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A COMPARISON OF THE PERFORMANCE OF LINEAR BALLSCREW DEVICES WHEN LUBRICATED WITH DRY AND LIQUID LUBRICANTS IN VACUUM

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ABSTRACT

ESTL has been performing a number of comparative tests in order to understand the performance of linear actuator devices in vacuum. These tests were performed in a newly designed test facility, and commenced with a series of comparative tests on ballscrews. Various space lubricants were employed and the results compared. A subsequent test on a hard preloaded ballscrew has shown the difficulty in maintaining hard preload for long periods in vacuum.

Currently tests are being performed on the roller screw devices and some simple tests are also planned for plain screws as a comparison.

These tests have shown that all the lubricants tested to date cannot prevent wear of the leadscrew, which has implications for hard preloaded systems.

1. INTRODUCTION

ESTL has been aware for some time that many applications are planned in Europe using linear actuators like ballscrews and rollerscrews, but that their performance in vacuum with the standard lubrication techniques has not been well investigated. This paper reports on a programme of work aimed to redress this balance.

Following the design of a dedicated flexible test facility, ESTL has first investigated ballscrews and is currently engaged on a programme looking at roller screws, of both the recirculating and planetary types, and plain screws.

2. TEST FACILITY

A General Assembly drawing of the test facility as configured for this test campaign is attached as Figure 1. The ballscrew is supported horizontally at either end in a bearing housing. At the drive end are a pair of preloaded bearings, whilst a radial bearing supports the far end. The leadscrew is rotated via a ferrofluidic feedthrough by a computer controlled 25,000 step per rev motor mounted outside the 40cm diameter vacuum chamber. The stepper motor works in open loop mode, with no linear positional feedback from the ballnut position.

The ballnut is carried in a yoke, see section, and the reacted torque is through a radial bearing into a close fitting slot in the main housing. The force (torque) is measured by a Kistler load washer mounted in line directly below the bearing. Applied axial load (not shown) is a deadweight hung from two steel wires connected to the ballnut yoke. The wires pass through holes in the support bearing housing and pass over two Vespel bushes/pullies to hang down the side of the vacuum chamber. Radial load can be applied to the ballnut by hanging weights directly from the yoke on the ballnut centreline.

The test is automatically controlled by a stepper motor drive indexer board mounted in a personal computer, which at a regular interval (currently 2,000 cycles) switches on a chart recorder to record five cycles of torque reaction force data.

One of the interesting and challenging aspects of this test rig has been location of the zero position on the torque trace, often difficult especially when using a piezo force transducer. For the ballscrew tests described here it was found that the counterbalance weight had to be mounted between the nuts on the upper length of threaded bar (top of section) and positioned such that the torque induced by the load deadweight at the lead angle of the screw is effectively nulled. In this manner the torque reacted when the load is lifted is measured correctly, since when the load is falling the ballscrew is following and requires zero torque to operate (i.e. without the motor the ballscrew cannot hold the weight and the system backdrives.)

3. TEST BALLSCREW

The ballscrew chosen for this series of tests is manufactured by RMB of type ED822X/V801X-J903/2 DRY. This ballscrew is manufactured to "space" standards from 440C stainless steel and utilising space compatible adhesives. Table 1 shows the size details of the ballscrew as taken from the catalogue:-

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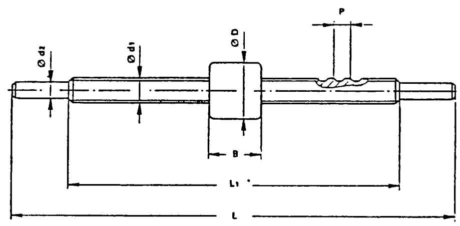

Nut	D	22 mm	B	18 mm
Balls	Ø	1.588 mm		
Screw	d_1	10.5 mm	P	2 mm
	d_2	8 mm	L	190 mm
	L_1	150 mm		
Static Load Ratings	Radial	147 N	Axial	559 N

Table 1.
Details of RMB type ED822X/V801X Ballscrew.

All ballscrews were supplied dry, precleaned and with a working clearance of up to 5 µm (i.e. no internal preload). The maximum pitch variation is given as 5 µm per 25 mm length.

