Validation of a Novel High Performance Magnetic Gearbox for Space

Ignacio Valiente-Blanco*, Judit Esnoz-Larraya*, Efrén Diez-Jimenez**, Juan Sanchez García-Casarrubios*, Cristian Cristache*, Fernando Rodriguez-Celis* and José Luis Perez-Diaz**

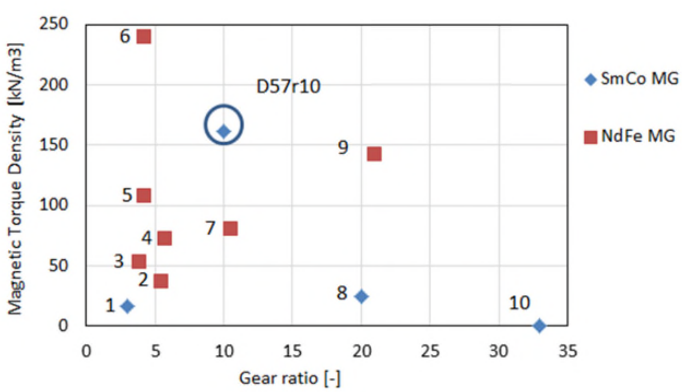
Abstract

In this paper, experimental validation of a novel high-performance magnetic gearbox for space applications, developed within the ESA ITI program is presented. This lubricant-free gearbox is manufactured using SmCo magnets, with a well know space heritage [1] and provides an unprecedented torque density for this sort of device (92.3 kNm/m^3, 15.4 Nm/kg). A high efficiency in an extended temperature range (up to 92% at -40ºC and 500 rpm) has also been demonstrated, showing a potential advantage of the technology for application in cryogenic environments [2]. Accuracy, zero backlash performance, and magnetic contamination are also investigated.

Introduction and State of the Art

The working principle of a magnetic gear (MG) is similar to a mechanical gearbox. However, teeth are replaced by permanent magnets so torque and speed conversion are produced by a modulated magnetic field [3]. Power is transmitted without contact, therefore, lubrication is not needed; the lack of contact eliminates wear and debris generation and potentially increases lifetime. They are also able to operate in a wider temperature range temperature range from -200ºC to 300ºC. Finally there is no backlash, which represents a potential advantage for accuracy applications [4] [5]. Additionally, MGs provide vibration isolation between the motor and the payload and its inherent overload protection mechanism prevents against potential catastrophic failures [6].

Despite all these advantages, up to now the technology has shown a low level of maturity and the developed demonstrators are frequently heavy, present low torque capability, reduction ratios typically below 6, and sometimes poor efficiency [7]. Magnetic pollution levels of previous breadboard models are significantly high and not compliant with ECSS space standards [8]. In addition, MGs are usually manufactured using NdFe magnets which are known to present several drawbacks for their use in space environments [9]. Figure 1 shows a summary of the state-of-art of this technology dividing between SmCo and NdFe magnetic gearboxes. Model D57r10 is the gearbox described in this paper.



Number	Author
1	Tsurumoto 1987 [10]
2	Fujita 2013 [11]
3	Iwasaki 2016[12]
4	Atallah 2004[13]
5	Penzkofer 2014 [14]
6	Uppalapati 2014[15]
7	Brönn 2010[16]
8	Pérez-Díaz 2013[17]
9	Jorgensen 2008 [18]
10	Kikuchi 1993[19]

Figure 1. Summary of the state of the art of Magnetic Gearboxes

* MAG SOAR SL. Valdemoro, Spain
** Universidad de Alcalá, Alcalá de Henares, Spain

Proceedings of the 44th Aerospace Mechanisms Symposium, NASA Glenn Research Center, May 16-18, 2018

