

Magnetic Gearing versus Conventional Gearing in Actuators for Aerospace Applications

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Abstract

Magnetic geared actuators (MGA) are designed to perform highly reliable, robust and precise motion on satellite platforms or aerospace vehicles. The design allows MGA to be used for various tasks in space applications. In contrast to conventional geared drives, the contact and lubrication free force transmitting elements lead to a considerable lifetime and range extension of drive systems. This paper describes the fundamentals of magnetic wobbling gears (MWG) and the deduced inherent characteristics, and compares conventional and magnetic gearing.

Introduction

Actuators are widely used on satellite platforms and will be a necessity for future space missions. There are numerous potential applications of actuators, such as antenna and solar arrays steering, robotic arms, rovers, and optical instrumentation. Gearboxes with conventional toothed gear wheels are the state-of-the-art solution for such actuator gears. Mechanical gear performance is highly affected by the vacuum conditions and wide temperature range of the space environment [1]. During launch, high vibrational loads and fretting leads to contact adhesion due to wearing-out of solid lubricants. In vacuum, evaporation leads to loss of oil and a subsequent contamination of satellite surfaces or optical components. Additionally, radiation can degrade some polymers or oxidize solid lubricants. Extended temperatures can cause an ineffective lubrication at temperature extremes. However, these gears require some sort of lubrication to maintain functionality throughout their entire lifetime.



Figure 1. MWG with Hollow Input and Output Shaft

The problem of compromised lifetime and degradation in gears can be identified as a problem of contacting surfaces and their proper lubrication [1]. In different kinds of gears, sliding contact is a critical issue. Friction losses and wear often limits the efficiency and lifetime. As it is commonly known, lubrication and space tribology are still areas of intense research aimed at reducing the effects of wear and tear. Until now, these harsh environmental conditions and the availability of appropriate lubricants often make it difficult to fulfill these needs in a satisfying manner.

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Magnetic Wobbling Gears

No contact, no sliding, no need of lubrication!

This is the simple answer to overcome lubrication problems in general, and particularly in space-related issues. Triggered by an idea for powerful and quiet actuation drives, the MWG emerged several years ago with astonishing properties. Beside quietness, which is not a main focus for space-related applications, the non-contact power transmission particularly seems to match most of the needs in space. Once the problem of lubrication has been overcome due to the lack of lubrication needs, the usual boundaries of conventional gearing no longer exist. Temperature ranges, lifetime cycles, and wear and tear problems are transferred to the question of proper dimensioning of bearings, where well-established solutions exist, starting from few Kelvins in cryogenic temperatures up to a few hundred degrees Centigrade for extended temperature ranges.

MWG Background

For a short time, conventional gears can be replaced by powerful magnetic gearing systems. In magnetic gears, the traditional load- and friction-bearing elements are replaced by preferably strong permanent magnets to transmit energy. There is absolutely no contact between the acting magnetic surfaces. The gearing parts are friction free and perform consistently without lubrication.

Regarding magnetic gearing in general, there are many different functional principles comparable to those in conventional gears. Besides the proposed MWG system, possible candidates for magnetic gears include magnetic worm gears, magnetic spur gears, magnetic bevel gears, magnetic planetary gears, magnetic cycloid gears and even magnetic superconducting harmonic gears. Table 1 shows a comparison of the performances of torque conversion devices with respect to different criteria.

Table 1. Comparison of Magnetic Gears

Torque Conversion Device / Year From: [5]	Torque Density [Nm/l]	Magnetic Syst TD [Nm/l]	Magnetic Syst TD [Nm/kg]	Maximum Torque [Nm]	Torque Stiffness [Nm/rad]	Gear Ratio
Magnetic worm gear / 1993 ^[5]	2	2				
Magnetic spur gear / 1974 ^[5]	20	20				10
Liquid cooled PM BL machine ^[5]	30	30				1
Magnetic planetary gear / 1991 ^[5]	90	90				8
2-stage high ratio magnetic cycloid gear / 2006 ^[4]	75	120				360
1-stage low ratio magnetic cycloid gear / 2006 ^[4]	183	295				20
Harmonic magnetic gear / 2007 ^[5]	110	-				210–860
Magnetic superconducting harmonic drive / 2013 ^[3]	50 – 100	50 – 100				
MWG, Type B (fully magnetic) / 2009 ^[2]	135	350	58	11	250	45
MWG, Type C (fully magnetic) / 2009 ^[2]				11	250	2025
MWG, Type B (fully magnetic) / 2012 ^[2]	170	500	82	50	1250	49
MWG, Type A / 2013 ^[2]		605	110	55	2500	51
MWG, Type A / 2014 (targeted data)			(>110)	(35)	(5000)	120

