperature) were applied to the model of the modulator.

Two boundary condition setups were established to analyze the system: one representing a worst-case loading scenario and the other a realistic loading scenario. In the worst-case scenario, the modulator was fixed at one end while torqued at the other. Although this method provides a quick resolution and establishes an upper bound for deformation, it is unrealistic since, in actual conditions, magnetic torques are applied along the lengths of the modulator poles. Both boundary condition setups were compared and analyzed. A depiction of the boundary condition setup is provided in Figure 10.

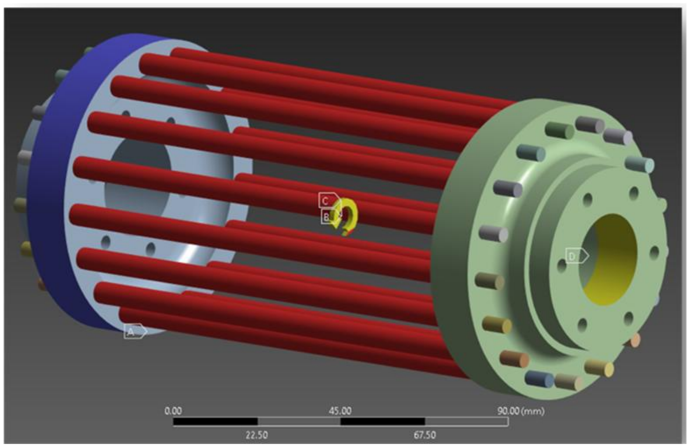

Figure 10 - Ansys simulation of flux modulator

Given that the previous modulator failed under centrifugal forces, it was essential to calculate the radial deformation of the modulator poles. Any centrifugal deformation should remain under the 1 mm mechanical tolerance to avoid contact with the magnets. The FEA deformation results converged to 1.15%. Under the worst-case scenario boundary conditions, the maximum deformation reached 0.511 mm, while the realistic loading scenario produced a maximum deformation of 0.187 mm, both being elastic. Corresponding factors of safety for these deformations were determined to be 1.81 and 5.35, respectively, and these results are summarized in Table 2.

Table 2 – Stresses, Deformations, and Factors of Safety

		Worst case	Realistic
Poles	Combined stress	134.9	91.085
	FOS	2.74	4.06
Modulator	Combined stress	44.82	22.02
	FOS	6.16	12.54
Radial Deformation	Combined stress	0.551	0.187
	FOS	1.81	5.35

Stress in MPa, Deformation in mm. FOS is unitless

The stress results were calculated and converged to 0.197% for both the steel poles and aluminum endcaps of the modulator. The modulator poles demonstrated a worst-case factor of safety of 2.74 and a realistic-case factor of 4.06. The aluminum endcaps showed a worst-case factor of safety of 6.16, with a more realistic factor of 12.54.

5. Test bed

The AC induction motor and Variable Frequency Drive (VFD) were purchased by the previous team and were used for this iteration of the design. The motor was a 240 vac 5hp model from US Motors. Attached to the motor was an ATO Digital Rotary torque Sensor. The team bought two torque sensors to read input and output parameters, one going before and one going after the gearbox. These parameters included torque, power, and RPM reading. The torque sensors were connected to brackets made from sheet aluminum. Following the output torque sensor was a Magnetic Particle Brake, also purchased from ATO. The brake was attached to a controller that allowed for the ability to incrementally increase and decrease the amperage of the brake, which was proportional to the load on the system. This would allow a load to be applied on the gear system. All items were attached to Flexible Iron Hub Shaft Couplings with rubber spiders matching respective shaft dimensions.

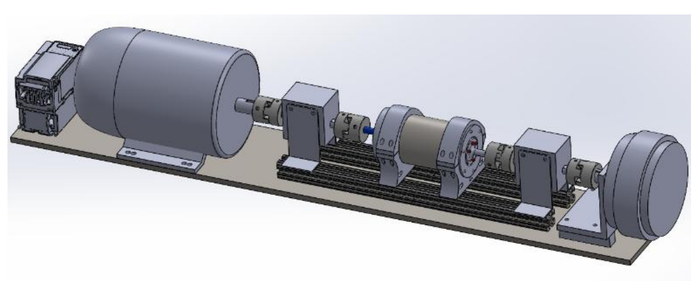
Figure 11 - CAD model of Test bed

6. Construction

The construction of the gear was split into two parts. First, the flux modulator was constructed around the sun gear, while the two sat on the input shaft. Manipulating all 17 poles to fit into the modulator cap was not easy with the sun gear's magnets pulling on them, but after some effort, the full modulator/sun gear assembly was constructed. That assembly was then fitted into the ring gear between its two end caps and bearings. The gear was then fitted into the test bed as shown in the figure below. A wood and polycarbonate shield was constructed using extra material in the Applied Lab and put around the gear for safety purposes.

