STATE OF THE ART AND RECENT ADVANCES FOR FLUID AND DRY LUBRICATED HARMONIC DRIVE® GEARS

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ABSTRACT

This paper serves to present the latest state of the art for fluid and dry lubricated Harmonic Drive® Gears especially developed for space applications.

Recent research and development project results show the latest status of achievable lifetime with liquid and dry lubrication in vacuum. Thus the main focus lies on broadening the potential of Harmonic Drive® Gear applications in space by optimal choice of lubrication strategy.

1 INTRODUCTION

1.1 Harmonic Drive® Gears

Harmonic Drive® Gears consist of three components as one can see in *Figure 1*. The circular spline is a rigid ring with internal toothing. The cylindrical flexspline with external toothing is elastic in its radial axis but resistant to torque. The third component, the wave generator, is an elliptical steel disc with a central hub and an elliptically deformable thin section ball bearing.

Figure 1: Harmonic Drive® Gear

Harmonic Drive® Gears based on the strain wave gear principle offer advantages such as zero backlash, high transmission accuracy and furthermore high torque to weight ratio. Ratios from 30 up to 320 in one stage are possible. The momentary tooth-engagement of about 30 percent as in *Figure 3*, enable high torque capacities. The high power density is a key aspect to many aerospace applications. Zero backlash over lifetime is achieved by preload within the tooth contact area resulting from coning as indicated in *Figure 2*.

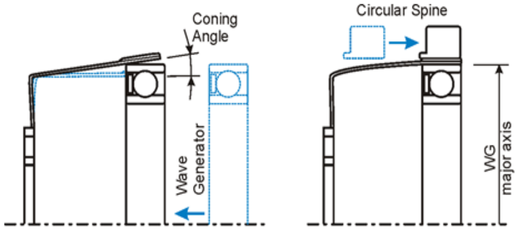

Figure 2: Coning

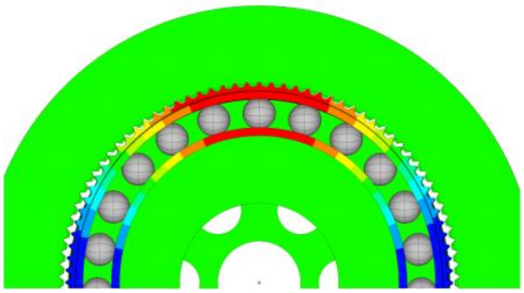

Figure 3: Tooth engagement

Harmonic Drive® Gears were first developed in the context of a space mission and installed in the wheel drives of the lunar rover from the Apollo mission. From then on the Harmonic Drive companies in Japan, Germany and the US have developed their gears to fulfill the needs of various industries such as robotics and automation, machine tools or defense and aerospace. The robotics industry generating roughly 30 percent of the overall 2015 annual revenue has thus far been the main recipient of Harmonic Drive® Gears. Present trends going towards human robot collaboration in context of industry 4.0 require constant research and development of Harmonic Drive® Gears regarding safety, weight and size in order to make projects such as the three generations of lightweight robots LBR 1 to 3 by DLR (the German Aerospace Center) as seen in *Figure 4* or lightweight assisting Roberta Robot by Gomtec possible.

Figure 4: LBR 3 by DLR [4]

Further examples for successful human robot interaction projects are the Agilus Robot by KUKA in *Figure 5* built for assistance during a production sequence and the dexterous hand by Wessling Robotics, a spin off based on the German Aerospace center. The DLR originally developed Dexhand (featuring more than 20 Harmonic Drive® Gears) as seen in *Figure 6* as a future space application to carry out repairs on Space devices in lower earth orbits such as ISS environment without the need of a human outdoor mission.

Figure 5: Agilus by KUKA [5]

Figure 6: Dexhand by DLR [6]

Hence the Harmonic Drive® Gears precise movements are not only crucial for a variety of industrial robots but also for applications in space such as Solar Array Drive Mechanisms, Deployment Mechanisms, Pointing Mechanisms, Stereo Vision Measurement systems, Planetary Exploration Rovers and Space Robotics.

1.2 The Harmonic Drive AG

Founded in 1970 founded Harmonic Drive AG is situated in Limburg, Germany and today consists of roughly 400 employees. The annual turnover is brought in by supplying industries such as robotics and automation, machine tools, medical, defense and aerospace. As technology leader in the field of high precision drive technology, Harmonic Drive AG is continuously developing sophisticated and tailored solutions for their customers. About 80% of the production feature individual solutions even with batch sizes of just 1. More than 23.000 products range from servo actuators, direct drives, planetary gears to a high variety of strain wave gear products.

