CRYOMECHANISM: A CRYOGENIC ROTATING ACTUATOR

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ABSTRACT

Initially developed for a ground based astrophysics instrument in the late nineties, the Cryomechanism (CM) was upgraded in order to cope with space environment as parallel activity to the JWST-MIRIM project.
The cryomechanism performs discrete rotation motions with an angular resolution of 1 degree for a 360° range and a positioning repeatability better than 100 microradians. It operates from room temperature down to cryogenic (20K) conditions, under vacuum or nitrogen atmospheres.
With the support (Centre National d'Etudes Spatiales), CEA (Commissariat à l'Energie Atomique et aux Energies Alternatives) started a space development program in 2011, leading to two flight models delivery in 2017 for the Euclid-NISP space instrument.
The submitted paper will give a presentation of the Euclid-CM design and operating principle. Then the results of ongoing tests will be described.

INTRODUCTION

Euclid [1] is an ESA space mission which launch is planned for the beginning of 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 satellite will be constructed by Thales Alenia Space and the payload module will be provided by Airbus Defense 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 year 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.

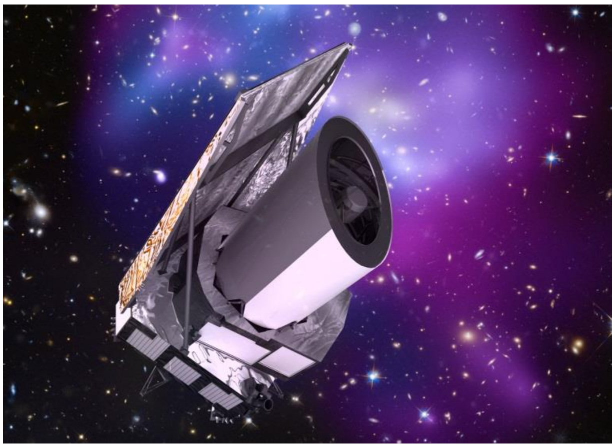

Figure 1: Euclid spacecraft.

The visible (VIS) instrument is managed by MSSL () under the global responsibility of the Euclid Consortium. VIS images all galaxies of the Euclid survey with very high image quality. It will be used to measure the shapes of galaxies and derive the gravitational lensing effects induced by large scale structures of the universe on galaxies. The VIS instrument is made of different subsystems that are the large scale focal plane (36 CCDs, 4096*4096 pixels each), the calibration unit, the shutter unit, the control and data processing unit and the power and mechanism control unit. The VIS instrument will have a field of view of $0.57deg^2$.

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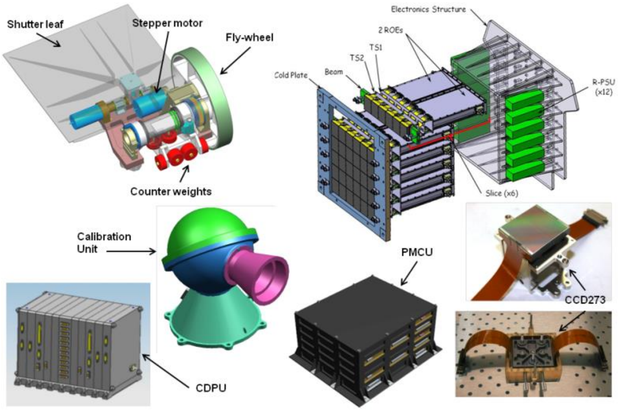

Figure 1: Vis instrument subsystems.

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. Combined with VIS images, NISP will provide near infrared (between 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.

