HIGH PRECISION LINEAR ACTUATOR DEVELOPMENT

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ABSTRACT

In the frame of an ESA contract for a High Precision Linear Actuator (HPLA) development, SENER has been in charge of design, development, manufacturing and testing at component and mechanism levels for such actuator. The objective of this development has been to demonstrate the feasibility of a competitive technology for a linear actuator, usable in highly accurate and dynamic pointing/scanning mechanisms.

This paper provides a synthesis of the technical results, the obtained parameters from the selected design vs. the required ones, the design evolution from the friction based and its problems to the frictionless concept and the results of the test campaign for both configurations. Lessons learned from test results of both concepts (related to movement non uniformities and life of flexible elements) are highlighted.

1. INTRODUCTION

The object of this project is the design, development, testing and qualifying of a High Precision Linear Actuator (HPLA) for space applications, contract reference19250/05/NL/IA.

A market survey about space commercial and scientific missions and identification of the potential applications of a high precision linear actuator, such as pointing system; deployment systems, reflector pointing mechanisms has been carried out at early stages.

The most developed technologies are electromagnetic, piezoelectric, thermal expansion, phase change and shape memory alloy. The performance requirements are increasing steadily and actuators must fulfil a complex set of requirements: high positioning accuracy and repeatability, high load capacity, long life, stable & predictable stiffness and a compact and light design at a competitive price. Taking into account the main requirements for the HPLA, the electromagnetic technology was considered the more adequate to reach the objectives.

Among the options the Harmonic screw was selected as this concept enables to obtain a very fine resolution in a single step, which allows reducing mass, decreasing occupied volume and improving system reliability.

The linear lead per revolution of this concept comes from the sliding of the thread. For roller screws (medium efficiency) the minimum lead per revolution is 1 mm and for ball screws (high efficiency) it is 2 mm. The selected concept allows for leads lower than 0.1 mm with efficiency similar to that of roller screws. To get the same lead with conventional roller screw or ball screw, additional reduction stage would be needed (for example, with a harmonic drive), see *Figure 1*.

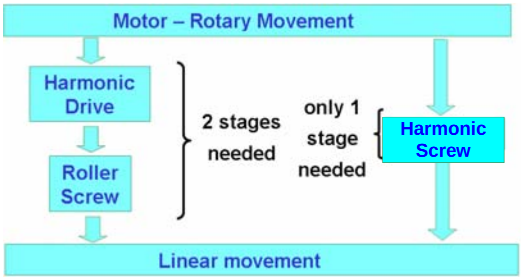

Figure 1.- Schematic of the motion conversion of harmonic screw concept

Two configurations were developed: a friction based option and another based on the frictionless concept, discarded as first option during the trade-off performed at first stages of the project but retaken after the EM test results.

Figure 2.- HPLA final configuration.

The test campaign has included functional tests at component and mechanism level and life test.

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2. DESIGN REQUIREMENTS

The major requirements for the HPLA can be summarised as follows:

2.1 Motion range

Linear stroke higher than 15 mm.

2.2 Motion accuracy

a) In Orbit – powered
   - resolution better than 0.005 mm.
   - repeatability better than 0.01 mm.

b) In Orbit – un-powered
   - position stability accuracy 0.01 mm.

c) On Ground
   - resolution better than 0.005 mm.
   - repeatability better than 0.01 mm.

2.3 Stiffness

The stiffness, as measured between the two interface flanges, shall be higher than 1×10^{7} N/m (Translation about movement axis).

2.4 Mass

A design goal in the order of 1.5 kg.

2.5 Fatigue life

The lifetime shall be tested for the number of cycles as defined in Table 1. The unit cycle is defined as the linear displacement of one motor step. Considering a nominal pitch of 27.5 µm and a stepper motor of 200 steps/rev, the unit cycle is 0.1375 µm.

The number of movements has been calculated considering 2 movements/day when shade (25 % of the year) and 1 movement/day the rest of the days. So in a year there are 456.25 movements (2 x 0.25 + 1 x 0.75) x 365 days. Assuming 15 years life duration, a total number of 456.25*15 = 6844 movements shall be performed during the in-orbit life of the HPLA.