2 SPACE HERITAGE OF HARMONIC DRIVE ® GEARS

In the following some of the many space applications with Harmonic Drive Gears® in use are presented. Space rated gears are always customized solutions, optimized considering the requirements of the application. Amongst many other projects where stainless steel Harmonic Drive Gears® are used in space are the imaging photopolarimeter of the interplanetary probe Pioneer 10/11 from 1972 or the Mars Exploration Rovers 1 and 2. In the second Mars Rover 19 Harmonic Drive® Gears were implemented in the drive actuator, mast, antenna and robotic arm.

In Solar Array Drive Mechanisms the actuators SEPTA31 and the more recent developed SARA21 carry Harmonic Drive® Component Sets to fulfill their function of orienting the solar panels towards the sun, meaning that the electrical power generated by the solar cells has to be transmitted via the actuator as well. These actuators, particularly SEPTA31 with its space heritage of more than a decade, have become standard space qualified actuators and are used in projects such as the Oceanic Exploration Satellite launched in 2001.

ESAs GAIA mission carries a sun shield deployment mechanism with a Harmonic Drive® Component Set which began its work in 2014.

In 2002 the DLR`s ROKVISS project as seen in *Figure 7* and *Figure 8* commenced and brought forth a remote controlled robot arm that successfully conducted experiments on the ISS outer environment.

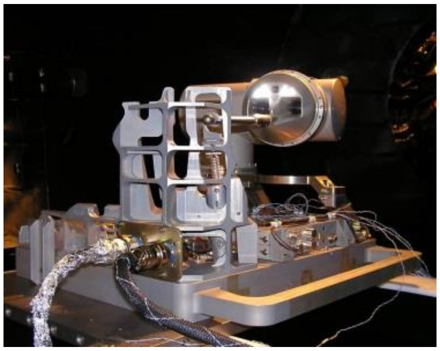

Figure 7: ROKVISS

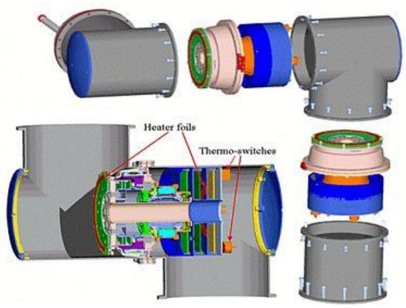

Figure 8: ROKVISS CAD-model [7]

Furthermore in ESA`s Sentinel-2 mission Harmonic Drive AG supplied gears for a calibration and shutter mechanism for multi spectral instruments as seen in *Figure 9*.

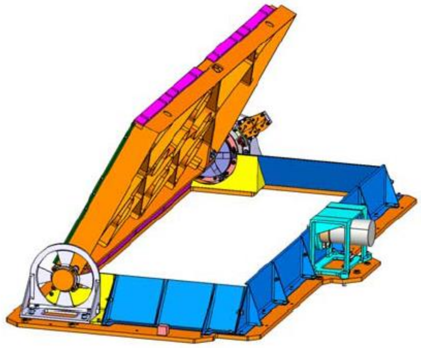

Figure 9: Sentinel-2 [10]

A current project for future launch is Nanokhod a micro rover for planetary exploration starring Harmonic Drive® Gears in its caterpillar drive, to be seen in *Figure 10*.

Figure 10: Nanokhod Micro Rover [8]

BEPI COLOMBO, a present planetary exploration project seen in *Figure 11* planned for launch in 2017 is technically approved by ESA. It features a very compact stainless steel component set with a width of only 29mm and outer diameter of just 70mm in the thruster pointing mechanism. Each one of the four thruster features two Harmonic Drive® Gears.

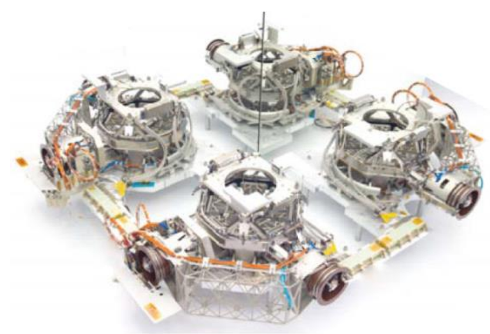

Figure 11: Bepi Colombo [9]

3 STATE OF THE ART OF LIQUID LUBRICATION IN VACUUM

Whereas in industry applications the wave generator bearing is the component which determines the achievable gear lifetime, space gears depend mainly on the lubrication regarding endurance. Presently only a limited range of lubricant choices for space mechanisms which have space heritage and are approved by ESA exists. This is calling for research and development programs to gain expertise in this field.

