QUALIFICATION OF EUCLID-NEAR INFRARED SPECTRO-PHOTOMETER CRYOMECHANISM

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ABSTRACT

Already presented at 2015 ESMATS symposium [1], the CEA-Cryomechanism (CM) is a cryogenic rotating actuator that can operate from room temperature down to cryogenic environments, under vacuum or nitrogen atmosphere. In the framework of the Euclid-NISP space program, after having built two bread board model (BBM) units, CEA has undergone the integration of three qualification model (QM) units, among which one unit is going through a full qualification program (the two remaining units are intended to be qualified at upper system level).
The cryomechanism was developed around 20 years ago and has a great heritage from ground based projects (VLT-VISIR). Originally, it included a combination of a stepper motor with a clutch system such as it was a discrete positioning actuator, providing high angular repeatability positioning capabilities (below 10 arcseconds peak to peak) for 360 stable positions a turn. For Euclid-NISP, the angular accuracy and repeatability specifications were widely relaxed after the CM preliminary design review. As consequence, the clutch system was removed from the CM design.
After a short introduction for CM presentation, the paper will show the lessons learns from BBM campaign and the qualification campaign carried out on the qualification units. This tests campaign includes bearings characterization, motion profile measurements, angular repeatability measurements in representative environments (110K, under vacuum), vibrations tests at qualification levels, micro vibrations and exported forces/torques, dimensional controls, thermal cycles, electromagnetic tests, and life-test.

INTRODUCTION

Euclid is an ESA space mission which launch is planned in 2020. The mission aims to study the dark energy content that is responsible of universe expansion acceleration. To achieve this, Euclid uses two major physical phenomena that are the weak gravitational lensing and the galaxy clustering. The Euclid spacecraft will be constructed by Thales Alenia Space and the payload module will be provided by Airbus Defence and Space.
Euclid will be equipped with a 1.2 m diameter mirror telescope feeding 2 instruments: a high quality panoramic visible imager (VIS) and a near infrared photometer combined with a spectrograph (NISP). With these instruments, physicists will probe the expansion history of the Universe and the evolution of cosmic structures by measuring the modification of shapes of galaxies induced by gravitational lensing effects of dark matter and the 3-dimension distribution of structures from spectroscopic red-shifts of galaxies and clusters of galaxies.
Euclid will observe 15,000 deg^2 of the darkest sky in a 6 years period, targeting hundreds of thousands images including billions sources out of which more than 1 billion will be used for weak lensing and galaxy clustering measurements.

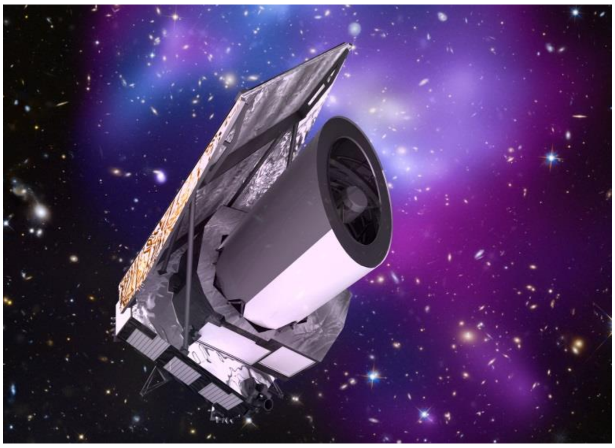

Figure 1: Euclid spacecraft.

The Near Infrared Spectrometer and Photometer (NISP) instrument is managed by LAM (Laboratoire d'Astrophysique de Marseille) and CNES under the global responsibility of the Euclid Consortium. NISP will provide near infrared [1000 and 2300 nm] photometry of all galaxies observed and near infrared low resolution spectra and redshifts of millions galaxies. The NISP data will primarily be used to describe the distribution and clustering of galaxies and how they changed over the last 10 billion years under the effects of the dark matter and dark energy content of the Universe and of gravity.