The targeted quantity of movement per day corresponds to 3 degrees peak to peak antenna "typical" rotation which corresponds to 17 mm of stroke. Therefore, , the type of cycles and the percentage of occurrence shall be as follows:

	Trim angle [degrees]	Actuator stroke [mm]	Percentage of occurrence
Small recovery	0.05	0.28 (2036 unit cycles)	80
Medium	0.2	1.13 (8218 unit cycles)	15
Full recovery	1.5	8.5 (61818 unit cycles)	5

Table 1.-In orbit cycles definition.

2.6 Strength Requirements

The HPLA shall withstand the loads due to the launch environment in accordance with the ECSS testing requirements under external load higher than 5000 N.

2.7 Thermal Interface Requirements

Operating Temp. [º C]	Non-Operating Temp. [º C]
-30... +70	-60...+80

Table 2.- Thermal requirements.

3. CONCEPT DEFINITION AND TRADE-OFFS

The main concept is doing the reduction and linear-to-rotary movement transformation based on a continuous deflection wave generated on a flexible element that achieves high mechanical multiplication between concentric parts. Two configurations were developed: a friction based option, and an option based on the frictionless concept, where the addition of a geared zone on the harmonic screw to allow the transmission of the rotation between it and the nut has been done.

HPLA FRICTION CONCEPT

The first HPLA model was developed from the previous LTD (Linear Transformation Device) design performed by SENER [1] and patent protected. The main concept is doing the reduction and linear-to-rotary movement transformation stages in only one stage (harmonic screw-nut).

Figure 3. – Sener LTD.

The working principle of the HPLA linear motion conversion is similar to the Harmonic Drive concept, based on a continuous deflection wave generated on a flexible spline element that achieves high mechanical leverage between concentric parts.

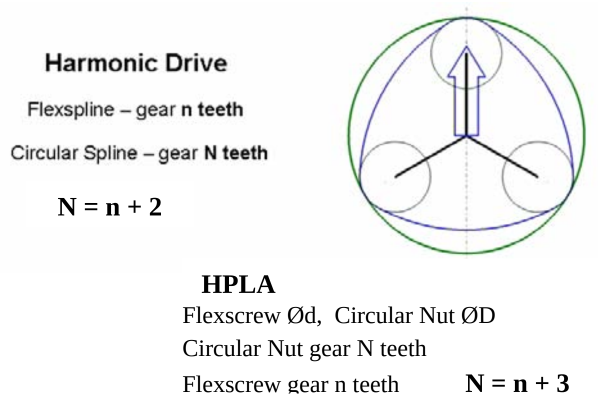


Figure 4.- Harmonic Drive vs Harmonic Screw.

The diameter d of the flexible element (***Flexscrew***) is smaller than the diameter D of the nut (Circular nut).

The ***Circular Nut*** is prevented from rotating but not from axially movement. The rotation is transmitted from a stepper motor to the main body that is connected to the flexscrew. Once the elliptical-triangular deformation of the screw turns the nut moves linearly. The threaded zone in both (flexscrew-nut) has the same lead ***p***.

The fact that the screw diameter is smaller than the nut makes the screw rotates in opposite sense and at a much smaller speed.

The HPLA main body, so called ***Wave Generator*** carries inside the Flexscrew and makes it to adopt the triangular-elliptical form in its threaded zone. Then, the three "vertices" of the Flexscrew engage with the Circular Nut. When the Wave Generator rotates with respect to the Circular Nut, the Flexscrew rolls without sliding by the Circular Nut by its three points of contact. When the Wave Generator has completed a revolution with respect to the Circular Nut, the points of contact also have done it, covering a length equal to the perimeter of the primitive diameter **D** of the Circular Nut.

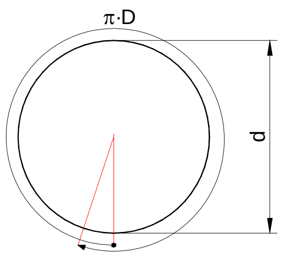


Figure 5.- Movement of the Flexscrew contact point during a revolution of the Wave Generator.

