DEVELOPMENT AND MANUFACTURE OF A PROOF-OF-CONCEPT MAGNETICALLY-GEARED ACTUATOR FOR USE IN EXTREMELY COLD LUNAR ENVIRONMENTS

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ABSTRACT

A magnetically-geared actuator is being developed for extremely cold space environments to avoid the wiring and significant efficiency penalty associated with heating grease-lubricated actuators as well as the stringent life and loading constraints imposed by dry film lubricated mechanical gears. This paper describes the lessons learned while designing, manufacturing, and assembling a proof-of-concept prototype similar to the preliminary design of the actuator.

1 INTRODUCTION

Most space mechanisms require actuators that employ lubricated mechanical gears. Grease lubricants offer long life but require heating to about -60 °C, which in the extreme cold of many space environments is a penalty that can be equivalent to up to a 90% efficiency reduction [1]. Dry film lubricants don’t require heating but are subject to restrictive design constraints on loading and have limited life, especially for the sliding contact between mating gear teeth. NASA’s Motors for Dusty & Extremely Cold Environments (MDECE) Project is developing a rotational actuator that can achieve long life in extremely cold environments without grease lubrication or supplemental heating. This actuator is a magnetically-geared actuator that eliminates the need for gear lubrication by using magnetic fields to transmit torque between ‘gears’ instead of mechanical gear tooth contact.

Three magnetic gears in the literature have been designed for space applications, built, and ground tested to various extents in either ambient or cryogenic vacuum environments [2]-[4]. The MDECE Project is the first to develop a magnetically-geared actuator (i.e., magnetic gears integrated into an electric motor) for space applications and to explicitly design for the dusty and extreme cold environments of the lunar surface, including permanently shadowed regions.

This paper presents the lessons learned from designing, manufacturing and assembling a proof-of-concept prototype of the magnetically-geared actuator. Section 2 summarizes the specifications and design of the prototype. Section 3 describes the manufacture and assembly of the prototype. Section 4 briefly discusses functionality testing of part of the actuator. Section 5 summarizes the conclusions, including comments on the viability of this technology for actuating space mechanisms.

2 SPECIFICATIONS AND DESIGN

This section summarizes the driving requirements of the MDECE actuator, the design of the prototype, and the notable differences between the prototype and the fully-functional actuator that will be built in the future and then tested in a relevant environment.

The purpose of building the prototype was to gain the experience of manufacturing the parts, assembling them, and then demonstrating their functionality in an ambient environment by controlling the actuator to rotate at a stable speed.

2.1 Requirements

The magnetically-geared actuator is specified to produce a continuous output of 105 Nm at 2 rpm (22 W power) and a peak output of 208 Nm at up to 1.5 rpm (up to 33 W power) for at least 20 seconds. These requirements are based on a flight qualified reference actuator and are suitable for large robotic arm or rover mobility applications.

The thermal requirements, detailed in [5], are defined in terms of the environment in which the actuator should operate and survive. The cold operating goal is a lunar permanently shadowed region with regolith temperature of 30 K (-243 °C). The hot operating goal is the sunlit lunar south pole at 85 °S with regolith temperature of 313 K (40 °C).

Design objectives are defined for the mass, envelope volume, and length-to-diameter aspect ratio. However, these were relaxed for the proof-of-concept prototype.

2.2 Prototype design and differences from fully-functional actuator

The actuator consists of an outer stator type magnetically-geared motor [6] with a gear ratio of 13:1 connected to a cycloidal type magnetic gear [2] with a gear ratio of 43:1. These subcomponents are tightly integrated in the final, fully-functional actuator. In the prototype, they are separate to enable independent testing of the gear and motor. Fig. 1 depicts the prototype configured to test the motor and gear as a complete actuator. The air gap between rotating and stationary components (nominally 0.25 mm) matches the final design of the actuator. This small air gap was selected for the final design to reduce the actuator’s size and weight at the expense of tighter constraints on structural deformation and geometric tolerance stack-up. The prototype was not intended to demonstrate the actuator’s mass. Thus, the prototype’s cost and lead time were reduced by allowing some structures to be made of stainless steel instead of titanium and simplifying some features whose only purpose was reducing mass.

