ROLLER SCREW LIFETIME UNDER OSCILLATORY MOTION: FROM DRY TO LIQUID LUBRICATION

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Abstract

The increased lifetime demanded of state-of-the-art telecommunications satellites has necessitated the tribological redesign of an electric thruster pointing mechanism which is currently used in-orbit on the scientific ESA telecom satellite ARTEMIS. The change from dry to liquid lubrication will be described and results of in-vacuo tests under oscillatory motion will be presented. The tests were performed both at Austrian Aerospace (Austria) and at ESTL (UK). Results of strip-down inspections will be described and the lessons learned stated.

Introduction

A new mechanism concept was qualified for the European ARTEMIS satellite in 1997 (see references RD1-4), and the two flight models have been successfully operating in space since January 2001. The Ion Thruster Alignment Mechanisms (ITAM) also made a valuable contribution in the incredible recovery of the spacecraft after its wrong orbit placement caused by an Ariane 5 upper stage malfunction.

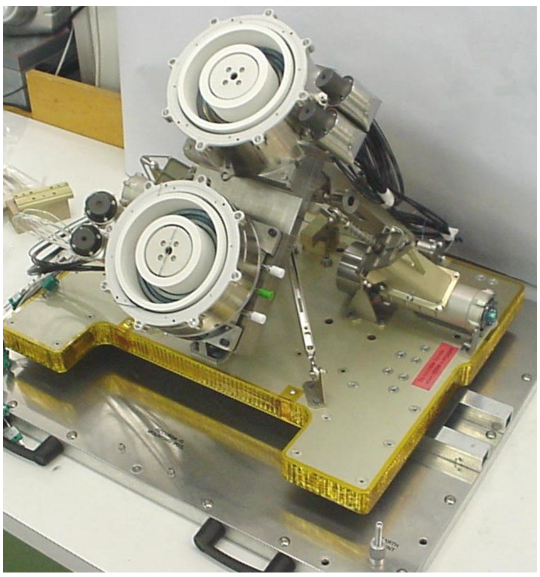

Fig. 1: TPM STM with ROS2000 thrusters

AAE is now engaged in the follow-on development of the ITAM, called the Thruster Pointing Mechanism (TPM, see fig. 1 which presents the structural test model with ROS2000 thrusters mounted to the mobile platform). The TPM will part of the Alternative Thruster Module Assembly (ATMA) of the Eurostar-3000 commercial telecommunications satellite. This activity is a joint effort between ASTRIUM SAS, ESA and AAE.

Design Description

For a detailed mechanism description please refer to RD2-4.

The tribologically critical and lifetime limiting item of the mechanism is the Drive Unit (DU, a dummy is represented in fig. 1, a section is shown in fig. 2).

Two Drive Units are required for one pointing mechanism, in order to operate the two DOF´s of the Platform. Each Drive Unit (see fig. 2) consists of the following main components:

- Spindle-Nut Unit (1), Recirculating roller screw 8x1 mm, hard preloaded, material AISI440C, supplier Transrol/SKF
- Spindle Bearings (2)
- Gimbal Joint (3)
- Coupling (4)
- Stepper Motor (5)
- Limit Switches (ITAM) / Hall Sensors (TPM)

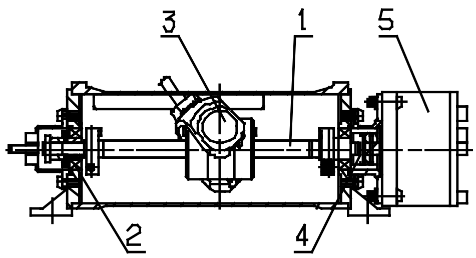

Figure 2: Drive Unit Assembly

A preloaded Recirculating Roller Screw (RRS) has been selected to transform the rotational motion of the stepper motor into linear motion. The RRS is "hard" preloaded to avoid backlash, which is acceptable for this application because isoexpansive materials are used for spindle, rollers, nut and housing.

One pair of spring preloaded angular contact ball bearings is used for support of the spindle. The actuating stepper motor and the gimbal joint feature angular contact ball bearings as well, all bearings are manufactured from stainless steel AISI440C.

Dry Lubrication

A dry lubrication concept was selected for the ARTEMIS mission because of moderate lifetime requirements. The RRS was coated with sputtered MoS_2 (on all involved parts: spindle, rollers, housing) to achieve minimal friction and the bearings were lubricated with ion plated lead (coated races and lead-bronze cage). Both lubricant coatings were applied by ESTL.

The successful ITAM qualification thermal vacuum life test performed in 1995 comprised 15000 movements (= 7500 cycles and 12840 degree total path) of the spindle over 4 revolutions each, performed around a fixed position on one spindle, and performed at –50°C and +70°C. The worst case load originated by harness and piping was applied on the movable platform via a dummy spring.