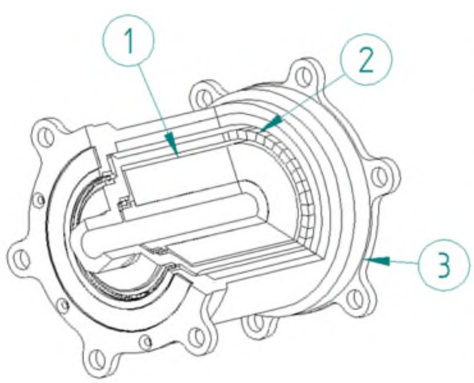
The Innovation

In this paper, experimental validation of magnetic gear in a controlled laboratory environment is provided. The MG is made of SmCo magnets with known space heritage. A high torque capability, a reduction ratio of 1:10 and low magnetic pollution levels according to ECSS standards were demonstrated. A high efficiency up to 92% at 500 rpm and -40ºC is one of the strongest points of the technology. The elimination of contact allows the optimization of power transmission in terms of efficiency. This provides the opportunity of high weight savings in motor-gear assemblies at low temperatures where the use of solid lubrication highly limits the efficiency and torque capacity of the systems. The performance demonstrated by this MG is far superior to the current state of the art of the technology and opens the window for several potential applications in space.

Model Description

The magnetic gearbox presented in this paper is composed of three main elements: an input rotor (1), an output rotor (2) and a stator (3) as shown in Figure 2. Input rotor and stator are mainly composed of SmCo XYG 32 permanent magnets while the output rotor is mainly composed of laminated soft magnetic alloy teeth. Magnets in the stator are arranged in a Halbach configuration to maximize magnetic flux density inside the gearbox. 72 magnets are used in the stator, with 18 soft magnetic teeth and 4 input magnets. According to the reduction ratio calculation formula [20], the reduction ratio of the gearbox presented in this paper is equal to 10.

Four ball bearings are used to support the radial loads (theoretically spurious) during operation and to allow relative motion between the moving parts and the stator of the device. The selected bearings were lubricated with low-temperature grease. Titanium grade 2 alloy has been used as structural material for the housing, flanges and internal parts of the gearbox to obtain a good structural performance with a reduced mass penalty. The relatively high electric resistivity of titanium also contributes to an improvement of the efficiency of the gearbox at high speeds. Standard mechanical interface flanges have been designed. Fig. 2 shows the magnetic gearbox after assembly and the summary of the main physical properties and performance specifications:



Specification	Value	Unit
Reduction ratio	10	
Max. Output torque (25ºC)	17.8	Nm
Operational Temperature Range	[-40 to 70]	ºC
Envelope (D x L)	57x76	mmxmm
Weight	1.15	kg
Torque Density (25ºC)	95	kNm/m3
Specific Torque (25ºC)	15.4	N/kg
Magnetic dipolar moment (1 m distance)	1	Am^2
Efficiency (-40ºC, 500 rpm)	92%	-
Ripple torque	<3%	Nm/Nm

Figure 2. Assembled gearbox and summary characteristics

Test Set Up and Results

A dedicated test bench was set up to accurately characterize the breadboard model under different temperature conditions from -40ºC to 70ºC, speeds and load conditions from 0 to 100% output load (lock situation). Functional characterization tests were conducted, including static and dynamic performance, temperature influence, gear ratio, transmission error, backlash, and efficiency and magnetic field contamination.