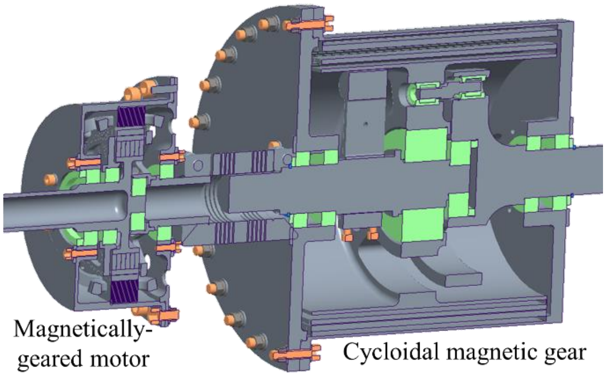

Figure 1. Proof-of-concept MDECE actuator configured to test the actuator as a whole; bearings and their preload springs depicted as simplified green cylinders.

The prototype magnetically-geared motor is very similar to the final design of the actuator. The key differences are (a) the aforementioned change in structural material, (b) small changes in the geometry of the modulator structure’s geometry to improve manufacturability, and (c) small changes to the geometry of the magnetic components to reoptimize the final design for worst case airgaps and the mass reduction needed to achieve the goals of the project. The final motor was also designed for field oriented control of its stator. The prototype’s stator was designed for block commutation. The change to field oriented control was made because it was predicted to provide an appreciable increase in efficiency and a significant reduction in torque ripple. Field oriented control is expected to be possible using the selected motor controller.

The prototype cycloidal magnetic gear differs from the final actuator in multiple ways, but it captures the key features that needed to be demonstrated. One notable difference is that the prototype’s active length is considerably longer, which increases the moment arm between the magnetic forces on the shafts and the bearing supports in the housing. Consequently, structural analysis revealed an excessive change in air gap under load. To compensate for this, the housing thickness was significantly increased, and a pair of bearings was used at each end of the housing.

3 MANUFACTURE AND ASSEMBLY

This section describes the notable successes and challenges experienced throughout the process of manufacturing and assembling the proof-of-concept prototype.

3.1 Manufacturing lessons learned

In electric motors and magnetic gears, eddy current losses occur in electrically conductive materials that are exposed to time varying magnetic fields, like those experienced by the magnetic and structural components in the magnetically-geared motor’s modulator subassembly. Fig. 2 depicts the components of the prototype’s modulator. The modulator’s structural posts are also subjected to mechanical design constraints, because the magnetic gear’s specific torque is maximized when the modulator pole pieces are radially thin (often < 2 mm) [7]. The ability of the structure to react the applied loads (radial and torsional magnetic forces along with centrifugal forces) and maintain small air gaps typically limits the thickness of the pole pieces to some size greater than optimum. Heat rejection must also be considered, because the pole pieces can incur the second highest loss in a magnetically-geared motor designed for space mechanisms [5]. Consequently, the preferred material properties of the modulator structure are high stiffness, high strength, low electrical conductivity, and high thermal conductivity. Ceramic materials are thus an attractive option if their manufacturing limitations are acceptable.

The combination of trying to eliminate eddy currents in the modulator’s structure and achieve a very small air gap of 0.25 mm was found to be a difficult challenge. For the prototype actuator, the modulator structure was initially designed with a ceramic and a manufacturing trial was carried out. No ceramic machine shop or manufacturer was found that would commit to fabrication tolerances less than ±0.025 mm to ±0.050 mm. These tolerance values are larger than what is desired for proper fit of super precision bearings in their housings or tight fits between mating structures in the modulator. This lower than desired tolerance was accepted for the proof of concept, because bearing life is not critical for the prototype and machining at assembly after bonding the modulator together could be used to achieve the target air gaps.