Obviously, the points of contact of the Circular Nut are the same on each revolution, but not those of the Flexscrew, because it has a smaller perimeter and it will contact at the point that results from covering the perimeter of the primitive diameter of the Circular Nut, that is somewhat advanced with respect to the one of the previous revolution.

However, this length is equivalent to **D/d** times the perimeter of the primitive diameter of the Flexscrew, so the new point of contact on the Screw is **D/d-1** revolutions advanced with respect to the initial one. As the point of contact wrt the Circular Nut has not rotated, the Flexscrew will have to turn in the opposite direction of the Wave Generator.

The flexscrew rotation will be converted into axial movement in the threaded zone. Considering that the Flexscrew rotates, but it doesn't move, the Circular Nut will have to move the axial distance corresponding to **D/d-1** revolutions of the thread with the lead **p**. Therefore, the lead per revolution of the actuator will be **p·(D/d-1)**.

Reference architecture

The baseline converts the rotary motion of the power input component into linear motion of the output component by means of a strain wave imposed upon a flexible sleeve member of the assembly, which is flexed into intermittent screw engagement by a member which is motor-driven to rotate relative to the periphery of the flexible sleeve. The actuator eliminates the need for gear reductions such as are normally required in typical screw type actuators; and therefore is of much more simplified and less costly construction. The actuator allows for leads lower than 0.1 mm with an efficiency similar to that of roller screws.

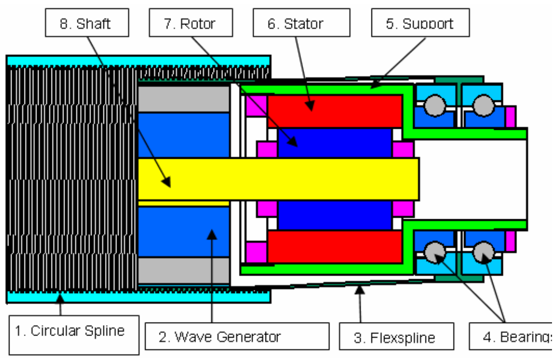


Figure 6.- Harmonic screw concept.

The selected architecture comes from this actuator concept but several changes have been included. The linear transformation device consists of three main elements:

- The Circular Nut (1), is a rigid tube of mean diameter **D** (60.8 mm) with an inside threading of lead **p** (1.5 mm). Rotation is limited but translation is allowed.

- The Wave Generator (2), is a piece with three "fingers" to configure the triangle vertices of the contact zones. Each finger can rotate with respect to the longitudinal axis.

- The Flexscrew (3), is a very thin tube (flexible), with an outer threading of the same lead p than the Circular Nut (1). Axial movement is limited but it can rotate. Its shape allows to place a pair of contact bearings in its outer diameter. Thread mean diameter is 60 mm.

