HEXAPOD / SAGE III ROLLER SCREWS LIFETIME AND LUBRICATION TESTS

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ABSTRACT

This paper reports on the results of a lifetime and lubrication test campaign performed to develop a novel pointing system (Hexapod Pointing System) for an experiment (Sage III) located on the International Space Station main truss.
The rationale for this test campaign is the lack of information on roller screw mechanism performances and lubrication behavior for vacuum exposed long mission, where no maintenance is foreseen.
The tests were made on three different types of roller screws, wet lubricated by Braycote 601 grease applied after lead ion plating surface coating.
The tests addressed the screw selection in terms of lubrication and pre-load behavior, accuracy, efficiency to get indications of roller screws performance degradation due to launch load patterns and to their operative life.
The test campaign results demonstrated that all the screws could be successfully implemented and highlighted the best performances achieved by the soft pre-loaded screw.

1. INTRODUCTION

The Hexapod Pointing System (HPS) is intended to provide a stable nadir pointed platform to the NASA instrument Sage III. The Stratospheric Aerosol and Gas Experiment III (SAGE III) is a remote sensing instrument developed by NASA Langley Research Center for monitoring global distribution of aerosols and gaseous constituents of the Earth atmosphere by using the solar occultation approach. The HPS / Sage III will be carried on one Express Pallet Adapter (ExPA) Nadir oriented payload accommodation facility, located on the Integrated Truss Assembly of the International Space Station (ISS). The core of the HPS positioning/pointing mechanism is made by six electromechanical linear actuators disposed as three trapezoids between two reference planes, indicated as the lower and the upper platforms. The lower platform is fixed to the ExPA and the position and the attitude of the upper one is defined by the lengths of the six linear actuators.

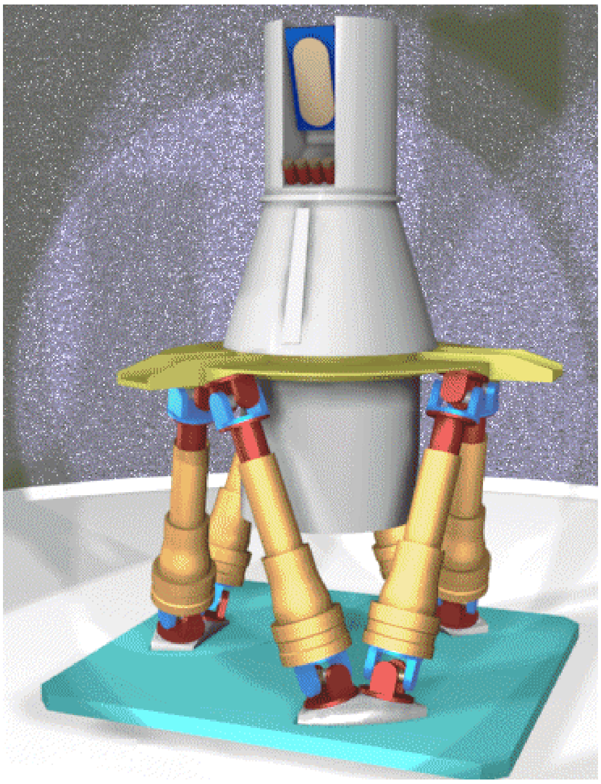

Figure 1. Hexapod / SAGE III layout.

The HPS includes an external off-loading device designed to partially support the launch loads, thus optimizing the actuators performances for on-orbit environment. The control and pointing function are powered and commanded by an electronic subsystem, the Hexapod Control Unit.
The Hexapod Pointing System is a project developed under an ESA contract, with the involvement of Alenia Aerospazio (as prime contractor) and Carlo Gavazzi Space, with the participation of ADS International and AEA/ESTL to these lifetime tests activity.

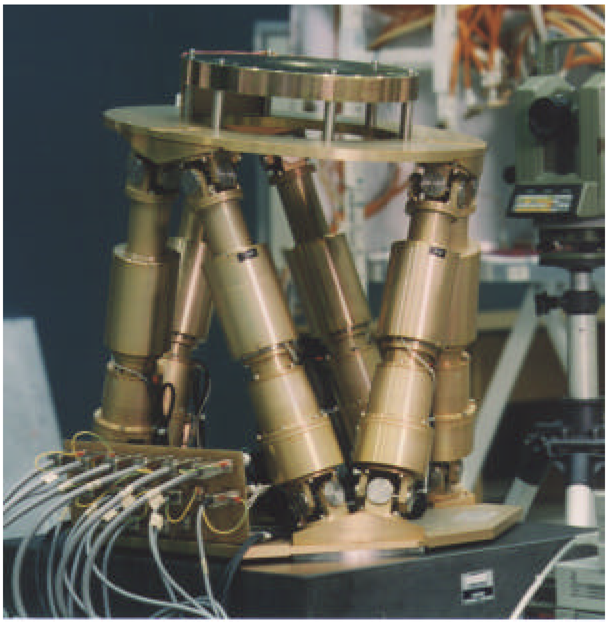

Figure 2. Hexapod Development Model.

