EUCLID M2 MIRROR MECHANISM

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ABSTRACT

Euclid spacecraft is an ESA scientific programme whose main objectives is first to understand the origin of the Universe's accelerating expansion and secondly to probe the properties and nature of dark energy, dark matter, gravity from the measurement of the cosmic expansion history and the growth rate of structures.

The focusing of the Euclid telescope is done on the M2 mirror which is installed on an orientation mechanism (M2MM). This mechanism shall accurately adjust the secondary mirror (M2) of the Euclid telescope to ensure the required optical quality in 3 degrees of freedom (translation in Z axis and rotations around X and Y axes).

SENER is the contractor for the development of the mechanism and its driving electronics.

This paper is prepared to explain the design and full test campaign of EUCLID M2MM Proto-Flight Model.

1. INTRODUCTION

The M2 Mirror Mechanism (M2MM) is a 3 degrees of freedom (dof) positioning mechanism which allows an accurate motion/adjustment of the secondary mirror (M2) of EUCLID telescope to ensure the required optical quality in orbit (recovery of misalignments of the telescopes due to the discrepancies between on-ground and in-orbit environments).

The mechanism is based on the use of the actuator developed and successfully operated in orbit for GAIA mission. Mechanism design has been improved in view of the difficulties found in the GAIA mission:

- Full symmetrical arrangement of the actuators (the GAIA M2MM was not).
- Optimum stability and minimum excursion of the mirror position from assembly temperature at ambient up to operational one at 100K.
- The actuators position sensing is improved with the integration of two sensor for turns counting (mainly useful for on-ground testing).

The mechanism is submitted to a complete test campaign. Difficulties and lessons learnt found for the demonstration of the performances and successful outcomes will be presented:

- Resolution, calibration and accuracy demonstration were performed at ambient temperature inside low humidity chamber using a robust set-up and optical encoders.
- As the mechanism does not include a hold down for launch, a good prediction of the structural behaviour is mandatory. The good correlation between predictions and the vibration tests results will be shown.
- The challenge during thermal vacuum (TV) test is to perform the functional performances test at 100K. The required test set up using interferometer and autocollimators to measure the six degree of freedom of the mirror movements will be presented.

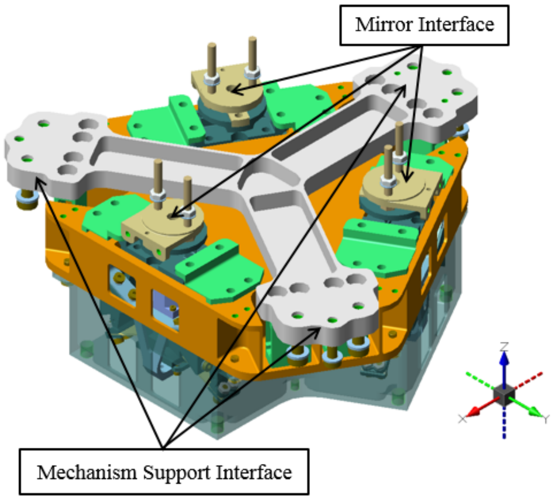

Figure 1 EUCLID M2MM configuration

2. DESIGN REQUIREMENTS

Main requirements of the mechanism:

- Overall stroke of mechanism is 400µm and +/-1.5mrad
- Resolution shall be better than 0.1µm and 2.5µrad
- Accuracy shall be kept below ±3µm
- Withstand the mass of the mirror (3.1 kg) without a hold down device
- Full performances to be demonstrated at 100K
- Mechanism mass lower than 3.5 kg

3. GENERAL M2MM CONFIGURATION

The M2MM is the link between the optical bench and the secondary mirror and shall provide capability to adjust it in three dof, one translation and two rotations. The M2MM shall also maintain the position of the M2 mirror from the position defined during telescope alignment on ground, launch and in orbit transfer environment without any hold down device.

The M2MM is composed of three linear actuators, which provide the desired three dof motion. The displacement in Z is obtained with the three actuators acting at same time. The two rotations are obtained by a differential linear displacement of the three actuator, which are placed in a triangular symmetrical arrangement.

