LIFE TEST OF AN INDUSTRIAL STANDARD AND OF A STAINLESS STEEL HARMONIC DRIVE

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1. ABSTRACT

Early in 2008 two stepper motors with integrated harmonic drive (HD) gears (HFUC-11) were qualified for the X-Band Antenna Equipment XAA [1] of Kompsat 3.

For a first life test under vacuum conditions one standard industrial gear stage and one stainless steel space gear of the same type were lubricated with MAPLUB PF 101-a. They were assembled and qualified together with identical PHYTRON stepper motors after performing a successful life test.

An upcoming project similar to the XAA required additional lifetime. Therefore a second lifetime test campaign was started in 2010 with the actuators from 2008 but lubricated with the new MAPLUB PF 101-b formulation [3].

In this paper, we present, describe and compare the different lifetime test conditions, test procedures and test results from the first and from the second lifetime test campaign and some lessons learnt.

2. INTRODUCTION

Due to a longer delivery schedule of the space stainless steel version [4] of the HFUC-11 harmonic drive gear, the life test actuator #1 was mounted first with the industrial standard HD version.

After receipt of the stainless steel gear version the life test actuator #2 was integrated. Both gear stages have a ratio of 50:1 and were lubricated with MAPLUB PF 101-a in the harmonic drive gear stage and BRAYCOTE 601 EF in the motor and gear shaft bearings.

In order to allow comparison of the two different gear versions and characteristics, a lifetime test identical to the #1 test was performed for actuator #2. Both actuators passed the lifetime test successfully.

After life test and between 2008 and 2011 the two life actuators were used at ASTRIUM for additional internal needs (e.g. micro jitter investigations).

Due to the fact that a new upcoming project required a longer lifetime than tested so far, the lifetime test was re-started and extended in 2011.

The two available life test actuators equipped with the same industrial and stainless steel HD gears were used as in the original test, however with a different gear lubrication.

The originally used MAPLUB PF 101-a had been reformulated in 2009 to a b-type [3] so that for future projects the use of the original type –a was no longer recommended.
Therefore both existing life test actuators were dismantled, the gears were cleaned and inspected with the REM method. Now the gears were relubricated with MAPLUB PF 101-b before restarting the life test.

Due to schedule constraints, the first part of the extended life test was carried out in dry nitrogen atmosphere. As a result of the higher thermal conductance of $N_2$ atmosphere, a higher number of test cycles became possible without overheating the motor allowing a shorter cycle time.

It was clear from the beginning that a life test in nitrogen atmosphere might not be fully representative compared to a pure vacuum test. The study of Pepper [4] shows the effects of absorbed water between UHV and a dry nitrogen gas atmosphere at 760 torr (=1033 mbar).

In order to clarify the potential influence of nitrogen and vacuum test conditions in the given application an additional vacuum test was carried out.

In the following figure the overall test flow is shown. The following chapters are referenced to the numbers in this table (e.g. #1Va means: Actuator 1/Vacuum test/Lubrication Maplub type A).

### 3. GEAR CHARACTERISTICS

In the following table, the material characteristics of the two tested HFUC-11 gears (50:1) are listed.

<table>
<thead>
<tr>
<th>Material</th>
<th>Standard Gear</th>
<th>Space Gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular spline</td>
<td>FCD 80 ductile iron</td>
<td>SUS 630 stainless steel</td>
</tr>
<tr>
<td>Flex spline</td>
<td>SnCM 439 alloy steel</td>
<td>SUS 304L or 15-5PH stainless steel</td>
</tr>
<tr>
<td>Wave bearing</td>
<td>SUJ 2 bearing steel</td>
<td>SUS 440C stainless steel</td>
</tr>
<tr>
<td>Wave plug</td>
<td>S 45 carbon steel</td>
<td>SUS 630 or SUS 304L stainless steel</td>
</tr>
<tr>
<td>Bearing retainer</td>
<td>nylon 66 with glass-fibre reinforcement</td>
<td>phenolic resin</td>
</tr>
</tbody>
</table>

*Fig. 4 Gear material characteristics [6]*

### 4. LUBRICATION

Since 1996 MAPLUB greases were used in space projects and are internationally recognized and considered for liquid lubricated space mechanisms. In order to meet new international requirements related to the limitation of greenhouse effects (e.g. ozone layer protection), MAP has reformulated their greases.