4. LUBRICANTS

Six ballscrews have been tested under this work package, lubricated with various space lubricants, as shown in Table 2 below:-

Lubricant Type	Quantity/Thickness
Fomblin Z25 Oil	**80µl**
Braycote 601 Grease	**0.75 cc**
Pennzane SHF X-2000	**500µl**
Sputter Coated MoS_2	1**µm**
Ion-plated Lead	1.5**µm**
Braycote 601 + Ion-plated Lead	1cc + 1**µm**

Table 2.
Table of Lubricant Types Tested.

The two dry lubricant coatings were applied by ESTL, to standard procedures, without removing the ballnut. The nut was parked at one end of the leadscrew, and coating applied to the leadscrew in two stages by rotating the assembly through 180° between coating runs. No attempt was made to coat either the internal surfaces of the ballnut or the balls. All testing was subsequently performed in the coated region of the leadscrew. Note that an increased amount of the Pennzane oil (Nye oil type 2001A, i.e. without additives) was used compared with the PFPE oil, since on first running it did not maintain its position on the ballscrew tenaciously and was thrown clear as the ballscrew motion reversed.

5. TEST CONDITIONS

For the endurance testing, each ballscrew had a deadweight axial load of 70N applied to the ballnut housing. Starting from an initial zero position, the cycles listed in Table 3 were performed in the sequence shown:-

Axial Stroke	*Rotations*	*Quantity*
80 mm	40	250,000
40 mm	20	750,000
8 mm	4	1,000,000
	Total Return Strokes	2,000,000

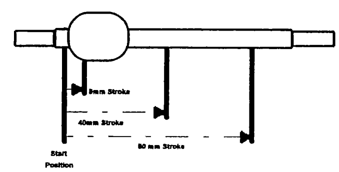

Table 3.
Table of Motion Profiles & Stroke Quantities.

The motion profile is trapezoidal, running at a maximum speed of 20 rps and accelerating/decelerating at 200 rps^2 (with the exceptions of the ion-plated lead coated ballscrew which ran at 10 rps and 100 rps^2 and the Braycote 601 lubricated ballscrew which ran at 20 rps and 100rps^2).

All tests were conducted at vacuum pressure levels starting at $<10^{-6}$ mbar and reducing during the test period to around 2×10^{-7} mbar. The temperature of the test facility was laboratory ambient of 20±2°C. A typical test would take about eight weeks to complete given no operational problems.

6. TEST RESULTS

The PFPE oil and the related grease product were inadequate in that they degraded by polymerisation after a limited number of return strokes (60-70k). The use of the synthetic oil Pennzane SHF X-2000 has been shown to be an option for extended duration running by completing the test sequence, however there has been wear of the loaded flanks of leadscrew. It should also

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be noted that this oil does not tend to "cling" in the same manner as the PFPE variants, hence the application in this test of a significantly larger quantity of this oil.

The two dry lubricants tested gave surprising results, perhaps implying that there is more sliding occurring in these tests than the expected rolling motion. The use of ion-plated lead alone proved inadequate, failing after 400k return strokes, whilst the MoS_2 sputter coated ballscrew survived the full test campaign of 2 million strokes, however it should be noted that there was polishing of the loaded contact zone . It should also be remembered that very limited amounts of in-air running were performed with both these samples, and that the influence of this aspect would need to be investigated thoroughly prior to selection.

The use of an ion-plated lead "barrier" coating applied to the leadscrew prior to lubrication using Braycote 601 proved a success, reaching the full test requirement of 2 million return strokes. This performance clearly demonstrates the synergistic effect of combining these two techniques, far outstripping the performance of either technique in isolation.

