PERFORMANCE AND LIFE OF HARMONIC DRIVE® GEARS
FOR SPACE APPLICATIONS

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ABSTRACT
Harmonic Drive® Gears (HD Gears) have a remarkable performance record in space mechanisms. Even though successfully used for decades in space missions, the quest for improvement is a constant companion. Environment related test data on component level for the gears as well as accompanying analysis play an important role. This paper presents a comprehensive overview of state of the art of fluid and solid lubricated HD Gears for space applications. Performance and life of solid lubricated and fluid lubricated (PFPE and MAC based lubricants) HD Gears are presented. Focus is set on present project “Harmonic Drive® Gears for space applications”, which is based on achievements of previous projects with the main goal to reduce lack of environment related tests. The project was initiated within the frame of ESAs Artes 5.1 program.

1. HARMONIC DRIVE® GEARS
Harmonic Drive® Gears (HD Gears) provide excellent transmission accuracy, high stiffness, zero backlash, high power density (torque to weight ratio) and a high single stage reduction ratio. Main components of a HD Gear are shown in Fig. 1. These are Circular Spline (CS), Flexspline (FS) and Wave Generator (WG).

Materials used in space applications differ from the ones used in industrial applications mainly due to environmental constraints. Typically used materials are shown in Tab. 1.

![Figure 1. Harmonic Drive® Gear components](image)

2. TRIBOLOGICAL CONTACTS HD GEARS
Harsh environmental conditions in space applications (especially present vacuum) lead to significant shorter life compared to life achieved in industrial applications.

![Figure 2. Cross section Harmonic Drive® Gear](image)

Lubricant degradation and starvation, resulting in inadequate lubrication, are main life limiting factors. Furthermore, space suitable lubricants provide minor lubrication properties compared to usually applied greases, which are specifically developed and optimized for industrial applications. In order to increase the life, tribological contacts need to be tailored to the prevailing conditions. This includes choice of a suitable lubricant as well as choice of suitable base material with optimized geometry. Environmental and operational conditions must be considered as well. A cross section showing the tribological contacts of a HD Gear is depicted in Fig. 2.

The tribological contacts differ in kind of friction (sliding/rolling), relative motion (speed and distance) and stress. Hence requirements on base material and lubricant differ in principle as well.

Different gear characteristics are dominated by different contacts. Efficiency of the gear e.g. is mainly influenced by the lubrication conditions of the WG bearing. Transmission accuracy (correct alignment of parts provided) and stiffness are mainly influenced by condition of the toothing. This allows for assessment of the condition of different contacts based on measurement of gear characteristics during test.
3. SPACE SUITABLE LUBRICATION OF HD GEARS

Lubricant shall be compatible with the environment to which it is supposed to be exposed. For space applications, especially temperature and outgassing are limiting factors. Beside general suitability in terms of environmental conditions, the lubricant, as part of a tribological contact of a mechanism, shall also meet operational requirements. The prevailing requirements lead to a limitation of options.

It can be differentiated in solid and fluid (grease/ oil) lubrication. Guideline for selection of lubricant in general can be found in [1]. Nowadays typically fluid lubrication is used for HD Gears. In general, HD Gears today are in their geometry optimised towards grease lubrication for terrestrial applications. As fluid lubrication is linked to outgassing and a limitation of operational temperature, effort is put into optimising HD Gears for solid lubrication and vice versa (see section 3.2). In this context, first prototypes of a new HD Gear type (ZirconLine®) were developed [2].

3.1 Fluid lubrication of HD Gears

For space applications either PFPE based or MAC based lubricants are typically used. A combined lubrication by use of grease and oil is recommended. Grease shall be applied to Flex spline and Circular Spline teeth, Wave Generator outer surface and Flex spline inner surface. Oil shall be applied to Wave Generator Bearing balls. In case of fluid lubrication, impregnated cotton reinforced phenolic cages are typically used. [3] lists different lubricants used in published tests with corresponding life test results.

Being used in past ([3], [4], [5], [6]) and running projects (results presented herein), this paper focuses on the following lubricants, as most test data is available for these configurations:

- **(Z-type) PFPE-based**
  - Grease Maplub® SH100b/ Oil Fomblin® Z25

- **MAC-based**
  - Grease Maplub® SH100b/ Oil Nye® 2001a

PFPE based lubricants are characterized by very low vapour pressure. However, PFPE fluids tend to degrade when used in metallic tribological contacts under boundary lubrication conditions [1]. [7] reports appreciably longer lifetime for MAC-based lubricants. Lubricants have a significant influence on performance of HD Gears (and mechanisms in general). Hence their performance is reflected in the performance of the gear. Especially the viscosity and its dependency on temperature shall be mentioned. Temperature dependency of viscosity of Fomblin® Z25 and Nye® 2001a is shown in Fig. 3. Consequently, the trend of the curves is also reflected in HD Gear test data (section 6).

