SCAN MECHANISM FOR MASTER LIMB SOUNDING INSTRUMENT

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ABSTRACT

Earth observation appears to be one of the most important missions in the frame of space industry. New trends on mechanism performances require parallel technology developments to demonstrate the feasibility of new design concepts. In particular, future advanced limb sounding instruments devoted to atmosphere chemistry missions impose very stringent requirements to the instrument and its mechanisms.

Scanning/pointing mechanisms associated to large and flexible reflectors have to be controlled with very high accuracy and stability minimising induced perturbances on the satellite. This particular application constitutes a challenge for the mechanisms, and therefore it requires a specific development for a technology demonstration of the existing critical areas.

1. INTRODUCTION

A Breadboard Model (BBM) has been developed to demonstrate the feasibility of pointing/scanning mechanisms required for future advanced limb sounding instruments.

This BBM has been designed, manufactured and tested in the frame of a development co-funded by SENER & ESA - General Support Technology Program (GSTP)-.

Figure 1: BBM of MASTER Scan Mechanism

The design is based on preliminary configuration studies for MASTER instrument having as a reference the requirements imposed to earth limb sounding mechanisms.

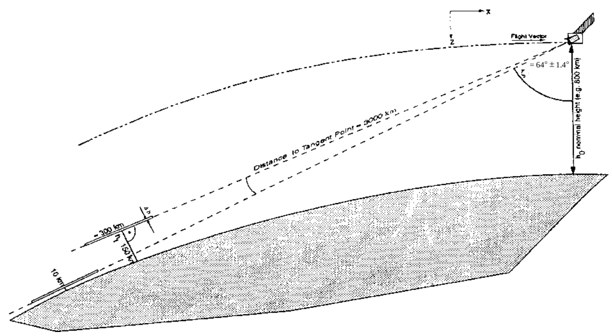

Figure 2: Limb sounding geometry for a satellite with near polar orbit

The development includes mechanism, dummy structure (reflector), electronics and control algorithms that simulate the behaviour of the mechanical elements involved in the instrument.

The mission is based on mechanism scans, which are repeated continuously during the whole lifetime period of the satellite. This fact requires the capability to perform millions of scan cycles covering a determined atmospheric height (from -2 Km to 47 Km) without performance degradation of the mechanism. After a certain number of scan cycles, the instrument is calibrated at hot temperature (pointing at -12 Km height) and cold temperature (pointing at +150 Km height) for three seconds each.

2. DESIGN REQUIREMENTS

The design of the MASTER Scan Mechanism is driven by the main design requirements imposed by the MASTER limb-sounding instrument.

The most important technological challenge is related to the precise control of the movements of a large and flexible reflector (30 kg mass & 7.5 kg·m^2 inertia) with high accuracy/stability and within a small angular range. This mechanism shall be designed for infinite life preferably in order to cope with the extended number of cycles required. The performance degradation caused by infinite life and temperature influence shall be minimised as much as possible.

These requirements, which can be grouped in two separate categories, namely, performance and operational, are described hereinafter.

2.1 Performance Requirements

- Mechanical performances

◊ Mass: Mechanisms < 12 kg
Drive Electronics < 2 kg

◊ Stiffness: In launch > 70 Hz
In orbit > 10 Hz (closed loop bandwidth)

- Electrical performances

◊ Power consumption:
- Peak power < 40 W
- Average power < 12 W

- Pointing performances

Pointing performances are the most stringent requirement for the mechanism, since they determine the angular coverage required for the scan mechanism and the scanning profiles according to which the mechanism has to operate.

The scan profile consists of five measurement periods with the associated repointing phases of the antenna. In addition, a cold and hot calibration of the instrument is undertaken every five measurement periods, according to the scan profile shown in Figure 3.

This scan profile must be achievable in two different modes, namely, a discrete (step by step) scan mode and a continuous scan mode. This latter mode has eventually been selected for MASTER instrument.