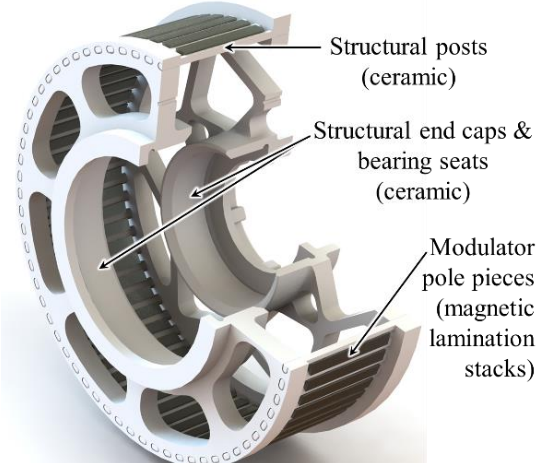

Figure 2. Modulator subassembly for the proof-of-concept actuator's magnetically-geared motor

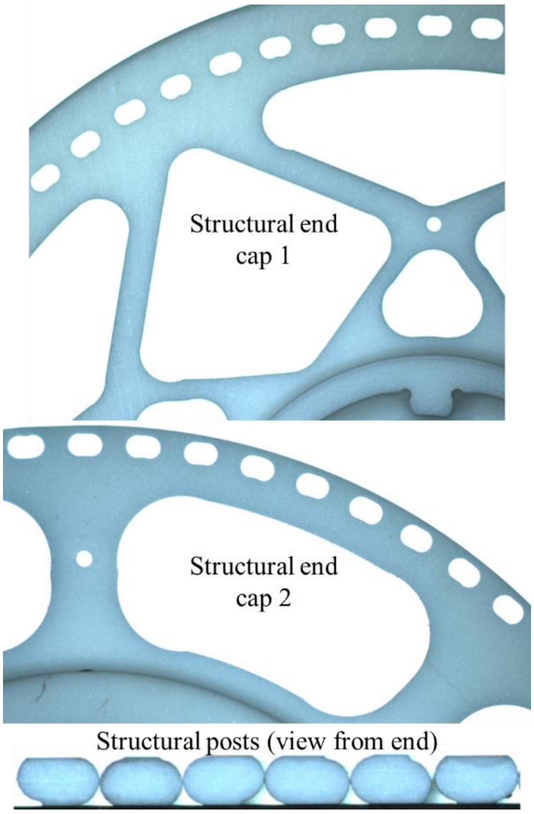

Figure 3. Errors in form of the slot interface in the proof-of-concept actuator's ceramic modulator parts as seen on an optical comparator

The ceramic modulator structures received were not within specifications. As shown in Fig. 3, the support posts and their mating slots in the end caps had irregular shapes that made assembly of the components impossible. The errors in form would have also made it impractical to keep the modulator assembled under the designed spring preload without epoxy or other means of securing the posts in one end cap. Therefore, the original ceramic modulator design had to be abandoned for the proof-of-concept actuator. Improved results are expected if the size of the slot is enlarged or if the interface is made round, because round features lend themselves to tightly controlled geometry with finish grinding.

To replace the ceramic parts, a duplicate set of modulator structures was fabricated from G10, which has been used by others [8], [9]. G10 will have reduced performance in the modulator relative to ceramics due to its lower modulus, anisotropic thermal expansion, and lower thermal conductivity. Although the G10 modulator has not been assembled yet, the quality of the individual parts is clearly better than the ceramic ones. One would need to demonstrate that the thermal and structural designs close with G10, but G10 seems to be a viable alternative to ceramics that compromises on mechanical and thermal performance but still avoids eddy current losses and allows for easier and more precise manufacture.