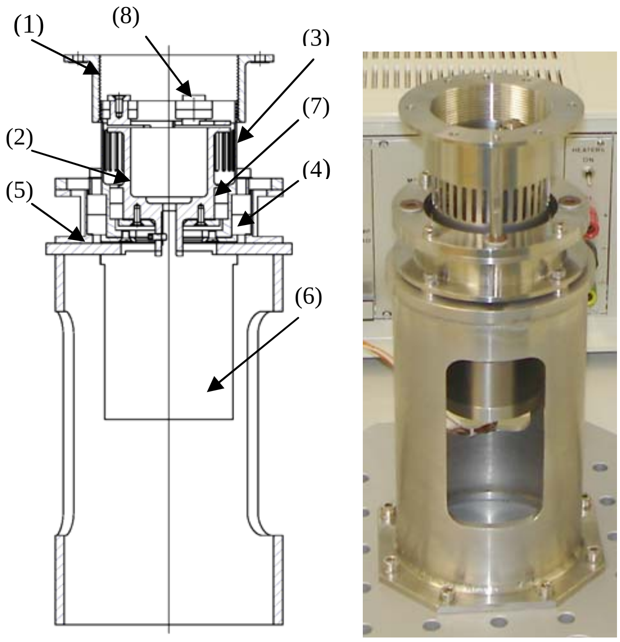


Figure 7.- Friction option architecture

Since the Flexscrew (3) has to transmit linear stresses and turn, it is guided in its rotation by a pair of angular contact bearings (7) attached to the Wave generator (2) and by an additional pair on the outer diameter (4) connected to a dedicated support (5). As it has very little rotation, no big losses are expected. The motor (6) is connected to the Wave Generator by a shaft with a flat face.

The Wave Generator must roll on the Flexscrew working area; therefore it is necessary to use some rollers/bearings to achieve this task. These elements, so called "fingers" (8), have three rollers at the threaded zone.

The first prototype of the HPLA was made of Ti 6Al 4V (to allow higher radial deformations in the flexscrew). Although Titanium presents a bad tribological behaviour, a coating of MoST^{TM} were applied to both contact surfaces to avoid fretting-wear. That reduces the friction coefficient and the achieved conditions of friction-preload are not enough to avoid the slippage.

As Titanium needs to be coated to avoid fretting-wear, but the coating introduces uncertainty about the friction coefficient between surfaces and can reduce it more that allowed a second prototype was made changing the flexscrew and nut material to Stainless steel 15-5PH.

Figure 8.- Wave generator inside flexscrwew with cut-outs in the threaded zone.

Some problems have been detected during functional tests, some related to the HPLA performances and some related to the tribology / friction between components. Among these are a non-regular resolution, loss of accuracy in the movements and a non-infinite life in fatigue.

Although these problems are mainly caused by the level of preload it could be also affected by the misalignment between flexscrew-nut or/and by the thread contact characteristics. As result this problem can be really difficult to address. The measured advance per revolution is lower than expected.

The test program does not verify the compliance of the model with respect to its specific requirements except w.r.t the torque margin.

The advance per step (resolution) is not uniform, the maximum peak is about 1.127 microns, there is a bandwidth of +/- 0.5 microns covering most of the range. However step size varies a lot per each step, being quite higher than the nominal calculated value (0.1 microns) in some areas and being opposite to the desired direction in other zones

The precision (repeatability) goes from 0,01784 to 0,05974 mm. The required value is 0.01 mm

One of the lessons learned is that friction based mechanism for very small and accurate displacements does not work properly.

Considering these results it was decided to implement the concept where the friction effect could be avoided.

HPLA FRICTIONLESS CONCEPT

The main difference wrt to the previous one is the addition of a geared zone to allow the transmission of the rotation between the flexscrew and the nut. This model has a new flexscrew design and also a new nut, separating the thread and teeth area to eliminate the needed of friction (this is the reason of the frictionless name), a new guiding system to ensure the alignment of the mechanism, and two angular contact bearings in the outer part of the flexscrew.

The Flexscrew is deformed till contact the nut by rollers at three equally spaced zones of its perimeter (and at the geared and threaded zones). The threaded zone in both elements (flexscrew-nut) has the same lead ***p***. The geared zone on the nut has 3 more teeth than the flexscrew.

The materials for the main components are:

- Flexscrew: AISI 440C
- Circular Nut: Nitronic 60
- Wave Generator: Ti6Al4V

The configuration is depicted in next figure.