New (confidence) tests have now been performed with a dry lubricated flight spare spindle and bearings integrated into the ITAM QM (on loan from ESTEC, test-setup see fig.3, original actuator with 100 steps/rev used, step frequency 12 Hz), in order to get an impression of the maximum lifetime capability of this lubrication system. Representative loading was achieved via a dead-weight mounted to the movable platform, which is equivalent to a 5 Nm resistive torque to be actuated by the mechanism. This resulted in an axial load of 20 N and a radial load of 24 N acting on the roller screw nut.

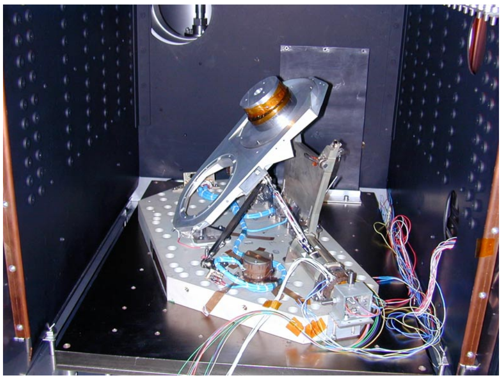

Fig. 3: Life Test Setup with ITAM QM

One cycle was defined to be as ± 0.96 rev of the roller screw. Intermediate cycles of ± 3.6 rev were performed every 200 cycles to simulate referencing or large thruster movements.

It should be pointed out that there is no "invariant point" when using a roller screw, because the roller length is 20 mm for our size, and moving an invariant (fixed) point for e.g. 1 mm still accumulates the lifetime on the same location of spindle, rollers and nut. There is only a very small part of the "new" spindle that is used when moving the fixed point, all other parts are accumulating the revolutions.

The test was performed in two parts, the first part from 0-37500 cycles with a radial screw load of 9 N and around one fixed point, the second part from 37500-61600 cycles with a radial load of 24 N and 1 mm away from the first spindle point.

The following figure presents the test result, which is the sum of the friction torques of the Drive Unit, consisting of the roller screw friction and of the spindle and motor bearing friction. Although no discrimination between ball bearings and spindle could be made in this set-up, calculations from unit level tests showed that 70% of the friction originates in the RRS. The torque was monitored through measurement of the motor current.

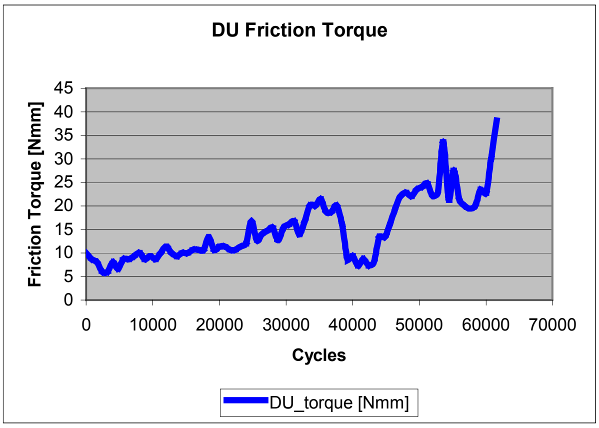

Fig. 4: Dry lubrication lifetime test with ITAM DU

A run-in effect within the first 2000 cycles could be observed. Following the load increase and position change a temporary recovery of the friction torque could be observed, with a continuation at roughly the same magnitude as for the first run.
The test was stopped at 61600 cycles because of clear indications of end-of-life of the lubricant (EOL torque > 3x initial torque, loss of actuator steps, destructive trend).

A subsequent strip-down inspection of roller screw and bearings showed the following:
Roller Screw: increased lubricant wear was detected on the used surfaces of spindle, rollers and housing, no metallic wear could be observed. The inspection was performed by the supplier Transrol/SKF.

Fig. 5: Roller screw spindle: used area

Spindle Bearings: we detected two interrelated misbehaviors there, one was the interaction between the bronze bearing cage and the surrounding structure, and one was related to chatter marks on the bearing races. Both of these problems were caused by inappropriate design tolerances of the drive unit parts, and the chatter marks were estimated to be caused by the cage contact to the housing. The bearing inspection was performed by ESTL.

Fig. 6: Bearing race, chatter marks

As there was still lubricant on all bearing parts and because of the dominance of the roller screw friction the latter was mainly responsible of the rapid friction increase leading to the test termination.

As the achieved lifetime did not satisfy the required E3000 lifetime requirement it was decided to change to a grease lubrication system.

Liquid Lubrication

A detailed trade off has been performed in order to select the most appropriate liquid lubricant, the main selection criteria, besides temperature / evaporation / heritage, was the high lifetime demand of > 300,000 oscillatory (low amplitude) cycles.
The selected system was a MAC (multiply alkylated cyclopetane) grease with PTFE and MoS_2 additives. Its synthetic hydrocarbon base oil was used for impregnation of the phenolic bearing cages.