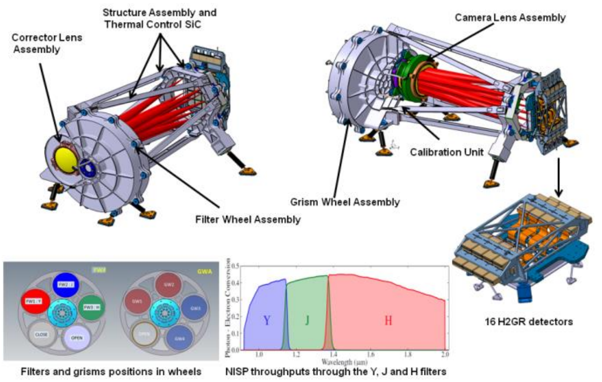

Figure 2: the NISP instrument

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 shared with VIS. 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 with a mean image quality of about 0.3 arc-second. The spectroscopic channel will be equipped with 4 different low resolution near infrared grisms (R=380 for a 0.5 arc-second diameter source), 3 "red" (1250 nm – 1850 nm) and 1 "blue" (920 nm – 1250 nm), but no slit ("slitless spectroscopy"). 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 the help of the cryogenic rotating actuator so called "cryomechanism" (CM) developed by CEA.

BACKGROUND

The history of the cryomechanism [2] started in the late nineties when CEA was involved in the construction of an imager/spectrometer for the Very Large Telescope in Chile. In the frame of the VISIR project (VLT Imager Spectrometer for mid Infra-Red)[3], CEA started the development of cryogenic actuator to rotate the optical wheels inside the cryostat. The research and development program for CM started with the association of industrial products with the aim of making a simple and robust design. The foundations of the CM stands on few key parts: a stepper motor providing the motion, ball-bearings supporting and guiding the load and an industrial electromagnetic clutch system. After mechanical engineering studies and few mockups, CEA produced the first CM in the frame of the VISIR project in 2002. The CM was tested in cryogenic conditions and showed repeatability in the range of 20arcsec down to 20K, under ~$5x10^{-6}$mbar vacuum.

At the time of the VISIR first light in 2004, 10 CM were present in the instrument. Today VISIR is still operating and the CM that are actuated several times a day, have no reported failure up to now.

Few years after VISIR fist light, CEA decided to improve the CM design in order to get ready for space missions [4], with a funding support from the French space agency CNES.

Relying on the results from VISIR tests and from observation campaigns, the cryogenic and vacuum environment compatibilities, as well as the reliability requirements were fulfilled. With respect to infrared astrophysics ground devices, the major change that has to be implemented deals with the compatibility with vibrations induced during the spacecraft launch.

In 2008-2009, CEA was in charge of the delivery of the Mid InfraRed IMager (MIRIM) for the James Webb Space Telescope (JWST). In this device, the mechanism to rotate the filter wheel [5] was under the responsibility of Max Planck Institute from Heidelberg. The MIRIM filter wheel is made of aluminum and has a mass around 1 kg, a moment of inertia of $1.1x10^{-2}$ kg.m² and holds 18 optical elements. When mounted on the rotating mechanism, with its interface and its support, the filter wheel becomes a Filter Wheel Assembly, further noted FWA. The FWA specifications were used as baseline for the CM test campaign including:

•the ball-bearings friction torque measurement,
•the positioning repeatability,
•thermal cycles from room temperature down to 80K and back to room temperature with a 15K/h average

slope,
•vibration tests at MIRIM qualification levels,
•a life-test carried out on 150,000 randomized motions,
•a verification of the ball-bearings friction torque and the angular positioning repeatability.

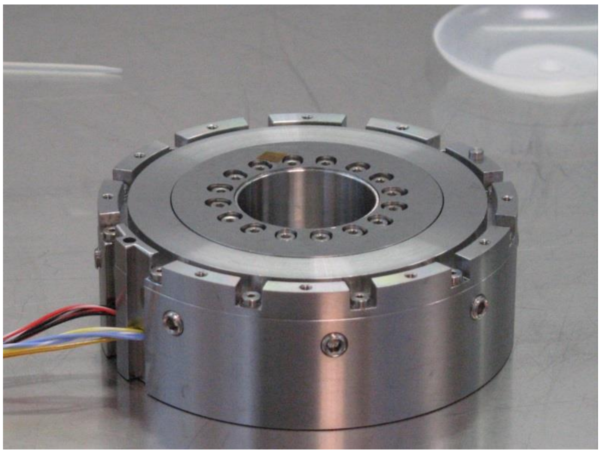

Figure 3: the MIRIM type cryomechanism (100mm diameter)

