OPTIMAGDRIVE: HIGH-PERFORMANCE MAGNETIC GEARS DEVELOPMENT FOR SPACE APPLICATIONS

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ABSTRACT

Space environmental conditions force to use solid lubricated gears for many applications. The use of solid lubrications limits the torque capacity and efficiency of the gearbox drastically, making the overall system significantly heavier and bulky. In addition, solid lubricated gears suffer from wear, debris generation and from a rapidly degraded performance.

Magnetic Gears transmit torque without contact; no lubrication is needed, they do not suffer wear, debris generation and could provide a very stable performance during an extended lifetime. Previous developments of MG are too heavy, show poor performance and present higher magnetic contamination than ECSS requirements.

MAGSOAR, in the frame of the ESA ITI OPTIMAGDRIVE project has demonstrated a new generation of magnetic gears in a relevant environment (-40ºC to 70ºC) with unprecedented performance (high reduction ratios up to 1:75, high torque density up to 93kNm/m3 and low magnetic contamination) making the technology very attractive for space applications.

Keywords— magnetic gears, solid lubrication, mechanisms, cryogenic environment, high efficiency gears.

INTRODUCTION AND STATE OF THE ART

Gearboxes are used for force/torque conversion combined with motors to meet the specific requirements of torque and positioning mechanisms of each application. When mechanisms have to work in cold environments, classic mechanical gears need solid lubrication. Then, the maximum torque capacity and the efficiency of the gear are drastically reduced. In addition, wear and debris generation are a major concern that can lead to a catastrophic failure in the kinematic chain.

Meanwhile, Magnetic Gears (MG) are able to transmit contactless forces using the property of attraction and repulsion between permanent magnets. By providing a contactless transmission, the need of lubrication is eliminated and the efficiency of the gear is boosted. In addition, they are able to operate in extreme temperature environments (from -200ºC to up to 300ºC) and in clean environments, close to optic instruments because there is no debris generation. The lifetime of the gearbox is potentially infinite with a proper mechanical design. Moreover, the elastic nature of the transmission allows complex dynamic control and vibration attenuation between the payload and the motor. Additionally, its inherent overload protection prevents the entire kinematic chain from potential failures (in case of an overload, the magnet will simply slide, instead of producing a tooth breakage).

Despite those advantages, previous developments are frequently heavy and bulky, with low reduction ratios, poor efficiency and poor torque densities. All this facts, limit their application for space applications. In order to make the technology competitive for space applications, gears must be smaller, lighter and provide high gear ratio and high torque density. Other critical aspect to take into account is the magnetic contamination that shall be below the ECSS limits (0.2µT at 1 meter).

This paper presents a new generation of gears developed in the frame of an ESA ITI activity which demonstrated a TRL 4 level. The objectives of the project were to improve the state-of-the-art of magnetic gears [1-,3], to demonstrate high actual torque density, around 100kNm/, and to reach a reduction ratio higher than 1:50. It was also an objective to achieve efficiency over 70% at 500rpm even at low temperatures.

Similarly to a mechanical gearbox, the reduction ratio is determined by the number of element´s teeth of the transmission [4,5]. However, magnetic gears replace teeth with permanent magnets providing forces' transmission between non-contact parts.

The Gear ratio (Gr) is given by the Number of pole-pairs on low speed rotor (Noutput) and the Number of stationary steel pole-pieces (Nstator), can be expressed as

$$G_r = \frac{N_{output} - N_{stator}}{N_{output}} \quad (1)$$

As an example of magnetic configuration, Fig. 1 shows one model of MG with a reduction ratio of 1:10.

