ADVANCES IN MAGNETIC GEARING TOPOLOGIES - HOW EASY MANUFACTURING IS REALIZED SIMULTANEOUSLY WITH HIGH TORQUE DENSITY AND HOLLOW SHAFT DESIGN

Gregor Puchhammer (1), Karlo Radman (2)

(1) COBOT Dynamics gmbh, Lechthalergasse 49/30, 1230 Vienna, Austria, Email: gregor.puchhammer@cobot-dynamics.com

(2) LCM - Linz Center of Mechatronics, Altenberger Straße 69, 4040 Linz, Austria, Email: karlo.radman@lcm.at

ABSTRACT

Magnetic gearing has clear advantages in applications where lubrication and temperature issues are of special interest. The main technological advantages for space applications are the lack of lubrication and a long lifetime even in extended temperature ranges, with high efficiency performance down to low temperatures (-100°C and below).
A new topology of a magnetic wobbling gear is proposed in order to simplify the manufacturing process and increase robustness. As a result, the multipole magnetic system is realized by a conventional single ring magnet. The torque density of the new magnetic system is comparable to the existing state of the art magnetic gear boxes, showing room for improvement of the the angular stiffness .

1 STATE OF THE ART IN MAGNETIC GEARING

The main technological advantages for space applications are absence of lubrication, a long life capability even in extended temperature ranges and high efficiency performance down to very low temperatures. Although these advantages appear attractive, no magnetic gear stage is commercially available for space applications until now. The obstacle lies in manufacturing issues of the complex magnetic system, which affects production reliability, and therefore raises production costs to a very high level.
Common to all existing magnetic gear topologies is that these systems are typically made up of multi-pole magnetic bodies that act as stators and rotors within the topology. These magnetic bodies consist of numerous specially shaped magnets that have to go through a complex manufacturing and assembly processes.
Most of the known high-performance magnetic topologies are based on the coaxial alignment of one or more rotor and stator disks. This coaxiality can have a major impact on the tolerance chain and negatively affect the air gap dimensions.
The magnetic wobbling gear MS2R5 (as seen in Figure1) was developed during the ESA ITI-B16986 project (2016-2019). The gearbox dimensions for the engineering model were chosen with an outer diameter of 26 mm, an axial length of 50 mm, which resulted in a weight of 116 grams while producing a maximum torque of 210 mNm.

Figure 1: Small magnetic gear MS2R5 designed for space applications

During the prototyping phase of the MS2R5, it turned out that the multi-step manufacturing processes of the magnet system were very complex, challenging and time-consuming. Part of this process chain was the repeated cutting, gluing and grinding of permanent magnets and back-iron, as well as the combination of these subassemblies to new magnetic multipole bodies (as shown in figure 2). These bodies were then fabricated through additional cutting, recombination, and a sphere shaping processes. A final cleaning process was necessary for removing magnetized particles debris.

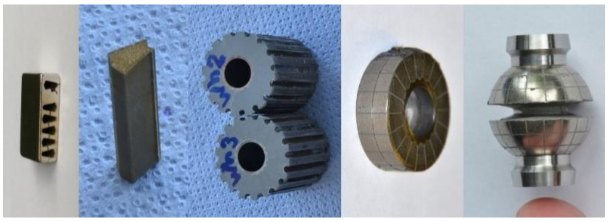

Figure 2: Complex manufacturing steps (1 - 5) for the magnetic structured parts for the MS2R5: 1-2 Single permanent magnets are processed by wire-EDM, 3 - assembling to full magnetic multipole bodies, 4 – turning, slicing and recombination, 5 - final sphere shaping process.

A major issue in the production was the handling of the

brittle permanent magnetic material. Milled and grounded particles from each processing step where stuck to the tooling and assembly. Therefore, all intermediate cleaning, which required removing chips and production residues from the machined body, were time-consuming, as were the final cleaning operations of the fully magnetized magnet bodies.
The rotor shaft and the inclined wobble/tilted shaft coaxial aligment made it difficult to meet the spherical nominal air gap of 0.1 mm set by the MS2R5 project tolerances.

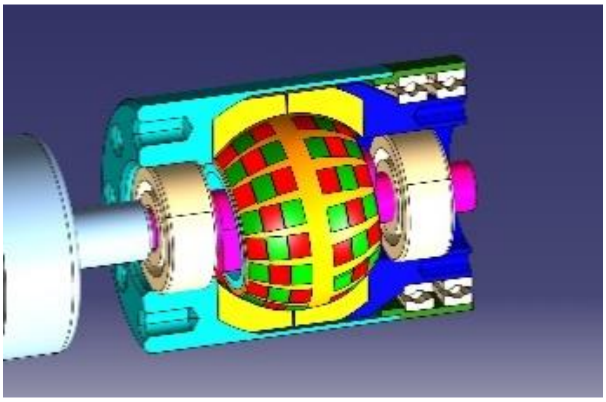

Figure 3: Simple mechanical structure and complex magnetic topology of the MS2R5 magnetic gear

Although the mechanical design of the magnetic gear is rather simple, these manufacturing problems prevented further industrialization. A solution for a new magnetic topology was needed.