7. SURFACE PROFILOMETRY

Some comparative data has been obtained from a UBM laser profilometer regarding the surface finish on the flanks of some of the leadscrews. Three sets of plots are shown in Figure 2. Each plot is of the surface finish along a distance of about 0.6mm, starting from near the tip of leadscrew on the right and going down towards the root on the left. The upper plot shows a height profile from an as supplied ballscrew. Note that the surface finish is not particularly good when compared with a ball bearing and equates to an Ra value of ~0.8µm. The two lower plots are taken from the ion-plated lead ballscrew and the sputter-coated MoS_2 ballscrew. Each plot is in two sections, the upper shows a reflectance value for the laser signal, and clearly shows the dark MoS_2 in place apart from in the contact zone around the 0.4-0.5mm position of the traverse. The lower plots in each case show the measured height profile. For the MoS_2 there is a trough of up to 2µm deep where the MoS_2 has presumably been removed, whilst the ion-plated lead screw shows a similar trough but with a built-up ridge of debris to either side. Further profilometer measurements have not been taken at this stage.

8. PRELOADED BALLSCREW

Following the study on the relative performance of six different lubricants on un-preloaded ballscrews, ESTL tested the performance of a preloaded recirculating ballscrew lubricated with ion-plated lead and Braycote 601 grease.

The ballscrew was again supplied by RMB of type reference ED822X/V801X-P/7000-J374..J903/2-J613/-DRY. The ballscrew was identical to the initial tests except that an internal preload was incorporated set to 70 N to allow a direct comparison with the external loads applied by ESTL in the previous ballscrew tests.

With no external loads applied, the ballscrew completed a total of 940,000 return strokes, 250,000 return strokes of 80mm and 690,000 return strokes of 40mm, before the test was halted. After starting at an initial torque of 250 gmcm, the torque fell off rapidly to 50 gmcm after 30,000 return strokes as the preload was removed due to the wear/polishing action (see Figure 3). On removal from the test chamber the ballscrew was still smooth when rotated by hand. No deterioration in the lubricant was observed. Based on the previous test results it can be concluded that the ballscrew would have completed 2 million return strokes without subsequent degradation of the lubricant, especially with the preload effectively removed.

This test has shown that the use of preloaded ballscrews in vacuum is not acceptable since wear of the system components rapidly removes the preload, however should preload be required only during the launch phase, for stiffness purposes, then this approach could be successful. Precautions are required however to show that on-ground testing, particularly in vacuum, has not effectively removed the preload prior to launch.

In order to assess the amount of wear on the ballscrew some comparative data has again been obtained from a UBM laser profilometer reading of the surface finish on the flanks of the leadscrew. Figure 4 is of the surface finish along a distance of about 1.0mm, starting from the root of the leadscrew on the left and travelling over the loaded flank to the right. The edge of the flank is defined by the change in slope of the plot at about 0.5 mm. Figure 5 shows the same plot but the area just to the left of the loaded flank (as marked on the plot) has been expanded to give a clearer view of the specific area of wear. In the lower figure the area of wear is defined as the area below the zero line over the 60 µm to 120 µm zone. The depth of the wear scar varies but can be averaged out to about 5 µm overall.

The upper plot of both figures shows the reflection off the surface of the ball screw as the laser takes measurements. The very low reflections along the wear scar can be attributed to the effects of grease and the debris on the ballscrew. The large reflection just at the tip of the flank is where there is the least debris and

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grease and the laser was in the optimum position for reflection.

The results from the laser profilometry on the ballscrew clearly show that the ballscrew has experienced a significant amount of wear. This is more than sufficient to lose the 70 N preload applied to the ballscrew since it is believed that the stiffness of this ballscrew is >100N/μm.

9. ROLLERSCREWS

A little recent experience has also been gained in the performance of roller screws, both the planetary and recirculating types. A proving test was performed on a Balinit C coated hard preloaded planetary roller screw supplied by Rollvis (type RV531/12.4 R6, 200N preload) and lubricated with Fomblin Z25. The hard coating was used in an attempt to delay the onset of polymerisation of the oil. Initial running again showed a decrease from 1200 to 800 gmcm in the measured torque as the surface was worn down in the first 2,500 return strokes. The torque then stabilised and the test continued to around 20,000 return strokes when the torque levels increased dramatically. By pausing the test the torque would fall back again, but by 30,000 strokes the test was halted with peak torques some 5x the starting value recorded. On inspection it was seen that the Balinit C had worn, thus reducing the preload and the debris had interfered with the performance of the screw. Unfortunately ESTL has not been able to test a standard supply screw at this stage.

