Additive manufacture of a flux focusing magnetic gear

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Abstract

Magnetic gears have been researched for potential application in wind and ocean energy turbines, given their inherent overload protection and their minimization of wear based failure modes. These attributes would make the turbines more robust given the variable environmental loading conditions and reduce the need for regular maintenance, both of which contribute to a more competitive levelized cost of energy. In this research, a radial-flux-focusing magnetic gear was designed, simulated, and ultimately built using a high resolution desktop stereolithography printer. The additively manufactured components included a fixed outer rotor of magnets, an inner rotor of magnets coupled to the input shaft, and an intermediate rotor of field modulating steel pieces coupled to an output shaft. The use of clear resin for some parts allowed the inner motion of the assembly to be visible during operation, but pigmented resin was found to produce more accurate parts.

Keywords

Additive manufacturing, magnet, gears

Magnetic Gearing Background

Magnetic gears have been proposed for years as a mean of non-contact transmission of torque while speeding up or slowing down the rotational speed[1]. The earliest gears were modeled off of spur gear designs and suffered from low torque densities as a result of both geometric properties and material properties. Improved performance from rare-earth magnets as well as clever topologies that increase the number of magnets that are simultaneously transmitting torque have opened the door to magnetic gears being considered for applications that have historically been met by traditional mechanical gears.

Magnetic gears are particularly suited to applications with variable loading conditions and limited access for service and maintenance. The nature of the magnetic gear torque transmission provides inherent overload for extreme transient loads. Unlike meshing mechanical gear teeth which could break, distort, or fatigue under transient loading, a magnetic gear will simply slip until the transient torque phenomenon passes and the torque values drop back into the expected range. Similarly, magnetic gears do not have the cyclical Hertzian contact stresses that arise from teeth meshing and separating during operation. The elimination of these two contact based failure modes make magnetic gearing attractive for applications where the designers expect variable input loading, but do not want wear based failure modes that necessitate frequently scheduled maintenance or servicing. Wind and marine energy generation are seen as key markets for magnetic gearing as the power takeoff transmissions have to withstand naturally varying input conditions and be designed to operate with minimal maintenance to be cost competitive with established energy generation.

While numerous variants of magnetic gears have been explored, this research deals with flux focusing magnetic gears, where steel pieces are introduced into the gear assembly for the purpose of directing the magnetic field to achieve higher flux densities. The higher flux densities generate greater forces and torque transmission, improving the performance of the gearbox as measured by the volumetric torque density, a measure of how much torque the gearbox can transmit for a given size. This metric allows for comparison to traditional mechanical gearboxes as well as direct drive permanent magnet motors.

Additive Manufacturing Background

Additive manufacturing (AM) is a collection of technologies that produce a part by building it up layer by layer instead of as traditional machining processes like milling, drilling, and lathe work which create the final geometry through subtractive means. The dominant AM technologies are fused filament fabrication (FFF), stereolithography (SLA), selective laser sintering (SLS), and 3D printing (3DP). While these technologies vary in terms of materials, resolution, and build times, they all share the ability to produce complex geometry without the need for intermediary fixtures or setups. In the past five years, these technologies have migrated from large companies and specialized service bureaus into homes and small businesses as key elements of the technology have come off of patent, allowing an explosion of new companies entering the market. Universities have also benefited from the increased prevalence of additive manufacturing, establishing both Makerspaces[2] to support research and new curriculum to educate students on the applications of additive manufacturing[3].

While FFF is the dominant desktop AM technology on the market, as seen in the popular MakerBot and Cube product lines, Formlabs introduced desktop SLA with the Form 1 following a successful Kickstarter campaign[4-5]. The additive manufacturing in this research was performed on the Formlabs Form 1+ due to its ability to produce higher resolution parts, which were critical for accurately holding magnetic components in the assembly to maintain the specified airgaps. The Form 1+ is also compatible with a variety of resins, including the clear resins which were used to showcase the inner workings of the gear assembly during operation.