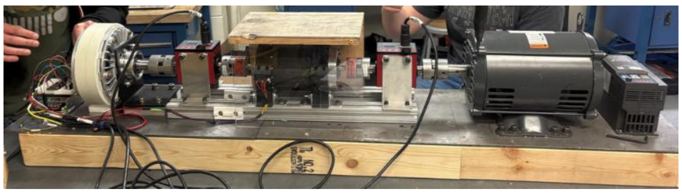

Figure 12 - Complete Test bed

7. RESULTS AND DISCUSSION

Place results and discussion here. *Authors should make sure that all tables, graphics, and equations fit within the columns and do not run into the margins.* All figures, graphs, tables, etc. should be numbered. Ensure that all text is in black and that there is no highlighted text.

The CMG created was expected to hit objectives and requirements discussed with the sponsors, Flowserve. These targets revolved around size, torque, temperature, efficiency, and speed.

Specific Requirements:

For size, the gear was expected of two requirements. The first requirement was for the gear to display a gear ratio between 3:1 and 2:1. By utilizing the sun gear and ring gear from the previous team's design, this objective was completed as the gear produced a 17:6 ratio, which in decimal form is about 2.83. The second requirement was for the gear to be a certain size in length, and diameter. The diameter requirement was expected to be 177.8 mm (7-inches) and for the length requirement to be 215.9 mm (8.5 inches). Benefitting from the previous team's parts, a flux modulator to fit the dimensions and operate between the sun gear and ring gear was required to complete this goal.

For torque, the gear was expected to produce at least 6 Nm of torque. This was a scaled-down requirement from the previous team, as the previous design was claimed to be unable to achieve the previous requirement. With the improvement of structure and material selection, the gear reached a maximum output torque of 55 Nm. This torque output nearly exceeded the requirement by a factor of 9. In addition, the gear was expected to achieve and scale to different torques as tested. With the property of the Magnetic Particle Brake, the gear was able to increase and decrease the torque output for the system by increasing or decreasing the power of the brake. The gear demonstrated that while these targets were achievable, it was important to focus on the duration of the test for the optimal production of the gear.

For temperature, the gear was expected to operate up to 205° Celsius (400° Fahrenheit). Testing for this objective required endurance testing of the gear and observation of the patterns and trends of the gear as time elapsed. After testing the gear with mild load for 1 hour, the gear hit a maximum internal temperature of 188° Celsius (370° Fahrenheit). It was observed with the testing constraints that were given that the gear began to plateau its temperature reading at around this time. Caution played a role in testing to ensure that the gear functioned properly through the testing and that parts other than the gear were not overheating due to fatigue. Since the inside of the gear is sealed by bearings, single use temperature stickers were applied to the modulator to record the internal temperature.

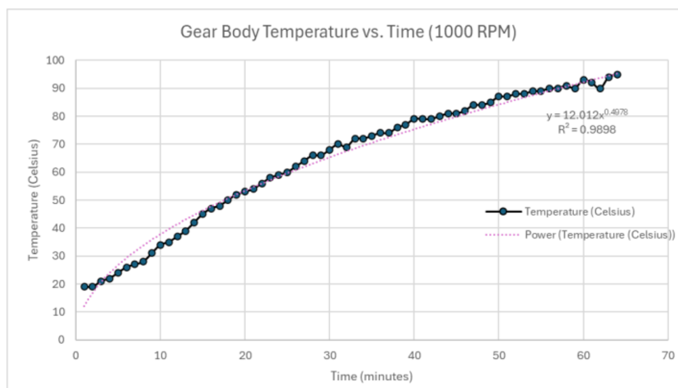

Figure 13: Gear Body Temperature vs Time Graph

For efficiency, the gear was expected to demonstrate a mechanical efficiency of 95%. This goal aims for the CMG model to match an efficiency range for a typical concentric planetary gear design. With the iteration of the CMG created and under testing constraints, the gear demonstrated a maximum efficiency of 89%. Failure to hit the 95% mechanical efficiency range is due to the testing constraints as well as enough loss through the system of testing, For speed, the gear must be able to perform in a ramp-up speed test of 20 seconds up from 0 RPM to 3600 RPM. Utilizing the 5HP motor purchased from the previous team, the gear was able to go from 0 to 3600 RPM in about 13 seconds. While making the quick jump, the flux modulator did not de-couple, and the ramp-up speed appeared to be limited by the VFD.

Discussion:

Figure 14 shows the power output of the gear. Each line represents constant torque ranging from 0 to 20 Nm. Testing was done from 250 to 2250 RPM instead of the maximum 3600 to avoid heat soaking and to quicken testing. As expected, as torque and speed are increasing, so does the power output. The peak power output of 1967 Watts was achieved at 2237 RPM and 11.52 Nm of torque.