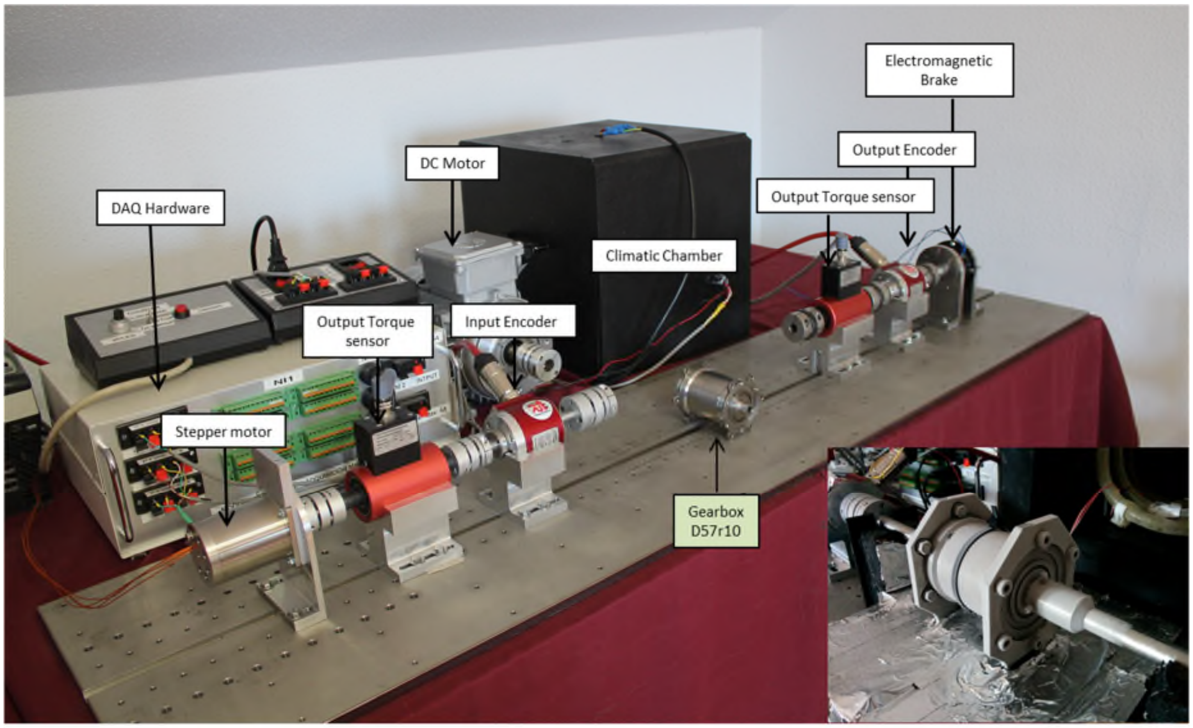


Figure 3. Dedicated test bench and a view of frozen model after -40ºC test

<u>Maximum Output Torque vs. Temperature</u>
To evaluate the maximum output torque capacity of the gearbox, an infinite impedance is set at the output shaft (braking torque significantly higher than the maximum expected torque in the gearbox). Then, the input shaft is rotated slowly until slip occurs. The process is repeated 10 times in CW and CCW directions to have a statistical characterization. The maximum output torque measured at different operational temperature is depicted in Fig. 4 and compared to magneto-static FEM calculations. Results are in good agreement with the simulation models.

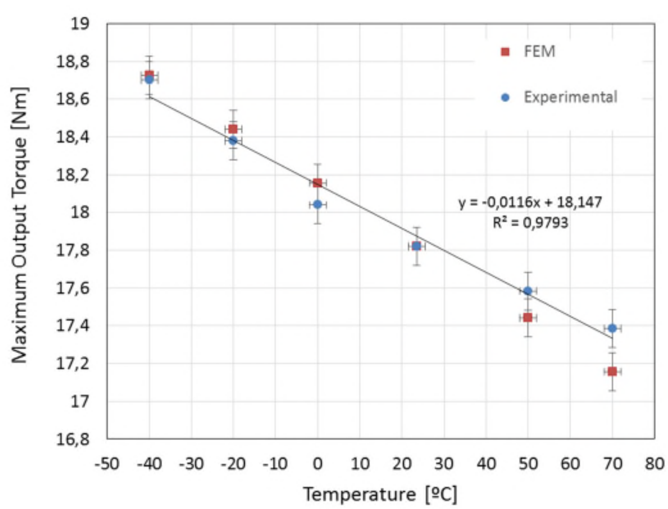


Figure 4. Maximum output torque vs temperature characterization

Maximum output torque at 25ºC is 17.8±0.1 Nm. It is clear that the maximum output torque increases at low temperatures. A temperature sensitivity about -0.012 Nm/deg has been calculated. The measured value of maximum output torque provides an actual torque density of 92.3 kNm/m^3 and actual specific torque 15.4 Nm/kg at room temperature. The actual torque density is different from active torque density.