In the MIRIM CM design, the ball bearings are soft-preloaded and the stiffness of the elastic flange, providing the bearings preload has been optimized to limit the balls gapping. At the second vibration test campaign, the CM modes were checked by sinusoidal excitation in [5Hz; 2000Hz] range. The FWA main modes are at300 Hz, 344 Hz, 950 Hz, 1050 Hz, 1200 Hz and 1974 Hz. These patterns do not change after random vibrations at 13.6 g rms in the X, Y and Z directions, neither in terms of in frequency modes (<10% different), nor in terms of amplification factors.
In 2009-2010, CEA took the opportunity of infrared camera CAMISTIC to develop a small scaled version of the cryomechanism (see *Figure 4).* This model was also tested in cryogenic conditions (20K) and showed the same level of repeatability (<10 arcsec).

Figure 4: CAMISTIC type cryomechanism (65mm diameter)

In 2011, CEA was officially selected to provide the mechanisms to rotate the filter wheel and the grism wheel of the Near Infrared Spectrometer Photometer (NISP) instrument for the Euclid space project.

SPECIFICATIONS

Among the hundreds specifications that applies on Euclid CM, the following ones are extracted to highlight the needs of improvements in the CM-design with respect to the previous models. When compared to MIRIM filter wheel, the Euclid wheels mass increased by a factor 6 and the inertia increased by a factor >10.

Wheel mass	6.8kg
Wheel inertia	0.16kg.m²
Operating T (margins included)	313K-110K
Design limit load	35g
First Eigen frequency with concentrated mass.	>150Hz
Random PSD	9.6grms
Qualification sinus	+/-27mm [5-15Hz] 25g [15-100Hz]
Positionning capabilities (repeatability) before PDR	0.3arcmin
Positionning capabilities (repeatability) after PDR	0.3deg
Life time (for a 6 year space mission)	~6000 motions on ground ~1,000,000 motions in orbit

Table 1: extract from CM-specifications

At preliminary design review, the specification on positioning capabilities was largely relaxed from 0.3arcmin to 0.3degree; it was then decided to remove the clutch from the CM design, as its presence in the CM was no more needed to fulfill the requirements and it could represent a single point of failure. Nevertheless, the present paper includes the clutch test results. The following chapter will detail the clutch principle.

DESIGN, WORKING PRINCIPLE.

The cryomechnism is designed to operate from 300K down to 20K under vacuum. It rotates a load (optical wheel) at any of the 360 discrete positions (1 stable position/degree) and has around 100µradians repeatability on each of them. The wheel is directly couple to the CM rotor, without any gearbox in between. The CM operates in open loop drive.
It is based on few key elements mounted in a stainless steel frame (see *Figure 5*):

- stepper motor: SAGEM 35PP space qualified motor, 360steps/rev,
- hard preloaded superduplex angular ball bearings from ADR,
- clutch system with Hirth gears (360 teeth/rev),
- monostable electromagnet + bellows: the

electromagnet allows releasing the clutch with a peak of current and the bellows allows closing the clutch without power consumption,
- athermal interfaces: the stainless-steel frame is able to match any wheel or structure material by the help of specific interfaces based on Hirth gears couplings.