PFPE (perfluoroalkylpolyethers) based products were not chosen because of their tendency to degrade when used on steel components operating under boundary lubrication over long periods (catalytic attack) .

The DU was redesigned to get a "sealed" concept by introducing labyrinth seals in order to minimise loss of evaporated oil over the long lifetime (16 years) of E3000 missions. The tolerance concept was updated. The movable strut exit was closed via a sliding plate in favour of a flexible bellows because of torque and fatigue issues (sketch see fig. 7):

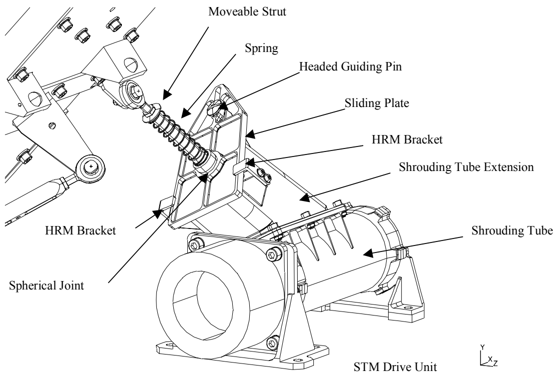

Fig. 7: New DU concept with labyrinth seals

The grease confidence tests performed were twofold:
1. In-vacuo parameter testing of the RRS alone at the application temperature extremes of –25°C and +40°C to get the required data for the DU actuator dimensioning (see fig. 8)
2. In-vacuo lifetime testing of the Drive Unit (RRS + Bearings) at ambient temperature and in a dedicated test set-up (see fig. 11)

<u>Results of ESTL Roller Screw Parameter Testing:</u>
Measurement of peak and running torque over one cycle (2 revs ccw; 2 revs cw) at speeds of 1, 50 and 100 rpm and –25°C / ambient / 45°C were performed.

At the higher speeds of operation examined (50 and 100 rpm) the torques increase appreciably as the temperature decreases below 15°C and achieve their highest values at the lowest temperatures examined (-23°C).

In contrast, tests performed at 1 rpm indicate that the torque sensitivity to temperature and viscous effects is much less, indeed the plot of mean torque as a function of temperature is essentially uniform.

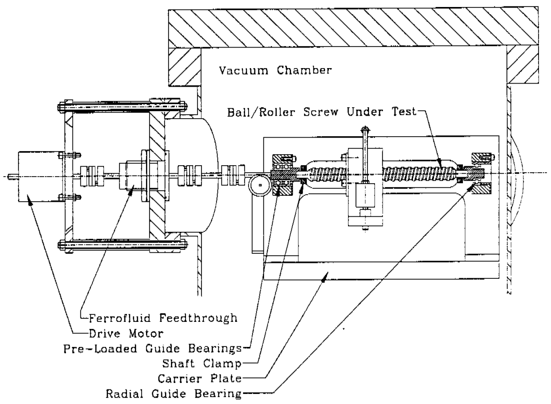

Fig. 8: ESTL screw test facility

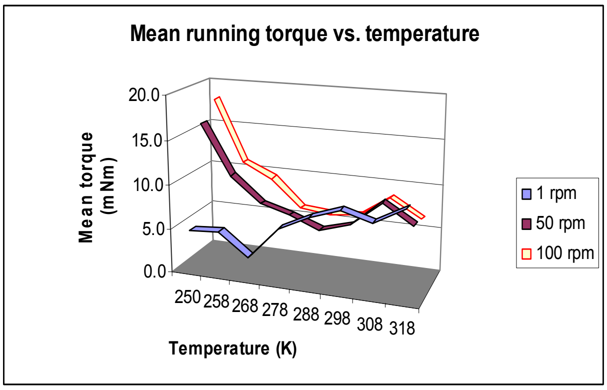

Fig. 9: RRS mean torque as a function of temperature and speed (ESTL)

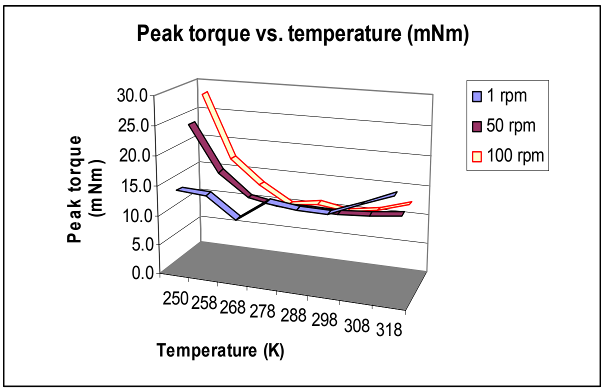

Fig. 10: RRS peak torque as a function of temperature and speed (ESTL)

Results of AAE Life Testing:

It was required to perform 7 x 42600 cycles for ±0.5 rev at 7 fixed spindle positions and at a distance of 0.41 mm between each other, which yields a total number of 298,900 cycles. The RRS nut loading was 20 N in axial and 24 N in radial direction. A representative actuator was used with 24 steps/rev, driven at 5 Hz step frequency.