![Figure 3. Kinematic viscosity of Fomblin® Z25 and Nye® 2001a, approximation acc. ASTM D341](image)

### 3.2 Solid lubrication of HD Gears

Over the last years several projects dealt with solid lubrication of HD Gears. Base material, geometry as well as coating was optimized in order to increase operational life and load bearing capability. A significant progress was achieved. However, solid lubricated HD Gears have a significantly shorter life compared to fluid lubricated HD Gears. Development is still in progress. Hence, they should not be considered as standard component and the necessity for a solid lubricated HD Gear should be carefully reflected. Although material and geometry need to be adapted to solid lubrication, this section focuses on the solid lubricant and provides an insight in its development.

A solid lubricant can be considered a thin film composed of a single solid or a combination of these introduced between two rubbing surfaces for the aim of reducing friction and wear. Solid lubricants can be classified into different categories, depending on chemistry, crystal structure and lubricity [8]. Among the different options, lamellar solid lubricants such as the dichalcogenides (MoS₂, WS₂), graphite or hexagonal boron nitride are very attractive since these can provide very low friction coefficients. The range of friction coefficients that can be obtained in this type of solid lubricants can be wide, since friction can be sensitive to test environment, condition and/or configuration. Additionally, the specific form in which the solid lubricant is applied (e.g. as a thin film, powder, bulk, composite, and crystalline or amorphous states) can also play a significant role [8].

Molybdenum disulphide (MoS₂) is reportedly the most widely used inorganic solid lubricant. It provides very low friction values, usually in the range of 0.002 to 0.25. A great deal of literature on molybdenum disulphide lubrication has been published, and the work of Lansdown [9] provides a comprehensive review on the history, properties, lubricating mechanisms and deposition methods of MoS₂.

The presence of moisture in air has a detrimental effect on the lubricity of MoS₂ [10]. The excellent performance of MoS₂ under vacuum is not reproduced under...
atmospheric conditions, since it readily oxidizes in air [10] and can lead to irreversible damage to the films. To overcome the limitations, research has been focussed on MoS2 films co-sputtered with various metals (e.g. Au, Ni, Ti, Pb, C, etc) and compounds (TiN, PbO, SiO3, etc.) to improve their performance in air. The aim was to reduce the sensitivity of MoS2 to water vapour and oxidation, and to suppress the formation of porous, columnar microstructures.

TECNALIA has developed magnetron sputtered MoSx-WC coatings. Within HarmLES a comparison of the developed coatings (MoSx-WC) with the solid lubricant coating was performed on polished gear steel. Within HarmLES a comparison of the developed coatings (MoSx-WC) with the solid lubricant coating was performed on polished gear steel. Lifetime decreased. Even further relevant to HD Gears. When testing those coatings on significantly increased lifetimes in contact to pins applied on samples with medium roughness showed of the MoSx–WC coatings. Tribological tests on coatings finally proven to be the optimum range regarding lifetime of the gear components was the one applied to discs. It was in range of Ra = 0.1-0.4µm. The achieved roughness on parameters and revealing in lower "medium" roughness machining of the gear components using new machining substrates (Ra<0.6µm). This initiated a change in the substrate plays an important role. First tests on MoSx-WC coatings failed because of the high roughness of the substrates (Ra<0.6µm). This initiated a change in the machining of the gear components using new machining parameters and revealing in lower “medium” roughness in range of Ra = 0.1-0.4µm. The achieved roughness on the gear components was the one applied to discs. It was finally proven to be the optimum range regarding lifetime of the MoSx–WC coatings. Tribological tests on coatings applied on samples with medium roughness showed significantly increased lifetimes in contact to pins relevant to HD Gears. When testing those coatings on polished gear steel lifetime decreased. Even further increase in lifetime of the MoSx-WC coatings on samples was obtained, after performing pre-treatment of the steel surface. This leads to improved mechanical support of the solid lubricant coating. Within HarmLES a comparison of the developed coatings (MoSx-WC) with the "state of the art" pure MoS2 coating was performed on HD Gears, showing the over-performance of MoSx-WC specially at low contact stresses.[2]