The modulator's pole pieces and the backiron for the two magnet arrays in the cycloidal gear are composed of stacks of laser cut magnetic laminates. The small radial thickness (2-3 mm) of these parts was at the limit of what the selected vendor could produce, and it led to additional manufacturing and assembly difficulties. Due to their thin sections, they could not be laser welded together and had to be bonded together to their full stack height. The bonded laminations and the aspect ratio of the backirons for the cycloidal magnetic gear led to a more fragile lamination stack structure that needed to be delicately handled until it was bonded onto its mating titanium structure. The desired precision of these parts pushed the tolerance limit for stacking. The mating interface on one structural part needed minor machining to make assembly possible. More refinement of the manufacturing processes is needed to make assembly of thin and high precision lamination stacks more practical. However, an opportunity was identified to reduce mass by eliminating the cycloidal backirons [5]. This change was implemented for the final actuator.

Two important and unusual parts of the actuator are the input shaft and pins in the cycloidal magnetic gear, as pictured in Fig. 4. Each of these parts contains a bearing seat with an axis eccentric to the primary axis of the part. This feature is required to create the gear ratio but must be carefully dimensioned and toleranced to ensure functionality and an acceptable tolerance stack-up. The dimensioning approach and tight tolerances specified were achievable without excessive cost, but they were outside the capability of some vendors. The parts received met the drawing specifications without the need for rework.

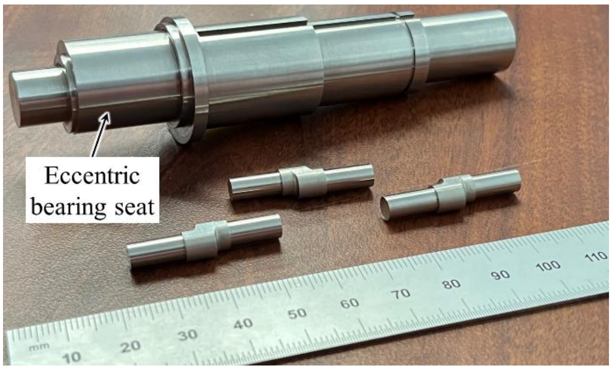

Figure 4. Input shaft and eccentric pins for the proof-of-concept actuator's cycloidal magnetic gear

The manufacture and assembly of the prototype's magnet arrays and the combined stator and ring gear in the geared motor were similar in difficulty to the stator and magnet arrays in conventional motors. Fig. 5 depicts the prototype's sun gear. The specified thickness of magnet laminates, which was predicted to achieve high efficiency, was well within the capabilities of the selected vendor. Relative to conventional motors, bonding the ring magnets on the stator adds an extra assembly step, but with standard practices it can be accomplished with a similar repeatability. Conventional motors with a tight air gap require finish grinding of the stator's bore just like the prototype motor did. The high aspect ratio of the magnets in the prototype's cycloidal gear led to a higher-than-expected scrap rate during assembly and one rework. Although, this concern is mitigated by design changes in the final actuator, whose longest magnets are about half the length of those used in the prototype.

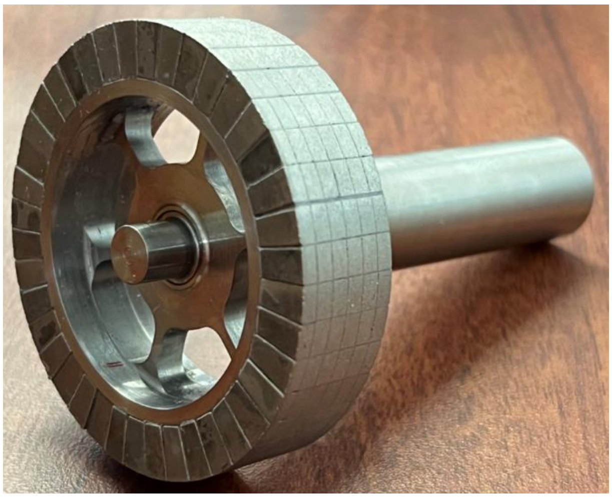

Figure 5. Sun gear for the proof-of-concept actuator's magnetically-geared motor

The structural metallic parts in the proof-of-concept actuator were fabricated using conventional machining and grinding processes. In preparation for the final actuator, additive manufacturing processes and alternative grinding approaches were investigated as a means to reduce lead time and cost while effectively eliminating many factors contributing to the tolerance stack-up of the air gaps. Manufacturing the final actuator's titanium structures to a very high precision does not seem to be a problem with the processes uncovered.