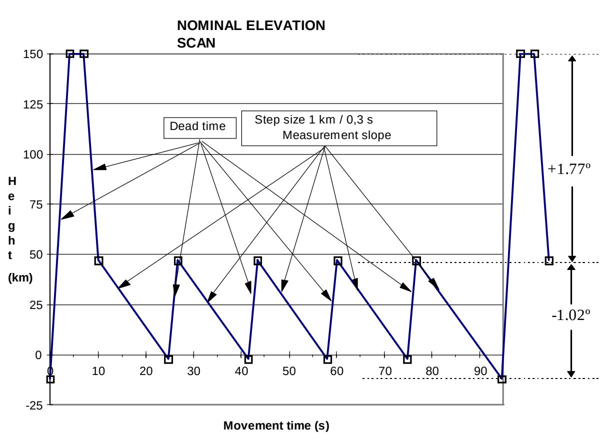

Figure 3: Scan profile

◊ Angular coverage

The angular coverage of the scan mechanism along the elevation axis is defined as the total field of view to which the mechanism can point the antenna. This angular coverage is derived from the atmospheric height to be scanned by the antenna and the additional excursions required for calibration (see Figure 3).

The minimum angular coverage along the elevation axis shall be 64° off nadir ± 1.4°.

◊ Step by step scan

The discrete scan mode consists in allowing short periods of time for antenna pointing and stabilisation before carrying out the actual measurements in static mode at each position along the measurement slopes.

Pointing performance requirements associated to this scan mode are the following:

- Pointing range: ± 1.4°
- Pointing step size: 62.5 arc sec
- Pointing step accuracy: 3 arcsec
- Pointing stability: 3 arcsec
- Step measurement time: 0.2 s
- Repointing time: 0.1 s
- Pointing knowledge: 3 arcsec

◊ Continuous scan

The continuous scan mode consists in performing smooth continuous movements along the measurement slopes, at the same time that the atmospheric chemistry measurements are actually carried out.

Pointing performance requirements associated to the continuous scan mode are shown below.

- Tracking range: ± 1.4°
- Pointing accuracy: 3 arcsec
- Pointing stability: 3 arcsec
- Pointing rate: 1 km/0.3 s
- Pointing knowledge: 3 arcsec

- Disturbances

The mechanical disturbance torque generated by the mechanism at the S/C reaction wheels shall be lower than ± 0.2 Nm in any axis.

2.2 Operational Requirements

- Lifetime

The in-orbit operation lifetime of the mechanism shall be 5 years, what implies a total 10.4 x 10^6 cycles for lifetime demonstration:

  - ◊ 2.1 x 10^6 at calibration range (+1.77°,-1.02°)
  - ◊ 8.4 x 10^6 at measurement range (+0°,-0.85°)

- Environment

  - ◊ Thermal environment
    - Operating: -10°C to + 40°C
    - Non operating: -35°C to + 70°C

  - ◊ Mechanical environment:
    - 20 g in the worst spatial direction.

3. DETAILED DESIGN

The BBM of the MASTER Scan Mechanism basically consists of:

- support structure;
- dummy of the MASTER antenna reflector;
- two flexural hinges;
- voice coil actuator;
- angular encoder;
- launch locking device;
- gravity compensation device;
- linear actuator control electronics;
- control algorithms.

The most significant elements of the design will be explained in next paragraphs.

3.1 Flexural hinge

One of the most outstanding novelties of this mechanism is the design of the flexural hinges, based on monolithic elements that are assembled together in one hinge. Furthermore, no welding is required in the manufacturing process, avoiding potential problems due to vibrations and fatigue life. These hinges permit a limited rotation capability (±2° for this application) based on a thin blade frictionless concept that results in an infinite life design. The flexural hinge can be adapted for larger angular coverage (i.e. ±10°), the main implication being the reduction of life. The complete hinge assembly has very low stiffness in rotation and high stiffness in radial direction making this design a robust alternative suitable for the current application.

Each flexural hinge consists of an outer ring, that is fixed to the structure, and inner ring which moves together with the reflector dummy, and three flexural blades that provide the rotation capability of the mechanism about the elevation axis.

Figure 4: Flexural hinge-encoder assembly

The accommodation of an encoder on the flexural hinge becomes of relevant importance when dealing with high accuracy applications. The hinge geometry is designed to permit a simple and accurate positioning of the encoder disc and the four reading head stations.