4. GEAR CONFIGURATIONS

Two types of HD Gears are subject of this paper: HFUC and ZirconLine®. Type HFUC is a standard Harmonic Drive® Gear type. For applications in harsh environment of space the standard acc. to HDAG catalogue needs to be modified. Hence catalogue values serve as first guidance only. Usually materials and lubricants are substituted by space suitable products, while one relies on the general gear design. Type ZirconLine® goes beyond that modification. ZirconLine® is optimized for harsh environment and solid lubrication. Tests with first prototypes proved suitability of design concept [2]. A selection of previously life tested fluid lubricated HFUC gears is listed in Tab. 2.

Table 2. Previous life tests fluid lubricated HD Gears

<table>
<thead>
<tr>
<th>ID</th>
<th>Gear technology</th>
<th>Lubrication</th>
<th>Ref. to</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;HFUC1&quot;</td>
<td>HFUC-20-160</td>
<td>PFPE</td>
<td>[3]</td>
</tr>
<tr>
<td>&quot;HFUC2&quot;</td>
<td>HFUC-20-160</td>
<td>PFPE</td>
<td>[3]</td>
</tr>
<tr>
<td>&quot;HFUC4&quot;</td>
<td>HFUC-20-160</td>
<td>PFPE</td>
<td>[4]</td>
</tr>
<tr>
<td>&quot;HFUC5&quot;</td>
<td>HFUC-20-160</td>
<td>PFPE</td>
<td>[5]</td>
</tr>
<tr>
<td>&quot;HFUC7&quot;</td>
<td>HFUC-20-160</td>
<td>MAC</td>
<td>[6]</td>
</tr>
</tbody>
</table>

Configuration of previously life tested solid lubricated ZirconLine® is shown in Tab. 3.

Table 3. Previous tests solid lubricated HD Gears

<table>
<thead>
<tr>
<th>ID</th>
<th>Gear technology</th>
<th>Lubrication</th>
<th>Ref. to</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>ZirconLine-20-100</td>
<td>MoSx/WC</td>
<td>[2]</td>
</tr>
</tbody>
</table>

Configurations shown in Tab. 2 and Tab. 3 (and corresponding test results) serve as benchmark herein. Past tests focused on gears of size 20. Size 20 was retained for present tests presented herein (Tab. 4).

Table 4. Present tests

<table>
<thead>
<tr>
<th>ID</th>
<th>Gear technology</th>
<th>Lubrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;HDGSA Dry#1&quot;</td>
<td>HFUC-20-160</td>
<td>MoSx/WC</td>
</tr>
<tr>
<td>&quot;HDGSA Dry#2&quot;</td>
<td>HFUC-20-160</td>
<td>MoSx/WC</td>
</tr>
<tr>
<td>&quot;HDGSA Dry#3&quot;</td>
<td>HFUC-20-100</td>
<td>MoSx/WC</td>
</tr>
<tr>
<td>&quot;HDGSA Dry#4&quot;</td>
<td>HFUC-20-100</td>
<td>MoSx/WC</td>
</tr>
<tr>
<td>&quot;HDGSA Fluid#1&quot;</td>
<td>ZirconLine-20-100</td>
<td>PFPE</td>
</tr>
<tr>
<td>&quot;HDGSA Fluid#2&quot;</td>
<td>ZirconLine-20-100</td>
<td>MAC</td>
</tr>
</tbody>
</table>

Based on tests in configurations shown in Tab. 4 a test gap between past projects is closed by project “Harmonic Drive® Gears for space applications”. Furthermore, a lack of tests is reduced, and environment related test data is provided. As a novelty, gears based on HFUC technology were solid lubricated based on findings of ZirconLine® development. Furthermore, ZirconLine® gears were fluid lubricated (no coating) in order to check whether implemented design changes promote gear performance also in fluid lubricated configuration.
5. ANALYSIS AND SIMULATION

Analysis and simulation enable targeted assessment and comparison of different gear configurations. Furthermore, knowledge of tribological parameters allows for basic testing like e.g. Pin on Disk testing.

Friction path toothing

Based on a specially developed Matlab – Tool, the simulation of the tooth engagement of a HD Gear can be performed. The tool furthermore allows the calculation of the friction path at zero load on the output for one tooth engagement. According to the calculation, the maximum friction path per one tooth mesh and for an output revolution is shown in the Tab. 5.