Selection of the Radial-Flux-Focusing Magnetic Gear Topology

There are several topologies for flux focusing magnetic gears, including axial and radial. While operating along the same magnetic principles, axial-flux-focusing magnetic gears direct flux in the axial direction (parallel to the axis of mechanical rotation) and radial-flux-focusing magnetic gears direct the flux in the radial direction (perpendicular to the axis of mechanical rotation) as shown in Figure 1 and Figure 2 .

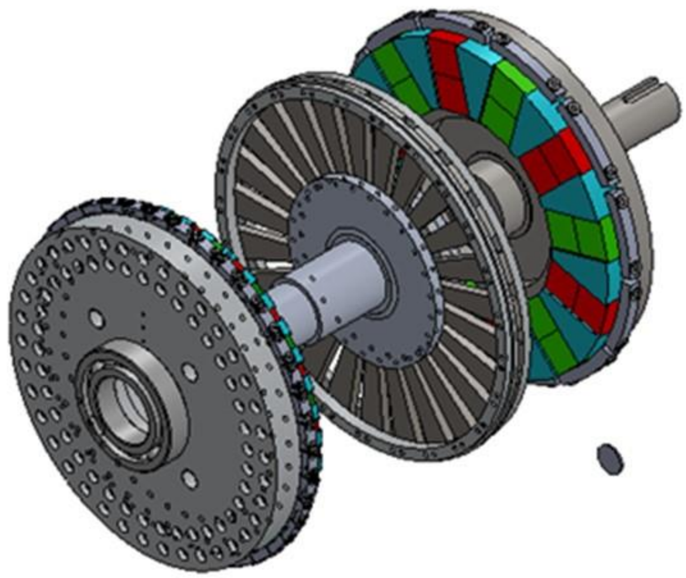

Figure 1. Example of an axial-flux-focusing magnetic gear, showing a low speed rotor, spoke rotor, and high speed rotor. Green and red correspond to magnets of opposite polarity in this figure.

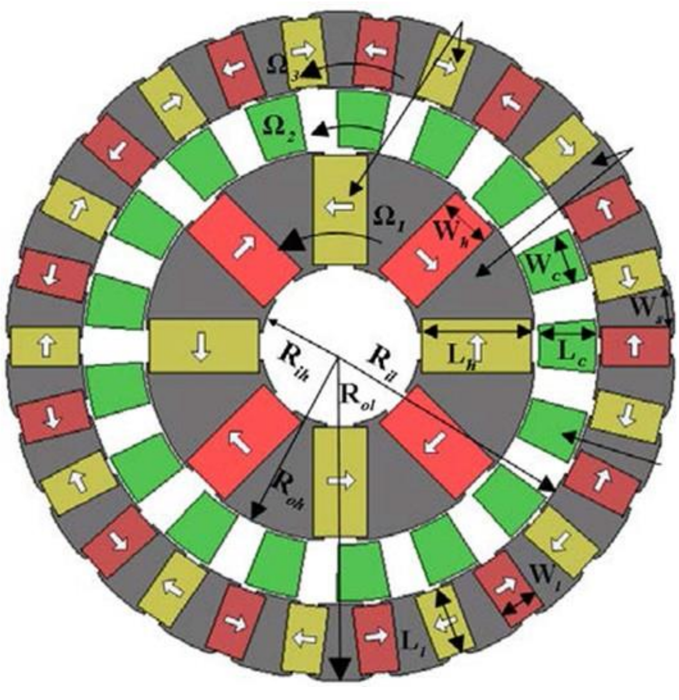

Figure 2. Example of a radial-flux-focusing gear, showing the outer rotor, cage rotor, and inner rotor[2]. Red and gold correspond to magnets of opposite polarity in this figure, with green representing the steel flux focusing pieces.