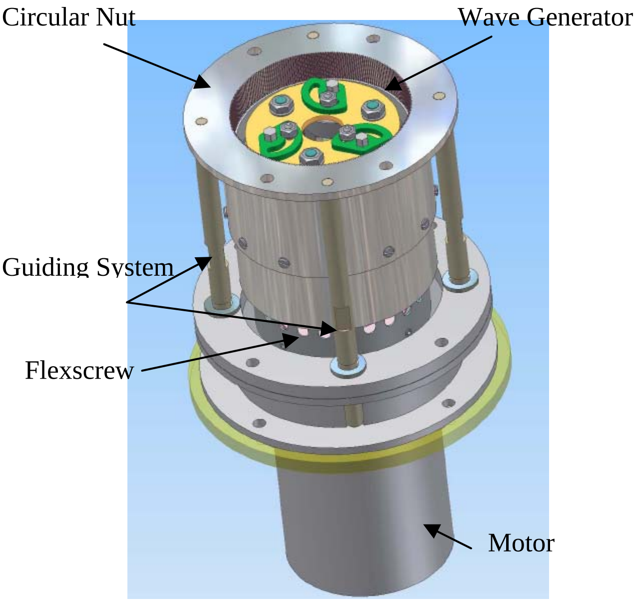


Figure 9 Frictionless HPLA

Flexscrew

The flexscrew is a thin cylinder-shaped metal rim component (60 mm diameter) with an external geared zone at the top part and an external threaded zone at the middle. For the purpose of achieving a good deformation-length ratio and to increase the flexibility on the flexscrew, some slots have been included.

Circular Nut

The circular nut is a rigid flanged cylinder (60.75 mm diameter) longitudinally splitted in two halves that can be attached through 12 M4 screws. The circular nut has a bigger diameter than the flexscrew and it is the component that interfaces with the external load.

Figure 10.- Circular Nut assembly.

Wave generator

The Wave generator is an assembly of several pieces: the main body (the part connected to the motor), the "fingers" (the rollers plus the shaft), the top plate, the special washers and the connecting guides.

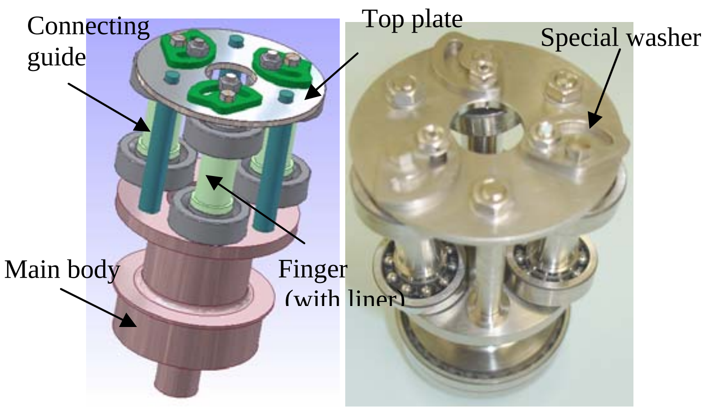


Figure 11 Wave generator assembly

The assembled configuration with the three preloaded zones can be seen in the following figure.

Figure 12.- HPLA frictionless option top view.

Motor

The selected motor is a stepper designed for extreme environment including vacuum conditions. The model is Phytron VSS 57.200.1.2 HV, 200 steps, 0.63 N-m holding torque.

Mechanical Envelope

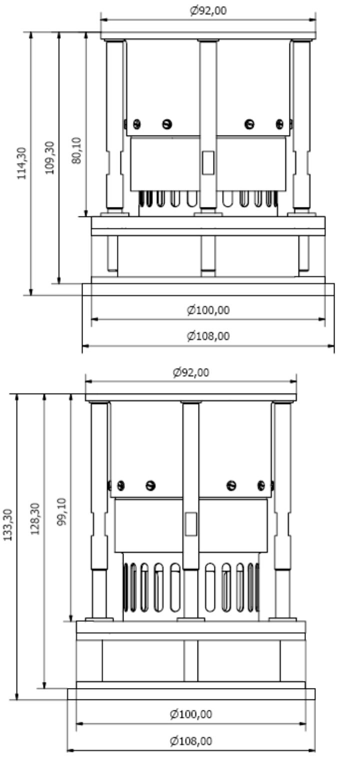


Figure 13 HPLA envelope extreme positions.

4. TESTING

The tests performed were the following:

- HPLA physical measurement tests
- Grounding/Bonding electrical properties
- Functional tests
  - Torque margin
  - Stroke measurement
  - Resolution measurement
- Life tests

Torque margin

This test was performed to check that the HPLA actuator can move the mentioned mass of 10 kg, as required (up and down) along the stroke of the actuator.