<table>
<thead>
<tr>
<th>Type-Size-Ratio</th>
<th>Max. friction path per tooth mesh [mm]</th>
<th>Friction path per OPR [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFUC-20-100</td>
<td>0.12</td>
<td>24.0</td>
</tr>
<tr>
<td>HFUC-20-160</td>
<td>0.08</td>
<td>25.6</td>
</tr>
<tr>
<td>ZirconLine®-20-</td>
<td>0.04</td>
<td>8.0</td>
</tr>
</tbody>
</table>

As expected, the sliding path per tooth engagement is larger for the ratio 100. This is linked to larger teeth and higher deformation of FS. Sliding path over one output revolution shows, that driven by the ratio, the overall friction path is nearly identical for both HFUC type gears. Gear type ZirconLine® is specifically tailored to solid lubrication. Comparison of maximum friction path per one tooth mesh of HFUC type and ZirconLine® type gear shows shorter maximum friction path per one tooth mesh within the ZirconLine® toothing. This was intended during development.

Contact stress toothing

The maximum contact stress within the toothing of the respective gears at an applied output load of 4 Nm are shown in Tab. 8. It can be seen, that higher ratio provides lower contact stress within the toothing. Furthermore, newly developed gear type ZirconLine® provides reduced stresses. This was main target of the development.

<table>
<thead>
<tr>
<th>Gear configuration</th>
<th>Max. contact stress toothing [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on HFUC 20-160</td>
<td>580</td>
</tr>
<tr>
<td>Based on HFUC 20-100</td>
<td>1020</td>
</tr>
<tr>
<td>ZirconLine® 20-100</td>
<td>320</td>
</tr>
</tbody>
</table>

Friction path toothing between FS and WG

With regards to the relative movement between FS and WGB only the axial share is deterministic. During operation there is also a small difference in the rotational speed of the WGB outer ring and the Flexspline. The rotational share is neglected herein as it is non-deterministic. Anyway, as the axial motion between the two parts causes an oscillating movement with small amplitude, which is known to be critical with regards to fretting, the knowledge of the sliding path in axial direction is important information. Peak to peak values of friction path in axial direction between FS and WGB are shown in Tab.6.

Table 6. Maximum contact stress within the toothing, load at output: 4Nm

<table>
<thead>
<tr>
<th>Type-Size-Ratio</th>
<th>Friction path (p2p) [mm] measured</th>
<th>Friction path (p2p) [mm] calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFUC-20-100</td>
<td>0.063</td>
<td>-</td>
</tr>
<tr>
<td>HFUC-20-160</td>
<td>0.033</td>
<td>0.032</td>
</tr>
<tr>
<td>ZirconLine®-20-</td>
<td>0.063</td>
<td>0.063</td>
</tr>
</tbody>
</table>

Contact stress Wave Generator bearing (WGB)

The peak Hertzian contact stress (Wave Generator bearing balls /inner race and outer race) is calculated based on the maximum load acting on the Wave Generator bearing balls. General load distribution in a Wave Generator bearing is shown in Fig. 4 (no absolute values). With increasing output load the maximum force on a WG ball (indicated in Fig. 4) increases. The number of balls in ‘intense’ contact to races increases as well.

<table>
<thead>
<tr>
<th>Gear configuration</th>
<th>Max. contact stress WGB [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on HFUC 20-160</td>
<td>“HDGSA Dry#1”</td>
</tr>
<tr>
<td>Based on HFUC 20-100</td>
<td>“HDGSA Dry#2”</td>
</tr>
<tr>
<td>ZirconLine® 20-100</td>
<td>“HDGSA Fluid#1”</td>
</tr>
</tbody>
</table>

Figure 4. Wave Generator bearing ball force

Peak contact stresses within the WG bearing of gears in configuration shown in Tab. 4 at an output load of 4 Nm are listed in Tab. 5. Dependency of Peak Hertzian contact stress on gear ratio is revealed.
6. TESTING

Harmonic Drive® Gears were tested at company Aerospace and Advanced Composites GmbH (AAC) in two devices (SALOTTE1 and HADES) in frame of project “Harmonic Drive® Gears for space applications”. Both have similar setup: input shaft (motor, torque sensor and angle resolver) as well as an output shaft (actuator, torque sensor and angle resolver). The gear is driven by the input side and on the output side the actuator is programmed to apply a defined torque load. The basic idea is to have a unique drive motor and to have changeable internal setups. The chamber can also be used for testing of complete actuators (just use output shaft), planetary gears (using the external motors as brakes for applying torque loads from 100mNm to 50Nm) or even bearing setups. Temperatures can be provided from -150°C up to +200°C.