The joint between fixed interface (I/F) and tray and M2 mirror and tray is based on flexible elements.

4. GENERAL ACTUATOR CONFIGURATION

The linear actuator for the EUCLID M2MM is a mechanism that provides 55nm resolution over a travel of 400µm with stable position at any point of the stroke. It also has high load capability to withstand launch loads without back driving.

The different components of the actuator are basically:

- A motor-reducer from CDA Intercorp, which includes a stepper motor and three stages gear reducer with a M3 thread spindle at output.
- A symmetrical flexible structure, which includes two levers, two flexural joints or pivots, the output interface providing a reduction ratio and the I/F to fix to the M2MM tray.
- A primary Vespel SP3 nut which joins the flexible structure via two blades to the spindle.
- A secondary Vespel SP3 nut preloading the primary nut contact at any position within the stroke.
- Two end stops at the beginning and end of the stroke for nut and blades protection and zeroing.
- Two micro-switches one main and one redundant for turns counting.
- A support structure where the motor-reducer and the top support of the spindle are mounted.

Resolution at Motor-reducer and Actuator Level

The selected stepper motor is a 6 pole motor (30 deg/step) with a reduction stage at the output of the motor of 90. Hence, rotational resolution at motor-reducer output is 0.333deg/step.

This motor actuates a spindle-nut, providing a linear displacement in the axis of symmetry of a mechanism (called actuator input). The shaft pitch is 0.5mm. Linear resolution at motor-reducer output is 0.463µm/step.

The flexure structure provides a reduction ratio from this linear movement of the output. As this reduction mechanism is variable, the output displacement is different for the same step increment. The reduction ratio varies from 12.4 to 8.1. Maximum resolution at actuator output is 0.057µm/step and minimum resolution at actuator output is 0.037µm/step.

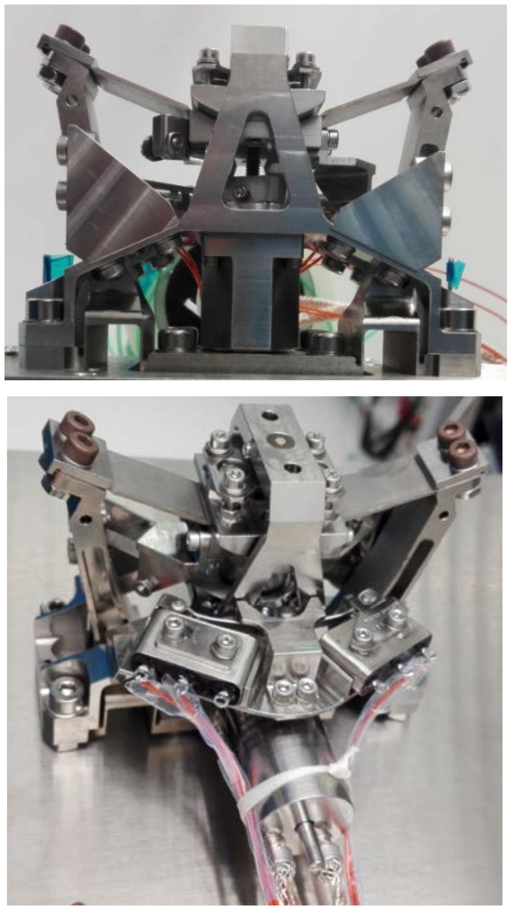

Figure 2 Actuator

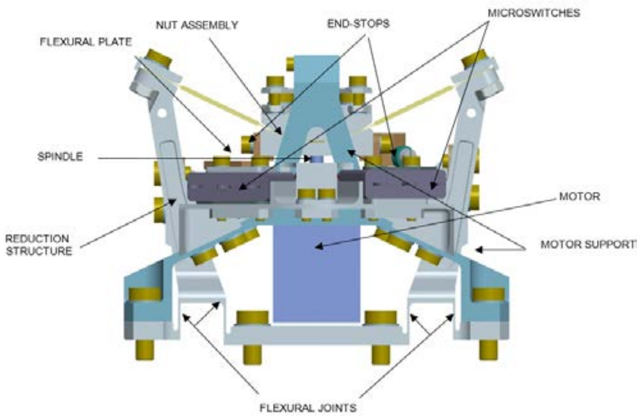

Figure 3 Actuator main parts

Motorization Margin

The motor torque capabilities shall be at least 2 time larger than the factorized resistive torques.