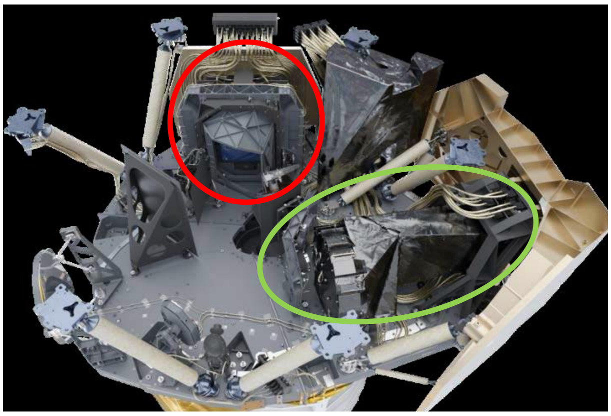

Figure 2: The EUCLID payload module with VIS (red) and NISP (green) instruments

The NISP instrument is made of the focal plane (16 Teledyne detectors, 2000×2000 pixels each) covering a field of view of 0.53 deg^2. The photometric channel will be equipped with 3 broad band filters (Y, J and H) covering the wavelength range from 1000 nm to 2000 nm. The spectroscopic channel will be equipped with 4 different low resolution near infrared grisms, 3 "red" (1250 nm – 1850 nm) and 1 "blue" (920 nm – 1250 nm). The filters and the grims optics are respectively mounted on the filter wheel assembly (FWA) and grism wheel assembly (GWA). Each of these wheels is actuated by a cryogenic actuator so called "cryomechanism" (CM) developed by CEA.

DESIGN

Since EUCLID-NISP preliminary design review, the cryomechanism (CM) design is established. The clutch subsystem, that was presented in ESMATS 2015 paper [1] has been removed as the positioning specification was relaxed (+/-0.3°).
The current design of the CM includes a stepper motor that directly drives the wheel, a set of ball bearings and a reference position sensor. All these components are mounted in a stainless steel frame, which coefficient of thermal expansion (CTE) matches the one of the bearings material. To ensure this, ESA-ESTEC carried out a CTE measurement campaign for various stainless steel and titanium samples.

The CM size is approximately 105mm of diameter, 65mm thickness and its weight is 2.8kg.

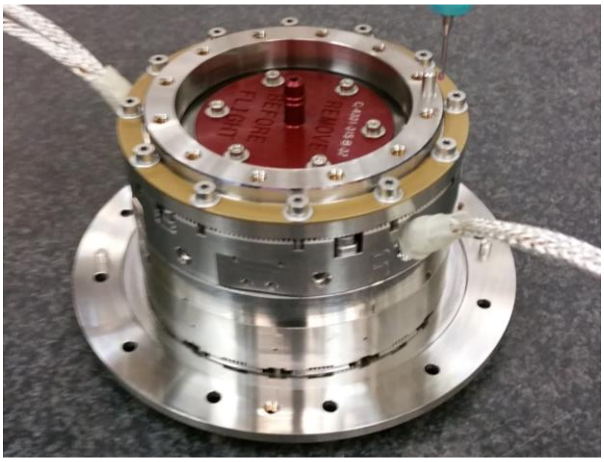

Figure 3: Picture of the CM.

The stepper motor is a 360 steps/rev pan cake motor from SAGEM-DS. This motor provides up to 0.55N.m torque driven with 0.15A/phase (one phase ON). It is driven in microstepping mode with 32µsteps/step resolution. For troubleshooting, the motor can be driven with currents up to 0.21A, resulting in motor torque around 0.7N.m. The detent torque is about 0.045N.m.
The motor has a full cold redundancy as the windings are doubled.

The ball bearings are provided by French company ADR.
The bearings are angular contacts ball bearing in back to back arrangement, with a superduplex configuration: the pair is made with a monolithic outer ring, while there are two separated inner rings.
The rings, as well as the balls are made of 440C stainless steel with MoS2 coating according to ESA recommended process (coating performed by ESR-technology, UK).
The balls separators are PGM-HT cages designed by ADR and manufactured by JPM-USA.
Ball bearings are hard preloaded at the level of ~300N and the cryomechanism design ensures that the bearings clamping force is controlled to be ~2000N.