Meanwhile the active torque density considers only the magnetic parts, the actual torque density considers the whole volume of the device (bearings, shields, etc). Taking into account the material used (SmCo), the gear ratio and the active torque density obtained, these results provide a significant improvement of the previous state of the art [21].

Reduction Ratio

Kinematic reduction ratio is evaluated in dynamic conditions for various operational speeds between 50 and 1000 rpm, different load conditions and temperatures. Figure 5 shows a typical speed profile for the kinematic reduction ratio characterization test.

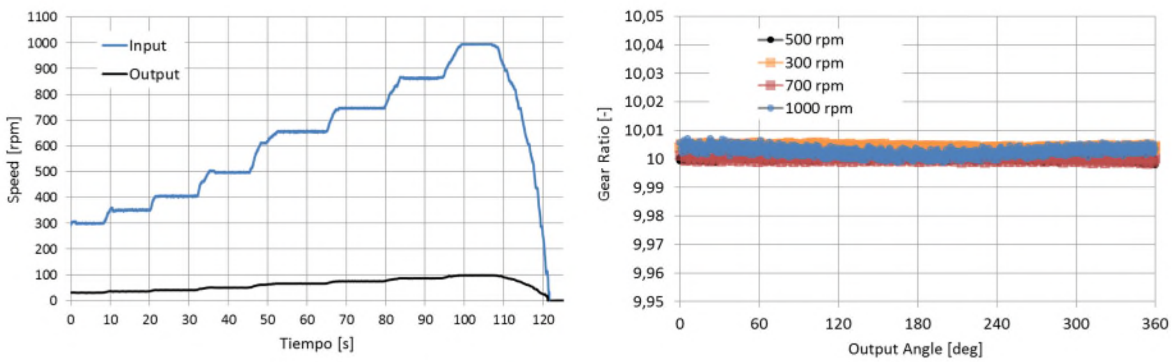


Figure 5. Test bench and three breadboard models

The overall reduction ratio has been calculated at about 10±0.01 with no significant dependency on the operational speed, load condition, or temperature.

Transmission Error

Transmission error of a gearbox is defined as:

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

where

θ_{output} is the angle measured in the output shaft.

θ_{input} is the angle measured in the input shaft.

r is the theoretical gearbox reduction ratio, r=10.

The transmission error has been calculated at different speeds, load conditions and temperatures. Fig. 6 shows, as an example, the transmission error measured at 5 rpm, zero load condition, and room temperature. Two main contributions to the transmission error have been found at about 2 and 9.2 output degrees. Average RMS values of the transmission error under different load and temperature conditions are calculated at about 290 arcsec. The same value was obtained under different temperatures and operational conditions. The fact that the contribution to the transmission error can be deterministically defined opens new opportunities to highly improve the accuracy of the gearbox by motor active control.