Although most of the resistive torques are due to the loading of elastic elements where a factor of 1.2 is required, we have considered that all resistive torques are factorized by 1.5, and therefore, a total margin between the motor and the resistive torques of 3 had to be demonstrated.

Actuator motorization torque has been measured via measurement of threshold current. It has been checked that the actuator moves with 1/3 of the motor torque capabilities without losing steps.

The worst point of the stroke is close to the lower end stop, where the forces for deformation of the guides are maximum and the motorization margin minimum.

The resistive force of the guides is maximum at 100K due to the increase of the Ti6Al4V stiffness.

5. EVOLUTION OF MECHANISM REQUIREMENTS AND PERFORMANCES

One point of interest is to show the evolution of the mechanism requirements and performances from the mechanism developed for the GAIA mission.

In Figure 4 is shown GAIA M2MM configuration to be compared with EUCLID M2MM, which is shown in Figure 5.

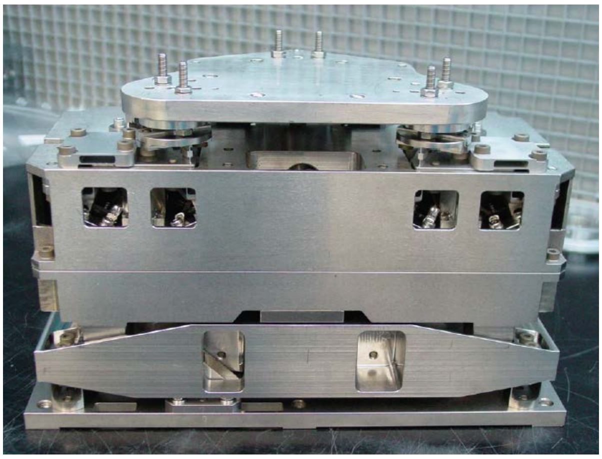

Figure 4 GAIA M2MM (PFM)

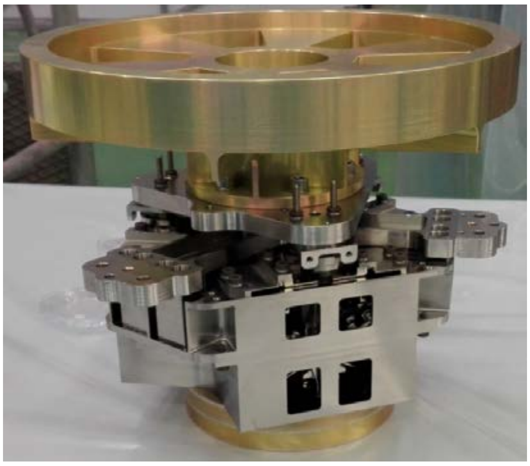

Figure 5 EUCLID M2MM

Table 1 shows the comparison of the main characteristics of the M2MM mechanism and actuator for GAIA and EUCLID missions.

Perform.	GAIA	EUCLID
M2 Mirror Mass	1.9 Kg	< 3.1 Kg
M2MM mass/QS	<5.0 Kg / 30g	<3.0 Kg / 28g
First resonance frequency	128 Hz	161 Hz
D.o.f. control	5 axes	3 axes
Actuator Total Stroke	+/- 315 µm	+/- 220 µm
Mechanism Op. Stroke	+/- 275 µm / +/- 2000 µrad	+/- 200 µm / +/- 1500 µrad
Mechanism Resol.	< 0.06 µm / < 2 µrad	< 0.055 µm / < 2 µrad
Op. Temp.	298K to 100K	298K to 100K
Volume	L 260 x W 110 x H 150 mm	Hexagonal 214 mm /H 150 mm
Position Accuracy	< ±3 µm <± 40 µrad	< ±3 µm <± 40 µrad

Table 1 GAIA vs EUCLID M2MM performances

6. EVOLUTION OF MECHANISM DESIGN

Mechanism design has been improved in view of new requirements and difficulties found in GAIA mission:

1. Thermo-elastic stability: With respect to XY plane, the implemented solution has been performed via a symmetric design to guarantee that the interface point with the M2 mirror does not move with thermo-elastic deflection. With respect to Z axis, the distance between mirror and mechanism interfaces has been decreased to the minimum leading to minimum thermo-

elastic distortions from ambient to operation temperature.