Currently Harmonic Drive® Gears in high precision space applications use liquid lubricants. Gears are a major factor in determining the lifetime of an application with no accessibility for maintenance and thus have to be optimized to fit space environment. The main challenge consists of providing a high precision backlash free gear with high endurance.

Currently space applications carry a reduced amount of lubricant relative to industrial mechanisms to ensure required efficiencies. Major complications in using liquid lubricants in outer space are the risk of outgassing and thus contamination of sensitive surfaces such as lenses for optical devices, creeping and the temperature dependent viscosity. The latter is tended to by either heating elements or larger sized motors. These solution approaches for cryo environment have enabled the applications with liquid lubricated gears to function successfully but still pose a compromised solution regarding weight and size issues. Recognizing the impact of lubrication on devices operating in space the European Space Agency has funded a range of programs involving the partners Harmonic Drive AG and ESTL (European Space Tribology Laboratory). The projects were in context of ESA`s long running, large scale program Artes 5 (Advanced Research in Telecommunications Systems/ Harmonic Drive® Gear Evaluation Using Space Lubrication) to support the development of advanced communication satellite products and services. The program commenced in 2008 and ended in 2015. The research activities were dedicated to bring forth the availability of space rated Harmonic Drive® Gears including lubrication for the Space Community based on approved ECSS (European Cooperation for Space Standardization) Procedures and Standards. Further objective was enabling the European based Harmonic Drive AG to offer their customers a recognized and consolidated expertise tailored to space applications. Additionally the availability of Harmonic Drive® Gear performance data sheets tailored to space rated Harmonic Drive® Gears based on expertise and representative test campaigns primary for Solar Array Drive Mechanisms should be ensured in the future. These objectives followed the need to lower qualification risks for customers and thus promote choice for the optimal solution based on sufficient tests instead of choice solely based on flight heritage.

Selection criteria for a representative Harmonic Drive® Gear were defined as the following:

- Mass to reduction ratio,
- Compactness,
- Backlash free,
- Stiffness,
- Reversibility,
- Flexibility of integration,
- Possible hollow shaft and
- High transmission accuracy.

Furthermore main requirements regarding telecommunication satellites were defined as

- Very low output speed, less than 0.1 rpm,
- Low output running torque: < 5Nm,
- High gear ratio for high resolution,
- 15 years operation in orbit,
- Temperature range -40°C to 90°C
- Gear should run in air and in vacuum and
- 100,000 output revolutions lifetime.

Subject to the tests was a HFUC-20-160 gear, meaning a 2.0 inch pitch circle diameter of toothing and reduction rate of 160. The two presently only space liquid lubricants that are approved by ESA due to their outgassing characteristics and temperature range and have flight heritage were tested with the gear under thermal vacuum. Tested with the gear were a PFPE (Perfluoropolyether) based and a MAC (multiply alkylated cyclopentane) based lubricant. For Artes 5 the PFPE based Braycote 601EF micronic/ Fomblin Z25 and the MAC based Maplub SH 100b/ Nye 2001a were chosen. Already in 2007 until 2013 a PFPE lubricant was tested in ESA`s Tribology Application Program under thermal vacuum. The HFUC gears in this program were given the numbers 1 to 4.In *Figure 14* the test parameters for the more recent Artes 5 program are shown. The gears for this testing were given the Numbers 5 to 8. Gear 6 and 8 were not subjected to tests. In *Figure 12* and *Figure 13* the amount and locations of lubrication for HFUC Nr.5 and 7 can be seen. Also to be seen in *Figure 12* is the new materialwise hybrid wave generator bearing made from CroniDur® with Spheres made from ceramic material. This wave generator bearing from European Suppliers was first tested in the context of the Artes program and poses the main advance from the Tribology Application Program to today`s Artes 5 activities.