As the cryomechanism is intended to be an open-loop system, it requires a reference position sensor that allows to discriminate one single step within the possible 360 steps. To achieve this, CEA placed an order to CEDRAT-Technologies to develop an inductive position sensor. The sensor mixes the principle of an Eddy current sensor and a LVDT (linear variable differential transformers) sensor.
This sensor gathers on the same printed circuit board an excitation coil (in blue on Figure 4) overlapped with two detection coils (in pink on Figure 4). The excitation

coils is driven with 500 kHz, 20 mA current and couples equally with each of the detection coils. As the detection coils are wounded opposite and in series, the resulting voltage is null. This PCB is mounted on a stator part of the CM.
An electrically conductive part (in light yellow on Figure 4), screwed onto the rotor part of the CM moves with the rotor and comes in front of the detection coils. Pending on the tooth position with respect to the detection coils, the voltage at detection coils level is high amplitude/in phase, null, or high amplitude/phase inverted with respect to excitation current (red plot on Figure 4 bottom side).
A read-out electronic triggers the home position flag when the phase inversion is sensed on detection coils voltage.

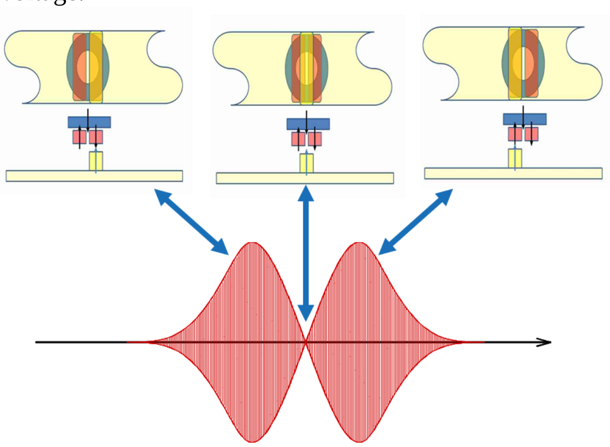

Figure 4: CEDRAT-Technologies reference sensor operating principle. (Courtesy of CEDRAT-Technologies)

The PCB holds two independent sensors for cold redundancy. It is designed to fulfil ECSS rules for PCB design.

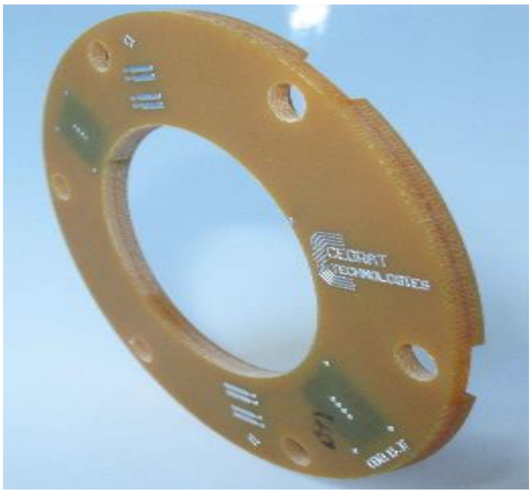

Figure 5: CEDRAT technologies reference sensor picture. (Courtesy of CEDRAT Technologies)

LESSONS LEARNED FROM BBM PROGRAM

CM BBM program has been performed in 2015 and 2016. This section deals with the issues and lessons learned during this campaign.

Ball bearings friction torque

During CM integration process, the ball-bearings are mounted before the stepper motor in order to make the ball bearings friction torque measurement in vacuum conditions, at room temperature and at 110K.
The BBM CM ball bearings are made of 440C stainless steel rings and balls coated with MoS_2 and includes PTFE toroid separators. Preload was initially set to 315N.
Early in BBM program, although friction torque at 293K was nominal, some unexpected friction torque appeared at 110K [1]. Two allegations were made; one was rejected by tests (bad control of bearing clamping force) and the other was impossible to verify with BBM (additional stress on the ball bearings coming from residual stress after machining).
In order to confirm that our investigation has to focus on ball bearings and not on frictions from surrounding mechanical parts, BBM ball bearings were replaced by a set of paired ball bearings, with no preload and made of 440C rings, cages and balls (coated with MoS_2). Friction torque test was performed and showed no difference between friction torques at 293K and 110K.
Our investigation then turned to the material and the nature of the PTFE toroid ball separators.
An order was placed to ADR manufacturer to replace these separators by a PGM-HT cage without changing the other components of the bearing (only a little reduction of the balls number). Preload was set to 327N.
This new bearing was mounted into a CM BBM and friction torque tests were performed.
The mean friction torque at 110K increased by 52% with regards to the 293K value and the peak friction torque increased by 72%. But after 1000 turns of run-in at 110K the mean friction torque value was better than the 293K value and the peak values were only 12% higher. Furthermore all the absolute friction torque values of the PGM-HT cage bearings were lower than the PTFE separators bearings ones.