1.1 Scope of the test

As already identified in the previous phase of the project (namely pre-phase B), the linear actuators lubrication selection is an important design issue in order to achieve the required on-orbit performances.
During phase B some investigations have been carried out to identify a lubrication method for the HPS flight unit. Nevertheless, a lifetime lubrication cycling development test has been planned to support the choice of the most suitable lubricant for the roller screws (with associated pre-load) and to identify potential performance degradation caused by 5 years of operation.
Dry lubricants have not been selected on the base of Alenia and ESTL previous experiences.
The wet lubricant, already used for space applications, selected for Hexapod linear actuators is:

- BRAYCOTE 601 CASTROL Grease (operative temperature range -80/+200 °C) composed by BRAYCOTE 815Z (basic fluid) and PTFE (gelling agent) applied to a roller screw made of AISI 440C after lead ion-plating surface treatment.

The scope of the random vibration and lifetime lubrication tests can be summarized in the following points:

- to address the screw selection in terms of lubrication and pre-load behavior, accuracy and efficiency;
- to get indications of possible roller screws performances degradation due to launch load patterns;
- to get indications on the lubricated and coated roller screw performances degradation over their operative life.

2. ACTUATOR ROLLER SCREW

Two kinds of roller screws with different pre-load application were identified in phase B as candidate for the HPS linear actuators:

- planetary roller screw with hard pre-load application (RV hard);
- planetary roller screw with soft pre-load application (RV soft);
- re-circulating roller screw with soft pre-load application (RVR soft).

All these roller screws were manufactured by Rollvis SA (Geneve, Swiss) to be fully representative of the flight model.

2.1 Screws Test Activities

The roller screws overall activities performed can be summarized as follows:

- screws manufacturing (at Rollvis premises);
- ion-plated lead application on all roller screw components (at ESTL laboratory);
- screws integration and lubricant application (at Rollvis premises, under ESTL supervision);
- acceptance test execution (at Rollvis premises);
- random vibration test execution (at Alenia laboratory);
- functional test execution (at Rollvis premises);
- thermal vacuum lifetime test execution and subsequent high level inspection (at ESTL laboratory);
- final functional test execution (at Rollvis premises).

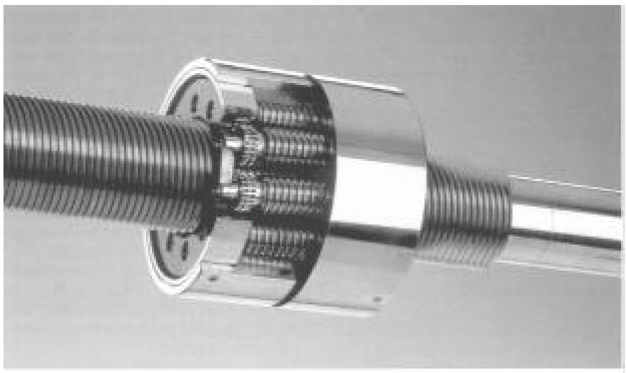

Figure 3. Satellite Roller screw sample.

2.2 Random Vibration Test Level

A text fixture has been manufactured to simulate the boundary and loading conditions that will be experienced by the single actuator during the launch phase.

First bending frequency	FEM predicted on F.U.	Fixture predicted (by analysis)	Fixture characteristics
Axial	57 Hz (without actuator axial stiffness)	140 Hz (including actuator axial stiffness)	292.3 Hz
Radial	50 Hz	50 Hz	48.9 Hz

The calculated fixture stiffness is:

$$k_{AX} = 6 \text{ N} / \mu\text{m}$$
$$k_{LAT} = 5.5 \text{ N} / \mu\text{m}$$

The qualification spectrum level was derived from the applicable document to the Sage III/Hexapod/ISS and was applied to each screw during the random vibration tests.
Each test lasted 180 sec. The random vibrations were applied along Z axis (axial) and X axis (radial).

Figure 4. Random vibration test fixture.