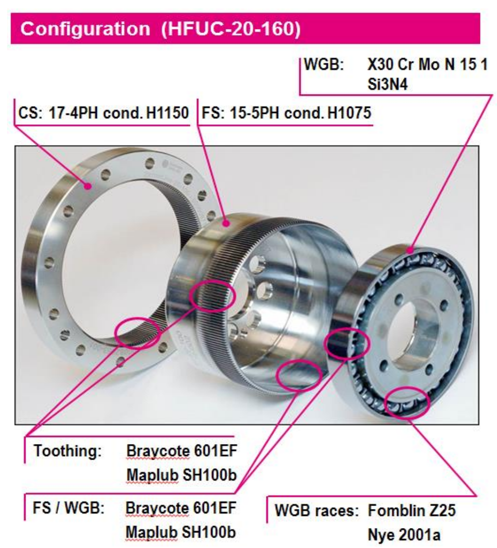

Figure 12: Configuration of gear material/lubrication

Area	PFPE	MAC
	HFUC5	HFUC7
Circular spline toothing	500mg	302mg
Flexspline toothing	100mg	61mg
Flexspline ID	200mg	121mg
Wave generator bearing OR	40mg	25mg
Wave generator bearing	180mg	84mg

Figure 13: Lubrication Details

Parameters HFUC-20-160		
Test Parameters	Values for PFPE and MAC based lubrcation	Values for standard industrial lubrication
Load	4 Nm	Rated torque: 40 Nm
Speed (I/P)	50 rpm	2000rpm
Temperature	90°C	Operational surrounding Temp.: 0 to 40°C
Vacuum Level	< 10^{-6}mBar	
Failure Criterion	Efficiency <40% see *Figure 15 and 16*	

Figure 14: Space vs industrial Standard

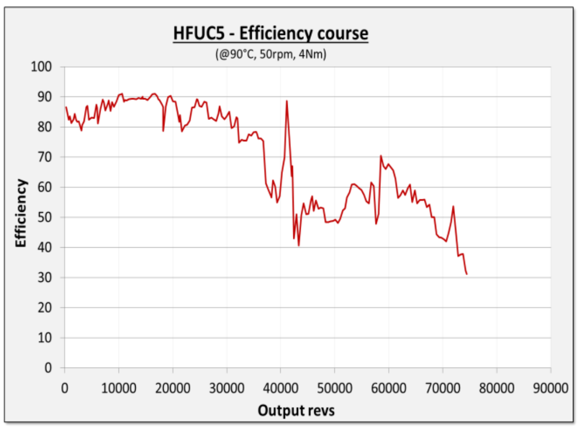

Figure15: Efficiency Course of PFPE lubricated gearbox HFUC-5 at 90°C, 50rpm, 4 Nm during endurance testing

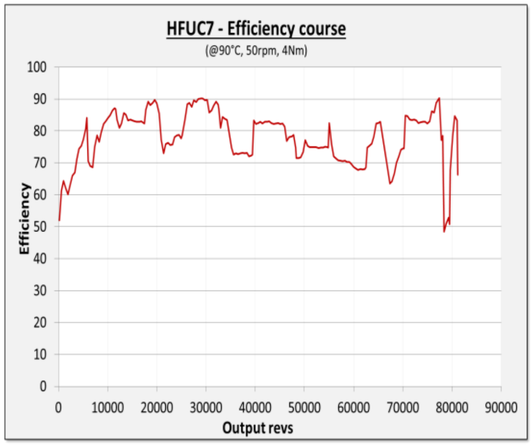

Figure16: MAC lubricated gearboxHFUC-7dring endurance testing at 90°C, 50rpm, 4 Nm

The results for a PFPE space lubricant were at 75.000 OPRs with high efficiencies of approximately 80% until 40.000 OPRs. An increase of friction between the flexspline and the wave generator occured and was confirmed by the appearance of the flexspline. Also micro pitting within the running track occurred. A decrease in efficiency was linked to the lubricant within the wave generator bearing.

The MAC based lubricant performed an endurance of approximately 80.000 OPRs at the same high efficiencies. A severe wear within the flexspline`s inner diameter in line with the friction measurement was found. A drawback here was the accumulation of the thickener. The reason for efficiency decrease will be under further investigation. Currently in Context of the Artes 5.1 Program more tests are being conducted with dry as well as fluid lubricants.

Remaining lubricants within toothing were found to be in good condition after the tests. Starting in 2015 a further Tribology Application Program investigates the usage of Harmonic Drive® Gears for the use of small oscillatory motions.