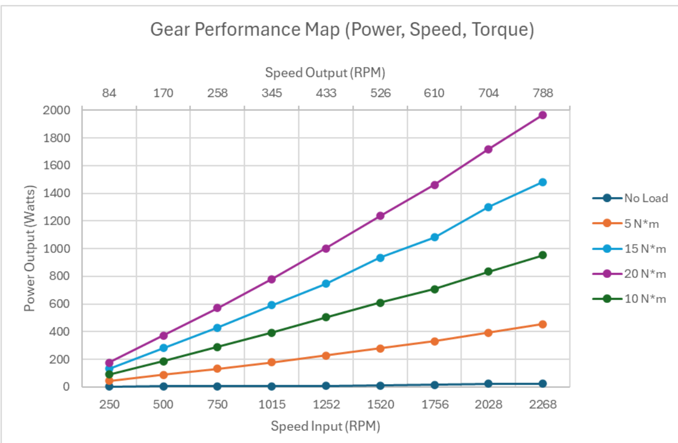

Figure 14: Gear Performance Map

It was found that efficiency decreases with respect to speed. Looking at **Figure 15**, it shows that as the speed input is increased, the mechanical efficiency slowly drops. It is assumed that there are eddy currents induced in the Flux Modulator that cause efficiency to drop. This is because as the gear's speed increases, we dump useful energy into heat. Interestingly, it can be seen that at higher torques and low speeds the system reaches its maximum efficiency. Looking at **Figure 16**, the table displays changing torques over speeds and has a mechanical efficiency for each scenario. Looking at 234 RPM and 20 Nm, it identifies the highest achieved mechanical efficiency of 89%. As the chart increases speed, the mechanical efficiencies drop as the colors displayed signify losses.

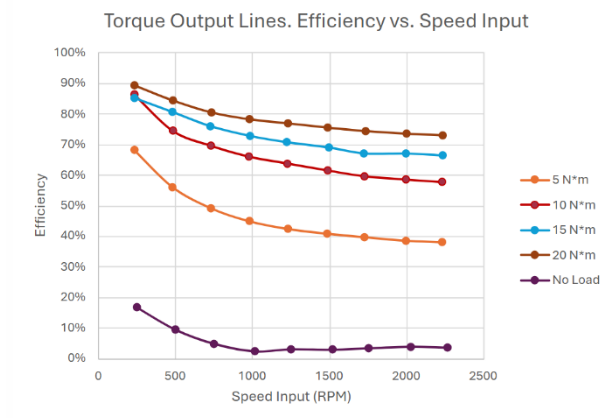

Figure 15: Efficiency over Speed Input with Fixed Torque Outputs

Torque Output, Speed Input, and Efficiency

Torque Output (N*m)	234	484	736	981	1232	1491	1734	2001	2237
20	89%	84%	80%	78%	77%	75%	74%	73%	73%
15	85%	81%	76%	73%	71%	69%	67%	67%	66%
10	86%	74%	70%	66%	64%	61%	60%	58%	58%
5	68%	56%	49%	45%	42%	41%	40%	38%	38%
0	17%	9%	5%	2%	3%	3%	3%	4%	4%

Speed Input (RPM)

Figure 16: Torque Output over Speed with Efficiency Readings for Each Condition

Finally, when looking at power loss, it can be determined that losses are not affected by torque. Looking at Figure 17, it shows that no matter how much the output torque changes within the system, the amount of power loss is nearly constant. Therefore, this explains that power loss is related to speed. This makes sense when we assume our maximum losses are due to eddy currents which are known to increase in magnitude with speed. Therefore, to reduce losses within the gear system, the system must be able to mitigate more of these eddy currents.

Figure 17: Power Loss over Speed Input

8. CONCLUSION

The development and testing of the Concentric Magnetic Gear (CMG) system demonstrated substantial progress toward the objectives outlined by the industrial sponsor. The final prototype satisfied key design requirements, including target gear ratio, torque transmission capacity, spatial constraints, and thermal endurance. The CMG achieved a maximum output torque of 55 Nm and sustained temperatures approaching 188 °C under extended loading conditions. Although the system did not attain the target mechanical efficiency of 95%, it achieved a peak efficiency of 89%, with losses attributed primarily to eddy current effects exacerbated at higher rotational speeds.

Simulation results further corroborated the mechanical integrity of the redesigned flux modulator, confirming sufficient structural robustness under realistic and worst-case loading scenarios. The test bed enabled comprehensive performance mapping, highlighting the proportional relationship between torque, power, and speed, while also revealing the inverse relationship between efficiency and rotational speed. These findings suggest that future iterations could benefit from further mitigation of eddy current losses to enhance efficiency and thermal performance.

Overall, the CMG exhibits several advantages over conventional mechanical gear systems, including reduced noise, minimized vibration, and lower maintenance requirements. The results support the viability of magnetic gearing in industrial pump applications, providing a promising pathway for continued research and development.

ACKNOWLEDGEMENTS

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