The MAPLUB PF 101-b product is now on the market and replaces the former MAPLUB PF 101-a. Consequently re-testing in terms of performance and life behaviour became necessary for projects using the new type –b grease.

This approach follows the recommendation: “….testing a mechanism qualified with a MAPLUB-a grease version, does not keep its qualification status, if we replace the grease with its equivalent -b ….“ [3].

An additional hint for a different lubrication characteristic was found in the study of Buttery [5]. The results created with a spiral orbit tribometer shows a similar lifetime but a higher friction coefficient for the MAPLUB b-formulation.

In the life test configuration described hereunder, the HD industrial version was equipped with the original nylon 66 [6] bearing retainer. The space version used a phenolic resin retainer which was vacuum impregnated with the MAPLUB base oil (Fomblin Z25).

No anti creep barriers were used in any configuration.

The transferability of any test results gained from literature was clearly not given in our case.
<table>
<thead>
<tr>
<th>HFUC-11 (50:1 ratio)</th>
<th>catalog values</th>
<th>test torque</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>rated torque</td>
<td>3.5 Nm</td>
<td>2.0 Nm</td>
<td>57.14%</td>
</tr>
<tr>
<td>limit peak torque</td>
<td>8.3 Nm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>limit for repeated peak torque</td>
<td>17 Nm</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 5 torque load overview

5. CONDITIONS FOR TEST #1VA/2VA

The first life test performed used the following conditions:
- life goal: 67,200 cycles (corresponding to $3.36 \times 10^6$ wave generator turns)
- external torque 2.0 Nm
- one motion cycle correspond to +180 deg rotation, stop time of 500 ms followed by a -180° rotation back to the zero position and a stop time of 500 ms again.
- vacuum quality: between $10^{-5}$ and $10^{-6}$ mbars.
- thermal cycling: between -40°C and +70°C.

A mass, attached to the gear output, produced a torque of 2.0 Nm on the gear shaft. One operating cycle was defined as a turn from the zero position by 180° in clock wise (cw) direction. After 100 ms stop time at a holding current of 0.6 A, the motion was reversed and 180° counter clock wise (ccw) rotation was performed back to the start position, followed again by a stop time of 100 ms.

Fig. 6 vacuum test facility

No re-lubrication cycles by performing one or more full gear rotations was integrated into the test sequence. 4 k-type thermocouples and two data loggers monitored the temperature (of gear housing, motor-gear flange, rear motor flange and inside the motor windings) continuously over the complete test time with 1 minute sampling rate.

For energizing the stepper motors a linear PHYTRON amplifier (MCC-2 LIN) with 24V supply voltage was used.

Pre torque tests under ambient condition showed that approx 290 mA running current (corresponding to 48.3% of nominal current) was needed during operation (external torque applied).

6. TEST RESULT #1VA, VACUUM, (HD INDUSTRIAL VERSION)

During the first 11,000 test cycles the test setup was optimised in order to adjust the acceptable motor operation mode under vacuum conditions, at different environmental temperature levels and at minimised cycle time. The optimisation yielded an input current to the motor of 340 mA (loaded condition) at a step frequency of 5,600 Hz in 1/8 mini step mode (corresponding to 700 Hz full step). After 21,000 cycles no degradation effects could be observed. After 50,500 cycles the torque load direction was changed and a slight adjustment in the motor current to 380 mA (4,800 Hz in 1/8 mini step mode corresponding to 600 Hz full step) was made.

Note that the roughly 10% current increase was introduced for the sake of a more stable operation under vacuum conditions and was not related to any degradation effects. Back driving torque measurements before life test and after the first 21,000 cycles showed a small back driving torque reduction of approx. 6.26% (average values, start value scaled to 100%). This effect was most likely related to a gear “running in” effect.

After 67,327 load cycles the back driving torque values were measured again and a smaller torque reduction of 3.12% compared to the initial status was observed.

The starting current values were at all three measuring points identical to 90 mA (unloaded gear condition). In summary, the test data identified a running in process at the beginning with a 6.2% back driving torque decrease followed by a very small degradation effect that consumed approx. 3% of the 6.2% back driving torque reduction. This still resulted in a positive torque effect of about 3.1% at the end of the life test. Subsequent dismantling of the gear and inspection with the raster electron microscope (REM) confirmed that no mentionable post-test degradation or wear was identified. (refer to pictures below).