Table 1 : friction torques comparison

	Mean friction torque (mN.m)		Peak friction torque (mN.m)	
	293K	110K	293K	110K
Bearings with PTFE separators	55	88	94	150
Bearings with PGM-HT cages	35	26	58	65

In conclusion, it was decided to choose the PGM-HT cages instead of the PTFE separators for the continuation of the CM program.

Stepper motor stator clamping

During the BBM campaign, some damages appeared on the mechanical part designed to clamp the stepper motor stator and to cover the CM.

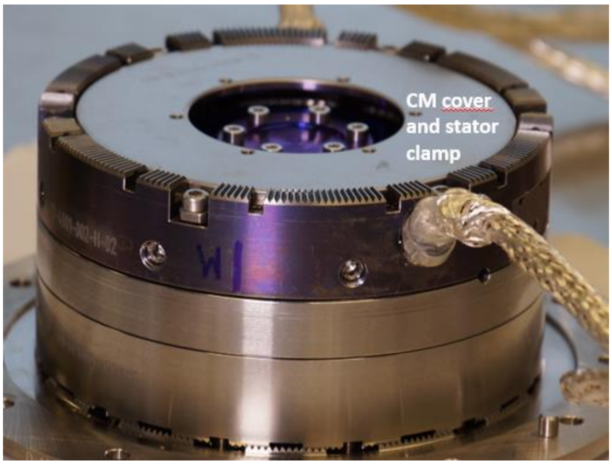

Figure 6: CM BBM with its cover

Two of the little legs that allows the part fixation on CM body have been broken during mounting and dismounting operations.

Figure 7: Two legs broken

Investigations have highlighted that this part endures a great clamping force on little legs as it maintains the stepper motor stator in place. Moreover, the mechanical clearance was such as the “leg” elastic limit can be exceeded. During BBM AIT activities, the cover had been mounted and dismounted too many times. It was decided to move from one mechanical part to two, in order to separate the CM covering and the stator clamping functions.

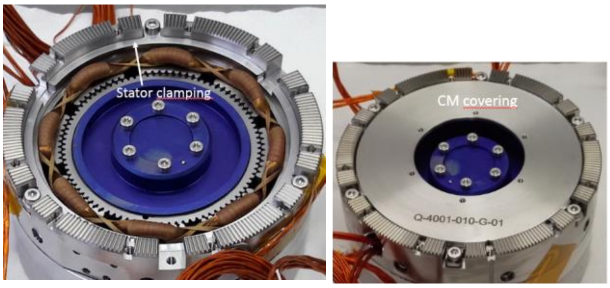

Figure 8: On QM model, one part for stator clamping and another for CM covering

New parts have been tested with success on QM models.

CM materials

In order to avoid some differential dilatation issues, the BBM CM mechanical main parts were made of 440C stainless steel which is the same material than the ball bearings rings.
According to ECSS standards, the 440C stainless steel has a low resistance to stress-corrosion cracking. In order to meet standards and considering the broken parts issue described above, CM team decided to modify the CM main material.
The 440C was replaced by 15-5PH H1025 stainless steel. This material has a CTE closed to the ball bearings rings one (11 µm/m.K for 15-5PH, 10.2 µm/m.K for 440C at 293K) and is in line with ECSS standards if it is hardened above 538°C (1000°F). In addition, the steel parts are immerged in liquid nitrogen before final machining. This ensures that all thermomechanical deformations already occurred when the parts are finished.
This new material was not tested on CM BBM but used on CM QM with no negative impact on mechanism.