Selection criteria for the 'best suited in space' magnetic gear are shown in Table 1. As the required amount of space on a satellite platform seems to be of importance, weight is of much higher priority. To get an idea of the magnetic performance, the magnetic system torque density rated in [Nm/kg] describes the amount of material of the magnetic system itself, which is necessary to produce the maximal torque. It consists of magnets and back iron, and defines the weight. This seems to be an effective way to compare the power of different torque conversion devices, including conventional gearing systems as well as magnetic systems in general and magnetic gearing systems alone. This is also a better method than regarding only the magnetic system, rated in [Nm/l], without bearings but including the amount of internal magnetic working range.

Different Types of MWG

There are several possibilities for setting up a magnetic gear based on wobbling kinematics (Fig. 2). As basic kinematics, a wobbling motion must be generated by a rotating input shaft, which has a cranked region (dash-dotted line) onto which the wobbling bearing (not shown in Fig. 2) is fixed. The outer race of the bearing is coupled with the magnetic wobbling wheel (Wh2, Wh2-3). The input shaft is rotating with the input speed. The wobbling wheel performs the wobbling motion with the same frequency as the input shaft, and has a superimposed rotation with the reduced speed of the output shaft. Both magnetic wheels (Wh1, Wh2) are magnetically coupled over an air-gap and perform the magnetic gearing due to a difference in 'magnetic pole pairs on wheel' numbers between them. The gear ratio in MWG can be computed in the same simple manner as for conventional wobbling gears by substituting the number of teeth with the number of 'pole pairs on wheel'. Whereas the basic kinematics of wobbling gears is the same for all three MWG types, there are some possibilities for generating the actual output shaft rotation. As the wobbling wheel's useful output rotation is superimposed by the wobbling motion, a functional element for 'dewobbling' action is needed for all three MWG types.

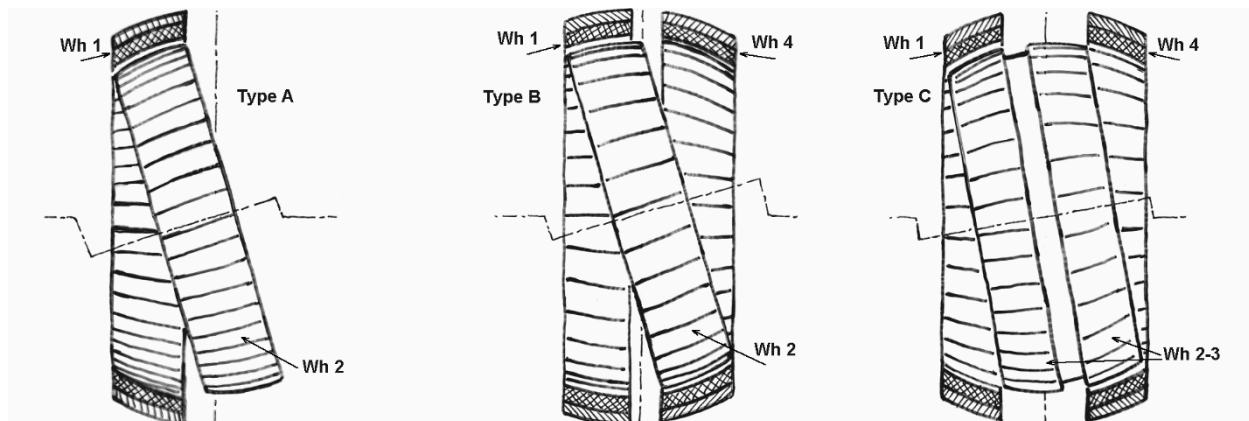


Figure 2. Working Principle of Three Different Types of MWG

- Type A consists of two single magnetic wheels. Wheel1 (Wh1) is fixed within the gear housing. Wheel2 (Wh2) generates the output motion by magnetic gearing. The 'dewobbling' motion is done by a universal joint, such as a cardan or a homokinetic joint, coupled between Wheel2 and the output shaft.
- Type B shows a MWG with three different types of magnetic wheels. Whereas Wheel1 and Wheel2 are acting in the same manner as in Type A, Wheel4 (Wh4) is part of the output shaft. The 'dewobbling' motion is performed by the magnetic clutch setup of the wheel-pair Wh2 and Wh4.