Encoder integration and set up procedures have proven simple and reliable, thus minimising risks on the critical elements of the design.

The selected flexural hinge design has the following advantages:

- easy adaptation of an encoder;
- frictionless design;
- infinite life;
- low angular stiffness;
- high radial stiffness;
- no welding;
- predictable behaviour;
- scalable to encoder dimensions or mechanism dimensional constraints.

3.2 Angular encoder

The selection of the appropriate angular sensor for the elevation axis is of major relevance, due to the stringent requirements put on this unit. The selected component is an incremental encoder ERO-725, which includes three elements:

- a grated disk;
- four optical scan units;
- two interpolation electronics.

The outer diameter of the ERO-725 disk is 182 mm, and it contains 18000 equally spaced lines (14.13 bit) at a grating diameter of 165 mm. Two additional reference lines 180° apart are also marked in the disk in order to define the counting reset point of the incremental encoder.

The distance between the encoder disc and the reticule of the scanning units must be accurately set to the values specified by the supplier so that the encoder can operate according to its performances.

Figure 5 shows the mechanical configuration of the encoder with a single scanning unit.

Figure 5: Angular encoder

The flexural hinges permit a direct and easy interface between mechanism and angular encoder, minimising alignment errors, which are critical to ensure the best accuracy. Several scan units are required to compensate for eccentricity errors, and thus, to improve the mechanism accuracy up to the instrument needs.

3.3 Voice coil actuator

The voice coil has been selected as the ideal actuator for this mechanism. In combination with the flexural hinge, it provides a frictionless high linearity actuation with high accuracy and repeatability, together with very low hysteresis and virtually unlimited resolution. On the other hand, it requires closed loop control and it does not provide damping.

Figure 6: E-shaped voice coil actuator

This concept is also compatible with the reduced angular rotation range (±2°). The low force/mass and force/dissipated power ratios are of secondary order in this application, since the impact in the total mass and power budgets is very low.

The selection of this motor was a compromise between reasonable power consumption and good dynamic performances (time constant). An E-shaped open configuration was eventually preferred due to its inherent low inductance.

3.4 Antenna dummy

The antenna/reflector dummy is the mechanical element that provides the dynamic properties of the elevation axis of the MASTER instrument (reflector plus elevation structure), that is, vibration natural frequencies, rotary inertia, amplifications, etc.

A FEM based on the current design of the MASTER instrument has been developed in order to obtain the frequencies and modes that could influence the rotation movement.

This element consists of a tubular shaft, two discs and two sets of flexural plates that provide the flexibility. This element represents the overall inertia and dynamic properties of the elevation axis of the MASTER antenna. The reflector dummy can be appreciated in Figure 7.

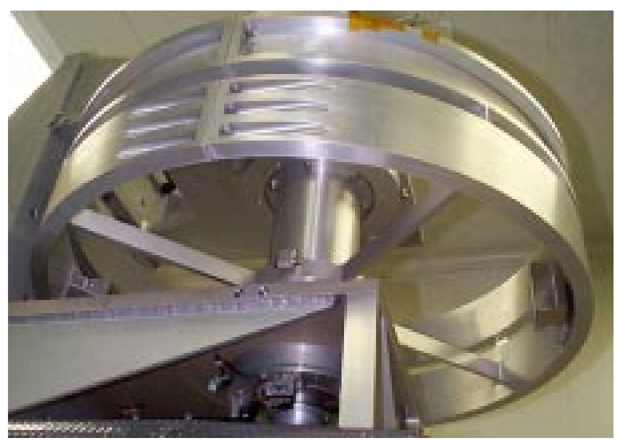

Figure 7: Reflector dummy

3.5 Support structure

Structural element aimed at providing support to the rotation axis for testing. It is the fixed reference part of the encoder and mechanism. The structure has been designed to be very stiff as the flexibility has been represented in the antenna dummy.

3.6 Gravity compensation device

The 0-g kit is aimed at supporting the weight of the elevation axis, so that the flexural hinges can work in real 0-g conditions.