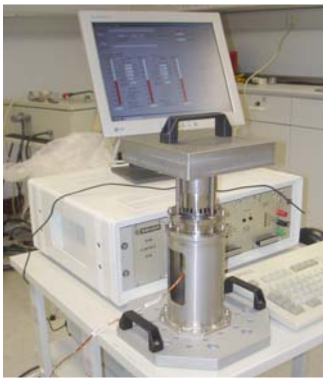


Figure 14.- Torque margin set-up

Resolution measurement

A laser interferometer was used for the linear displacement measurement (see *Figure 15*). The resolution of the measurement device is 0.05 microns.

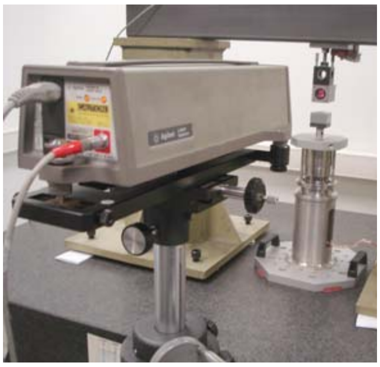


Figure 15.- Test set-up.

The requirement for the HPLA is better than 5 μm. To measure it the actuator was commanded 200 motor steps (one turn) upwards. The steps were commanded one by one with small intervals of time between them in which the motor remained powered and the position was measured in the steady state at each position.

The position measured after each step can be seen in Fig. 18 where it can be seen that HPLA does not show a linear behaviour when commanded it step by step.

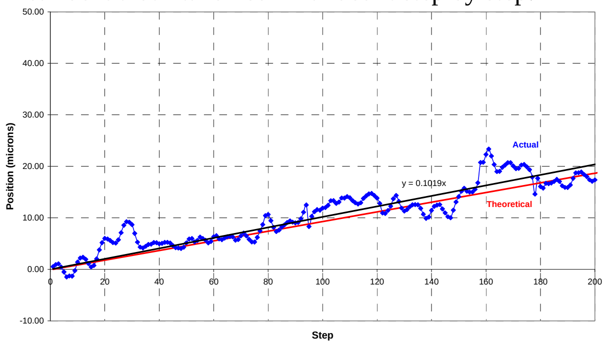


Figure 16.- Motor step by step linear advance.

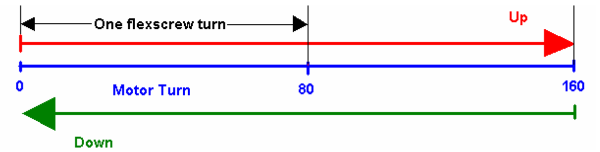
Sometimes the advance per step is in the opposite direction to the commanded. The mean value to obtain the line results on a slope of 10.19 (it corresponds to the resolution). The non-linear results obtained can be due to two main reasons:

- The manufacturing tolerances and integration misalignments
- The measurement system, if a small deviation of the laser reference from the center of the mass occurs it leads to a deviation of the linear advance.

The behaviour of the system in larger advances was also studied. The following advance measurements were performed. In all cases the measured values were taken in the steady state position with the motor powered.

1. Advance per motor turn

- 160 motor turns (two flexscrew turns) up & down



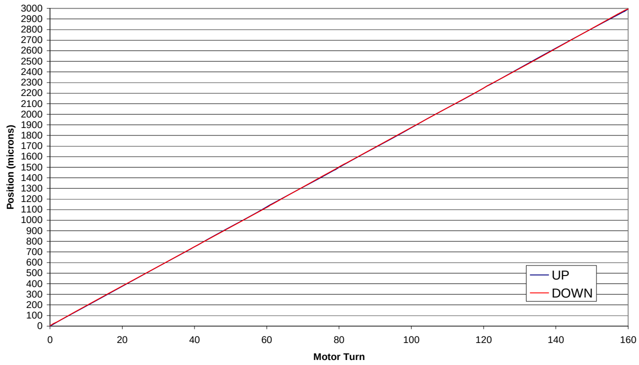


Figure 17.- 160 motor turns (up and down direction).