- Type C shows an arrangement with four different magnetic wheels, in which Wheel2 and Wheel3 are mechanically fixed and mounted on a common, single wobbling wheel Wh2-3. In contrast to the clutch setup of Type B, the magnetic wheel pair Wh3-Wh4 acts also as a magnetic gearing stage. The whole magnetic setup of Type C provides the possibility of generating extremely high reduction ratios with a squared ratio at the most, if compared to Type A and Type B.

All three types of MWG benefit from a ripple-free smooth output rotation. For space applications, Type A and Type C are the candidates of interest:

- Type A is characterized by one single magnetic coupling between Wheel1 and Wheel2, resulting in maximized torque stiffness, as well as torque density. As MWG can be easily scaled, it is a good choice for gear stages providing strong and powerful output shaft motion.
- Type C benefits from the potential of extremely high reduction ratios in only one single gear stage, and is useful as a small and compact first gear stage for high speed reduction.

General Characteristics of MWG

New properties must be considered when using magnetic gears. Most of these properties are highly favorable and are described in brief below. Some of these are related only to MWG.

- High precision: Magnetic systems in general are known for their extremely precise operation. Because of the absence of mechanical interaction, MWG deliver constant precision in both low and high load cycles. Mechanical backlash is approximately an order of magnitude less than in conventional precision gears.
- Abrasion free: As it is friction free, MWG perform consistently without lubrication.
- Overload friendly: At overload, the magnetic transmission acts naturally as a clutch, but remains fully functional. The elasticity avoids unnecessary stress to related components. The safety clutch is an extremely reliable component and also works without electronics. Hitting an emergency hard end stop after the failure of some control or due to excessive vibrational loads may not result in the degradation of the performance of a mechanism.
- Highly efficient: Magnetic gearboxes offer highly economical energy transfer. Energy conversion is practically seamless: losses via rolling friction and low magnetic hysteresis phenomena are minimal in operation.
- High transmission ratio: Because of the unique concept of MWG, only one gear stage is necessary to achieve high transmission ratios (Type A) or even extremely high ratios (Type C).
- Lifetime: All characteristics are quite constant all over the estimated life cycle and ageing effects are predictable. This is a new feature for gears. Lifetime is only dependent on the lifetime of bearings and not on wear and tear.
- Temperature operating conditions: One temperature limit for magnetic systems is the Curie temperature (T_c), in which a material's permanent magnetism changes to induced magnetism. Motors, steppers and also magnetic gears with permanent magnets are affected by this temperature and will lose their permanent magnetism at temperatures exceeding the T_c limit. The T_c depends mainly on the composition of materials with different properties and is a material property.
- High-torque capability: The MWG mechanism takes advantage of a constant air gap over the entire active area, which makes it superior to other magnetic concepts (Table 1). The result is a compact design with maximized torque, a crucial precondition for lightweight design.
- Elasticity: The inherent elasticity caused by the magnetic transmission in a powertrain can be very desirable, for example for compliant robotic applications. For other applications such as rigid structures, elasticity may be unacceptable. However, elasticity is a design target and can be influenced within certain limits. Recently, tremendous progress has been achieved (Table 1) by enhancing the torsional stiffness of the output shaft.

MWG Compared to State-of-the-art Mechanical Gears

Due to different available data of gears it is difficult to compare gears one with another. All data were taken from actual catalogues, and all gears were compared with the same reduction ratios, the same nominal torques and the same operating conditions, if possible.

As seen in [6] and [7], there are many different definitions of torsional loads: 'Limit for momentary peak torque', 'Limit for repeated peak torque', 'Limit for average torque', 'Rated torque at rated speed', or 'Limit for maximum overload torque'. In MWG, there is only one limiting torque, the so-called 'Maximum Torque'. Therefore, the definition of different rated torques is no longer necessary in MWG.