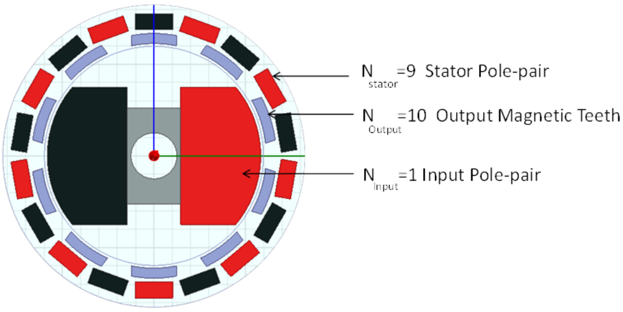

Figure 1. Model r 1:10

Fig. 2 represents a general behaviour of a MG comparing to convectional gear. In an overload situation the teeth in a mechanical gear will rapidly reach the maximum flexural strength dealing to an irreversibly damage. Meanwhile, MGs have an inherent overload protection. If the input shaft is forced to move MGs simply slide to the next magnet [6].

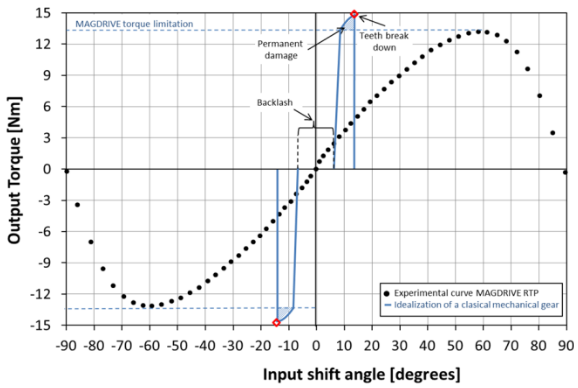

Figure 2. MG vs mechanical overload situation [4]

Although many concepts of MG have been proposed in the literature, they do not fit the requirements of torque density and gear ratio needed in most applications Tab. 1 shows a comparative study of the most significant previous developments of MGs. Despite they claim relatively high torque densities [7-9], it is only consider the active magnetic region of the device (Magnetic volume). They do not take into account the actual design of the device (including bearings, shield, etc.) which can reduce up to one order of magnitude the real torque density of the gear.

Author	Magnetic Gear characteristic comparative					
	Gear ratio	***Torque [Nm]***	***Magnetic Diameter [mm]***	***Magnetic Length [mm]***	***Magnetic Torque Density [kN/m^3]***	***Actual Torque Density [kN/m^3]***
[3]	1:5.5	9.4	90	40	36,94	12-13*
[4]	1:4.16	4.9	200	52	3	
[5]	1:3.83	11.8	106	25	53.48	13-19*
[6]	1:10.5	33	115	39.3	80.84	
[7]	1:4.25	731	228	75	239	
[8]	1:21	26	107	26	141.9	22.71

*Estimated from paper´s values

Table 1: State-of-the-art-technology

GEARS DESCRIPTION

Three gears where designed, manufactured and tested in a relevant environment from -40ºC to 70ºC and ambient pressure. The figure below shows the three gearbox models:

Figure 3. Breadboard models

The philosophy of this hardware generation for the activity was to demonstrate a wide range of properties in various common sizes and under different requirements specifications.

D34r44 gearbox (Outer Diameter 34, gear ratio 1:44) is a very common space size which provides high reduction. Model D57r10 aimed to obtained a very high torque density (92kN/m3 considering the total volume of the device), high efficiency at low temperatures and very low magnetic contamination (compliant with ECSS limits). Model D110r75 demonstrated a very high reduction ratio of 1:75 in a single stage maintaining a good balance between high gear ratio and torque density.