QUALIFICATION PROGRAM

Performances

The QM campaign includes some CM performances tests. During these tests, motion profiles are tested and CM positioning repeatability is measured at 293K under vacuum conditions and at 110K.
In order to perform these tests, the CM is mounted into a cryostat and loaded with a representative wheel (6.76kg - I_{zz}=0.188kg.m^2). The wheel supports an optical encoder on its periphery that allows to know the wheel position with an accuracy better than 1 arc minute.

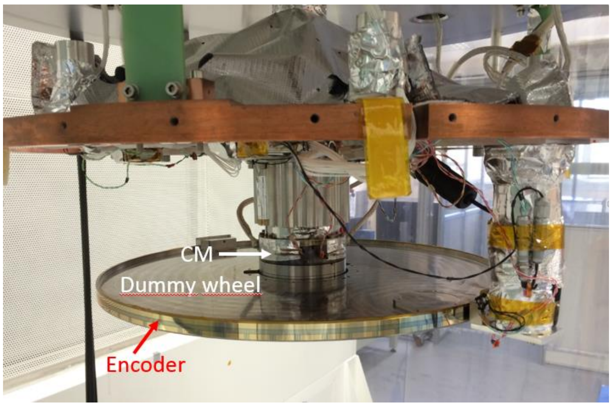

Figure 9: CM and its wheel installed in cryostat

Motion profile

The goal of these tests is to check that the CM fulfilled the NISP instrument specifications listed in Table 2 in terms of motion profiles.

Table 2 : Motion profiles specifications

	Specification	Tested
Accuracy of final position	±0.3°	
Max acceleration	0.3 rad/s²	0.314 rad/s²
Max velocity	0.7 rad/s	0.628 rad/s²

Nominals motion profiles are 144° and 72° movements done in 10 seconds, nevertheless tests are performed with movement duration from 4s to 12s for 72° and from 7 to 12s for 144°.
Different stepper motor currents have also been tested: 0.15A as nominal current, 0.21A for the boost mode and 0.05A as the lower current to perform the movement without any step loss (to prove that the motion can be performed without any step loss with a 2-factor of additional margin).

Results are good; for any combination of these parameters (motion angle, velocity & acceleration, current and temperature), the rotation is completed without step loss with a final position within ±0.1°.

In addition to these results, tests data have been explored in order to search the motion parameters (velocity and acceleration) that minimize the accelerations caused by the 3Hz mode. This natural mode is created by the stepper motor angular stiffness coupled to the wheel inertia [1]. This work is important as accelerations caused by 3Hz mode are affecting the motorisation margin.
As conclusion, the rotation profiles that are considered as baseline for EUCLID-NISP are listed in Table 3.

Table 3: Motion profile for EUCLID-NISP

	72° movement	144° movement
Duration	10s	10s
Max speed	0.139 rad/s	0.314 rad/s
Max acceleration	0.157 rad/s²	0.157 rad/s²

Positioning repeatability

The goal of this test is to check that the CM fulfilled the angular positioning repeatability specification (±0.3°) on 3 different positions reached after a movement of 72° or 144° repeated 100 times.

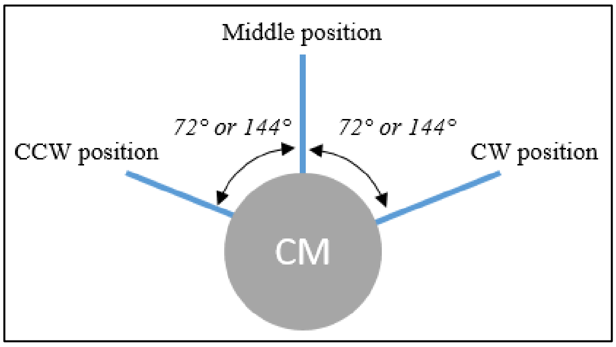

Figure 10: Angular repeatability test

The middle position is reached alternatively clockwise and counter clockwise. The extremity positions (CCW and CW positions) are reached always by the same orientation. Only the middle position angular repeatability results are presented as it is the worst case.
This test is performed several times during QM pre-delivery phase: at 293K and 110K, before and after vibrations test.
Results in Table 4 show that the CM angular repeatability fulfilled each time the ±0.3° specification (by a factor 4 at worst).