2 REDESIGN OF THE MAGNETIC TOPOLOGY

Considering the advantages and disadvantages of the chosen topology of the design of magnetic wobbling gears, two major disadvantages have to be solved by a new topology.
• The complex mechanical assembly of the magnet system must be replaced by a simpler structure.
• The de-wobble (torque transfer from the tilted rotor) task should be realized by a non-magnetic element.
The first requirement has a direct impact on production costs, as many complicated manufacturing steps can be eliminated. The second requirement moves the magnetic part further away from the interfacing airgap permitting the usage of more magnetic material. This can improve both the torque density and torsional stiffness. Since the new magnet system is only for torque generation and not for the de-wobble task, the space previously used for the de-wobble is added to the torque-generating magnet system. This also doubles the torsional stiffness, since only one magnetic coupling is active within the gear. The *MS2R5 had two couplings/interfaces and three independently moving parts, whereas that was now reduced to one magnetic interface between a single static (stator) and tilted rotating (rotor) part.* Both new requirements can therefore be realized and even reinforce each other in their effect.

The solution to a vastly simplified magnet topology came after a complete redefinition of the magnetic flux paths within the magnetic gear.
The idea was to transfer the complexity of the high number of alternating magnetic poles, and the assembly of these in a magnetized state, to a structural complexity of a mechanical body used as flux guiding medium. If so, the structural body may be manufactured with less processing steps, with less effort and with different manufacturing methods. In addition, the body does not need to be magnetized, which makes handling, assembly, and cleaning much easier. The new magnet system for the Magnetic Wobbling Gear (MWG) of the 5th generation only consists of a ring magnet and two other bodies for the flux guidance. For the magnetic material Samarium-Cobalt (SmCo) or Neodymium-Iron-Boron (NdFeB) can be selected as the magnetic material. SmCo alloys are preffered due to their chemical and thermal stability, and proven usage in aerospace applications.
In general, it is much easier to fabricate small structures from iron-based materials than multi-pole magnetic structures composed of tiny magnets assembled together. The cogging behaviour of the gear is implemented by a saliency in the airgap. Instead of a alternating magnet placement in the airgap, the magnetically interfacing surfaces are slotted, leading to an angle depended reluctance, as in classical stepper motors. Therefore, with the new topology, it is easy to fabricate a small-scale multipole-based magnet system. As a result, high gear reduction ratios (1:64) can also be implemented in just one gear stage only.
Assuming that the task of de-wobbling can be replaced by a mechanical element, the torque generation can be optimised in the given volume. A hollow design for the input and output shaft can easily be implemented, even with small intermediate gear stages. This reduces the mass and allows the hollow space inside the gear to be used for the de-wobbling mechanism.
By using a simple ring magnet a torque release feature can be implemented. By adding a electromagnetic coil, coaxially wound with the magnetic ring, the flux of the permanent magnet can be momentarily counteracted. By powering the coil the gear is weakened allowing free rotation of the output shaft.
These measures make the 5th generation MWG superior to previous versions and improve the torque density and torsional stiffness tremendously.

3 THE MAGNETIC WOBBLING GEAR - MWG 5th GENERATION

With the new magnet system topology in place, the MS5G1R1 - a 5th generation MWG - was designed to meet the needs of space applications. A maximal transfer torque of 1Nm was selected as the benchmark, five times higher than that of the MS2R5. In the first draft, the outer diameter was not limited in order to achieve higher specific parameters such as torque density or torsional stiffness, thus reducing the overall weight.

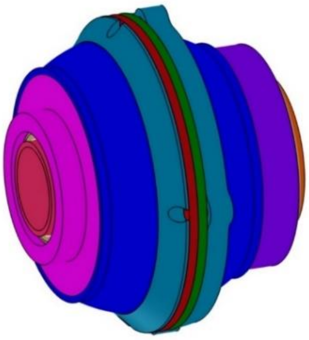

Figure 4: The new generation magnetic wobbling gear MS5G1R1 in frontal view

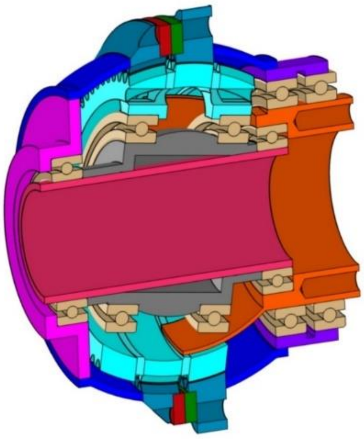

Figure 5: MS5G1R1 with hollow shaft in cross section

The outer diameter was then set to be not more than 50mm, and the axial length set to 38.5mm. As an perk, a coaxially aligned hollow shaft within, with an inner diameter of 12 mm was planned to route cables or radar beams through the gearbox.