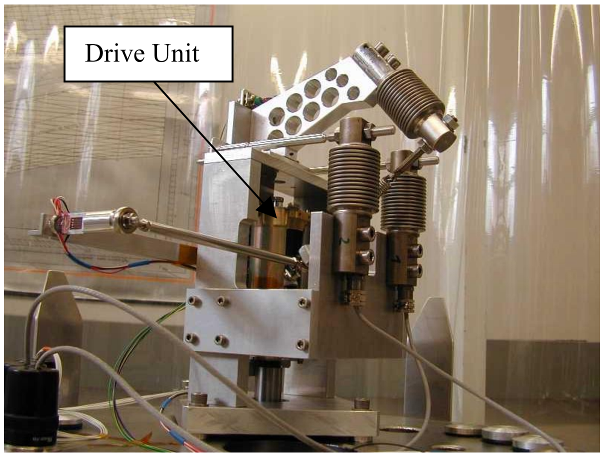

Fig. 11: DU life test setup (to be put in TV chamber)

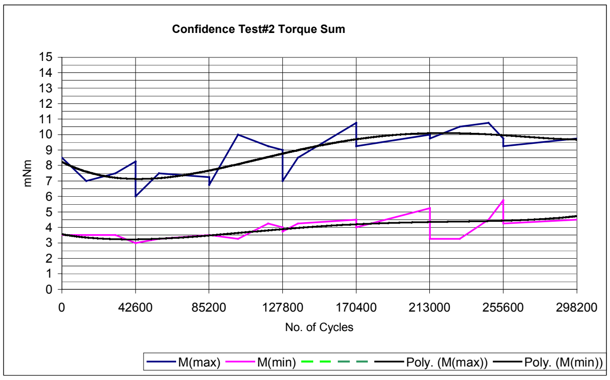

Fig. 12: DU min and max torque (ambient, up to 300000 cycles)

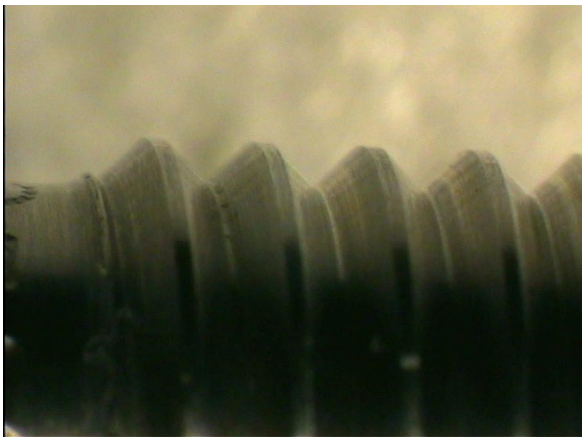

Fig. 13: Close up of cleaned screw, post test inspection

The overall conclusion from the tests performed at AAE and ESTL were:

1. The AAE and ESTL tests are considered fully successful and the TPM Drive Unit lubrication system is considered suitable for the increased

lifetime demand of 300,000 cycles and corresponding cycles definition. There were no signs of end-of-life.

2. At low speeds no temperature dependence of the friction torque could be detected for the chosen lubricant grease. However, at higher speeds and cold temperatures (only!) significant viscous torque effects could be seen
3. The ESTL tests showed in general slightly higher torques than those measured by AAE, which is assumed to be caused by the different test set-up design.
4. The strip-down inspection performed on the tested tribological items showed no anomalous wear.

Lessons Learned

The main lessons learned from this effort are:

- The life of sputtered MoS_2 on axially and radially loaded rollers screws may be insufficient for medium-to-high-duty applications. Where practicable, always carry out life checks on individual tribo-components prior to sub-assembly level tests.
- Carefully interpret torque plots from roller-screws because of the efficiency change in back-driving mode
- Should be obvious, but is often underestimated: Do not forget to perform worst case tolerance analyses to avoid misbehavior of high precision bearings.

Conclusion

The Thruster Pointing Mechanism for Eurostar-3000 has been successfully qualified to the increased lifetime demand of 300,000 cycles via modification to grease lubrication. The CDR of the TPM project is currently foreseen to be held by end of 2003.

Acknowledgement

We gratefully acknowledge the joint effort of ASTRIUM SAS and ESA/ESTEC for the continued support of the TPM qualification for Eurostar-3000.

References

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Back to Contents