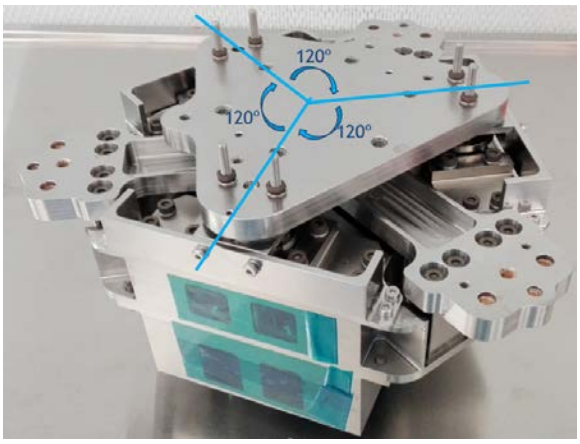

Figure 6 EUCLID M2MM with offloading devices

2. Three dofs instead of five dofs: The mechanism design is simplified by removing X and Y axes of movement. However, the drawback comes keeping the accuracy in X & Y axes having only the three Z axis actuators movements. Cross-talks displacements cannot be compensated.

3. Mass reduction: The mass of the mechanism is reduced to 3kg instead of 5kg.

4. Actuator sensors: They are implemented for on-ground purposes as a turn counter and since they are not allocated at 180º apart, the direction of rotation can be also known by noticing which one is switched on and off firstly with respect to the other.

   During functional tests it is verified the optimum repeatability of micro-switches activation.

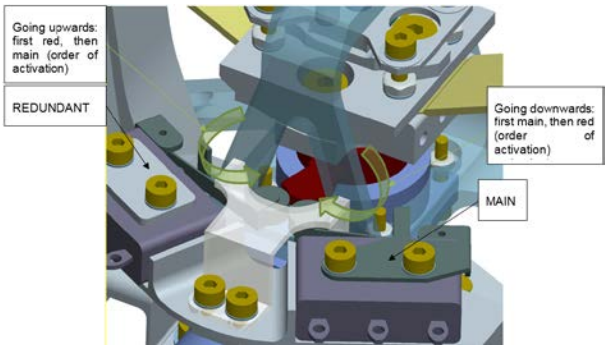

Figure 7 Micro-switches position into the actuator

7. PFM TEST CAMPAIGN

The whole PFM test campaign includes:

- CDA motor-reducer test at CDA premises
- Repetition of individual CDA motor-reducer test at SENER premises
- Actuator functional test (functional performances at ambient)
- M2MM functional tests
- M2MM vibration test
- M2MM TV test. Thermal cycling and functional test at 100K.

The major effort during the test campaign was dedicated to the functional performances verification. The final objective of the functional tests is to obtain the calibration curves for the kinematic model of the mechanism.

Two were the major difficulties to be solved during functional tests, derived from the lubrication of the motor-reducer and the high resolution of the mechanism.

Because of the MoS_2 lubrication of the motor-reducer ball bearings and gears, all the actuations of the mechanism and measurement at ambient conditions had to be performed in a humidity control chamber to prevent degradation of the lubrication. This limits the selection of the instrumentation, and makes more difficult the change between different configurations during testing.

The high resolution of the mechanism requires a careful selection of the test instrumentation, compatible with restrictions imposed by the humidity control chamber and TV chamber, and able to measure the small displacements of the mechanism movement. Finally, for ambient measurements linear encoders were selected, whereas for vacuum measurements laser interferometers and autocollimators.

Moto-reducer and Actuator tests

The objectives of the test are:

- To measure the motor and actuator friction, and to verify motorization margin
- To check functional aspects such as stroke, repeatability, and end stops operation
- To verify telemetry

All motor-reducer and actuator tests were done inside the humidity control chamber. The first step was to verify motor-reducer main requirements.