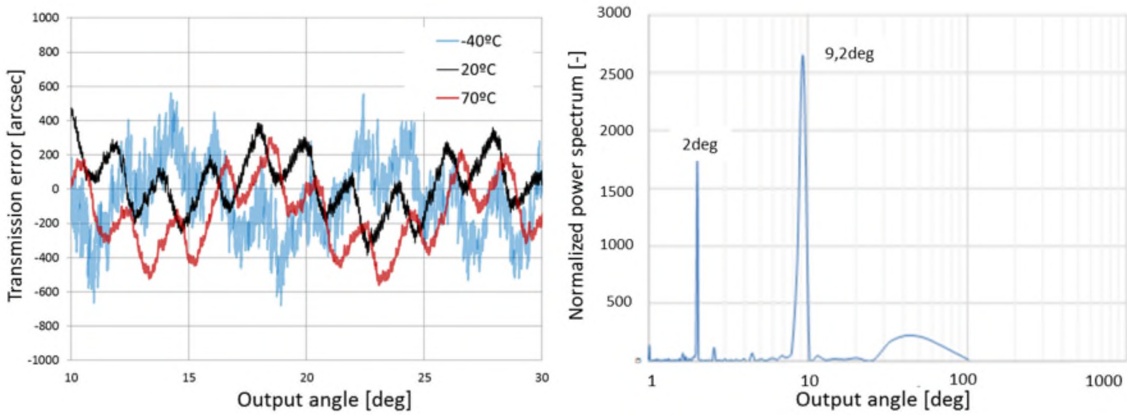


Figure 6. Transmission error and FFT amplitude

Backlash

Backlash was also characterized for the magnetic gearbox. Reciprocating quasi-static motion of low amplitude (from 1 to 10 deg) is induced in the input shaft. Then, the output rotation is observed and backlash characterized. The experiment was repeated at various temperature conditions and different input relative positions. The backlash observed was always below the DAQ system resolution (<20 arcsec).

Efficiency

The efficiency of the magnetic gearbox has been characterized at different operational conditions. In this paper, results at different speeds and temperature for an output load of 50% of the maximum output load are presented. Fig. 7 shows the efficiency measured at different temperatures and compared with FEM results. Both values are in relatively good agreement. Efficiency obtained from experimental data presents error bars up to 10% at low speeds due to test set up limitations. To improve the readability of the data, error bars were not plotted on graph. Efficiency seems to remain higher than 90% even at low temperature; this is one of the main strengths of the technology. On the contrary, mechanical gearboxes are highly affected by cold temperatures, with efficiency of solid lubricated gears rapidly reduced to 10% at -25ºC [22].

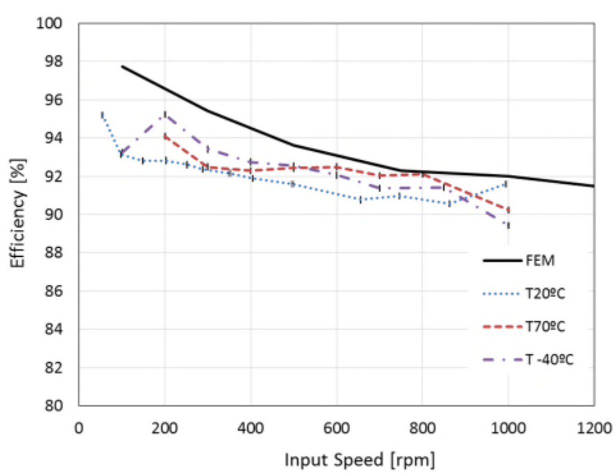


Figure 7. Efficiency test results at different temperatures

Magnetic Pollution

A critical parameter for instruments used in space is the magnetic contamination induced in the surroundings. Frequently, scientific missions and on-board instruments require very low magnetic contamination to assure that there is no interference with the satellite instruments. Scant attention has been paid to this critical issue in the past regarding magnetic gearboxes. Space standards establish that an acceptable limit for magnetic contamination is a value of 0.2 μT at 1-meter distance from the device.

Fig. 8 shows the magnetic field contamination in the most unfavorable direction (radial) from the gearbox vs. distance to the gearbox. A very good agreement with FEM results is observed. The measured magnetic flux density at 1-meter distance is extrapolated from the FEM model of the gearbox. The value obtained is equal to 0.15 μT, below ECSS limits. The equivalent dipolar moment calculated at 1-meter distance is about 1±0.2 A/m².