Presently the standard liquid PFPE and MAC based space lubricants still pose a compromise regarding number of revolutions and lifetime. Relatively to PFPE lubricants MAC based lubricants can achieve more revolutions but at a cost of shorter lifetime. With PFPE based lubricants higher lifetime is achievable but at a lower number of revolutions. Further research will aim at finding a space suitable lubricant fulfilling high requirements regarding both lifetime and revolutions.

4 STATE OF THE ART OF DRY LUBRICATION

Amongst the complications for presently used liquid lubrication are the risks of outgassing, contamination, micro vibrations, creeping and a temperature dependent viscosity which is tended to through heating elements or bigger sized motors. Besides efforts towards optimizing the combination of the Harmonic Drive Gear® and liquid lubricants, research and development regarding zero backlash, high endurance, space-qualified gears has focused on dry lubrication. The temperature range in vacuum for liquid lubricants is approximately -60°C to 90°C. Dry lubrication would significantly broaden the temperature range to even cryogenic applications, meaning temperatures ranging from -170°C up to 300°C. In terrestrial vacuum applications such as the DESY (German Electron Synrchotron) by XFEL, the German research facility, a dry lubricated Harmonic Drive® gear is already successfully in use at 4K (-269,15°C). This is only possible due to the rather low output torque of 0.3 Nm and input torque of 0.0049 Nm.

In June 2011 the European Commission funded research and development project HarmLES (Dry lubricated Harmonic Drive® Gears for Space Applications) began and lasted until February in 2015 bringing forth the most recent standard on dry lubrication in combination with a newly designed line of Harmonic Drive® Gears named ZirconLine®. The main research need followed the limited success to use off the shelf commercial coatings, as a result from previous projects and efforts. Objectives of HarmLES were the following:

- Understand the wear mechanisms that lead to early failures in present dry lubrication coatings with Harmonic Drive® Gears

- To develop coatings which enable long life times with Harmonic Drive® Gears

- Re-design of the Harmonic Drive® Gear towards the needs for dry lubrication

- Re-assessment of the materials presently used in Harmonic Drive® Gears

- Validate dry lubricated Harmonic Drive® Gears for long life time by field tests under thermal vacuum

- Install a user-group to setup requirements for future missions.

Key Participants in this Project were AC2T (the Austrian Center of Competence for Tribology) responsible for surface analysis (XPS: X-Ray photoelectron spectroscopy) and lubrication mechanisms, AAC (the Aerospace and Advanced Composites GmbH) for conducting vacuum tribology on samples and components, base material characterization and wear mechanisms by REM/FIB (Scanning electron microscopy/ focused ion beam). TECNALIA was responsible for the development of solid lubrication coatings. Harmonic Drive AG manufactured samples of Harmonic Drive® Gears and thus optimized the gears geometry. Before conducting trials, a consortium of companies and institutions connected to space applications defined demanding requirements as shown in *Figure 17* for the precision gear to be fulfilled at the end of the research program.

		Unit	Value
Char-acteristic	Transmission Accuracy	[arcsec]	60
	Repeatability	[arcsec]	6
	Stiffness	[Nm/rad]	$1.1*10^4$
	Zero Backlash	-	Yes
Per-formance	Output torque	[Nm]	4
	Endurance	OPR	17,000
	Temperature Range	[°C]	-200 to 150

Figure 17: Requirements on Gear Level

The project focused on an integrated approach and thus was setup into two lines running partly in parallel: The development on coatings and the development on component (gear geometry) level. As a starting point a CobaltLine® 20-100 gear was chosen which is originally designed for fluid lubrication. CobaltLine® Gears are the advancement of the HFUC series in industry applications. They provide higher torque capacity and longer lifetime. It was decided to benchmark with this gear type. After determining contact stresses via an FE-Model it was found that the contact stress especially within the toothing is strongly dependent on internal gear preload. Furthermore the sliding path was determined to be 0.1 mm per tooth engagement. With this knowledge the gear geometry was altered to fulfill the needs of dry lubrication.

As main tribological factors for low lifetime of recent standard dry lubricants the toothing was identified. A standard commercial gear and lubricant were benchmarked and samples varied regarding preload, tooth geometry, kinematic of tooth engagement, coating thickness etc. Through numerous test results testing only one parameter, a deep understanding of the impact of each component on the tribology at hand was achieved. Each test parameter was tested in a gear version.