Measurements are performed in two configurations using a DC external motor joined to a torquimeter and an angular encoder.

Holding torque and internal frictions measurements are done from motor shaft, as can be seen in Figure 8.

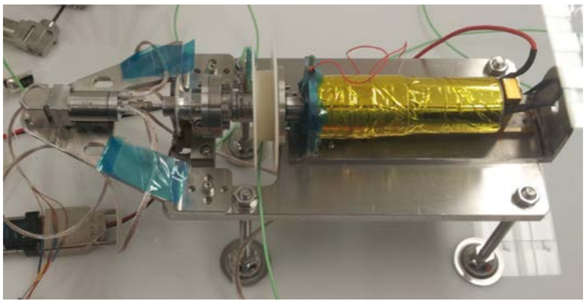

Figure 8 Motor-reducer test from motor shaft

The configuration shall be changed in order to measure motor-reducer backlash, back-driving and maximum torque. The DC external motor is joined to motor-reducer output metric screw.

The configuration of the set-up is changed inside the humidity control chamber, therefore, the motor-reducer is not exposed to ambient humidity.

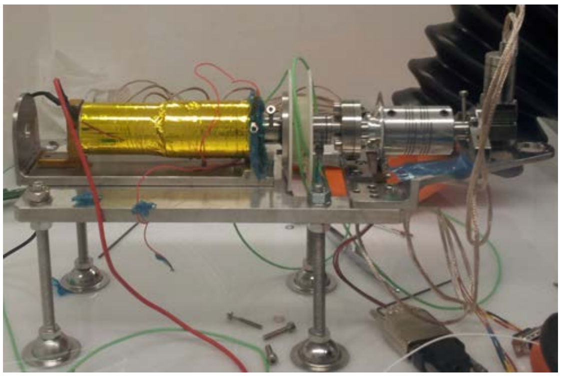

Figure 9 Motor-reducer test from output metric screw

Once the motor-reducer is assembled with actuator pieces, functional aspects at actuator level are verified again.

The main difficulty is to perform the adjustment of end stops and micro-switches inside the humidity control chamber as the motor-reducer must not run at ambient.

Actuator stroke is measured using 2 linear optical encoders, one at each side of the actuator. Preliminary calibration curves are obtained to be used as baseline in whole mechanism functional test.

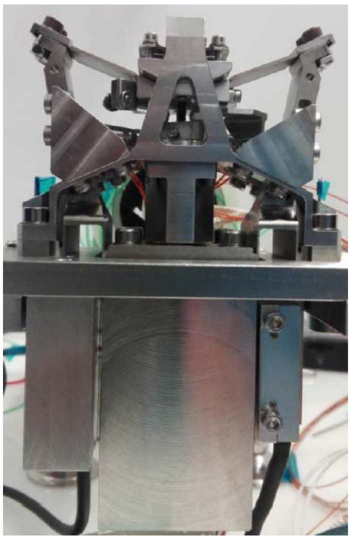

Figure 10 Actuator functional test

Calibration curve and calculated error for one actuator are shown in Figure 11 and Figure 12 respectively.

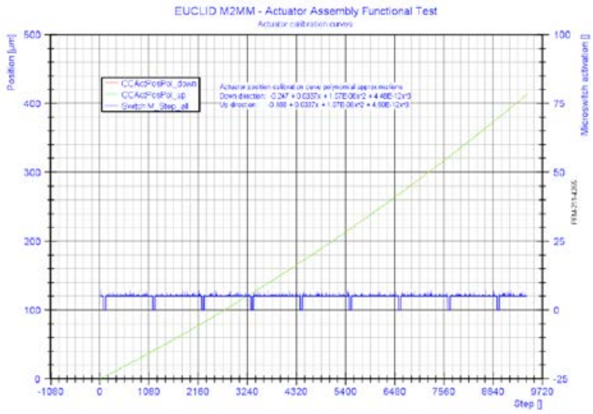

Figure 11 Calibration curve

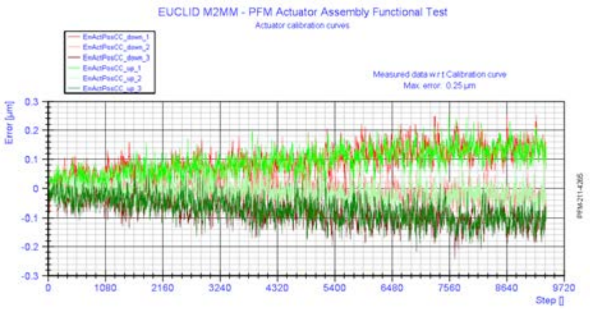

Figure 12 Calculated error

Functional Tests at Ambient

The first functional tests were done at SENER facilities at room temperature, inside the humidity control chamber.

