Magnetic Gearboxes for Aerospace Applications

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Abstract

Magnetic gearboxes are contactless mechanisms for torque-speed conversion. They present no wear, no friction and no fatigue. They need no lubricant and can be customized for other mechanical properties as stiffness or damping. Additionally, they can protect structures and mechanisms against overloads, limitting the transmitted torque. In this work, spur, planetary and "magdrive" or "harmonic drive" configurations are compared considering their use in aerospace applications. The most recent test data are summarized to provide some useful help for the design engineer.

Introduction

Magnetic gears were proposed almost a hundred years ago. The absence of contact and wear between teeth seemed a worthy feature to prompt their development, but low efficiency, difficulties with manufacturing techniques, and cost were strong handicaps. It was at the beginning of this century that attention has been paid to their development, using new magnetic materials with higher magnetization or permeability, new precise manufacturing techniques, and advanced magnetomechanical modeling tools. The number of papers devoted to magnetic gears has increased exponentially in the last two years and the technology has overcome many of the first difficulties.

The specific development of magnetic gears for aerospace has been the objective of several projects carried out in Universidad Carlos III and MAG SOAR SL, some of them funded by the European Community's SPACE and CLEAN SKY Programs ([FP7/2007-2013]) under grant agreements n° 263014 and nº 323423. Specific aerospace design techniques have been developed to increase their TRL [1-7].

The main advantages of magnetic gears are a consequence of the absence of contact between teeth. There is no wear. No lubricant is needed. They can be operated at a broad range of temperatures ranging from -270ºC up to 350ºC. They present intrinsic anti-jamming properties and there is a clutching effect if the applied torque exceeds a limit therefore protecting the output from overloads. This effect is completely reversible. No damage or wear is produced while operating.

The motion direction is also reversible with highly reduced backlash. Input and output axles can also be exchanged so that the same device can be used as a reducer or a multiplier. An additional advantage is that they are suitable for through-wall transmission requiring no joints or sealing. Magnetic gears are also compatible with the presence of dust, sand or non-magnetic particles. As there is a gap between the moving parts, sand can flow not producing significant scratches, wear or stalling.

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Classification of Magnetic Gears

Magnetic gears can be designed in configurations similar to conventional gears [8], mainly spur gears, planetary gears and “harmonic drives”.

<u>Spur gears and planetary gears</u>

Direct spur gears consist of a pinion & wheel set with permanent magnets alternating their poles able to magnetically engage. These poles are equivalent to the teeth in conventional gears. The characteristics of this sort of gears are greatly dependent on size, shape, materials and geometry. As in conventional spur gears only moderate ratios can be achieved. Although useful for some applications, spur gears are more useful when combined in planetary configurations to achieve high ratios with relatively low mass and volume.

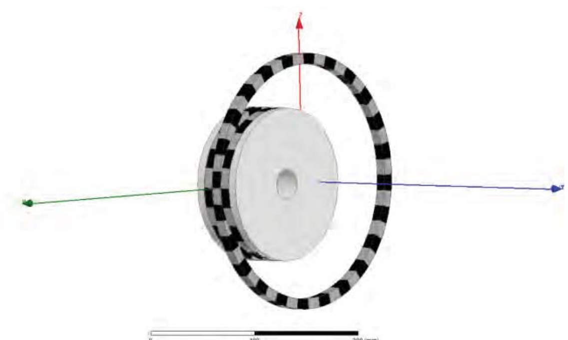

Figure 1. Model for a 1:2 Magnetic Spur Gear. Calculated Maximum torque: 24.2 N-m.

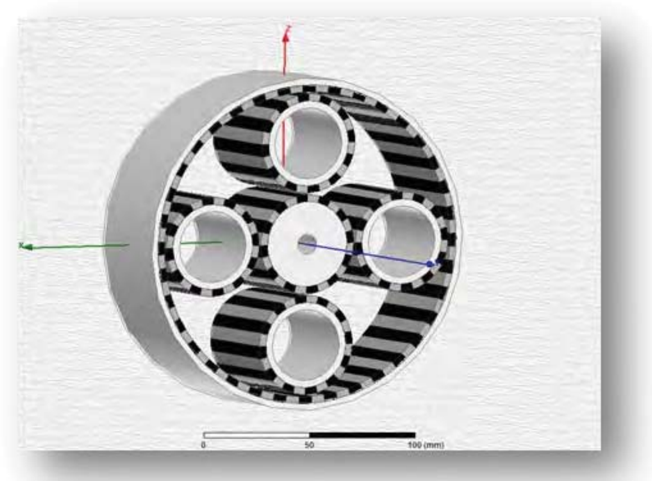

Figure 2. Model for a 1:5 Magnetic Planetary Gear. Calculated Maximum torque 32.0 N-m.