The radial-flux-focusing topology was chosen for this design based on the authors' past experience with the design[6]. A radial-flux-focusing magnetic gear consists of three primary elements; the inner rotor, the outer rotor, and the cage rotor. The inner rotor and outer rotor both contain magnets, while the cage rotor lies between the inner and the outer rotors and the ferrous cage bars serve to focus and modulate the magnetic fields between the inner and outer rotor. The speed relationship between the three rotors are given by Equation 1, which sets the number of poles needed for the rotors to interact through a common harmonic, and Equation 2, which is a simplification of the general equation of rotor motion when the outer rotor is fixed[1].

$$p_1 = |p_3 - n_2| \quad (1)$$

$$\omega_1 = \left(\frac{n_2}{p_1}\right)\omega_2 \quad (2)$$

where p_1 is the number of pole pairs on the inner rotor, p_3 is the number of pole pairs on the outer rotor, n_2 is the number of steel flux focusing elements, ω_1 is the rotational speed of the inner rotor, and ω_2 is the rotational speed of the cage rotor.

Magnetic Gear Design Process

The design of the magnetic gear went through alternating cycles of electromagnetic analysis and mechanical/manufacturing analysis as shown in Figure 3. The design team included both undergraduate research assistants, graduate research assistants, a post-doctoral researcher, and the two faculty mentors. The disciplines of electrical engineering, mechanical engineering, and engineering technology were all represented on the team.

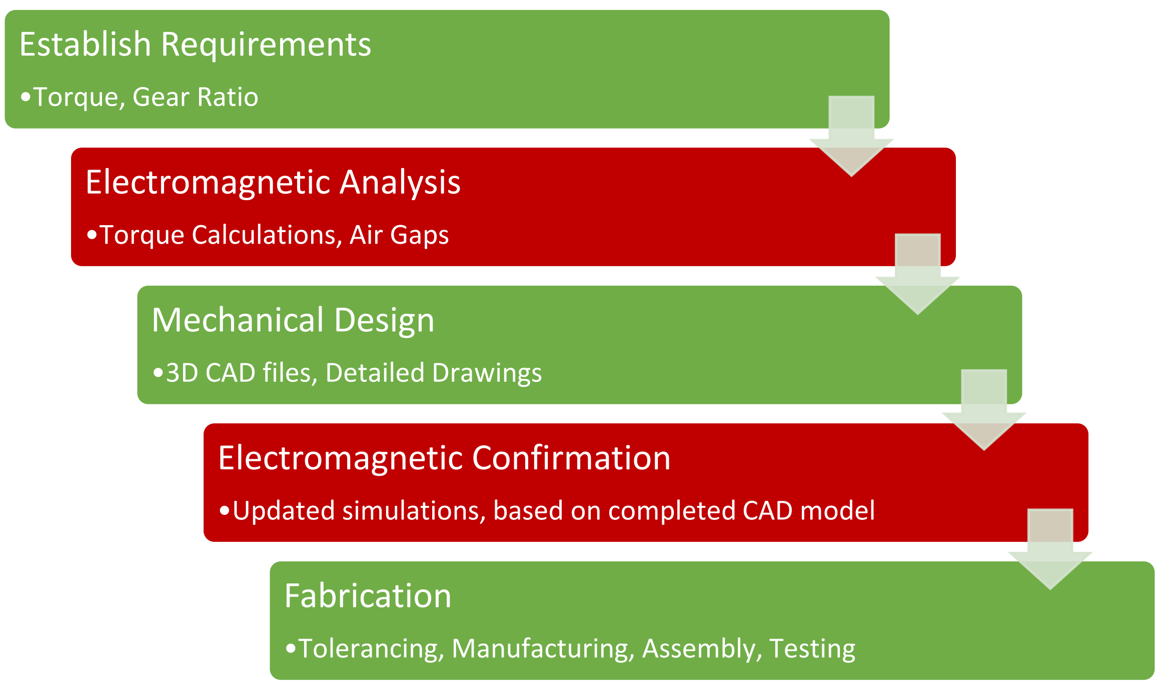

Figure 3. Magnetic gear design process, with primarily mechanical/manufacturing stages shown in green and primarily electromagnetic stages shown in red.