The main characteristics of the tested magnetic gears are summarized in the table below:

Parameter	OPTIMAGDRIVE Magnetic Gears		
	D34r44	***D57r10***	***D110r75***
Reduction ratio	1:44	1:10	1:75
Max. Output torque (20ºC)	~2.35Nm	~17.8Nm	~27.9Nm
Transmission error	66 arcsec	350arcsec	360arcsec
Efficiency at 500rpm (20ºC)	~75%	~92%	~50%
Max. Torsional stiffness (20ºC)	103Nm/rad	376 Nm/rad	2032 Nm/rad

Parameter	OPTIMAGDRIVE Magnetic Gears		
	D34r44	***D57r10***	***D110r75***
Magnetic pollution (at 1 m)	12±2 Am^2	1±0.2 Am^2	142±5 Am^2
Diameter	34mm	57mm	110mm
Weight	0.295 kg	1.157 kg	3.64 kg
Torque density	47.4 KNm/m^3	92.3 KNm/m^3	37.1 KNm/m^3

Table 2: Proyect results summary

EXPERIMENTAL SET UP

Fig. 4 shows the main test bench of the project, where gearboxes were installed for testing. A Phytron phyVacuum 57 stepper motor was used to generate the motion. Input and output torque meters (KTR Dataflex 16/10, 16/30 and 32/100) were used to measure the input and output torque of the gearbox. Two multiturn absolute encoders with 23 bits total resolution were used to characterize with high precision the angular position of the input and output shafts in real time. A vacuum chamber was manufactured with the capability to stabilize the environmental temperature from -40 to 70ºC. Friction electromagnetic brakes were used to simulate the output load for different operational condition.

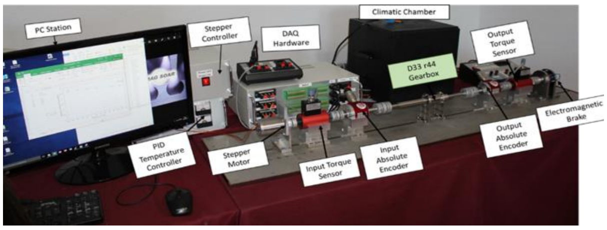

Figure 4. Test bench

Additionally, a simple test bench for magnetic dipolar characterization of the gearboxes in the axial and radial direction was designed manufactured and tested. A slider allows to move the Hall Effect sensors maintaining a good alignment between the gearbox and the sensors. By taking various measurements at different positions of the space, the magnetic dipolar moment of the gearbox is characterized in very good agreement with the FEM model results. Fig.5 shows a diagram of the magnetic contamination test bench.

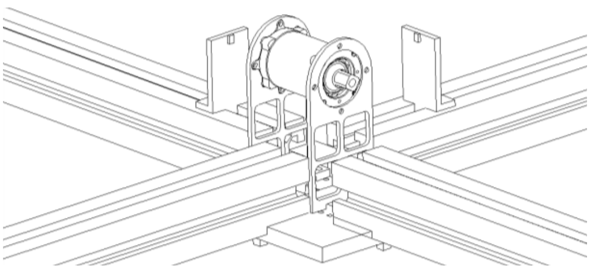

Figure 5. Test bench Magnetic pollution

EXPERIMENTAL RESULTS

Output torque and gear ratio

Gear ratio was obtained comparing input and output speeds or rotation angles. Fig. 6 shows the speed characterization of model D110r75.

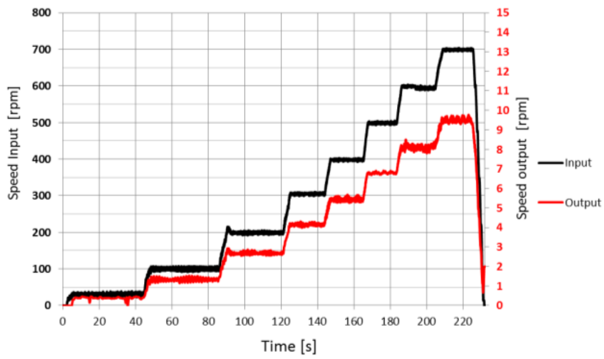

Figure 6. Speed characterization model D110r75

Fig. 7 shows the temperature influence on the maximum transmittable torque of model D110r75.