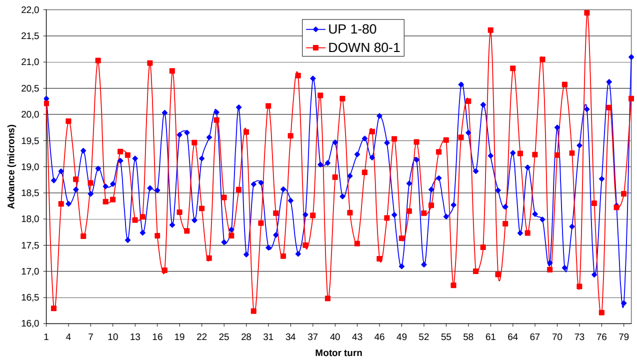


Figure 18.- 80 motor turns. Up and down direction.

- 20 motor turns up and down

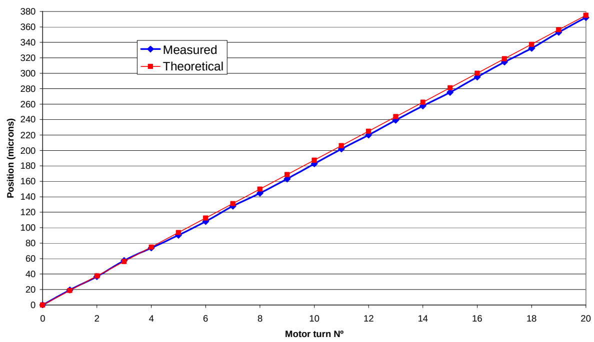


Figure 19.- Total advance for 20 motor turns (375 microns) up & down.

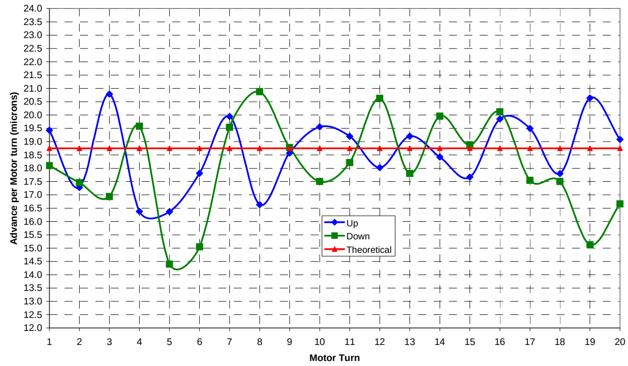
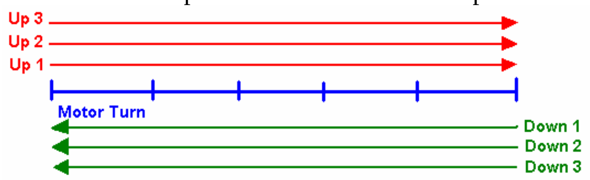


Figure 20.- Advance per motor turn. 20 turns up and down.

2. Advance per motor turn, 5 motor turns up and down repeated three times trying to find out if there is repeatability in the behaviour. This test has been performed at two different positions.



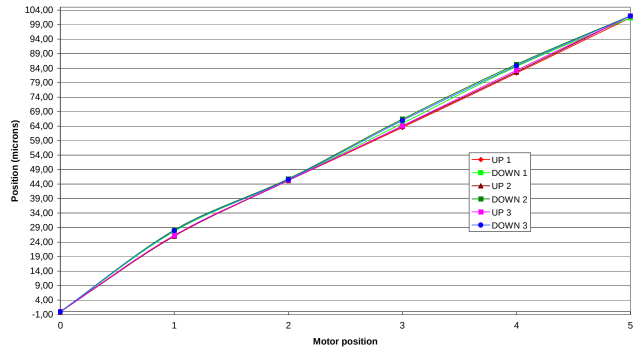


Figure 21.- Five motor turns up and down repeated three times. Position 0 mm

Repeatability and Accuracy measurements

Precision (or repeatability) is defined as the range of positions attained when the system is repeatedly commanded to one location under identical conditions. System repeatability is the maximum positional deviation from the average of the displacements.