The design process started with establishing the mechanical requirements of the gearbox. Chief among these were the transmitted torque and the desired gear ratio. These values influenced the magnetic materials chosen, the number of pole pairs, and the overall size of the gearbox. In a similar fashion to a mechanical planetary gear, a radial-flux-focusing magnetic gear can be driven a number of different ways, which are best described by which rotor (inner, outer, or cage) is being held fixed, while the others are free to rotate. For this design, the outer rotor was held fixed, while the inner rotor served as the input and the cage rotor served as the output. Given the four pole pairs on the inner rotor and 17 flux focusing bars on the cage rotor, this radial gear box was design for a gear ratio of 4.25:1.

Once the gear ratio was established, the design concept could be represented in the JMAG simulation software, which numerically solved the Maxwell's equations for the electromagnetics given the specified material properties, design geometry, and input dynamics as shown in Figure 4. In addition to the speed relationships and torque density, other parameters are used to characterize the performance of the magnetic gear. These notably include the magnetic forces and the torque ripple. The magnetic forces are used to determine the stresses and strains in the design to ensure that the components are mechanically sized appropriately, while the torque ripple is the amount of variation on the transmitted torque as the assembly goes through a complete rotation. At the conclusion of the stage of the design, the magnets, the flux focusing pieces, and their relative position in space were defined, but not any of the mechanical features or components required to fix these elements in space.