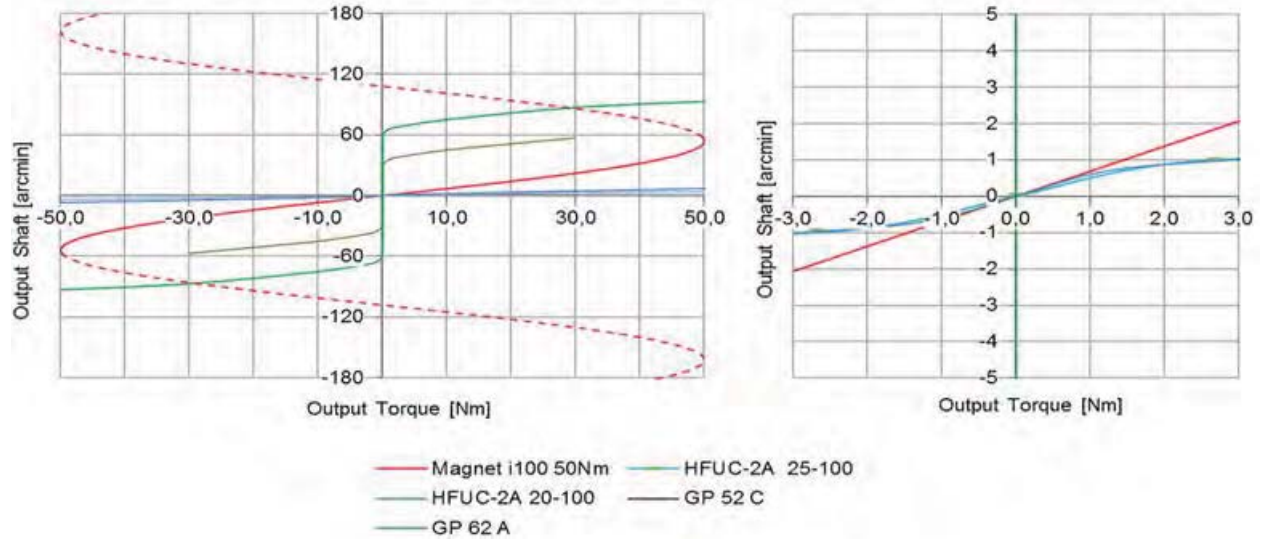


Figure 3. Torsional Stiffness with Blocked Input Shaft at Gear Ratio=100 and Nominal Torque=50 Nm: MWG, HFUC and Planetary Gear

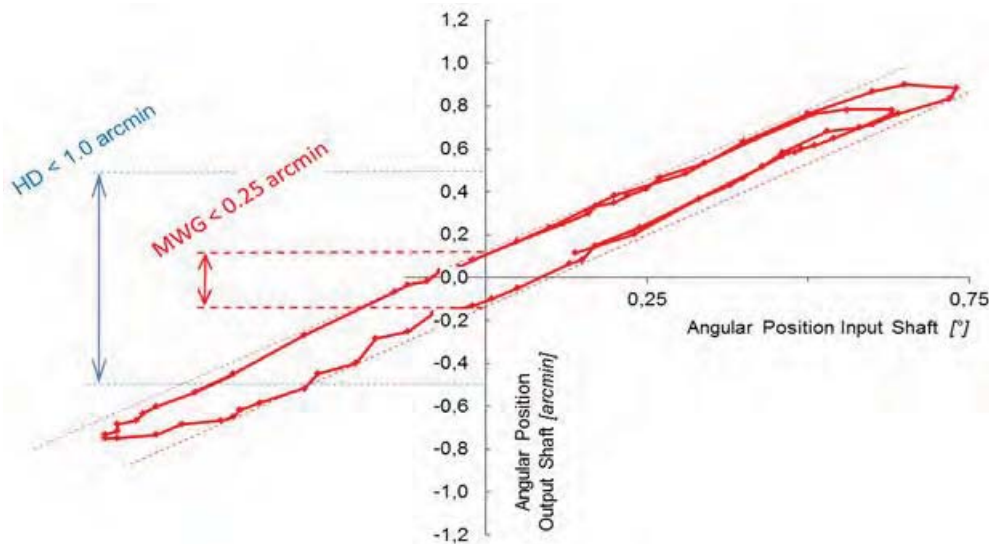


Figure 4. Hysteresis Loss of MWG ($i=45$, 11Nm)