Table 1 shows a comparison of a magnetic planetary gear and a mechanical planetary gear. The data shown for the planetary gear correspond to a general configuration not yet optimized. An optimization of parameters with a defined objective can typically improve greatly any of the characteristics.

Table 1. Comparison of performances of a magnetic planetary gear vs. a mechanical planetary gear.

Specification	Magnetic Planetary Gear (not optimized)	Mechanical planetary gear from HD company Size 14
Reduction ratio (i)	4	5
Max output torque (N-m)	26	23
Torque Density (kN-m/m^3)	24	81
Max input speed (rpm)	1500	4000
Max Efficiency (%)	95	-
Mass (kg)	3	1.2
Envelope: Outer Diameter x Length (mm x mm)	166 x 52	60 x 95
Max Operational Temp. (°C)	80	40
Min Operational Temp. (°C)	- 40	0

Magdrives

Another kind of magnetic gears can be obtained following a "Vernier motor" criteria similar to that of the conventional "Harmonic drives". We will call them "Magdrive" class. In fact the "harmonic drive" configuration was proposed by Chubb [9] for a magnetic gear some years before the invention of the "Harmonic drive". Magdrives use a magnetic field wave whilst Harmonic drives use a mechanical deformation wave.

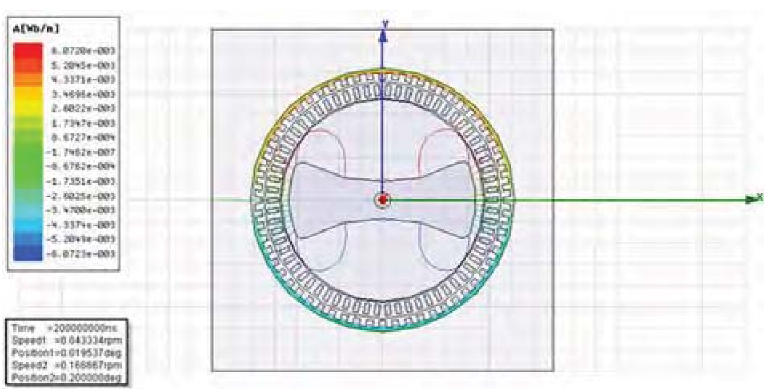

Figure 3. Model for 1:42 Magdrive.

Magdrives are provided with a permanent magnet fixed to the input axle that generates a magnetic field wave. This magnetic field induces a magnetization in a set of soft magnetic teeth which tend to align with an outer set of permanent magnets (or outer teeth). If the outer teeth are earthed, then the soft magnetic intermediate teeth are fixed to the output axle although other kinematic inversions are possible as well. This configuration can presumably provide ratios up to 1:200.