The qualification spectrum level used for the tests is defined by:

Frequency (Hz)	Level
20	0.01197 g²/Hz
20 – 111	+ 6 dB/oct
111 – 400	0.03991 g²/Hz
400 – 2000	- 7 dB/oct
2000	0.00469 g²/Hz
Composite	6.73 g (rms)

The qualification spectrum level is defined as acceptance spectrum + 3 dB.

2.3 Lifetime and Cycling requirements

The Hexapod lifetime assumed for these tests is 5 years on-orbit operation. The predicted number of cycles is derived from the operational modes of the Hexapod (pointing operation).

The basic assumption is that for 90% of the pointing operations the Hexapod rotates by 1 deg., while for the remaining 10% actuations the Hexapod changes the attitude of the sensor assembly by 2 deg.
Considering the possibility to have also “offset corrections” maneuvers, we assumed 20% increment of the number of pointing cycles on a reduced stroke. It is considered that the offset corrections are in the order of arcmin range.
Each orbit offers 2 events (sunrise and sunset), approx. 15% of the orbits offer a lunar event and approx. 1% of the orbits offer a moonrise and moonset event.

Events per orbit:	2.17 (2 solar events, 0.17 moon events)
Orbit per day:	16
Total orbits: (over 5 years)	16 · 300 **(*)** · 5 = 24,000
Pointing events:	2.17 · 24,000 = 52,080
Ground testing: (estimated value)	5,208 (equivalent to 10% of flight actuations)

(*) Total Sage III not operative period (due to Shuttle docking, ULC, reboost, Progress/Soyuz docking):
325 days in 5 years = 65 days per year

The 90% of the lifetime cycling were performed with 4 mm elongation in the two directions to simulate the 1 deg. Rotation. The remaining 10% were run with a 8 mm elongation in the two directions to simulate the 2 deg. rotation.

Some actuations were performed in ambient conditions to simulate ground operations occurring before launch, while the remaining were run in thermal vacuum (on-orbit simulation).

The number of actuations to correctly simulate the linear actuators life cycle are calculated in accordance to ESA applicable document (ref.2).

Predicted cycle	Factor **(#)**	Life test cycles
Ground testing		
Actuations: 5,208	5,208 · (4)	20,832
On-orbit		
Actuations: 52,080		
1 to 10 actuations	10 · (10)	100
11 to 1,000 actuat.	990 · (4)	3,960
1001 to 100,000 actuat.	51,080 · (2)	102,160

		127,052
Total operative pointing actuations		130,000

3. TESTS RESULTS

First of all, it must be outlined that all the three screws passed successfully the entire test campaign without evidence of major degradation or sign of significant damages.
From a lubrication point of view, there was no evidence of lubricant degradation and sufficient lubricant remained for continued operations.
The choice of the ion-plated lead with Braycote 601 grease as been shown to be acceptable under the thermal vacuum test conditions applied.

3.1 Acceptance Tests

The Acceptance Tests performed at Rollvis premises after lead ion plating application and lubrication certified that the screws were within the specified requirements in terms of static accuracy, torque value, pre-load (backdriving measure), stiffness and dynamic accuracy.

3.2 Random Vibration Test

The Random Vibration tests, performed at Alenia Spazio premises in Torino, had been executed with an increment of the PSD (in axial direction only) of about 20% with respect to the predicted one, being however more conservative than the specified excitation.
The effect of exposure to random vibration was measured by comparing the screws responses to low level harmonic vibrations before and after the random vibration sequence.
The results did not point-out any measurable effect due to the random sequence.

3.3 Functional Tests

After the random vibration tests, the functional tests were repeated at Rollvis premises. The results hereafter reported have to be compared to the acceptance tests ones.

- Planetary roller screw with soft pre-load did not show any decrease of the minimum backdriving load (150 N), while the average value reduced from 327 to 187 N. The friction torque decreased by 20% (maximum value) and by 15% (minimum value). For what concerns the dynamic accuracy a slight decrement had been highlighted (about 20%).
- Planetary roller screw with hard pre-load showed a reduction of the minimum backdriving load value from 150 to 100 N, while the average value went from 189 to 131 N. The friction torque value decreased by 40% (maximum value) and by 20% (minimum value). For what concerns the dynamic accuracy no significant variations had been pointed-out.