One of the main requirements imposed on this device is that it must present the minimum torsion resistance. Resistive torque must be provided by the flexural hinges exclusively, in order not to alter the actual working conditions of the mechanism under test.

3.7 Launch locking device

The position of the elevation axis during launch is significantly different to the nominal position during operation. In fact, the axis must be rotated 5 degrees in anticlockwise direction (until the magnet of the voice coil is completely separated from the coil) and then moved 0.4 mm in axial direction. In this position, the elevation axis is locked to the support structure preventing the axis from any movement during launch. After the launch locking device release, the nominal position of the mechanism is recovered due to the elastic deformation of the flexural hinge blades.

3.8 Linear actuator control electronics (LACE) and encoder electronics

Two different pieces of electronics are required, one for controlling the voice coil actuator (LACE), and the other for encoder interpolation. The overall configuration of the electronics is depicted in the following figure.

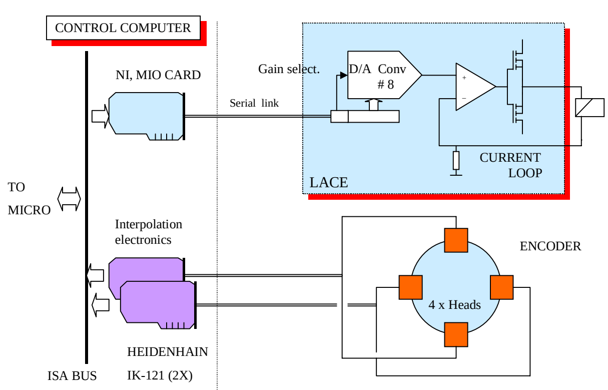

Figure 8: Electronics configuration

The LACE consists in a PCB MIO card connected in serial link with the Digital/Analogue converter (8 bits). The LACE electronics injects in the voice coil a current proportional to the command signal. The configuration is that of a current mode, push-pull output amplifier. The low resistance of the load allows the voice to be driven with relatively low voltages.

The encoder interpolation electronics are needed to meet the stringent accuracy and stability requirements of the mechanism. The encoder disk provides 18000 grid lines, what implies a period of 0.02º (72 arc sec). Several positions between each two lines can however be deduced by electronic interpolation. Two interpolation electronics cards are required (100 fold), one for each pair of opposite scanning units.

3.9 Dedicated control algorithms

The control algorithm implemented is based on a digital PID with limited integral authority (to incorporate anti wind up) and no gain scheduling.

The PID has been tuned for the specific scan profiles and several sample rates have been tested (from to 3 to 20 ms) with different pointing/scanning results. Control laws were tested and adjusted in the linear simulation models.

The control design generates a code that is used directly in the simulation and through the automatic code generation in the real time controller as well.

4. VERIFICATION / TEST CAMPAIGN

The test campaign of the MASTER Scan Mechanism includes tests at component and mechanism level according to the test plan shown in Figure 9.

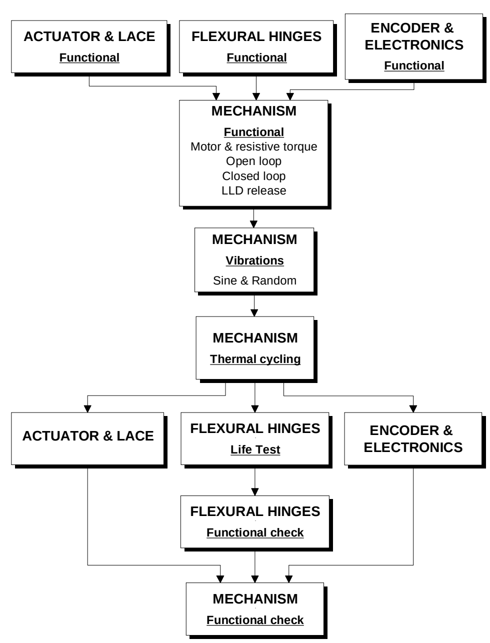

Figure 9: Test sequence

The verification campaign consists of functional tests, sine and random vibration, thermal cycling and life test. The following paragraphs describe the most outstanding results of this exhaustive test campaign.