Test device HADES can be seen in Fig. 5. The test box is fixed on a heating/cooling plate. For cooling LN2-tubes are used, for heating electrical heaters. The temperature is controlled via the temperature-sensor fixed on the heating-/cooling plate. At input and output shaft a high precision angular sensor (3 arcsec) is fixed close to the test box.

Figure 5. recent test device for gears in thermal vacuum

Available measurements (e.g. for Harmonic Drive® Gear):
- Continuous monitoring efficiency possible at constant speed and torque
- Efficiency profile (efficiency during torque-ramp, efficiency at various speeds)
- Transmission accuracy
- Stiffness
- Axial-force (between FS and WGB outer ring)
- No-Load-Running-Torque
- No-Load-Back-Driving-Torque
- Environmental data, temperature
- Residual gas analysis (mass spectrometer of outgassing particles)

Due to the extreme wide temperature range, support bearings are solid lubricated. A combination of MoS2 coating and cages made of a new material based on PTFE with MoS2 were used. This material was developed in ESA-project SLPMC2.

6.1 Testing in thermal vacuum (TVAC)

Performance and endurance tests were performed in thermal vacuum. Performance tests took place before endurance tests, during endurance test after defined intervals and at the end of the endurance tests. Comprehensive monitoring of the state of the gears was thus ensured in order to provide basis for test result interpretation. The following was measured:
- Transmission accuracy
- Torsional stiffness
- Axial force acting on Wave Generator
- Running torques and efficiency

Measuring of gear torsion is carried out with mechanical blocked input shaft while torque is applied to output shaft. Torsion of gear output side is measured with a high resolution measurement system. Torsional stiffness is derived from torque-torsion curve.

Endurance test parameters are listed in Tab. 9.

<table>
<thead>
<tr>
<th>ID</th>
<th>o/p Load [Nm]</th>
<th>i/p Speed [rpm]</th>
<th>Temp. [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>“HDGSA Dry#1”</td>
<td>4</td>
<td>200</td>
<td>23</td>
</tr>
<tr>
<td>“HDGSA Dry#2”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“HDGSA Dry#3”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“HDGSA Dry#4”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“HDGSA Fluid#1”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“HDGSA Fluid#2”</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Expected/ envisaged test duration plays an important role in planning personnel and test equipment requirements. Especially testing of fluid lubricated gears is challenging, as they usually provide longer operational life than solid lubricated gears. In combination with mostly very low operational speeds of actuators in space, testing would last up to several years, when one sticks to the operational parameters of the respective application. Hence, even though causing limited validity when testing fluid lubricated gears, accelerated testing is necessary. Limited validity up to invalidity of accelerated testing is caused by the dependency of the lubrication regime on speed. Based on analysis of tribological contacts this was considered during fixation of test parameters (Tab. 9).

Required input torque can be estimated based on Eq. 1.

\[ T_{in} = \frac{\tau_{out}}{\eta i} \]  

Eq. 1 reflects the dependency of the required input torque on load at the output \( T_{out} \), gear ratio \( i \) and efficiency \( \eta \). Dependency of efficiency on gear configuration (type, size, ratio, material and lubricant) and operating conditions (load, speed and temperature) should not be neglected. Hence their influence on the required input torque is of major interest for sizing a suitable motor. The results presented in the following make contribution to the knowledge about gear configuration related and operating condition related dependencies of required input torque/achievable efficiency. For sake of clarity only few selected trends are shown in the following.

**Input torque – temp. and o/p torque dependency**

Fig. 6 shows the required input torque for tested solid lubricated gear HDGSA Dry\#1 at begin of test (BOT). The shown family of curves reflects the output torque dependency. Acc. to Eq. 1, required input torque consequently increases with increasing output load. Furthermore temperature dependency (Fig. 6) of required input torque is reflected. The solid lubricated HD Gears showed no dependency of required input torque on temperature over the entire tested range from -150°C up to 170°C.