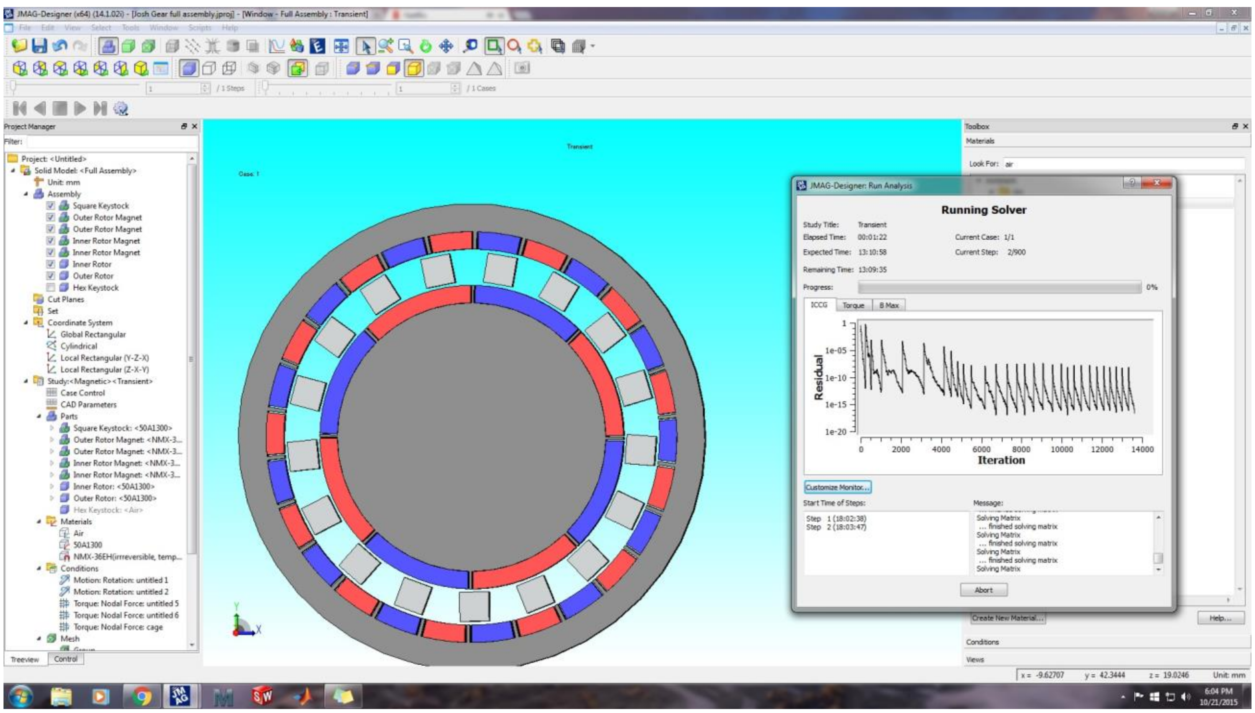

Figure 4. Screenshot of the JMAG simulation software.

Once the magnetics of the design were satisfactory, the mechanical design focused on the mechanical elements that would hold a) magnetic components in position during operation b) provide for torque input and output and c) constrain each component to the appropriate number of degrees of freedom. This included most notably the design of the inner rotor to house four pole pairs of magnets, the outer rotor to house thirteen pole pairs of magnets, the end plates for the securing the seventeen bars of cage rotor, and the end caps. The location of bearings and fasteners were also specified at this stage as well as cutouts to reduce the overall mass of the design. The final product of this stage was a complete Solidworks assembly as shown in Figure 5.

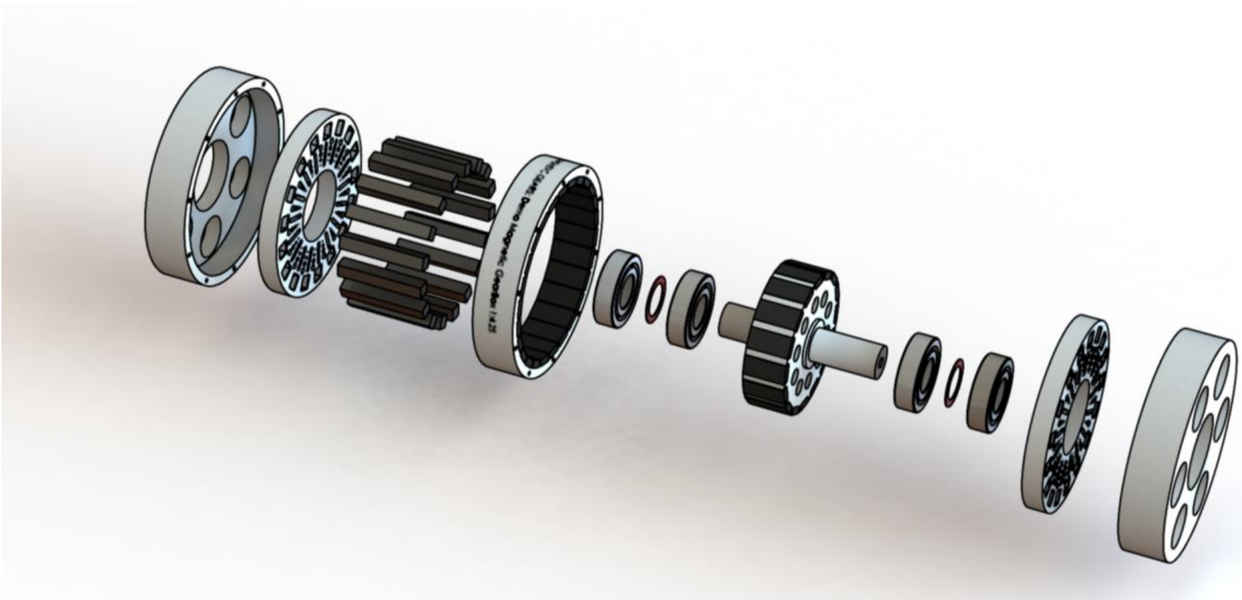

Figure 5. Solidworks exploded assembly view of the radial-flux-focusing magnetic gear.