4.1 Functional

The functional tests of the scan mechanism are aimed at verifying the mechanism performances in open and closed loop. Figure 10 shows the test set-up configuration for these tests, with a laser interferometer located at the lower side of the elevation axis. This device has been used to calibrate the encoder and to verify the scanning performances of the mechanism.

Figure 10: Test set-up configuration for functional tests

<u>Stiffness of flexural hinge pair</u>

The axial, radial & angular stiffness of the hinges was measured at the beginning and end of the test campaign, the values being identical:

- Axial stiffness: 4×10^5 N/m
- Radial stiffness: 2×10^7 N/m
- Angular stiffness: 6-16 Nm/rad (see Figure 11)
- Resistive torque: 0.35 Nm at 2° (see Figure 11)

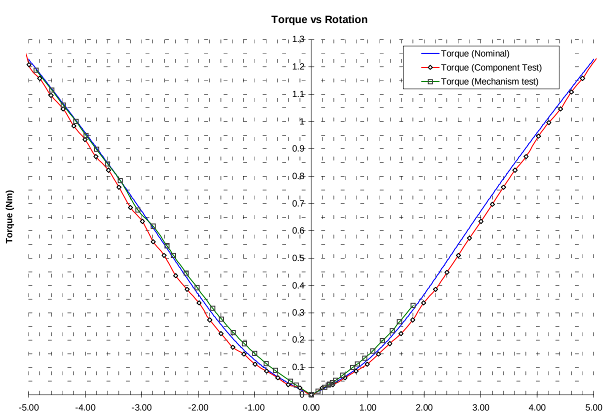

Figure 11: Resistive torque of scan mechanism

<u>Power consumption</u>

The power consumption at the voice coil actuator and the amplifier output stage was measured for both continuous and discrete scan modes:

- Peak power: 7W
- Average power: 2 W (0.5 W in continuous mode)

<u>Closed loop testing</u>

The objective of the closed loop testing is to assess the mechanism pointing performances along the specified scan profile. These tests were undertaken for the continuous and discrete (step by step) scan modes in ambient conditions. Different sampling frequencies were used for the control loop (3-20 ms), the best results being obtained for 3 ms.

- Continuous scan mode

  The absolute scan error of the mechanism was measured by means of a calibrated laser interferometer. These measurements revealed that the maximum difference between the demanded angle and the angle measured by the interferometer was below 1 arc sec (3σ) during the measurement periods, as shown in the figure below. This error is mainly due to the encoder calibration error, which is 0.75 arcsec (3σ).

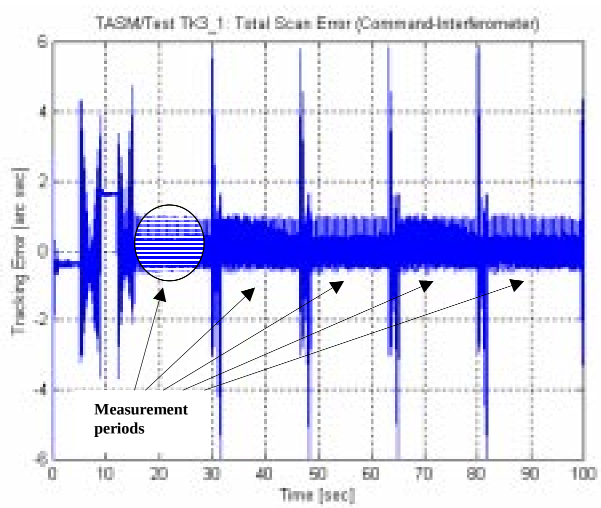

Figure 12: Absolute scan error in continuous mode

- Discrete scan mode

  Analogously, the absolute scan error of the mechanism was measured during the stabilised periods of the discrete scan. Figure 13 shows a detail of several scan steps. It can be appreciated that the time required by the mechanism to repoint the antenna and stabilise it within tolerance is below 0.1 seconds as required.