The integrated approach of developing coatings and gear geometry brought forth the prototype ZirconLine® Gears with altered tooth geometry, a MoS_2 coating within the wave generator bearing, a tooth coating of MoS_2-WC and a reduced preload. The ZirconLine® prototype exceeded the expectations of 17.000 OPRs under thermal vacuum. The gear was stopped without failure by roughly 22.000 OPRs meaning that even higher endurance is feasible. The toothing did not show significant damage as shown in

Figure 19. The gear characteristics like zero backlash, stiffness (*Figure 18*) and transmission accuracy remained unchanged throughout the tests. At room temperature high efficiencies of more than 80% are possible. It was shown that the prototype also reached several hundred revolutions at thermal vacuum at a temperature of -150°C.

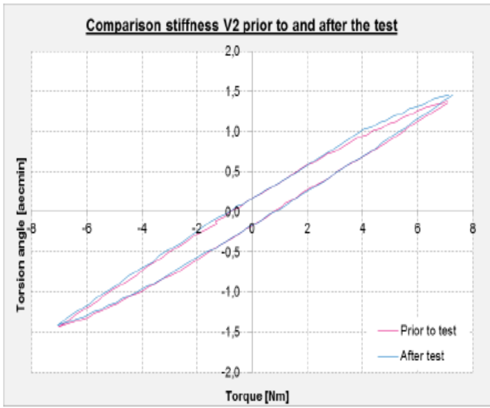

Figure 18: Stiffness prior to and after testing

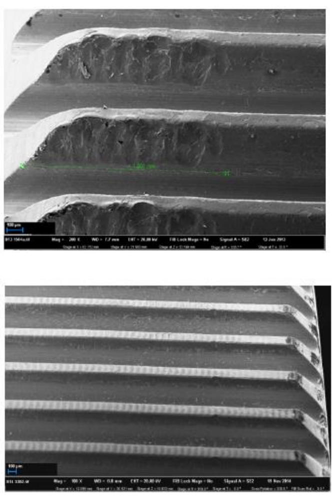

Figure 19: Upper SEM image of toothing after failure of endurance test in vacuum and lower SEM image of toothing after successful vacuum testing

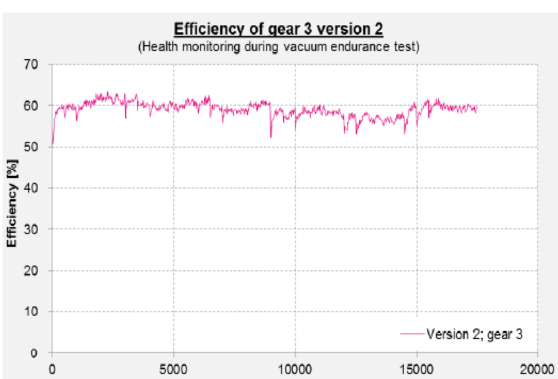

Figure 20 Gear efficiency

Further research and testing regarding reproducibility of the results and commercial production for the resulted gear of HarmLES are necessary. The ZirconLine® Gears presently undergo further trials to ensure solid reliable data sheets in context of the Artes 5.1 program (Harmonic Drive® Gears for Space Application) which started in November 2012 and will end in 2016.

4. CONCLUSION AND OUTLOOK

4.1 Fluid Lubrication Summary

From 2008 until 2015 the Artes 5 project`s overall goal was to support the development of advanced satcom products and in that context test and optimization of two liquid lubricants with a Harmonic Drive® Gear. Objective was a higher standardization and quality of products for space applications approved by the ECSS. To prolong lifetime a new hybrid wave generator bearing made from CroniDur® with Spheres made from ceramic material was used.

As a result of Artes 5 main tribological contacts were identified as lifetime influencing parameters. The gear lubricated with PFPE based Braycote601EF lubricant reached 75.000 OPRs whereas the other MAC based Maplub SH100b lubricant accomplished 80.000 OPRs. Both technologies left the toothing in good condition and had high efficiencies of about 80% for the first part of the testing. The trials focused on used materials and ambient conditions. Gear characteristics data depending on temperature, input speed, output load and operating time was gained, analyzed and documented. Still further research is planned for the future.