In addition, the suitability of using additive manufacturing processes (AM) as a reliable production process for small quantities was examined.

3.1 Torque

To investigate the working principle, the magnetic calculations were performed for a larger and more powerful magnetic gear for terrestrial use [2]. The performance was optimized for a twice bigger gear stage with an air-gap radius of 40mm and a reduction ratio of i=1:45. The output torque was maximized to 8.3 Nm. Since the torque to radius scaling factor is cubic in nature ($1/(2^3)$), a nominal torque of 1.037 Nm was assumed for the smaller version with an air gap radius of 20 mm.

A CAD model of the MS5G1R1 magnetic gear stage was designed with an outer diameter of 50 mm, a reduced length of 38 mm, a hollow shaft of 12 mm and an air gap radius of 20 mm, achieving a reduction ratio of 1:64 (see Figure 4). All weight of the assembly is estimated from the CAD model.Table 1 shows a comparison of the MS2R5 (as seen in Figure 1) with a MS5G1R1, first conventionally manufactured, and then optimized for AM .

3.2 Torque density

Torque density is one of the most important parameters in magnetic gear design. A key result of the magnetic calculations is the fact that the new MS5G1 design shows a promising increase in torque density. This can be explained by the larger diameters where torque generation is more effective, the better utilization of the permanent magnetic material whose flux is guided by the iron parts, and an overall reduction in mass. In the case of the MS5G1R1, the torque density of the entire gearbox is an astonishing 3.3 times higher than in the comparable case of the MS2R5.

3.3 Torque transfer and angular stiffness

As already mentioned, the task of de-wobbling is replaced by a mechanical element. Since the torque-transmitting element is intended to replace a magnet system, it must have similar properties to the one it replaces. Freedom of lubrication, freedom of debris, constant transfer properties at all temperatures. Therefore, a newly developed flexible spring is introduced as a compliant element for torque transmission.

For gears incorporated in mechanisms, angular stiffness is important because it greatly affects the natural frequencies. Therefore, high stiffness of gear box behaviour is desirable. Compared to the MS2R5 gear design (see Table 1), the stiffness increases from 0.815 to 42.27 Nm/rad, which corresponds to a gain in stiffness by a factor of 50. This high increase can be explained by the internal topology of the gearbox. While the MS2R5 internally has two magnetic gear stages with gearing ratios of 1:8, the MS5G1R1 has only one gear stage with a direct gear ratio of 1:64 and a mechanical de-wobbling compliant spring with very high angular stiffness. This makes the MS5G1R1 design superior in terms of angular stiffness.

3.4 Additive Manufacturing Capabilities

The new manufacturing capabilities like Additive Manufacturing (AM) can be used, especially for the magnetic flux guiding path. In the case of the MS5G1R1, the stator and the rotor are AM candidates. When using this manufacturing technique, there is the possibility of topology optimization, where the ferromagnetic material is only extruded where it is necessary from the magnetic flux perspective. . Table 1 shows a weight estimation if the ferromagnetic material is removed from the unused areas. As associated weights are reduced, the torque density increases.

Table 1: Comparison of MS2R5 and 5th Generation MWG (MS5G1R1)

		Proto-type [1]	Con-ven-tional	AM optimized
	Units	**MS2R5A**	**MS5G1R1**	**MS5G1R1**
Outer Diameter	mm	26,4	50,0	50,0
Length (with Interface)	mm	50,0	38,5	38,5
Diameter Hollow Shaft	mm	-	13,0	13,0
Weight of Gear Box	g	116,0	180,0	157,6
Weight of Bearings	g	17,0	34,4	34,4
Weight of Magnets	g	25,5	11,8	11,8
Weight of Back Iron	g	23,1	81,9	59,2
Weight of Magnetic System	g	48,6	93,7	71,0
Weight of Structural Parts	g	50,6	51,9	51,9
Air-Gap Diameter	mm	20,45	40,0	40,0
Air-Gap Width	mm	0,10	0,15	0,15
Torque max. (@ OS)	Nm	0,200	1,037	1,037
Overload Torque (@ OS)	Nm	0,200	1,037	1,037
Transmission Ratio	1	1:64	1:64	1:64
Gear Stages external / internal		1 / 2	1	1
Torsional Stiffness max. (@ OS)	Nm / rad	0,815	42,27	42,27
Torque density (gearbox)	Nm/ kg	1,724	5,76	6,58
Torque density (magnetic system)	Nm/ kg	4,115	11,06	14,61
Efficiency max. @ nominal torque (311mNm)	%	72,5	-	-
Life Cycles (@ OS) Depending only on bearings and lubricants	1	Not tested	> 10^6	> 10^6