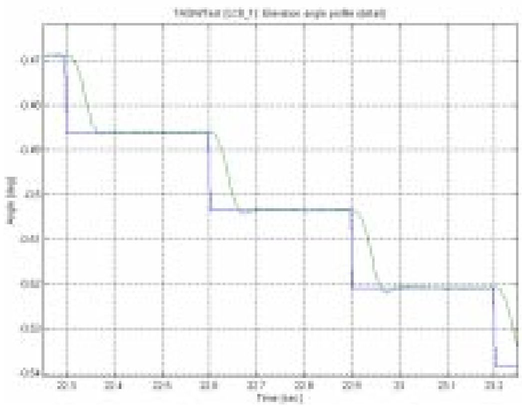

Figure 13: Mechanism response in discrete scan mode (measurement slope detail)

The scan error revealed by the interferometer during the measurement stabilised periods of the scan profile is below 1 arc sec (3σ), including an encoder calibration error of 0.8 arc sec (3σ).

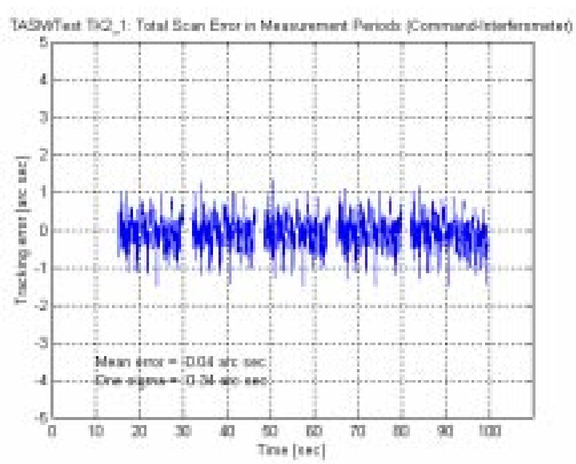

Figure 14: Absolute scan error in discrete mode

The scan and stability errors were assessed for lower sampling frequencies, the results being still acceptable. The following table shows the control loop pointing errors, which added to the encoder calibration error above mentioned give the absolute scan error.

Sample freq.	Type of scan	Scanning error [arc sec]	Stability error 1 σ [arc sec]
3 ms	Continuous	+0.0	0.2
3 ms	Discrete	-0.1	0.5
10 ms	Continuous	-0.0	0.6
10 ms	Discrete	-0.1	1.0
20 ms	Continuous	-0.9	3.9
20 ms	Discrete	N/A	

The disturbance torque at the S/C reaction wheel was obtained by simulation for both scan modes, the actual value being well below the 0.2 Nm requirement. This parameter is only significant during the long repointing periods at the beginning of each measurement slope.

<u>Natural frequencies in operation configuration</u>

The natural frequencies of the mechanism were evaluated in open and closed loop.

- Open loop frequencies

  The first three natural frequencies of the mechanism in open loop (without control) are 0.18 Hz, 100 Hz & 201 Hz. The first eigenfrequency is caused by the angular stiffness of the hinges, the other two being due to reflector dummy flexibility in rotation.

- Closed loop bandwidth

  The bandwidth of the mechanism in closed loop was assessed by means of a servoanalyser for both control laws (continuous and discrete) at different sampling frequencies.

  Since the overall system is non-linear due to the limited control authority, three levels of stimuli were used: 0.001, 0.01 & 0.1°. In fact, the drop in bandwidth that can be observed in the attached table is due to the need of further control authority, which can not be provided due to saturation of amplifiers at ±0.5 A.

		Stimulus Amplitude		
		0.1°	0.01°	0.001°
Control Law	3 ms (DS)	2 Hz	8 Hz	21 Hz
	10 ms (CS+DS)	2 Hz	6 Hz	17 Hz

4.2 Vibrations

The vibration testing of the MASTER Scan Mechanism includes sine & random excitation apart from the resonance survey for eigenfrequency determination.

Figure 15: BBM instrumented for vibrations

For these tests, the reflector dummy was substituted by other dummy that is representative of the reflector mass. In addition, the structure was reinforced with additional ribs in order to ensure that the actual vibration levels input to the mechanism did not exceed the specified values due to unrealistic structure amplifications.

- Frequency survey

  The first natural frequency of the mechanism in launch configuration appears at 129 Hz.