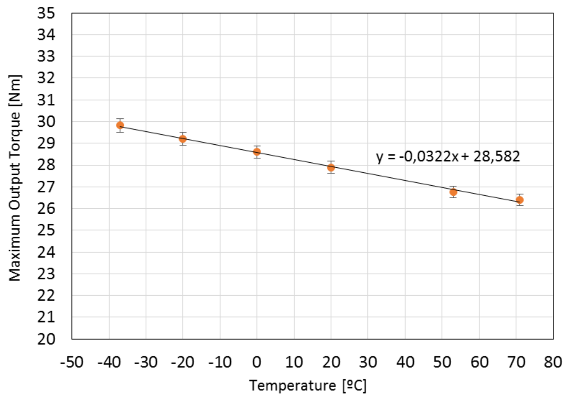

Figure 7. Output torque Temperature dependency

Although classic gears reduce their performance at lower temperatures, OTPIMAGDRIVE increases the available output torque as temperature drops. Influence of temperature in the gear ratio is not observed.

Transmission Error and Backlash

Accuracy of a gear is typically measured by the transmission error and by the backlash. Transmission error of the gearboxes was evaluated in many different speed, load and temperature conditions. It can be calculated, using Eq. 2

$$TE = \theta_{output} - \frac{\theta_{input}}{r} \tag{2}$$

For any of t l a relevant dependency of the transmission error on the load, speed or temperature conditions. Fig. 8 shows the transmission error of D34r44 for an input speed of 5 rpm, no output load and ambient temperature.

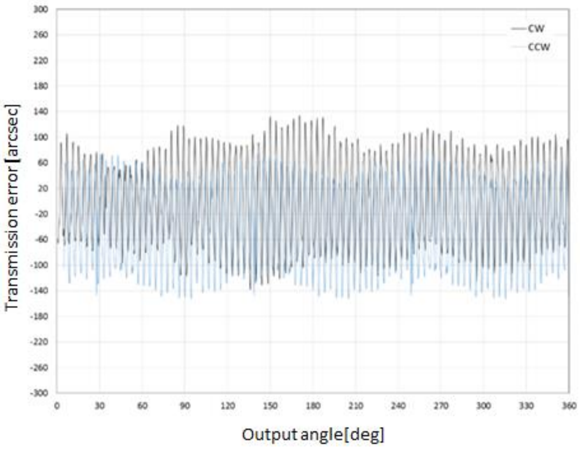

Figure 8. Transmission error model D34r44

Tests were conducted at different speeds and load conditions and three different temperature (-40ºC, 20ºC, 70ºC). The accuracy of D34r44 was calculated in 66 arcsec RMS not depending on the operational conditions.

Backlash

Backlash was measured in reciprocating motion in quasi-static conditions. A statistical approach was conducted measuring backlash at various angular positions in a full output revolution. Fig. 9 shows test result of D34r44 backlash. The apparent backlash observed (<30 arcsec) seems to be dominated by the static friction torque on the kinematic chain ($\Delta\theta\_friction \simeq 20$ arcsec). The apparent backlash observed will be established as a maximum threshold for the backlash of the gearbox. A more refined experimental set up would be needed to reduce such a threshold.

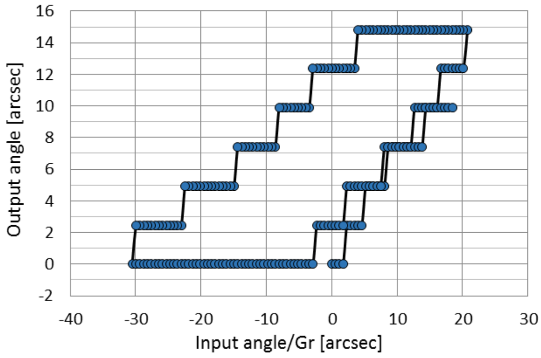

Figure 9. Backlash analysis

Efficiency

The efficiency of the gearbox was measured at different temperature, speed and load conditions. Experimental results were in very good agreement with FEM results.