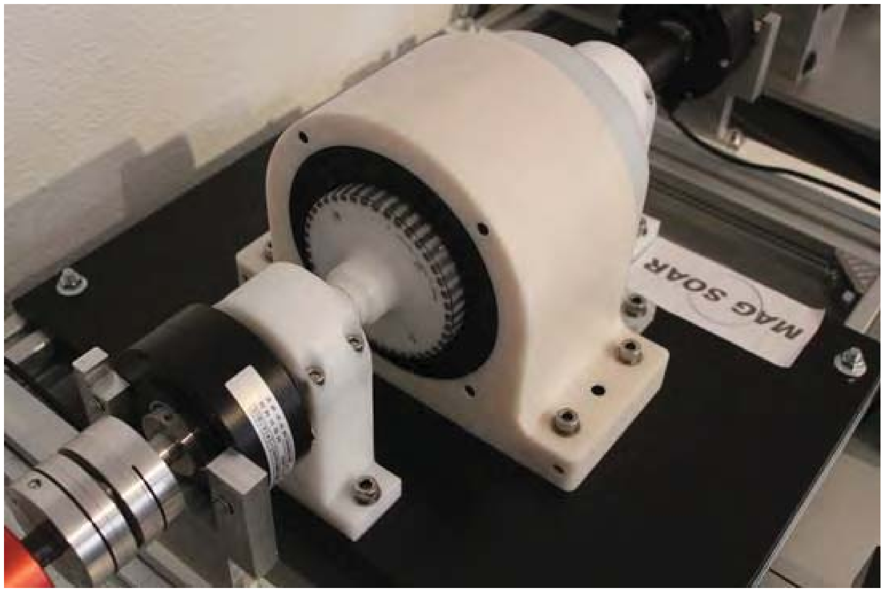

Figure 4. 1:21 Magdrive room temperature prototype and test bench. Max. torque 12 N-m

Figure 5. 1:21 Magdrive Cryogenic prototype with superconducting bearing and test bench. A perfectly cryogenic non-contact Magdrive. Max. torque 4 N-m, max speed 1500 rpm at 50-90 K. Weight 7.5 kg. Envelope 130-mm diameter. Length 600 mm.

Magdrives are suitable for cryogenic conditions. Particularly, a cryogenic Magdrive prototype, supported on non-contact superconducting bearings has been developed. Table 2 summarizes experimental results for this (column 2) and other Magdrive prototypes comparing to some conventional Harmonic drives.

Table 2. Comparison of experimental tests on Magdrive prototypes vs. Harmonic drives data obtained from manufacturer.

Specification	MAGDRIVE			Harmonic Drive	
	Room Temp. Prototype	Cryogenic Prototype	MAG SOAR MD-50	HFUC Size 17: Only component without bearings	PMG Size 14: including box
Reduction ratio (i)	21	21	51	80	88
Max output torque (N-m)	15	4	45	43	12.7
Torque Density (kN-m/m^3)	10.7	2.5	70	470	100
Max input speed (rpm)	500	1500	1500	1500	3000
Max Efficiency (%)	95	-	-	Temperature dependent.	Temperature dependent.
Mass (kg)	5	8	2	0.3	0.5
Envelope: Outer Diameter x Length (mm x mm)	120 x 110	120 x 400	100 x 80	60 x 32	50 x 80
Max. Operational Temp.(°C)	80	-180	+120	40	40
Min Operational Temp. (°C)	-40	-260	-196	0	0

Torque limiters

Other magnetomechanical devices that can be used for power transmission are magnetic torque limiters. They behave as 1:1 transmissions whenever the torque is under a limit. If the applied torque exceeds this limit they present an anti-jamming clutching effect that protects the output structure. Specific and optimized designs make these devices quite compact and competitive.

Figure 6. MAGSOAR TL-45 Magnetic Torque Limiter. Max. torque 45 N-m

Additionally, magnetic torque limiters provide a certain degree of torsional elasticity that can be used to reduce the transmission of torsional vibrations. These magnetic torque limiters do not emit any kind of magnetic field around them. They do not dissipate any kind of power while engaging (applied torque below limit). While not engaging (applied torque over limit) a reduced dragging torque and heat release can be customized.

A main and unique feature of magnetic torque limiters is that they do not suffer wear or fatigue independently of the times they act limiting the torque.

Table 3 shows a comparison between experimental data of a magnetic torque limiter and data from the manufacturer of a mechanical torque limiter.

Table 3. Comparison of a Magnetic torque limiter TL-45 manufactured by MAG SOAR SL and a KTR 01 2TFmechanical torque limiter manufactured by Ruflex.

Specification	MAGSOAR TL-45	Ruflex KTR 01 2TF
Reduction ratio (i)	1	1
Max output torque (N-m)	45	10-70
Torque Density (kN-m/m^3)	100	52-300
Max input speed (rpm)	15000	6000
Max Efficiency (%)	95	-
Mass (kg)	2	-
Envelope: Outer Diameter x Length (mm x mm)	135 x 40	68 x 52
Max Operational Temp. (°C)	80	80
Min Operational Temp. (°C)	-40	-20

Torque and Torsional Stiffness in Magnetic Gears

The most outstanding properties of magnetic gears are derived from the torque/torsion behavior. It is radically different from that of the conventional gears. If we block the output axle of a gear and increase the torque in the input axle to try to move it we will make evident the difference between magnetic and mechanical gears.