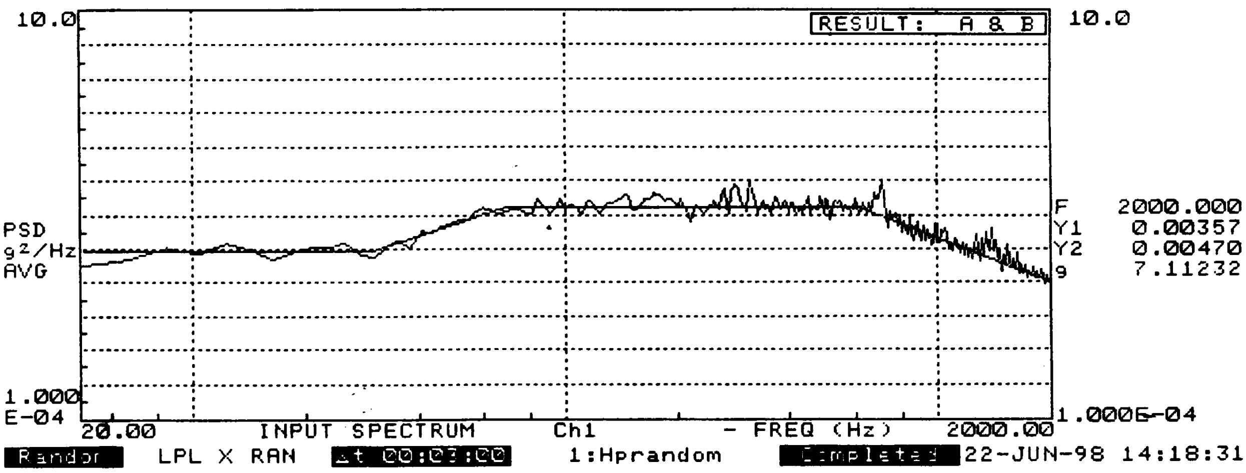

Figure 5. Random Vibration spectrum on the planetary soft preloaded screw.

- Recycling roller screw with soft pre-load did not showed any decrease in the minimum backdriving load (150 N), while the average value decreased from 250 to 215 N. The minimum friction torque value increased by about 10%, while no change on maximum value was observed. For what concerns the dynamic accuracy a slight increment had been highlighted (about 15%).

3.4 Thermal Vacuum Lifetime Tests

The activities relevant to thermal vacuum life-time, performed at ESTL laboratory, highlighted the following results:

- all three screws survived the test campaign;
- the hard pre-loaded screws lost some part of the pre-load due to wear in the initial vacuum test phase;
- there was no significant difference between the performance of the soft pre-loaded screws;
- both soft pre-loaded screws had pre-load remaining on completion of the test;
- the lubrication system showed no signs of degradation throughout the test.

Figure 6. Thermal-Vacuum chamber at ESTL.

3.5 Final Functional Tests

The execution of the final functional tests, performed at Rollvis premises, showed the following changes:

- Planetary roller screw with hard pre-load showed a decrease in the minimum backdriving load from 100 to 50 N and from 131 to 50 N (average value). The maximum friction torque value decreased by about 10% and the minimum one by 40%. For what concerns the dynamic accuracy a slight decrement has been highlighted (about 10%).
- Planetary roller screw with soft pre-load did not show any decrease of the minimum backdriving load (150 N), while the average value reduced from 187 to 169 N. The maximum friction torque value decreased by 20% and the minimum one value by 20%. For what concerns the dynamic accuracy a slight increment had been observed.
- Recycling roller screw with soft pre-load did not showed any decrease in the minimum backdriving load (150 N), while the average value reduced from 215 to 185 N. The maximum friction torque value decreased by 40% and the minimum one by about 35%. For what concerns the dynamic accuracy a slight decrement has been showed (less than 5%).

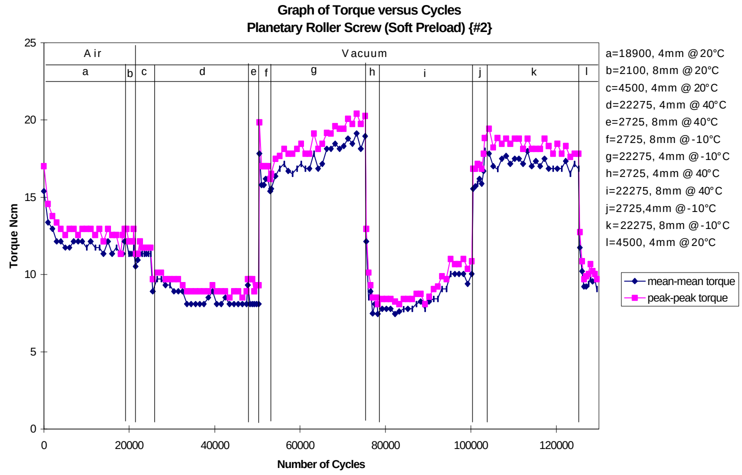

Figure 7. Torque vs cycles during thermo-vacuum test.