In order to characterize the movement of the M2 mirror dummy, attached to the M2MM, six optical linear encoders were used. Figure 13 shows the test set-up with the encoders inside the humidity control chamber. With this configuration, it was possible to measure the main movement of the mechanism (Z direction & X, Y rotations), and also the small translations and rotations in the other directions due to the cross-talk between axes.

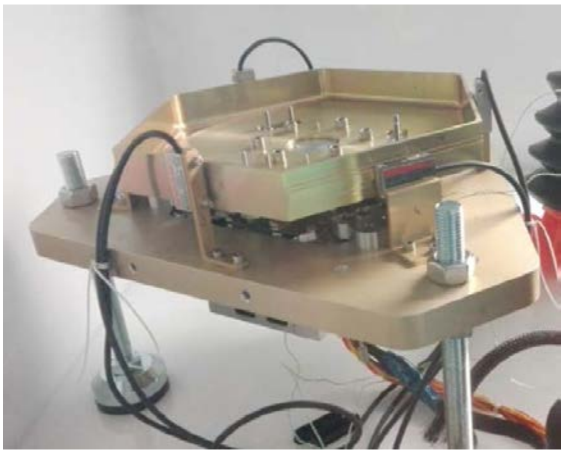

Figure 13 Test set-up for measurement of movement inside the humidity controlled chamber

One of the main objectives of this test was to measure the position of the mirror dummy for each step of the actuators. Therefore, optical encoders with 0.02µm resolution were selected, enough to achieve this goal.

Temperature of the mechanism was continuously monitored during testing with thermocouples, in order to determine the influence of the temperature variations on the measurement of the position.

The main objective of the test was to obtain calibration curves of the mechanism. The calibration curves are calculated via polynomial approximations. The position is measured accurately at several points along the stroke of the mechanism. This allows to stop the mechanism at desired points and to take a longer measurement for best filtering of the vibration.

Six cycles are performed to obtain calibration curves. Calibration curves are calculated as polynomial approximations. The average of six cycles is used for polynomial curve calculation. These approximation curves will differ from the final ones obtained in vacuum with interferometer but they have to be obtained for the predictions of the movements required for the start of the functional tests at M2MM level in thermal chamber. Final approximation curves are obtained during TV tests at M2MM level.

Resolution is calculated as the difference between two consecutive steps, and the polynomial approximation.

Positioning error is the difference between calibration curve and measured data.

During functional test it was also checked that micro-switches are activated at every turn.

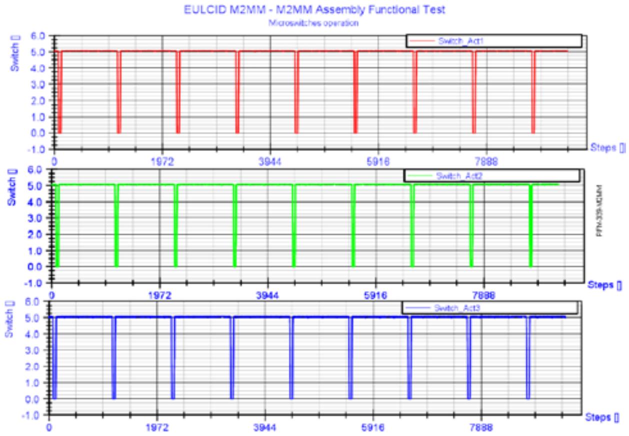

Figure 14 Micro-switches operation along the stroke

Vibration Test

The main goals of the vibration test were the following:

- Determine the first natural frequencies.
- Demonstrate the capability of the item to withstand the expected dynamic environment loads.
- Demonstrate that actuators remain in the same position during vibration.