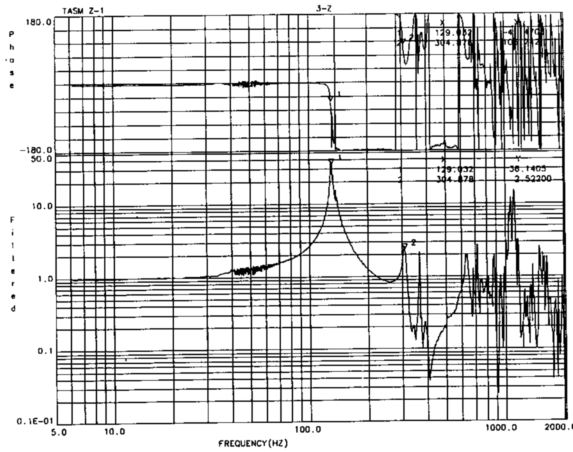

Figure 16: BBM resonance survey plot

- Sine & random

The maximum input acceleration during the sine test was 15g, no amplifications being found due to the absence of resonances in the frequency range of the test.

The random vibration test was run from o to 2000 Hz. This test was used to input the specified qualification accelerations to the mechanism (20 g). The input power spectral density was notched to a value of 11.3 g (3σ), with a maximum output acceleration of 27.5 g (3σ) at the flexural hinges.

4.3 Thermal cycling

The thermal cycling test was performed according to the specified test profile consisting in four complete cycles between the maximum and minimum non-operating temperatures, and functional tests at maximum and minimum operating temperatures (shaded circles in the figure).

Upon this test it was verified the survival of the scan mechanism under extreme non-operating temperatures. Moreover, the results of the functional tests showed that the dynamic performance of the mechanism is insensitive to temperature, the main results being virtually identical to those obtained in ambient conditions.

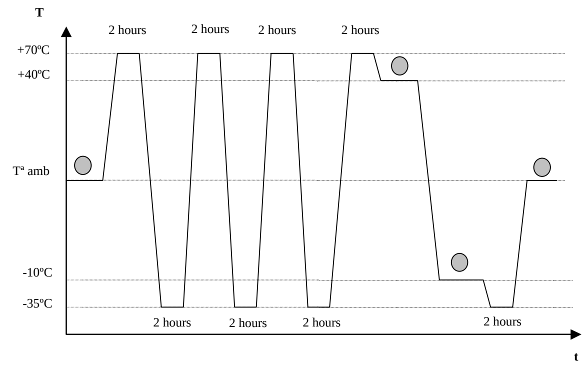

Figure 17: Thermal cycling test profile

4.4 Life test

The life test was performed at the flexural hinges at component level in order to accelerate the 10.4 x 10^6 cycles to be applied during the 5 years in orbit lifetime of continuous operation. This is justified by the fact that the hinges are the only element liable to damage due to repeated oscillation, since they represent the only link between fixed and mobile part.

The blades of the hinges were instrumented with strain gauges in order to certify the stability and correct performance of the hinges, the results obtained being very repetitive all along the test. The lifetime requirement was therefore successfully verified through life test with no degradation to the mechanism.

5. CONCLUSIONS

The feasibility of high precision scan mechanisms for atmospheric chemistry missions has been demonstrated through the design, manufacture and test of the BBM of the MASTER Scan Mechanism.

The mechanism was submitted to an exhaustive test campaign including functional tests in open and closed loop, vibrations, thermal cycling and an accelerated life test. The most remarkable results correspond to the excellent scanning performances in step by step and continuous scan modes, with outstanding accuracy and stability values in the order of 1 arc sec. The mechanism is designed to operate either in step by step or continuous scan mode, although the latter has been eventually selected for MASTER instrument.

The exceptional scanning performances, along with the absolute absence of friction in the mechanism (hinges, encoder and actuator), and the optimised design of the hinges guarantee the suitability of this scan mechanism concept for future high precision infinite life applications. This concept of flexural hinge ensures easy encoder integration, infinite life, no degradation in hostile environments and easiness for being tailored to the different size needs required for each application.