Magnetic gears will admit a shift angle in the input axle that increases linearly with the applied torque. Figure 7 shows experimental data of torque vs. shift angle for a 1:21 Magdrive (black dots). If we decrease the torque and change the sign of it, the angle will follow the torque without any significant hysteresis. In this sense magnetic gears do have zero backlash. If we increase the torque up to its maximum value, a non-linear dependence appears. If we try to increase the torque and pass the limit, then the axle simply turns. For the magnetic gears nothing breaks down.

The case is quite different in conventional gears (blue line in Fig. 7). A backlash is present due to the clearances needed for the movement. Therefore, if the movement is reversed there is a small but not negligible backlash around the origin. Once the gears are engaging, then the input axle presents a rigid behavior with stiffness on the order of magnitude of the flexural stiffness of the teeth. Once the maximum applied torque is reached, a plastic deformation and fracture appears with permanent damage of the conventional gear.

The radically different behavior of magnetic and mechanical gears makes the meaning of “maximum applied torque” to be quite distinct. For mechanical gears it means “if you exceed that value you break the device”. For magnetic gears it means “it will transmit the movement up to that value of the torque, but if you try to exceed it, it will slide and nothing breaks down”.

Non-contact and elasticity of magnetic gears make magnetic gears natural isolators for vibrations. Figure 8 shows axial vibrations measured on a bearing supporting the input axle of a 1:21 Magdrive and the corresponding vibrations measured on the bearing supporting the output axle. Damping is evident.

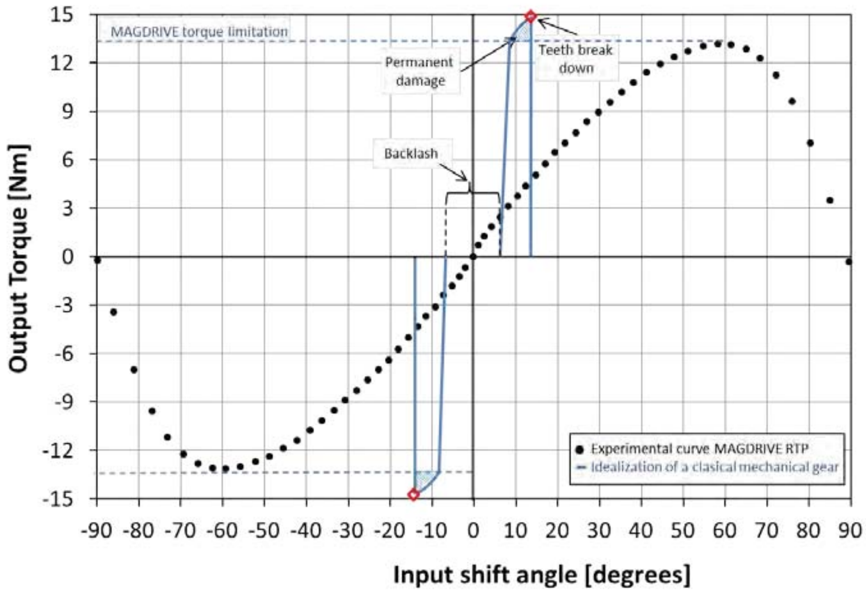

Figure 7. Experimental Torque vs. angle shift in MAGDRIVE Room Temperature Prototype (black dots) compared to a perfect mechanical gear (blue line). Magnetic gears do not present backlash but a linear dependence around the cero point. Magnetic gears, unlike mechanical ones, do not present damage if the torque overpasses the maximum.