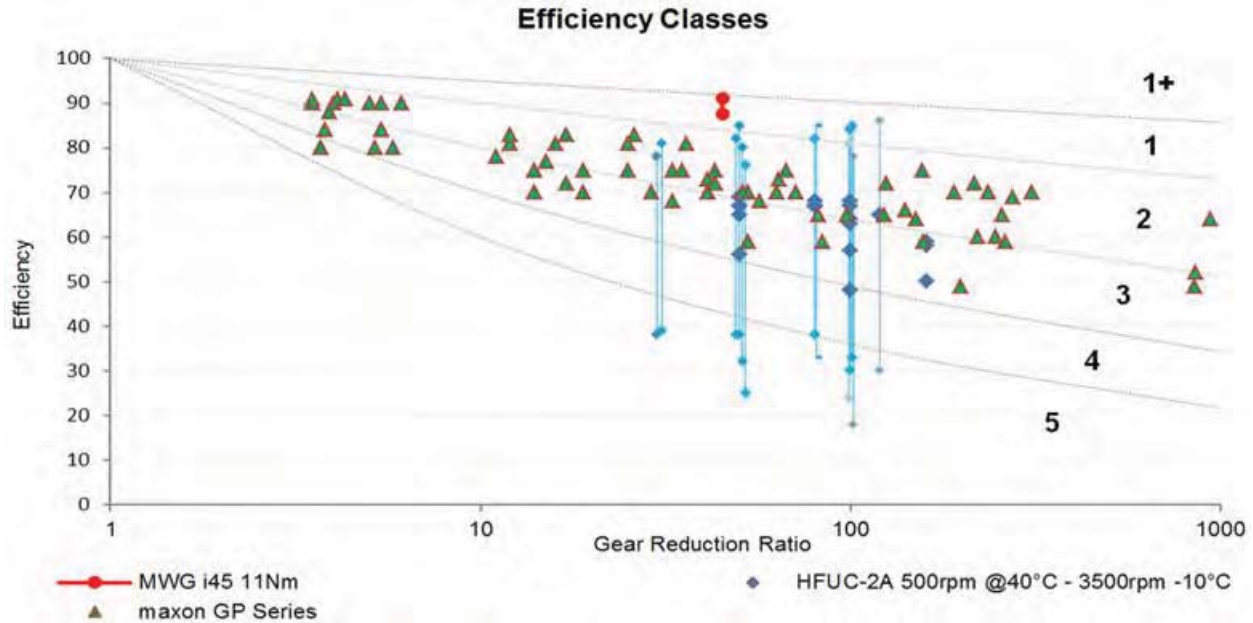


Figure 5. Efficiencies of MWG, HDG and Maxon GP's Series

The gear can be operated up to that torque at full input speed. If that torque is exceeded (Fig. 3, red dotted line), the output shaft will lose its torsional coupling and the gear will act as a safety clutch, unless the torque has decreased. No harm will result after a one-shot or repeated transgression of the maximal torque.

Torsional operation is the most important task of gears. As seen in Fig. 3, the torsional stiffness is also strongly related to mechanical backlash. Whereas most planetary gears (GP52C, GP62A) have nearly no stiffness in the region of zero torque transition, MWG and HD are nearly free of backlash and therefore can provide a significant amount of torsional stiffness. Although harmonic drive gears (HDG) are overall much stiffer than MWG, one interesting phenomenon around the region of zero torque transition (Fig. 3, right side) can be observed. The 'Lost Motion' in HDG leads to degradation of the torsional stiffness of these gears. In this region, the stiffness of HDG and MWG is approximately the same size. This can be important with respect to resonant frequencies of coupled mechanisms or space applications.

The mechanical backlash or hysteresis loss of planetary gears is considerably bigger than in HDG or MWG. HDG shows a hysteresis loss less than 1 [arcmin], whereas MWG shows even less hysteresis due to its friction-free force transmission (Fig. 4).

After introducing efficiency classes [11], it is easy to compare the efficiencies of various gears with respect to their reduction ratio and operating conditions. MWG shows an energy conversion rate in efficiency class 1 (Fig. 5) within different operating speeds. The planetary gear stages of Maxon GP-series define industrial standard quality (class 2 and 3). HDG can hit the efficiency class 1 but is restricted to optimized operating conditions such as 40°C and low input speed. Lowering the operational temperatures to -10°C, the efficiencies of HDG can reach class 5. This results from the HDG lubrication needs.

Conclusion

MWG is a gear designed to operate without contact between the force transmitting elements. It therefore overcomes the problem of lubrication and related problems in a new manner. Temperature-dependent lubrication effects, problematic contact stresses on the meshing gearing parts, hardening procedures of teeth and all related problems are no longer existent. The question of lifetime is transferred to the much simpler question of proper dimensioning of bearings. MWG benefits from extended lifetime and from extended operational temperature ranges with fairly constant mechanical properties.

Magnetic gears have less torsional stiffness than conventional, mechanically geared systems. Despite this fact, the torsional stiffness of MWG is partly equal (HDG) or even higher (planetary gears) than in conventional gearing systems. The torque density of MWG is steadily increasing, also lightweight design applications benefit from that new technology. MWG offers a simple internal structure with only a few components, and has the potential as high reduction, high precision gearing system.

MWG and its unique combination of features give way to new prospects in future space applications.

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