3.2 Assembly lessons learned

The following lessons were learned while assembling the cycloidal magnetic gear. The magnetically-geared motor could not be assembled in time for this paper, because a vendor's delivery of subassemblies was delayed.

One challenge that also applies to conventional electric motors is the presence of strong magnetic forces during assembly that attract the magnets and magnetic lamination stacks to each other. The nominally unbalanced radial magnetic forces and multiple axes of rotation in the cycloidal magnetic gear are complicating factors. The assembly of the cycloidal gear's rotating components was simple and completed quickly with the use of only a small, hand-operated mechanical press. This was possible because magnetic forces between parts were imperceptible during these assembly steps. Magnetic forces during these steps will be an even smaller concern in the final actuator, because it does not use stainless steel structures. Aligning the output shaft, cycloidal pins, and eccentric rotor was easier than expected, because the parts were accessible from both ends of the eccentric rotor.

Figure 6. Subassembly of all the rotating components in the prototype cycloidal magnetic gear

The subassembly of the cycloidal gear's rotating components, shown in Fig. 6, had relatively high out-of-plane stiffness with little out-of-plane backlash. This characteristic was useful when installing the rotating subassembly into the housing. Magnetic forces are strong during this assembly step due to the very close proximity of the inner and outer magnet arrays. The magnetic forces act not only radially but also axially. A lathe was used to react these forces, establish the alignment between housing and rotating subassembly, and move the subassembly in a controlled manner. The housing was held in the lathe's chuck while the rotating subassembly was held in the lathe's tailstock. One factor that was overlooked during the design process was the ability of the eccentric rotor and output shaft to pull away axially from the input shaft that was held in the tailstock. This was overcome by temporarily adding a secondary means of axially securing the output shaft to the input shaft. With this approach, the assembly was completed without any notable issues. The assembled cycloidal magnetic gear is depicted in Fig. 7.

Figure 7. Assembled prototype cycloidal magnetic gear

The assembly process for the proof-of-concept prototype did not require a controlled environment. As a result, a lathe could be used for the critical assembly step in which the large magnetic forces are encountered. However, the solid lubricated bearings used in the final actuator and the plan to conduct life testing necessitate that the actuator be assembled in a controlled environment, such as a clean room. Thus, revisions to the assembly process are needed. It seems likely that the lathe can be replaced by a positioning stage and clamps, possibly supplemented by guides.

4 PRELIMINARY TESTING

Due to vendor delays, the cycloidal magnetic gear could not be tested at speed in time for this paper. Functionality was tested by rotating the cycloidal gear's input shaft by hand and visually observing the resulting motion through holes in the gear's housing. The internal components moved as expected and produced the desired gear ratio. Although not expected to readily occur based on the anticipated loading, the cycloidal pins in the prototype are capable of moving axially by an appreciable amount and rubbing against another component. Axial motion did not appear to occur during the functionality test. During this test, a faint grinding-like noise occurred. Further investigation is required to identify the cause. The preliminary thought is that a small amount of fine magnet debris was left over from assembly of the magnet array and remained in the air gap. Some magnetic debris was observed on the inner magnets after the rotating components were assembled. An improved cleaning process will be implemented for the final actuator.

In an upcoming presentation, the prototype cycloidal magnetic gear and magnetically-geared motor will be tested for peak torque and at speed.