3.6 Final Evaluation

The results of the entire tests campaign can be summarized as follows:

- Planetary roller screw with hard pre-load showed a decrease of the minimum backdriving load from 150 to 50 N and the average value went from 189 to 50 N. The maximum friction torque value decreased by about 45% and the minimum by about 60%. For what concerns the dynamic accuracy the decrement showed is about 25%.
- Planetary roller screw with soft pre-load did not pointed-out any decrease of the minimum backdriving load (150 N), while the average value reduced from 327 to 169 N. The maximum friction torque value decreased by about 40% and the minim one value by about 40%, too. For what concerns the dynamic accuracy the decrement showed is about 10%.
- Recirculating roller screw with soft pre-load did not pointed-out any decrease in the minimum backdriving load (150 N), while the average value reduced from 250 to 185 N. The maximum friction torque value decreased by about 40% and the minimum one by about 20%. For what concerns the dynamic accuracy the increment showed is about 15%.

The results can be summarized in the following table:

Tests performed	Type of screws	Acceptance test (before random vibration tests)	Acceptance test (after random vibration tests)	Final Functional test (after lifetime tests)
Backdriving test	RVR (soft)	> 150 N (min)	> 150 N (min)	> 150 N (min)
	RV (soft)	> 150 N (min)	> 150 N (min)	> 150 N (min)
	RV (hard)	> 150 N (min)	> 100 N (min)	> 50 N (min)
Torque without load test	RVR (soft)	~ 8.85 N·cm	~ 9.65 N·cm	~ 5.9 N·cm
	RV (soft)	~ 9.35 N·cm	~ 7.0 N·cm	~ 5.45 N·cm
	RV (hard)	~ 10.3 N·cm	~ 6.75 N·cm	~ 4.95 N·cm
Dynamic Accuracy test (displacement accuracy)	RVR (soft)	11.3 µm (max)	9.0 µm (max)	9.4 µm (max)
	RV (soft)	6.1 µm (max)	7.8 µm (max)	7.5 µm (max)
	RV (hard)	7.1 µm (max)	7.3 µm (max)	8.5 µm (max)

4. CONCLUSIONS

The results of these lifetime and lubrication tests had been used as guidelines for flight unit screws selection.
It must be outlined that all the three screws passed successfully the entire test campaign without evidence of major degradation or signs of significant damages. For what concerns the remaining pre-load after the lifetime test, the only screw that does not satisfy the minimum pre-load specification is the RV with hard pre-load.
From a lubrication point of view, there was no evidence of lubricant degradation and sufficient lubricant remained for continued operations. The choice of the ion-plated lead with Braycote 601 grease has been shown to be acceptable under the thermal vacuum test conditions applied.
The planetary roller screw with soft preload was chosen as baseline for Hexapod Flight Unit design.

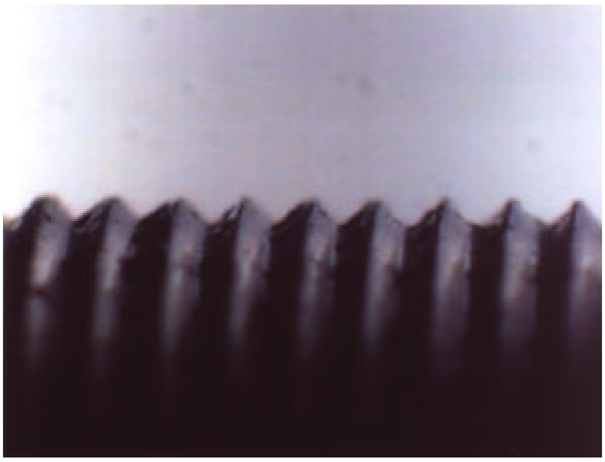

Figure 8. Planetary screw profile after tests.

Figure 9. Planetary screw profile after tests (detail of the grease at stroke limit).

Such screw gave the best performances from a dynamic accuracy point of view in terms of relative and absolute values.
The reduction of the preload measured after the test execution does not imply particular concerns during re-entry and landing phases. In fact, the backdriving load value remained always above the minimum value specified for such conditions.

5. REFERENCES

1) Hexapod Pointing System - Random Vibration and Lifetime Tests Report Data Package, HEX-ED-AI-0004, 30.10.1998.
2) Mechanical Engineering of Space Programs; ECSS-E-30-00 Issue 2