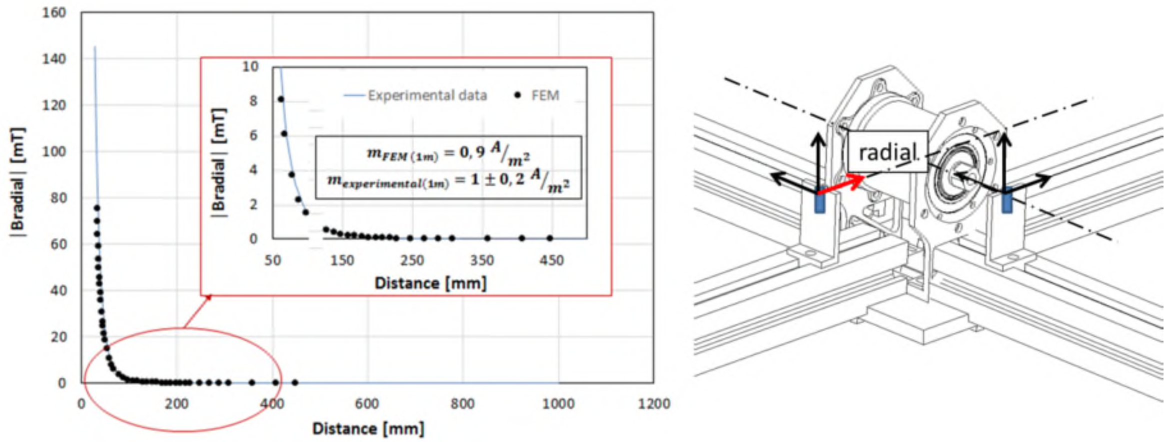


Figure 8. Efficiency and magnetic pollution test results

Conclusions and Lessons Learned

A high-performance breadboard model of a magnetic gearbox has been designed for space applications, manufactured and tested. The breadboard model demonstrated a reduction ratio of 10, with an unprecedented actual torque density (92 kNm/m³, 15.4 Nm/kg), high efficiency for operation even at low temperatures (92% at -40ºC and 500 rpm), and magnetic pollution levels compliant with ECSS requirement specifications. The results obtained showed a significant improvement in term of torque density and gear ratio compared to previous developments and prove that MGs are competitive against mechanical gearboxes.

During the project, the lessons learned are:

- High efficiency can be achieved for operation even at low temperatures by common techniques such as soft magnetic material lamination or selection of low conductivity materials.
- Efficiency and torque capacity are little affected by the environment temperature
- Sources of inaccuracy can be well predicted by FEM models. The deterministic nature of these errors allows multiple strategies to improve the accuracy and reduce the ripple.
- Magnetic pollution level is below ECSS standard requirements.

Acknowledgements and Previous Publication Record

This project was founded by ESA, under the contract number Nº 4000113972/15/NLCBi/GM ITI activity. A general view of the three breadboard models developed under this activity was summarized in ESMATS proceedings 2017 [9]. This paper present original information and tests results never published before