Fig. 10 shows the efficiency of one gearbox for a partial load of 50% of the maximum output torque at -40ºC.

Similarly to electric motors, the efficiency depends on the rotation speed. Thanks to an specific design to minimize power losses, the efficiency is as high as 92% at 50% output load, 500 rpm and -40ºC.

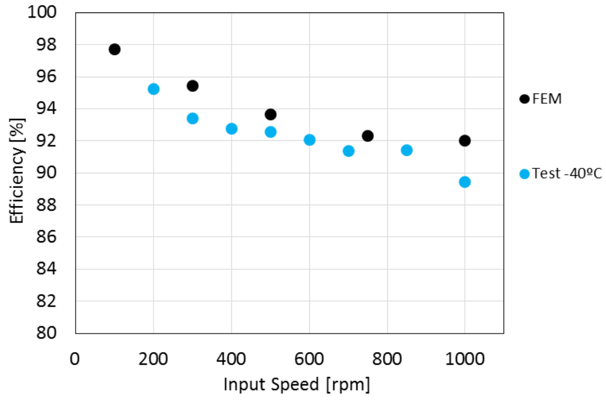

Figure 10.Efficiency D57r10 tested at -40ºC

Breadboard models showed to be in very good agreement with expected performance obtained in FEM models. The measured results of the three breadboard models are summarized in Table II.

Magnetic contamination

Magnetic contamination of the gearboxes was measured and compared in very good agreement with the FEM models. Fig. 11 shows the magnetic flux density measured at different points in the radial direction of the gearbox (most critical one) of D57r10.

The magnetic dipolar moment at 1 m distance is calculated in 1±0.2 Am^2 (FEM 0.9 Am^2), which makes the gearbox compliant with ECSS limits.

$$B_{(1m)}=0.15\ \mu T<\text{ECSS limits}$$

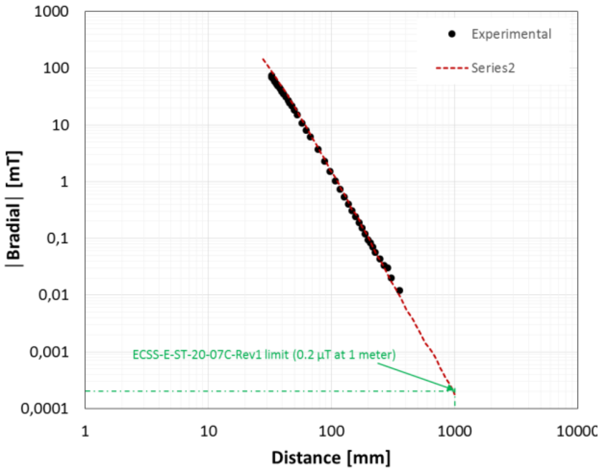

Figure 11.Magnetic Pollution

CONCLUSIONS

In this paper, three breadboard models of Magnetic gears were tested. Based on the results obtained, it can be concluded that the developed gearboxes are a step forward of the state-of-the-art of this technology.

The actual torque density was significantly improved, which makes them competitive against mechanical gearboxes in terms of weight especially when solid lubrication is mandatory. Efficiency is also a clear advantage of the technology, especially at low temperatures.

Model D34r10 presents a lightweight design, in combination with high reduction ratio and high accuracy, in a very common size for gearbox used in space applications. Very high reduction ratios in a single stage (up to 1:75) can be achieved, providing high output torque (up to 27.9N) and very high efficiency at low temperatures (demonstrated at -40ºC).

The main strengths of the technology are its cleanliness (which make a perfect solution for mechanisms close to optical instruments), its capability to work in extreme temperature conditions (from -200ºC to 300ºC), and its long service life making them very suitable for long term missions (grease or oil tend to evaporate in the long term). Finally, the good accuracy and the lack of backlash are key features for precision manipulators and robotic instruments.

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