With these components defined, the design returned briefly to the electromagnetic simulations to ensure that actual material selections, component, and feature placement did not adversely affect the design goals. Following that electromagnetic verification, the project moved into detailed design, where component tolerances were selected and features and components were given a final review for manufacturability.

Desktop Additive Manufacturing

Once the part design was finished, the additive manufacturing process started with exporting the part geometry from the CAD package (Solidworks in this case) as an STL file. The Form 1+ ships with PreForm software for postprocessing the model in preparation for manufacturing. After the STL file is imported, the part is then oriented to minimize the impact of support structures which connect the part (particularly overhangs) to the build platform during the fabrication process as shown in Figure 6. The density and size of the support structures can also be modified to minimize any blemishes on the part where support geometry connects with part geometry.

Once oriented, the user selects both the material and the layer thickness for the build. Two materials were used to produce this design, Clear Resin from Formlabs and Green SF from MakerJuice Labs. The clear resin was selected to offer visibility of the inner workings of the assembly during operation[7], while the SF resin was selected for its toughness and suitability for highly detailed parts[8]. Layer thickness are set at either 25 µm, 50 µm, or 100 µm, by balancing the need for detail in the part against the build time. For this assembly, the layer thickness were set at either 25µm or 50 µm depending on the component.

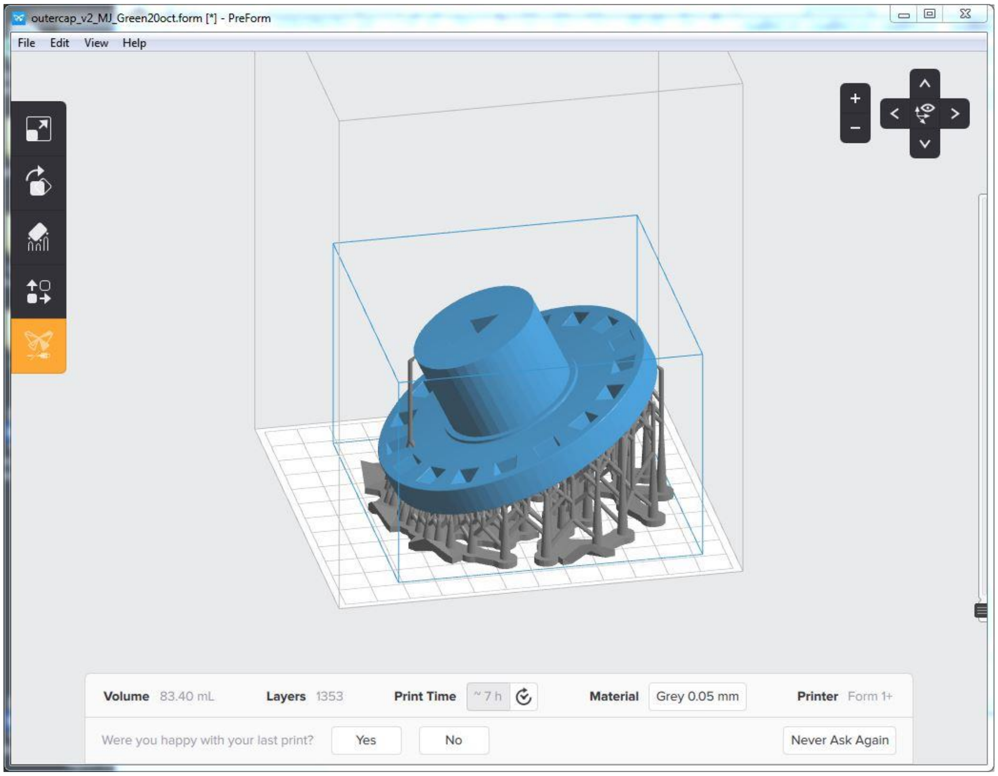

Figure 6. Screenshot of the PreForm software showing part orientation and the generated support structures.