Accuracy refers to actuator ability to position at a desired target point. The difference between the required (commanded) position and the average of the different readouts is the resultant value.

The tests were performed for three different initial positions: at 5 mm, at 9.375 mm and at 15.9375 mm from the lower position of the nut. Six times were repeated the tests for each position.

	Position: 5 mm (53334 steps) Speed: 200 steps/s	Position: 9,375 mm (100000 steps) Speed: 300 steps/s	Position: 15,9375 mm (170000 steps) Speed: 400 steps/s
1	4,99507	9,37035	15,93061
2	5,00148	9,36998	15,93591
3	5,00110	9,36916	15,93327
4	4,99761	9,36774	15,92910
5	4,99870	9,36500	15,92981
6	4,99671	9,36606	15,93005
Average Disp (mm)	4,99845	9,36805	15,93146
Position Dev (mm) Repeatability	0,003035	0,002302	0,00445
Accuracy (mm)	0,00162	0,00695	0,00604

Table 3.- Precision Measurements.

Life test

For test purposes, four (4) operational movements correspond to a complete test cycle.

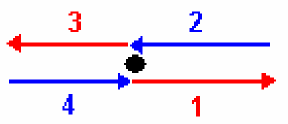


Figure 22.- Test cycle (4 operational movements).

The number of cycles to be performed by the HPLA is shown in Tab. 5.

	Actuator stroke [mm]	Nº of test cycles
Small recovery	0.28	3128
Medium	1.13	586
Full recovery	8.5	195

Table 4. - Test cycles

Only 1098 small recovery cycles were performed because a stepper motor malfunction was observed so the test was aborted to replace the stepper motor.

The mechanism was checked prior to the new stepper assembly and the visual inspection didn´t reveal any failure. The preload was slightly increased as one of the bearings didn´t contact the flexscrew inner diameter During the test an axial crack appears between the slots of the flexscrew causing the stop of the test.

The fact that the screw has failed after performing a small number of cycles (lifetime test) and several cycles of functional tests shows that the stress level in the thread zone was very high, so the crack has been caused by a cumulative fatigue cycles (Low Cycle Fatigue) and also by overpassing the nominal preload value (corresponding to 0.375 mm).

The threaded part of the screw is much more rigid than the top part, and because of this, for the same deformation, the lower part has much higher stress level than the top part. If the deformation reaches 0.5mm, the stress level would be around 1400 MPa. The preload adjustment is directly related to this deformation, a slightly variation on the preload means that high stresses can be reached on the flexscrew (higher than the expected ones) so a very fine adjustment has to be done; this is another lesson learned which will be considered in further development activities of the HPLA.

5. CONCLUSIONS

The Frictionless EM has demonstrated the achievement of the targeted requirements although the step by step motion presents a non uniformity.

- The required accuracy is less than 10 microns and the obtained values go from 1,62 microns to 6,95 microns
- The precision (repeatability) goes from 2,30 to 4,45 microns. The required value is 10 microns.
- The theoretical advance per step (resolution) is 0,09375 microns and the average obtained on a step by step command thru 200 steps (a motor revolution) is about 0.10 microns, although it is not uniform, the measured value can be justified by the reference location of the interferometer and also by the manufacturing tolerances and the assembly misalignments. The obtained value, although the observed variation is non-linear, complies with the requirement (less than 5 microns).
- The total stroke has been verified as the nominal stroke of 17 mm.
- The torque margin has been verified (move a mass of 10 kg).
- The achieved results should be continued supported on the identified lessons learned for developments based on applications such as the Large Deployable Antenna Reflector Trimming Mechanisms.

6. REFERENCES

1. M. Domingo, J. Vázquez, SENER (2003). Large Deployable Antenna – Reflector Trimming Mechanism LDA-RTM. *Proceedings of the 10th European Space Mechanisms and Tribology Symposium*, p. 191 – 198