Table 4: Angular repeatability test results

	Angular repeatability of QM 3	
	72° motion	144° motion
At 293K	±0.03°	±0.03°
At 110K	±0.04°	±0.07°
At 110K after vibrations	±0.03°	±0.06°

Vibrations

As 2 flight models are required, one for driving the filters wheel and the other one for the grism wheel, it was requested to have a unique specification document for both wheel.
In addition, a vibration test wheel was built in agreement with both teams to be representative of the grism and filter wheels.
A finite element model was created for the test wheel

coupled with the CM. This model, allowed to identify the main modes. A second model, using the “RBSDYN” software was created with the help of CNES mechanism expert to focus on the bearing stress and particularly on the Hertz pressure at balls to tracks interfaces. The combination of these two models gave a good level of confidence in the modal analysis. As results, a primary and a secondary notched were requested to the upper level (NISP instrument). These notches were based on two limiting factors: on one hand, they intend to limit the Hertzian pressure to 3600MPa for the in-plane vibration and to 3200MPa for the out-of-plane vibration; on the other hand, the notches aimed to limit the accelerations at 100g at the pseudo-optics locations.

Figure 11: Picture of the CM loaded with the vibration test wheel, which supports pseudo optics (metallic discs replace glass parts)

The vibrations tests were carried out cumulating the qualification levels and durations with the acceptance levels and duration. This choice was driven by the fact that the CM is a sub-system and flight units will be tested once again at upper level.
The vibration results showed a very good correlation with measured modes and predicted ones, as shown in the following table.

Table 5: Comparison of measured and predicted modes.

Direction	Measure (Hz)	FEA (Hz / %M)
X first mode	482 520	470 / 17 520 / 10 522 / 46
Y first mode	465 511	469 / 18 520 / 45
Z main modes	183 709	190 / 42 753 / 27

At the end of vibration tests, low level sinus were performed and highlighted some shift in the amplification factors between initial and final vibration tests. It is important to highlight that frequencies always remain stable. This phenomena was also observed on the 2 previous QM models and previous BBM models. The shift of amplification factors was deemed to be the consequence of the ball-to-track contact changes. As the wheel is not rotating during test, it might be possible that the MoS_2 coating locally compresses changing the bearings damping factor. As soon as the mechanism is actuated, the cage to balls and balls to tracks MoS_2 transfers operate and the system recovers original characteristics.
As it is written in the “performances” chapter, the CM performances were not affected by vibrations tests.

Electromagnetism

An electromagnetism test has been carried out on the qualification unit. As the CM is mainly a passive component, and because of the time constant of the stepper motor or temperature probe, is was agreed with the NISP project to have limited bandwidths for the different tests. The following measurements were performed:

- conducted emission in [100kHz; 100MHz] range,
- radiated emission in [30Hz; 30MHz] range,
- radiated susceptibility in [50kHz; 5MHz] range,
- conducted susceptibility in [50kHz; 5MHz] range,
- electrostatic discharge: 15 discharges with 15mJ/15kV pulses with repetition rate from 0.1 to 1 Hz.

The conclusion of EMI/EMC tests is that the CM is not affected by radiated or conducted susceptibility. Neither the stepper motor nor the reference sensor reacts to external perturbations. Both conducted and radiated emission measurement have shown full compliance to ECSS requirements; only a low level emission line at 500 kHz from the reference sensor was recorded

Thermal cycling

One of the CM QM has been exposed to 8 thermal cycles, which is thermally representative of the pre-lunch operations. A thermal cycle includes a first heating from 293K to 323K, a cool down to 110K and a warm-up to 293K.
Performances tests have been made before the cycles (293K), once at 323K, once at 110K and after the cycles. Performances are each time within specifications (no step loss during motion profiles and within ±0.3° of angular repeatability).
Furthermore, additional thermal cycles (40 cycles from 105K to 323K) have been performed with success at components level: reference sensor PCB, crimped contacts of connectors and SAGEM rotor gluing on CM rotor.

Life test

Facing planning constraints about flight models delivery milestone, combined with the overall duration of the life-test (1.6 million motions to run) and aiming to minimize the risk, it has been decided to split the life test in two separated tests.
As a first stage, a "simplified" life test has been subcontracted to ESR-Technology. This test aimed to get preliminary results in a couple of months.
The second stage of life test will use the CM QM which has already undergone thermal cycles, vibrations at qualification level and which performances have been checked.