Fig. 7 shows the required input torque for tested solid lubricated gear HDGSA Dry\#3. Acc. to Eq. 1, required input torque consequently increases with decreasing ratio (comparison Fig. 7 / Fig. 6). Furthermore the temperature dependency of performance of fluid lubricated gear HDGSA Fluid\#1 is shown in Fig. 7. The fluid lubricated gears showed a clear dependency of input torque on temperature. This dependency is caused by temperature dependent viscosity of the lubricant (see Fig. 3). Fig. 8 shows the required input torque during operation of HDGSA Fluid\#1 (PFPE-based lubricant) and HDGSA Fluid\#2 (MAC-based lubricant). Dependency of gear performance on choice of lubricant (especially at low temperature) is apparent.
**Input torque – temp. and speed dependency**

Same as for temperature, influence of speed on required input torque was found neglectable for solid lubricated gears (see Fig. 9).

In contrast to solid lubricated gears, fluid lubricated gears showed a dependency of input torque (and with that also of efficiency) on temperature. Caused by viscous losses, consequently required input torque of fluid lubricated gears showed also a dependency on operational speed, especially at low temperatures (see Fig. 9).

**Figure 9. HDGSA Dry#3 and Fluid#1 Input torque – temp. dependency**

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**6.2 Testing – TVAC endurance test**

Fig. 10 shows the trend of the required input torque as well as the derived efficiency over test for solid lubricated gears Dry#1, Dry#2, Dry#3 and Dry#4 (see Tab. 4). Respective end of test is indicated by red dashed lines. All tests were stopped because of an increase in required input torque (decrease in efficiency). For Dry#2 and Dry#4 this increase was observed during interim characterisation (therefore not reflected in Fig. 10). As expected, MoSx-WC coated gears showed better life-performance than the gears coated with pure MoS2. Furthermore it was shown, that, provided that coating is considered during gear shaping, solid lubrication of HD Gears based on standard-type HFUC provides high efficiency over certain no. of output revolutions. All gears provided efficiency higher than 0.9 over more than 2000 OPR. As expected, performance of solid lubricated ZirconLine® gears (up to 22,000 OPR, [2]) was not achieved.

Beside monitoring of efficiency during TVAC endurance test, stiffness, transmission accuracy and axial force acting on WG were measured after defined intervals. These parameters may serve as further test termination criteria. It was decided to terminate the tests based on efficiency as main criteria, even though stiffness (Fig. 11), transmission accuracy (Fig. 12) and axial force acting on WG may be of main relevance for an application. However, together with the knowledge about visual appearance after test, these values enable drawing conclusion about the state of tribological contacts over the course of test.

**Figure 10. Trend input torque during endurance test, Dry#1 ... Dry#4**

**Figure 11. Trend stiffness (0…7 Nm), Dry#1 ... Dry#4**

**Figure 12. Trend Transmission accuracy,Dry#(1…4)**
schematic trend of efficiency of a previous test [5] as basis for comparison is shown in Fig. 13. Both test configurations basically differ in type of HD Gear (test HFUC5, see Tab. 2: based on HFUC, test Fluid#1, see Tab. 4: ZirconLine®). Test showed the general suitability of type ZirconLine® also for fluid lubrication. In addition to it, test of Fluid#1 revealed, that also fluid lubricated HD Gears might benefit of measures implemented during ZirconLine® development. Furthermore, here, however, attention is drawn to the small no. of tests. Besides monitoring of efficiency during TVAC endurance test, stiffness, transmission accuracy and axial force acting on WG were measured. These values (see Fig. 14) showed no dramatic change during the test.

Beside monitoring of efficiency during TVAC endurance test, stiffness, transmission accuracy and axial force acting on WG were measured. These values (see Fig. 14) showed no dramatic change during the test.

**Figure 13.** Trend input torque during endurance test, Fluid#1

![Figure 13. Trend input torque during endurance test, Fluid#1](image)

**Figure 14.** Trend stiffness, TA and axial force inclination, Fluid#1

![Figure 14. Trend stiffness, TA and axial force inclination, Fluid#1](image)

7. **CONCLUSION**

Provided that appropriate adaptations are implemented, Harmonic Drive® Gears proved general suitability for solid lubrication. Wherever significantly shorter operational life of solid lubricated gears compared to fluid lubricated gears can be accepted, solid lubrication offers several advantages, such as temperature and speed independence of efficiency. Furthermore, tests showed, that also fluid lubricated Harmonic Drive® Gears for space applications might benefit of measures implemented during ZirconLine® development, which was primarily dedicated to gears optimized for solid lubrication. However, attention is drawn to still small no. of tests. Furthermore, development is still in progress. The presented tests made a significant contribution to reducing lack of environment related test data.

10. **ACKNOWLEDGEMENTS**

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