References

1. E. W. Blackmore, "Radiation Effects of Protons on Samarium-Cobalt Permanent Magnets," *IEEE Trans. Nucl. Sci.*, vol. 32, no. 5, (October 1985) pp. 3669–3671.
2. J. Perez-Diaz, E. Diez-Jimenez, I. Valiente-Blanco, C. Cristache, M.-A. Alvarez-Valenzuela, J. Sanchez-Garcia-Casarrubios, C. Ferdeghini, F. Canepa, W. Hornig, G. Carbone, J. Plechacek, A. Amorim, T. Frederico, P. Gordo, J. Abreu, V. Sanz, E.-M. Ruiz-Navas, and J.-A. Martinez-Rojas, "Performance of Magnetic-Superconductor Non-Contact Harmonic Drive for Cryogenic Space Applications," *Machines*, vol. 3, no. 3, (July 2015) pp. 138–156.
3. N. Niguchi, K. Hirata, M. Muramatsu, and Y. Hayakawa, "Transmission torque characteristics in a magnetic gear," in *The XIX International Conference on Electrical Machines - ICEM 2010*, (september 2010) pp. 1–6.
4. J. L. Perez-Diaz, I. Valiente-Blanco, E. Diez-Jimenez, and J. Sanchez-Garcia-Casarrubios, "Superconducting noncontact device for precision positioning in cryogenic environments," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 2, (March 2014)pp 598-605
5. H. Komiyama and Y. Uchimura, "Contactless magnetic gear for robot control application," *Electr. Eng. Japan*, vol. 184, no. 4, (September 2013) pp. 32–41.
6. C. Cristache, E. Diez-jimenez, I. Valiente-blanco, J. Sanchez-Garcia-Casarrubios, and J. L. Perez-Diaz, "Aeronautical Magnetic Torque Limiter for Passive Protection against Overloads," *Machines*, vol. 4, nº. 17, 2016.
7. D. Painter, "A Comparative Study of the Performance Capabilities of Magnetic Gears," Portland, OR, January 2016.
8. ESA-ESTEC, "ECSS-E-ST-20-07C-Rev1 Space Engineering, Electromagnetic compatibility," 2012.
9. C. L. Bowman, "Design Issues for Using Magnetic Materials in Radiation Environments at Elevated Temperature," *Proc. Nucl. Emerg. Technol. Sp.* ,(February 2013) p. 6801.
10. K.Tsurumoto and S.Kikuchi, "A new magnetic gear using permanent magnet," *IEEE Trans. Magn.*, vol. 23, no. 5, (September 1987) pp. 3622–3624.
11. T. Fujita, Y. Ando, K. Nagaya, M. Oka, and T. Todaka, "Surface Magnet Gears with a New Magnet Arrangement and Optimal Shape of Stationary Pole Pieces," vol. 5 nº 6, (June 2013) pp. 243–249.
12. N. Iwasaki, M. Kitamura, and Y. Enomoto, "Optimal Design of Permanent Magnet Motor with Magnetic Gear and Prototype Verification," *Electr. Eng. Japan*, vol. 194, no. 1, (January 2016) pp. 60-69.
13. K. Atallah, S. D. Calverley, and D. Howe, "Design, analysis and realisation of a high-performance magnetic gear," *IEE Proc. - Electr. Power Appl.*, vol. 151, no. 2, (March 2004) pp. 135–143.
14. A. Penzkofer and K. Atallah, "Magnetic Gears for High Torque Applications," *IEEE Trans. Magn.*, vol. 50, no. 11, (December 2014) pp. 1–4.
15. K. Uppalapati, J. Z. Bird, J. Wright, J. Pitchard, M. Calvin, and W. Williams, "A magnetic gearbox with an active region torque density of 239Nm/L," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, (September 2014), p. 1422–1428.
16. L. Brönn, R.-J. Wang, and M. J. Kamper, "Development of a shutter type magnetic gear," in *Proceedings of the 19th Southern African Universities Power Engineering Conference SAUPEC 2010, University of the Witwatersrand, Johannesburg*, January 2010.
17. J. L. Perez-Diaz, E. Diez-jimenez, C. Cristache, I. Valiente-blanco, M. A. Alvarez-Valenzuela, J. Sanchez-Garcia-Casarrubios, V. Castro, E. M. Ruiz-Navas, C. Ferdeghini, F. Canepa, H. W., G. Carbone, J. Plechacek, A. Amorin, J. Serrano, and V. Sanz, "Magnetic Non-Contact Harmonic Drive," *ASME Proc.*, November 2013.
18. F. T. Jorgensen, T. O. Andersen, and P. O. Rasmussen, "The Cycloid Permanent Magnetic Gear," *IEEE Trans. Ind. Appl.*, vol. 44, no. 6, (Nov-December 2008)pp. 1659–1665.
19. S. Kikuchi and K. Tsurumoto, "Design and characteristics of a new magnetic worm gear using permanent magnet," *IEEE Trans. Magn.*, vol. 29, no. 6, (November 1993), pp. 2923–2925.
20. R. Montague, C. Bingham, and K. Atallah, "Servo Control of Magnetic Gears," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 2, (April 2012) pp. 269–278.
21. J. Esnoz-Larraya, I. Valiente-Blanco, C. Cristache, J. Sanchez-Garcia-Casarrubios, F. Rodriguez-Celis, E. Diez-Jimenez, and J. L. Perez-Diaz, "Optimagdrive: High-Performance Magnetic Gears Development for Space Applications," *Proccedings of the ESMATS*, 2017.

22. E. W. Roberts, P. Bridgeman, M. Jansson, M. Schulke, and A. Tvaruzka, “The Performance and Life of Fluid-Lubricated Harmonic Drive® Gears,” *Proccedings of the ESMATS*, 2015.