The ESRT "simplified" test was intended to run a superduplex ball bearings at 120K for 1.6 million of 144° actuations. The so-called "simplified" test used a flight like bearings pair in a representative housing and shaft set-up. Thus, the test set-up used the same bearings design, preload, MoS_2 coating, housing and shaft clearances and clamping system.
When the CM will be in operation, the stator will slightly warm up under stepper motor dissipation, making the bearings preload increasing.
In ESR-technology simplified test set-up, the stator is cooled down by cryogenic fluid. In order to make the thermal corresponding increase of the preload, it was decided to make the internal ring rotate and the external ring static. Thus, the cooling process has the same effect in the simplified test that the stepper motor warming up in the real CM.

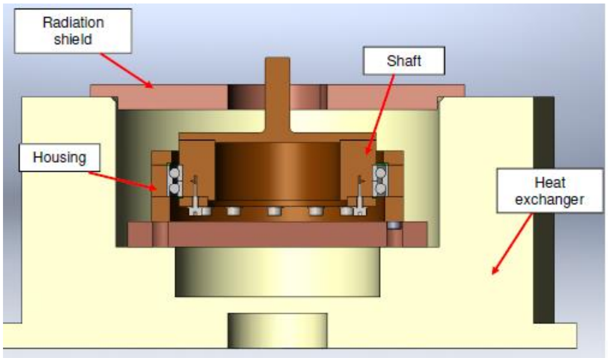

Figure 12: ESRT simplified test set-up

The ball bearing preload and friction torque were measured before starting the life-test.
The life test consisted in running the rotor for 5 actuations of +144° in 3 seconds, with 0.1 s rest in between followed by 5 actuations of -144° with 0.1s rest in between. This 10 actuations loop was repeated 160,000 times under vacuum, at temperature around 120K, leading to 1.6 million 144° actuations.
All along the test, the friction torque was monitored, providing a rough information about the bearings health ("cycle" plots in Figure 13). From time to time (14 occurrences along the test duration), the friction torque was accurately measured making the rotor moving 2 turns CW, 2 turns CCW, 2 turns CW and 2 turns CCW at 2 rpm. The associated measurements are shown as "reversal" plots in Figure 13.

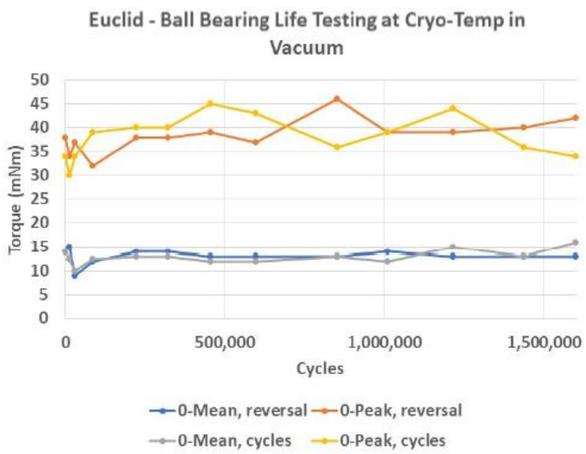

Figure 13: Summary of friction torque measurements along the life-time test

The major outcomes of this simplified life-test are:

- the bearings friction torque remained stable all along the test;
- the preload measurement didn't show modification before and after the 1.6 million actuation.

In addition, detailed inspection showed that all balls, tracks and cages were in good conditions. No wear occurred on steel parts. The cages didn't show significant wear out. All these statements give confidence in the fact that the life limit was not about to be reached.

At the time when this paper is written, the life-test operated on the CM QM has not started.

CONCLUSION

After a one year BBM campaign mainly dedicated to resolve bearings friction torque issue, the QM campaign has been realized in 6 months for 3 qualification units without any major issue.
Thanks to this campaign, we now feel confident that the CM performance requirements can be satisfied at the end of the lifespan test.

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[1]: JC Barriere et al., "Cryomechanism: a cryogenic rotating actuator", Proceedings of ESMATS 2015, Bilbao.