Fig. 7 flex spline tooth flanks
In the middle of the tooth flanks flattened areas were visible but still negligible compared to the original surface roughness.

The life test was started with the optimised motor parameters as for the first test. (380 mA running current and 4,800 Hz step frequency in 1/8 mini step mode, corresponding to 600 Hz full step and a stop time of 1,000 ms after each load cycle).

After approx. 50% of the required life cycles, the direction of the preload torque to the gear output shafts was changed.

The back driving torque measurements before life test and after the final 69,697 cycles showed a small torque increase of approx. +10.71% (average), compared to the starting value.

The measured value at the end of the life test was slightly higher than the starting value and thus should reflect some minor gear degradation.
On the other hand, the no load current at life test start was measured at 100 mA but ended up at 65 mA at the end of the test. This meant that a friction reduction of 35% compared to the starting value was observed while the back-driving torque compared to the starting value was increased by about 10%.

Compared to the standard gear, the no load start up current was lower after the test while the back-driving torque was slightly higher. After gear dismantling, no significant wear or degradation was found.

8. CONDITIONS FOR TEST #1NB/2NB AND #1VB/2VB

We used in the first lifetime phase a climatic chamber with dry nitrogen gas atmosphere.

Both actuators were assembled together inside a stainless steel test setup. The thermal cycling was reduced in the lifetime test from -40°C up to -10°C due to an additional thermistor on the gear head for the actuator flight version. Normally the heater is energized below 0°C so that no negative lubrication effects occur. The stepper motor ran with 3,520 Hz in 1/8 mini step mode (= 440 Hz full step) and produced with the 50:1 ratio a gear shaft speed of 2.64 rpm.

The earlier test setup with a vacuum feedthrough and a hanging mass on a wheel was replaced by a wheel segment directly on the gear shafts. The mass produced a torque preload of 2.0 Nm and a bending moment to the gear shafts. Higher cycle density and test time saving were the reason to reducing the pivoting angle from ±180° to only ±90°.
One operating cycle was now defined:
• one motion cycle correspond to +90 deg rotation, stop time of 500 ms followed by a -90° rotation back to the zero position and a stop time of 500 ms again.

No lubrication cycles were integrated.

Four limit switches were used as emergency stop. 4 k-type thermocouples and two data loggers monitored the temperature (of gear housing, motor-gear flange, rear motor flange and motor windings) continuously with a sampling rate of one minute.

Pre torque tests under ambient conditions showed that approximately 300 mA running current for the cycle operation (corresponding to 50% of nominal current) was needed to lift up the test masses.

200,000 complete (+/-90°) cycles were defined as a goal for the first test phase with a degradation control (starting current) measurement after every 20,000 cycles. Also after every 20,000 cycles the applied external torque direction was changed in order to generate a homogeneous load distribution scenario.

The second test phase (#1Vb/2Vb) under vacuum conditions was performed in a continuous mode without torque load direction change. Our aim was to compare potential wear effects between the two gear flank sides.

Fig. 18 vacuum test chamber

One flank side bore 100,000 cycles under nitrogen conditions while the other flank side saw the same cycles under nitrogen conditions and will see additional cycles under vacuum conditions.

9. TEST RESULT #1NB AND #1VB (HD INDUSTRIAL VERSION)

The life time phase-1 with 200,000 operating cycles (=5.0x10^6 WG rotations) under dry nitrogen conditions and 2.0 Nm preload created nearly no additional internal friction effects.

The definition of the failure criteria (FC) was that if the internal actuator friction increased to >140 mA starting current (no load current), we would stop the test for inspection and further investigations. Lifetime test phase-2 with additional 200,000 operating cycles (=5.0x10^6 WG rotations in total) is now running under UHV conditions and 2.0 Nm preload. 60,000 cycles have been made by the time this report was completed. No critical degradation effects were observed so far. At BOL-1 with MAPLUB PF 101-a we needed approx. 350 mA at 440 Hz full step, 24V to create 4.0 Nm torque at the gear shaft. Under this configuration we achieved a torque constant of approx. 62.5 mA/Nm. Due to the fact that the lifetime test is still running, the EOL-2 measurement with MAPLUB PF 101-b cannot be performed yet to calculate the EOL torque constant. In total the actuator system was submitted in the last years to:

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Rotations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st life time test</td>
<td>3.37x10^6 WG rotations (UHV, MAPLUB PF 101-a)</td>
</tr>
<tr>
<td>2nd life time test</td>
<td>5.0x10^6 WG rotations (dry nitrogen, MAPLUB PF 101-b)</td>
</tr>
<tr>
<td>2nd life time test</td>
<td>1.5x10^6 WG rotations (UHV, MAPLUB PF 101-b)</td>
</tr>
<tr>
<td>Total</td>
<td>9.87x10^6 WG rotations</td>
</tr>
</tbody>
</table>

Fig. 19 internal friction overview (standard)

Please note that this is not the HFUC gear efficiency under load. We saw a running in effect in the first 40,000 cycles followed by a stabilisation process.

Fig. 20 starting/ drop down current values
10. TEST RESULT #2NB AND #2VB (HD SPACE VERSION)

In lifetime phase-1 with 200,000 operating cycles (=5.0x10^6 WG rotations) under dry nitrogen conditions and 2.0 Nm preload created nearly no additional internal friction effects. Please note that this is not the HFUC gear efficiency under load. We saw a running in effect in the first 40,000 cycles followed by a slightly increased friction. In vacuum the internal friction is slightly lower. It is not clear at the moment whether the MoS₂ content in the MAPLUB creates the higher efficiency in vacuum.

11. QUALIFICATION SUMMARY

The actuator life test program was based on torque levels of 57 % of the rated gear torque capability.

It must be clearly understood that the test results show only tendencies and are not in all cases applicable or representative for other applications and conditions.

Wear in the tooth flanks, degradation and consumption of lubrication created over time an increased hysteresis loss. Well documented results exist [7].

The induced stress inside the flex spline increasing with the torque load, caused a torsional deformation (coning effect and torsional deformation = biaxial state of stress). Therefore the flex spline teeth showed a higher axial tilt compared to the tooth flanks of the circular spline which has a much higher stiffness than the flex spline [8].

As a result, a compromise between high flex spline stiffness and high flex spline flexibility has to be found.

We identified that under vacuum conditions the thermal characteristic between a space and an industrial HD gear version was slightly different. Effect based on different materials.

<table>
<thead>
<tr>
<th>Thermal Conductivity</th>
<th>Standard Gear [W/m*K]</th>
<th>Space Gear [W/m*K]</th>
<th>Ratio Compared to Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular Spline</td>
<td>31.1</td>
<td>12…16</td>
<td>45.0%</td>
</tr>
<tr>
<td>Flex Spline</td>
<td>51.9</td>
<td>15</td>
<td>28.9%</td>
</tr>
<tr>
<td>Wave Generator</td>
<td>48</td>
<td>15</td>
<td>31.2%</td>
</tr>
</tbody>
</table>

Fig. 24 different thermal characteristic

Free convection covers this effect under nitrogen.

Further lubrication and/or actuator life tests under vacuum conditions should take the thermally induced load from a motor into account.

Lower heat conductance of the stainless steel gear version creates under identical energy consumption and conditions nearly +4°C (duty cycle ~50%) higher temperature on the motor housing.

The stepper motor rotor and bearing system must operate generally at higher temperature levels in combination with the stainless steel gear unit.
The lifetime impact is still unknown but will be the focus of further investigations.

12. LESSONS LEARNT

Thermal losses inside the motor system and longer duty cycles create higher temperatures in the motor and inside the wave generator under vacuum conditions. Convection in a nitrogen atmosphere does not show this effect in both the standard and stainless steel gears. However, the effect of lower gear conduction of the stainless steel gear has to be especially considered when stainless steel gears are used under vacuum conditions.

An existing lubrication film inside the HD gear is essential but the viscosity of the lubricant can be influenced by the resulting motor temperature.

“Don’t change more than one parameter at the same time...” is a well known wisdom but in reality not always feasible due to the rapidly changing product features.

The internal friction measurement with the starting current under unloaded conditions was a sensitive detection method to see resulting lubrication degradation. Possibly this result does not correspond to the gear efficiency under load.

Gear efficiency measurement (under load) takes the complete wear effects inside the HD gear into account. A finely adjustable constant current driver together with a stepper motor create a sensitive and finely adjustable torque test device.

13. REFERENCES