Once started, the SLA process works by tracing a laser through a bed of photocurable resin, selectively curing any material the laser touches in that layer before the build platform is indexed and the process is repeated. As the laser traces through the next active layer, it cures that material, bonding it to proximate material in the previous layer. The process repeats as the Form 1+ builds the part in an inverted orientation, with the laser path coming from underneath the resin tank and the build platform indexing up as successive layers are finished. Build times for the larger parts ranged from five to seven hours, based on the build layer thickness and part orientation. An image of a finished part (cage rotor output shaft), inverted and attached to the build plate via scaffolding is shown in Figure 7.

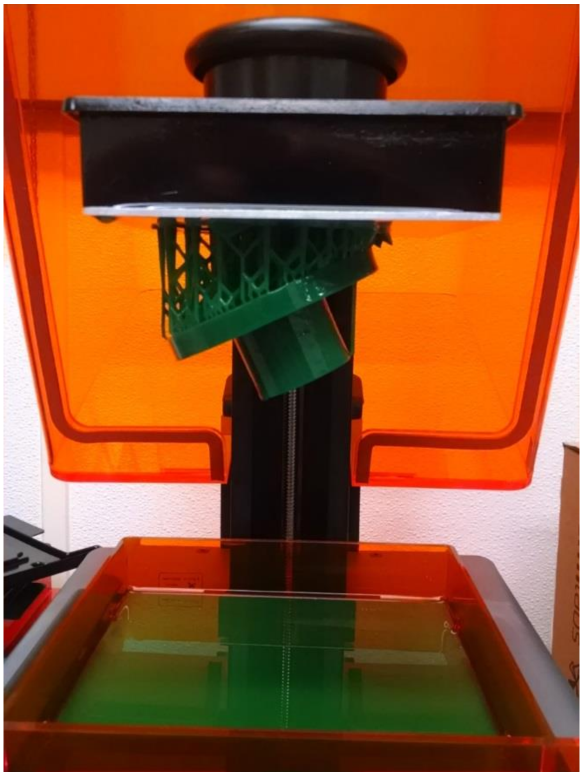

Figure 7. The cage rotor output shaft (in Maker Juice SF Green) immediately after fabrication on the Form 1+, inverted and attached to the build platform via scaffold structure.

Post Processing

Once the part was finished the entire build platform was removed from the Form 1+ and the part carefully popped off of the build platform. The part was rinsed in a solution of 91% isopropyl alcohol to remove any uncured resin that might be stuck to the part before being placed in a UV chamber for sixty minutes to finish curing. Once the part had been fully cured to achieve its full stiffness and stability, any remaining supports or support remnants were removed with flush cut clippers. Part surfaces that are oriented toward the build platform have the greatest number of support contact points. These contact points can leave blemishes on the surface when removed, so care was taken after clipping to sand away any remaining blemishes.

Some regions of the clear resin parts were intended to be transparent for internal visibility as noted before, which necessitated additional post processing of those parts. Those surfaces were first wet sanded with a series of higher grit numbers to achieve a uniform matte surface that improved with higher grit numbers toward translucent as shown in Figure 8. The surfaces were then polished with three stages of Novus scratch remover as detailed on the Formlabs website[5] to achieve optical clarity as shown in Figure 9.