A further test, reported in more detail in a separate paper in these proceedings, was performed on the planetary roller screw supplied by SKF for use in the MSG-REM mechanism. This screw utilised the ion-plated lead plus Braycote 601 lubrication technique previously described for the ballscrews. The test was a success, but it should be noted that the life requirement was only for a small number of strokes. Despite this there was still a noticeable drop in torque over <200 strokes. This was confirmed as being due to loss of preload due to wear of the roller flanks. It was also noted that there was wear present on the flanks of the nut thread at the position where the rollers re-engage in the transfer slot.

Further tests are currently planned in support of the HEXAPOD programme (Ref. 1), which will compare in more detail the performance of both types of hard preloaded roller screw lubricated with ion-plated lead and Braycote 601. The use of a soft preloaded system will also be investigated.

10. CONCLUSIONS

Linear actuator devices can be made to operate for extended numbers of strokes in vacuum with the correct choice of lubricant. In all the tests performed by ESTL to date however there has been wear of the loaded contact zones. This wear is significant if the system is reliant upon a hard preload, and the effective preload is rapidly lost with all the various lubricants tested. If preload is required throughout the life of the mechanism then a soft preload application is therefore preferred.

PFPE lubricants alone fail rapidly due to polymerisation, although it has been shown that this can be effectively delayed by coating the components with ion-plated lead. Alone, sputter coated MoS_2 lubricates longer than ion-plated lead but there are concerns about extended in air testing prior to launch. Pennzane SHF X-2000 tended to form globules on the surface of the ball screw and did not stop significant wear of the leadscrew.

Future work at ESTL will look at the two roller screw types in more detail. More involved dry lubrication techniques, perhaps incorporating more self lubricating elements, will be required if extended durations are to be achieved without wear of the underlying components of both ballscrews and roller screws.

11. REFERENCES

1) Genovese L et al, Hexapod Pointing System for Space Applications, *31st Aerospace Mechanisms Symposium*, NASA CP3350, May 1997, 215-230.

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Figure 1: ESTL Ball/Roller Screw Test Facility