4.2 Dry Lubrication Summary

Development in context of the HarmLES research projects started in 2011 and lasted until 2015. Objective was the development of dry lubricated vacuum suitable Harmonic Drive® Gears for space applications for a wide temperature range. After linking the tooth engagement as main tribological criteria to low endurances, an integrated approach was made of innovating gear design and development of suitable coating. Result of the HarmLES trial series and other development was ZirconLine®, a new Harmonic Drive® Gear type featuring altered tooth geometry and reduced preload and at the same time zero backlash and unaltered stiffness. The wave generator bearing was coated with a pure MoS_2 lubricant and the toothing with a MoS_2-WC based lubricant. Coating thickness was found to have minimal impact compared to tooth geometry and reduction of the preload. The test requirements including 17.000 OPRs were exceeded and fulfilled with the prototype defining HarmLES as a successful project. Further research will be conducted on the new ZirconLine® Gears in context of the already in progress research and development program Artes 5.1 (Harmonic Drive® Gears for Space Applications).

4.3 Outlook Regarding Future Potential of Lubrication

Figure 20 and *Figure 21* show state of the art concerning the choice of materials and lubrication in space application versus industrial applications.

Gear Component	Materials	
	Industrial gears	Space flight
	Tempered Steel	15-5PH cond. 1075 (AMS 5659)
	Cast Iron	17-4PH cond. 1150 (AMS 5643)
	100 Cr6	SUS 440C X30CrMoNi15-1/Si_3N_4

Figure 20: Material Choice regarding industry

Industrial applications	Space flight applications	Cryogenic applications
• Special lubricants adapted to the tribological needs • E. g.: • Flexolub A1 • SK-1A • 4BNo.2 • Temperature range: -40°C to 120°C • Lubrication strategy: Full lubrication	• Selection driven by environmental conditions (mainly vacuum) • E. g.: • Braycote 601EF • Maplub SH100b • Temperature range: -60°C to 90°C • Lubrication strategy: Min. quantity lubrication	• Selection driven by environmental conditions (mainly temperature) • E. g.: • MoS_2/WC • MoS_2 • (Dicronite® DL5)

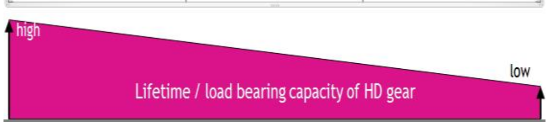

Figure 21: Lubrication Standards regarding applications

Current lubrication technology for space applications consist of on the one hand dry lubricated gears with backlash to perform at high efficiency and endurance, on the other hand high precision applications with zero backlash and liquid lubrication. In order to penetrate further into space and explore planets with extreme environments or for example jovian moons with cryogenic environment the need for high precision zero backlash Harmonic Drive® Gears with dry lubrication has come up due to the limitations of liquid lubrication to a certain temperature range. Of course liquid lubrication will also be subjected to further research and development due to their positive space heritage for suitable environments. In the future there shall be a choice between liquid and solid lubrication, both qualified and tested to ensure an optimal solution.

Zero maintenance is only one aspect of future application potential of a space standardized dry lubricated gear. Additionally the storage of gears is an issue. The storage time gap of up to 5 years between production, lubrication and the actual begin of usage of the gear is an obstacle which will need further research in order to be overcome. Another point is making space projects more cost efficient. A major part in satellite costs are launch costs, typically ranging from 10.000€ to 15.000€ per kg. That is why mass reduction and compactness play an immense role in space application planning. Using Harmonic Drive® Gears instead of planetary gears already enables mass reduction by factor 2 to 3. With a average Harmonic drive® Gearbox of about 500g and the mars rover, 4.5 kg and thus about 45.000€ of launch costs would be saved. Liquid lubrications today are often combined with heating elements to adress the temperature dependent viscosity. A dry lubrication method with equal performance would reduce mass by making the heating elements irrelevant.

Harmonic Drive AG will participate in future research and development programs in order to keep its technologically advanced position for optimal customer support. For example Harmonic Drive AG is going to supply lubricated gear boxes for space applications instead of just a gear component set, thus making it easier for customers to accomplish their projects with less concern about the number of parts. Each component bears a failure risk. A complete gearbox offers the possibility of having a circular spline integrated into housing and therefor lowering said risk.

The technology generated by the mentioned research projects is not only suitable for numerous space applications but as well offers potential for uptake in a range of non-space sectors. The further research and development of the Harmonic Drive® Gear with focus on lubrication method has proven a valuable path and will be further pursued.

Acknowledgement

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