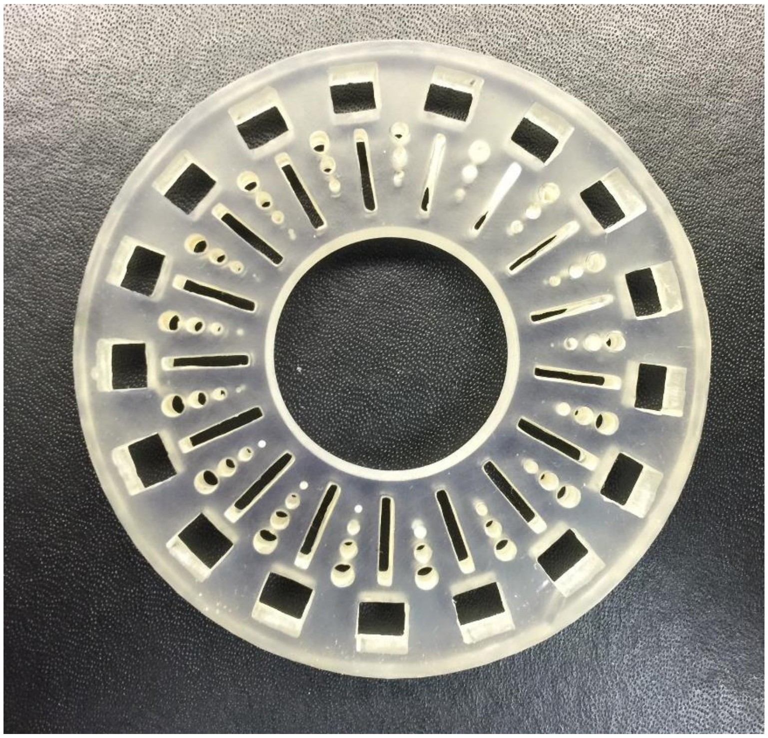

Figure 8. Cage rotor plate manufactured from Clear Resin after wet sanding to translucence.

Figure 9. The radial-flux-focusing magnetic gear partially assembled showing the optical clarity through the cage rotor plate following fine polishing, allowing visualization of both the inner and outer rotor magnets.

Assembly

The magnetic gear assembly was done in stages, with the parts being sanded and polished as soon as they came off the Form 1+ and had been through the final cure in the UV chamber. Rare earth magnets were epoxied into place on the inner and outer rotors, with alternating pole orientation. The cage rotor was assembled by inserting lengths of square keystock into the square cutouts on the cage rotor endplates. These square holes were found to be consistently undersized on the clear resin part, requiring manual filing of those inner surfaces before the keystock would slide into position. The matching cage rotor plate on the opposite side was produced with the SF resin and only had two square recess that required manual filing to fit the keystock.

Handle components for the input shaft were also additively manufactured on the Form 1+ using clear resin and when attached to the input shaft completed the assembly as shown in Figure 10. Torque is transmitted from the handle to the input shaft/rotor via recessed square head bolts. Operation was verified by turning the handle and observing relatively smooth operation. A single revolution of the output shaft required 4 ¼ turns of the handle, matching the expectations for the gear ratio from Equations 1 and 2.

Figure 10. Completed radial-flux-focusing magnetic gear assembly.

Conclusions, Educational Outcomes, and Future Work

The additive manufacturing process was found to produce sufficiently accurate parts to assemble a radial-flux-focusing magnetic gear. While the clear resin did provide increased visibility of the internal components of the gearbox, it was generally found to be less accurate than the SF green resin. This is believed to be due to the opacity of the green resin limiting the travel of the laser illumination to unintended regions of previous layers (overcure) as was likely occurring with the clear resin. Even with these limitations, desktop additive manufacturing was a viable strategy as it produced components for a working assembly without the delays and expense associated with traditional machining of these detailed components. The mechanical properties of the resin materials used in this research are not appropriate for heavy use, but other materials available for the Form 1+ would be more suitable for extended testing[9]. By quickly producing low-cost, geometrically accurate parts, additive manufacturing enables quick prototyping of magnetic gearbox topologies to ensure fit and function before committing to more expensive materials and manufacturing.

The mechanical students involved in this project gained insights into the magnetic factors impacting the design, while the electrical students came to realize some of the challenges involved in manufacturing their preferred geometries. One of the undergraduate researchers involved in this project proposed a follow-up project for his senior design capstone experience. In that project, five students will integrate a similar radial-flux-focusing magnetic gearbox into the power transmission of a vertical axis wind turbine. Finally, the designs and assembly instructions are being compiled for use in Portland as a summer research for high school students.

Acknowledgements

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