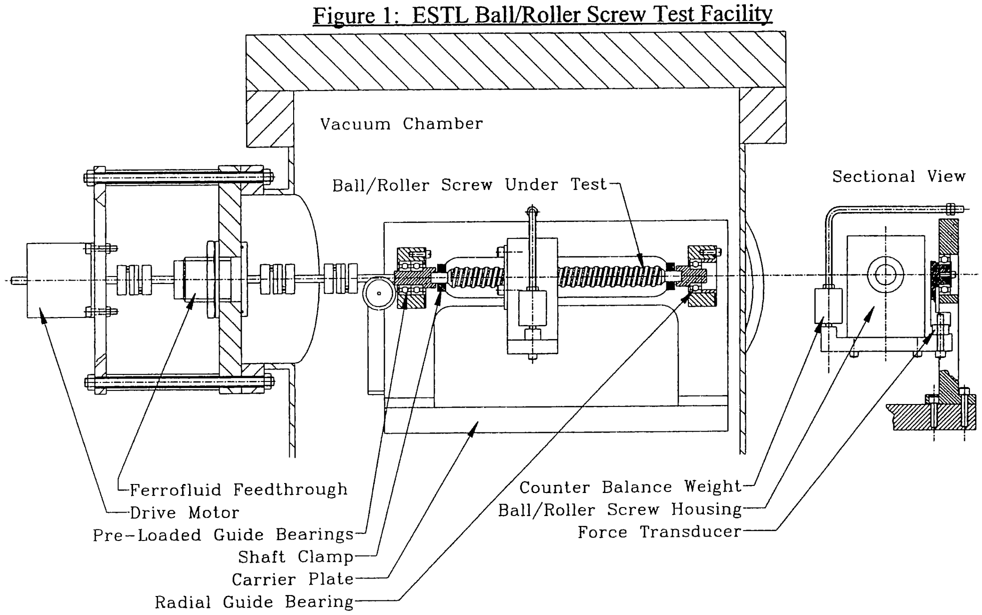


Figure 2: Laser Profilometer Plots

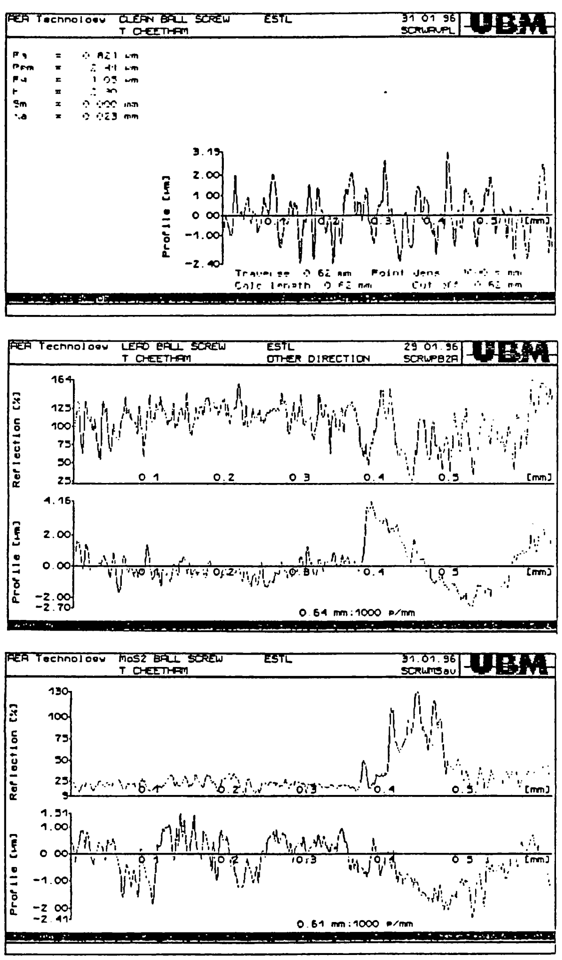


Figure 3: Preloaded Ballscrew Performance Curve

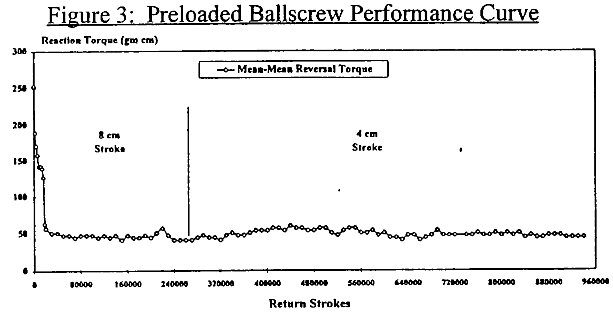


Figure 4: Preloaded Screw Laser Profilometer Plot

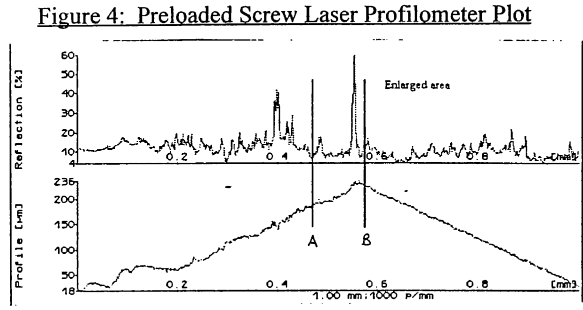
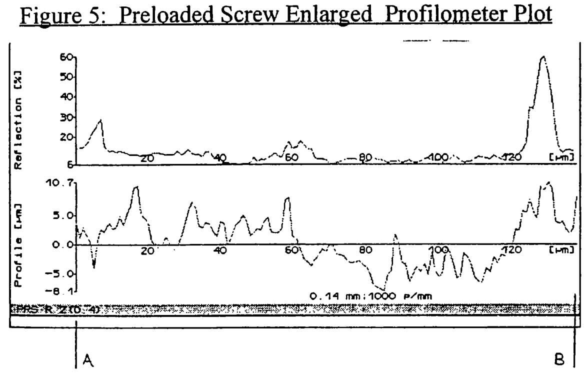


Figure 5: Preloaded Screw Enlarged Profilometer Plot



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