4 MAGNETIC CIRCUIT

The magnetic circuit consist of slotted stator and rotor discs. Through the slots a toothed surface is achieved. The rotor consist of three, and stator of two layers of shifted toothing. A permanent magnetic ring is situated between the two layers of the stator, which leads to a permanent magnetic flux in the airgap. With the rotor tooth sliding along the stator tooth a reluctance force is exerted leading to a counteracting torque, trying to bring the system back into the minimal energy state with aligned tooth.

If the rotor is driven by a too high torque the rotor ring will slip into the next stable position one tooth away. As there is no mechanical contact between the stator and rotor, there is no damage to the gear if the maximal transfer torque is overridden. The working principle is analogous to the unpowered holding torque of a stepper motor which is also used in aerospace applications to increase the actuator stiffness.

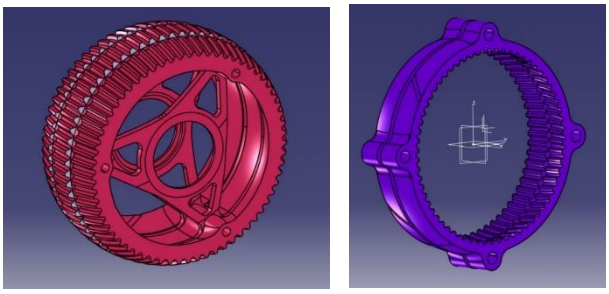

Figure 6: MS5G1R1 rotor(left) and stator (right) with complex shape for AM manufacturing

5 PROTOTYPING

The evaluation of the performance of the new topology is to be carried out on a breadboard model of the M5GR4. The prototype is currently in the manufacturing phase and will be ready in the third quarter of 2023. As can be seen in Figure 7, the simplified single-piece rotor is already completed as part of the new magnet system. Machining was carried out on a conventional turning machine with driven radial tools.

Figure 7: Prototype of the rotor of the M5GR4, manufactured on a conventional turning/milling machine

The evaluation of the physical and gearing properties will be done on the test bench TB10 (as seen in Figure 8), where a Hotting Brüel & Kjaer precision measurement system QuantumX MX840B is used. Angular measurement sensors with 21bit resolution will be used, as well as HBM and ETH torque measurement sensors. The dynamic behaviour of the breadboard model is measured on the unique test bench TB13-Dynamic

Balancing Measuring System, which is adapted to the special needs of the dynamic balancing of wobbling gears.

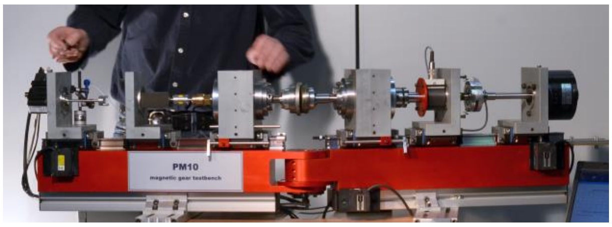

Figure 8: Test bench TB10, designed to measure magnetic gearing wheels with tilted axes alignment

6 CONCLUSIONS

The 5th generation of MWG design shows up with advantageous features, especially when used in space applications.

Costs: The production costs can be limited to a reasonable level, so that even the New Space Market can profit from the availability of a new reliable gearing technology based on magnetic gears.

Reliable production method: It is much easier to produce and assemble gearing parts and gearbox components without gluing and mechanical cutting of multiple permanent magnets. The whole cleaning process of permanent magnetic particles can be avoided by the prefabricated single magnet.

Magnetic material can be any type of hard magnetic material, preferably SmCo or NdFeB magnets.

Hollow shaft design and high reduction ratio in 1 stage (here 1:64)

Improved torque density and torsional stiffness due to new magnetic concept without damage if maximum torque is overridden

Long life capability and expected good efficiency down to low temperatures (below -100°C)

7 REFERENCES

1. Puchhammer, G. (2019). *ITI-B16986 FR TN4_final*, European Space Agency, Noordwijk, The Netherlands, p107.

2. Radman, K. (2023). *Magnetic modelling of a reluctance based wobbling gear with a torque influencing coil*, Linz Center of Mechatronics GmbH, FFG project report, 2023