The M2MM was tested assembled with dummy of the M2 mirror, as in Figure 15.

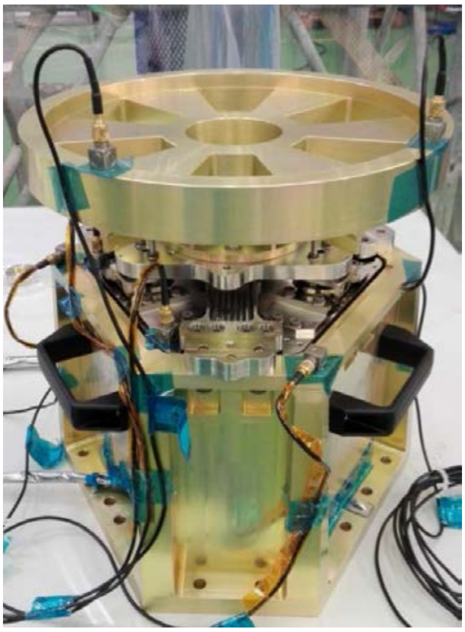

Figure 15 M2MM with mirror dummy installed

The M2MM was covered with a bag purged with 5X Nitrogen during vibration test in order to maintain ISO 5 cleanliness condition.

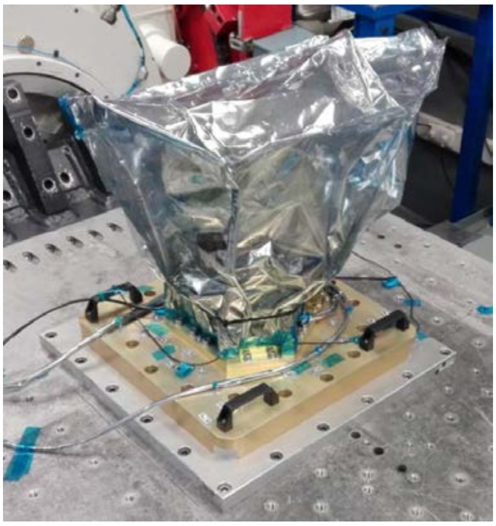

Figure 16 M2MM ready for vibration test

The first resonance frequency of the M2MM was at 161Hz.

During the test, it was also confirmed the good correlation between the predictions of the FEM and the results of the test, as can be appreciated in Figure 17 and Figure 18.

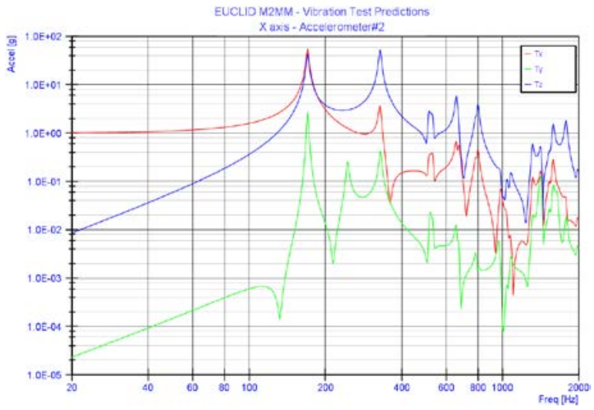

Figure 17 FEM prediction for X-axis low level sine

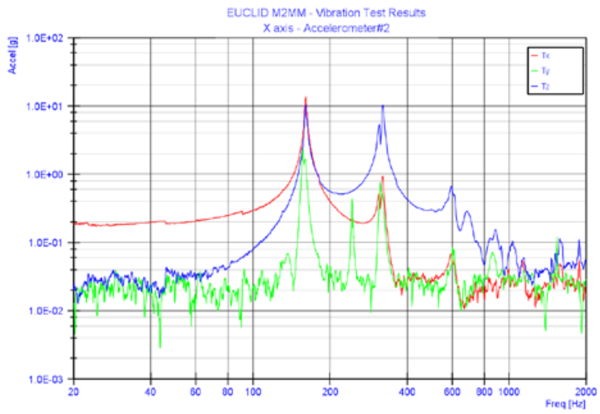

Figure 18 Test results for X-axis low level sine

The main modes in each direction are summarised in Table 2, analysis data and measured data are compared:

Mode	Main direction	Analysis data f [Hz]	Measured data f [Hz]	Diff. [%]
1 & 2	X & Y	165	161	2%
4 & 5	X & Y	309	320	-4%
6	Z	341	336	1%

Table 2 Main modes

Sine qualification level vibration loads are up to 28g in the frequency range of 25Hz to 35Hz and 5g at 140Hz. As the first eigenfrequency (161Hz) is out the sine vibration frequency range, no notching is required during sine qualification level.

Random qualification level are $17g_{RMS}$. The specified input is notched to $14g_{RMS}$ in the fundamental global resonant frequencies, in order to limit the loads in the M2MM Interfaces.

After the test, it was verified that the three actuators of the mechanism remained in the same position during vibration, maintaining the location of the M2 mirror dummy. The actuator is moved downwards and the micro-switches are activated at same step from upper end stop than one recorded during functional tests.

Moreover, it was verified the correct performances of upper and lower end stops of the three actuators.

Functional Thermal Vacuum Test

Thermal vacuum cycling is performed at LINES laboratory at INTA facilities, including one non-operational cycle between 333K and 100K, and three operational cycles between 323K and 100K. Functional tests will be performed at beginning and end of cycling, at 22ºC and at 100K, in order to measure the movement in 6 dof (Z translation, X & Y rotation, and cross-talks displacements and rotation) of the M2 mirror dummy at the top of M2MM. Functional tests at beginning of the cycling will be done to obtain the calibration curves of the mechanism. During the last cycle, functional test will be done to verify the pointing performance with the calibration curves obtained during the first cycle.

The functional measurements at vacuum will be done with optical methods through two of the optical windows of the TV chamber. The following instrumentation will be used:

- Three one-axis differential interferometers to measure translations along principal axes of the mechanism.
- Two electronic autocollimators to measure rotations around principal axes of the mechanism.

There are two main problems for measuring accurately the position: the vibration of the mechanism and thermal effects. The main contribution to the vibration is the thermal vacuum chamber and cooling system. Regarding the thermal effects, the temperature of the M2MM is quite well controlled inside the chamber. These factors are especially unfavourable for the measurements of translations, so as to minimize its impact, two optical cubes will be used: one mobile on the M2 mirror dummy, and one fixed (close to the other) on the test jig to be use as reference for interferometers (see Figure 19). This reference improves significantly the noise and the stability of the measurement of the translations; however, it also increases the difficulty of the alignment of the optical instrumentation.

Figure 19 M2MM ready to install in TV chamber

The purpose of the test is to obtain calibration curves and to verify the torque margin at 100K.

Calibration curves are obtained as polynomial approximations. Same procedure as in ambient functional test is used for calibration curves calculation.

Positioning error also appears in the measurement in vacuum, as the difference between calibration curve and measured data.

The calibration curves obtained during the first thermal cycle will be verified during the last one. In this test, the M2MM is commanded to achieve a set of positions moving the three actuator together with their calibration curves, covering the full range in the three dof of the mechanism. For each position in the set, the error is computed as the difference between measured position and target one.

8. CONCLUSIONS

The EUCLID M2M mechanism is based on the use of the actuator developed and successfully operated in orbit for GAIA mission. However, several challenges have been faced by SENER during the design and test phases of the EUCLID M2MM.

The main design issues were to reduce the thermal loads with a symmetrical design and to reduce thermo-elastic excursion from ambient to 100K.

It must be highlighted the difficulty found during test campaign due to the high resolution of the mechanism and the constraints regarding environmental conditions during functional testing.

9. ACKNOWLEDGEMENTS

We would like to thank the LINES team at INTA, especially Tomás Belenguer and Gonzalo Ramos, for their fundamental contribution to the success of the project, performing the optical measurements to verify the functional performances of the mechanism during thermal vacuum testing.

10. REFERENCES

1. Compostizo, C., Lopez, R. & Rivera, L. (2011). GAIA M2M Pointing Mechanism Qualification. ESMATS 2011.