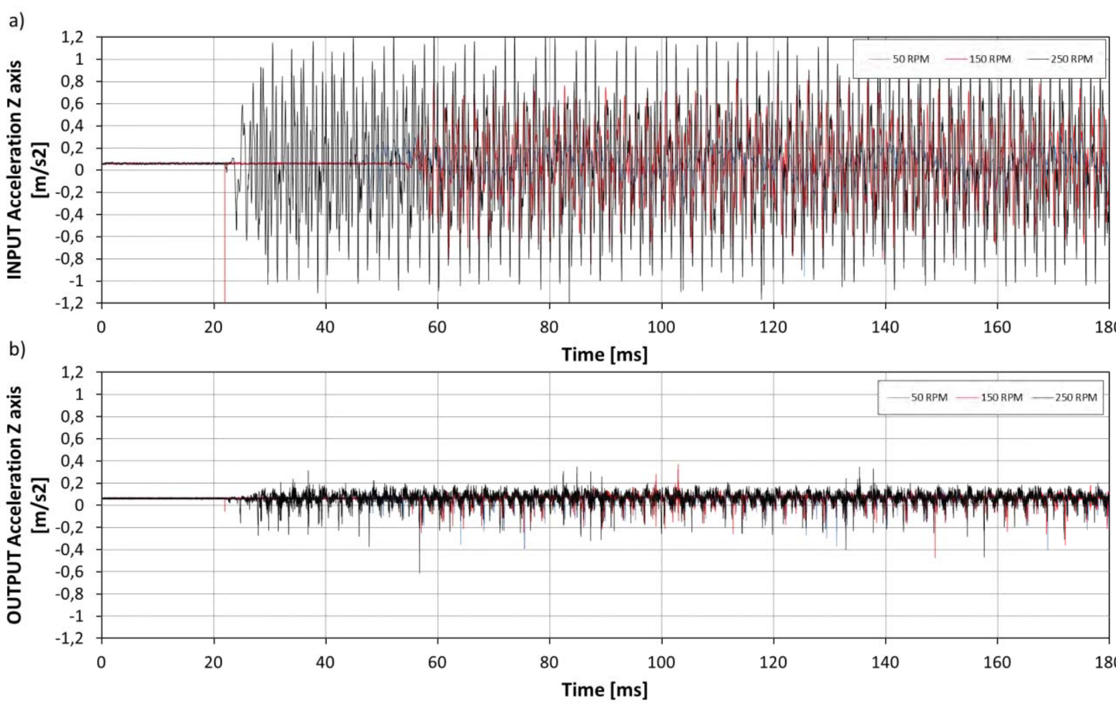

Figure 8. a) Transversal Acceleration on a bearing supporting the input axle of a 1:21 Magdrive when vibrations are induced on it. b) Transversal Acceleration on the bearing supporting the output axle of the same system.

Conclusions

Magnetic gears are becoming competitive alternatives to conventional gears. They present no contact and no wear. They do not produce debris and they do not require lubricant, being able to be operated at a broad range of temperature ranging from -270ºC up to 350ºC. They present intrinsic anti-jamming properties and there is a clutching effect if the applied torque exceeds a limit therefore protecting the output from overloads. This effect is completely reversible without any damage or wear. The TRL of this technology is currently increasing making it available for consideration for aerospace uses.

The radically different behavior against torque overloads, the isolation of vibrations, the absence of maintenance, the compatibility with sand or dust, broad temperature range and the through wall capability are some properties that make these devices attractive for aerospace.

Table 4 summarizes the state of the art of magnetic gears and torque limiters with a qualitative comparison of magnetic torque limiters, magnetic planetary gears and magdrives with respect to their best available mechanical equivalents. For the elaboration of Table 4, the authors have developed original software able to interpolate current-state data of magnetic gears. The user can select the ratio, speed and some other parameters. The software provides maximum torque, size, weight and even an estimation of the cost of the magnets for a magnetic spur gear, a magnetic planetary gear and a Magdrive.

Table 4. Qualitative comparison of magnetic torque limiters, magnetic planetary gears and magdrives with respect to their best available mechanical equivalents.

Specification/characteristic	Magnetic Torque Limiters	Magnetic Planetary Gears	Magdrives	Mechanical equivalent
Reduction ratio	1:1	1:50	1:100	1:160
Torque density	+++	++	++	★
Torque specific density	++++	++	++	★
Max output torque	★	+++	+++	★
Max input speed	★	++++	★	+++
Accuracy (Low Backlash)	★	★	★	+
Torsional stiffness	+++	++	++	★
Damping/Isolation of Vibrations	++++	++++	★	+
Efficiency at room temperature	++++	+++	+++	++++
Efficiency at low temperature (-40ºC)	++++	+++	+++	+++
Efficiency at cryogenic temperature	++++	+++	++++	++
Compactness	++++	++	++	★
Wide Operational Temperature Range	★	★	★	+++
Lifetime at room temperature	++++	++++	++++	++
Lifetime at cryogenic temperature	++++	++++	++++	+
Outgassing	++++	++++	++++	++++
Time between maintenance ops.	★	★	★	+++
Low generation of debris	★	★	★	++
Lubrication	Not required	Not required	Not required	Yes
TRL of technology	TRL 7	TRL 5-6	TRL 5-6	★

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