5 CONCLUSIONS

The design of the proof-of-concept magnetically-geared actuator indicated that the worst case loading for structural deformation-induced reductions in the cycloidal gear's air gap occurs at zero output torque. This has been found to remain true in simulations of the final actuator at < 30 K. It was not too difficult to avoid excessive deformation of the magnetically-geared motor's air gap, which occurs at peak output torque. Another key design lesson learned was that if the cycloidal gear's structural design is not improved relative to this prototype, the selection of a relatively large length-to-diameter aspect ratio will require increased housing and bearing mass to ensure air gap deformation is acceptable. Increasing the minimum air gap can alleviate this but will reduce magnetic performance.

Overall, the prototype actuator was found to be sufficiently manufacturable and capable of being assembled. Either design changes to the motor's modulator structure or ceramic manufacturing improvements are needed to enable the use of ceramic modulator structures. G10 may be a viable alternative. More refinement of the manufacturing processes is needed to make assembly of thin and high precision lamination stacks more practical. However, the results were acceptable after minor rework of one part. The manufacture and assembly of the prototype's magnet arrays and the combined stator and ring gear in the geared motor were found to be similar in difficulty to the stator and magnet arrays in conventional motors. When performance needs to be maximized, there isn't always room in the design to accommodate best practices for manufacturability.

Assembly and functionality testing of the cycloidal magnetic gear did not uncover any significant concerns. The only notable change in assembly process needed for the final actuator is to replace the assembly hardware used for the prototype's final assembly step with something that can be used within a controlled environment.

Based on the manufacture and assembly of the prototype actuator and the design of the prototype and final actuators, magnetically-geared actuators are a viable technology for space mechanisms that are ready for demonstration in ambient and cryogenic vacuum environments. Magnetic performance and bearing life are key areas of experimental interest. Some manufacturing challenges remain to realize the full potential of the technology, but a high magnetic performance prototype could still be successfully manufactured at a reasonable cost and assembled into a functional magnetic gear prototype. Alternative magnetic gear and magnetically-geared motor configurations can be considered if these challenges become limiting in the future.

6 REFERENCES

1. Scheidler, J.J. et al. (2022). The Impacts of Heating Actuators in Extremely Cold Space Environments. In *Proc. 2022 IEEE Aerospace Conference*, pp1-8.

2. Praslicka, B. et al. (2021). Practical Analysis and Design of a 50:1 Cycloidal Magnetic Gear with Balanced Off-Axis Moments and a High Specific Torque for Lunar Robots. In *Proc. 2021 IEEE International Electric Machines & Drives Conference*, pp1-8.

3. Esnoz-Larraya, J. et al. (2017). Optimagdrive: High-Performance Magnetic Gears Development for Space Applications. In *Proc. 17th European Space Mechanisms and Tribology Symposium*, pp1-5.

4. Perez-Diaz, J.L. et al. (2015). Performance of Magnetic-Superconductor Non-Contact Harmonic Drive for Cryogenic Space Applications. *Machines* **3**(3), 138-156.

5. Scheidler, J.J. et al. (2023). Detailed Design of a Magnetically-Geared Actuator for use in Extremely Cold Lunar Environments. In *Proc. 2023 IEEE Aerospace Conference*, pp1-12.

6. Tallerico, T.F. et al. (2020). Outer Stator Magnetically-Geared Motors for Electrified Urban Air Mobility Vehicles. In *Proc. 2020 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, pp1-25.

7. Tallerico, T.F. et al. (2019). Electromagnetic Mass and Efficiency of Magnetic Gears for Electrified Aircraft. In *Proc. 2019 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, pp1-25.

8. Gardner, M.C. et al. (2019). Performance Impacts of Practical Fabrication Tradeoffs for a Radial Flux Coaxial Magnetic Gear with Halbach Arrays and Air Cores. In *Proc. 2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp3129-3136.

9. Baninajar, H. et al. (2023). Experimental Evaluation of a 63.3:1 Dual-Stage Coaxial Magnetic Gear. *IEEE Transactions on Energy Conversion* **38**(1), 158-169.