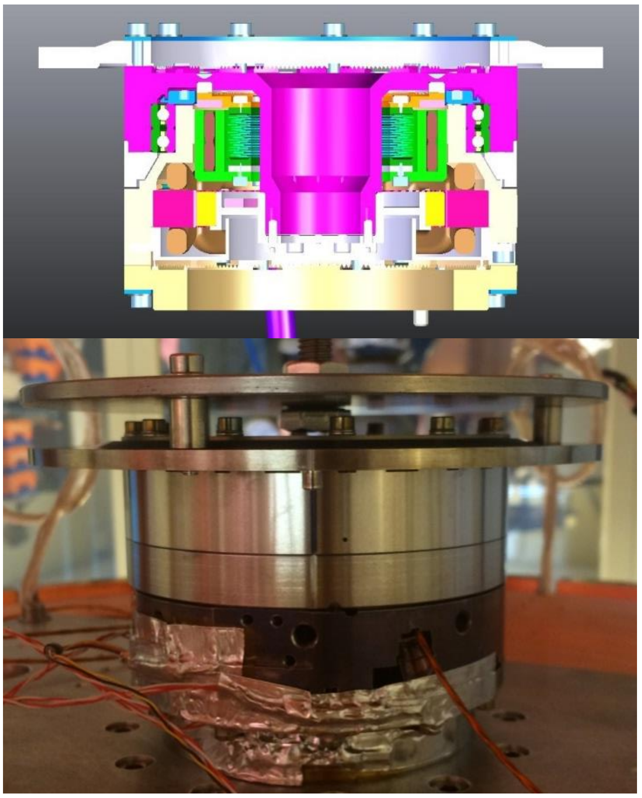

Figure 5: CAD cut view and picture of the Euclid cryomechanism

In the CM, the rotating parts are:

- permanent magnet of the stepper motor,
- outer tracks of the bearings,
- shaft of the mechanical housing associated to Hirth gear.

The static parts are:

- inner tracks of the ball bearings and their housing,
- clutch electromagnet,
- stepper motor stator and its housing.

Some other parts link the rotor to the stator in stand-by modes: clutch Hirth gear and bellows; they have pure translation motion.

Operating principle

When running, the cryomechanism is the association of 2 « motors » mounted in series. The stepper motor performs a coarse positioning, rotating the wheel at any of the 360 positions within few arcmin of accuracy. During this motion, 5 degrees of freedom (DOF) are locked by the bearings assembly. The only DOF which is free, is the rotation around bearings axis.
When arrived at required position, the clutch closes under the spring action of a bellow, performing a fine positioning with very high repeatability. As the clutch gear is mounted on a bellow, its motion can be considered as a pure translation. The bellow has very high stiffness in torsion and is quite flexible in translation. Closing the clutch allows to lock the last degree of freedom; the wheel is then completely immobilized.
The typical sequence for a motion is described by the following sequence:

- open the clutch (Power the clutch coil ON),
- power the stepper motor ON,
- drive the stepper motor to rotate the wheel at required position (motor ON, clutch ON),
- close the clutch (power the clutch coil OFF),
- power the stepper motor OFF.

The CM is powered only while actuation is required. When not operated, during observations, storage periods or during launch, the cryomechanism is fully OFF. This OFF state is the most common status in a CM life.

TEST PLAN

The development plan includes early mock-up tests at component levels. They concern the athermal interfaces, the bearings friction torque measurements and an accelerated life-time test for the clutch gears; some details are given hereafter. Once these tests are over, the CM development plan breaks down into a full functional model (Bread Board Model, BBM) that will be intensively tested in operating conditions. The test results of the BBM will trigger the manufacturing of the qualification models (2 QM) in parallel with the electrical model so-called AVM and finally the flight models and flight spare (2 FM+1 FS)

Tests at component level

The Hirth gear couplings are used in the CM design at the clutch level as well as at the athermal interfaces level. The principle of the Hirth gears shape is that the teeth are cut radially with a unique convergence point (top of the teeth and teeth grooves are oriented towards the same central point, see Figure 6).
When a gear enlarges or shrinks under thermo-elastic effects, the dimensional changes are homothetic from the convergence point. Even if the gear overall dimension changes, the teeth profile is invariant at a fixed radius. Consequently, two gears made of two different materials will shrink different but the teeth coupling will be kept unchanged. This principle has been verified by coordinate machine measurements of 440C steel gears coupled with aluminum, titanium and invar gears, at different temperatures.

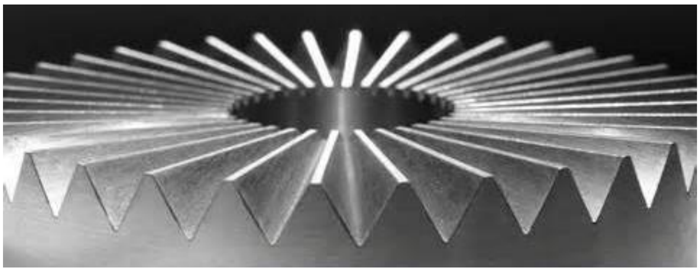

Figure 6: typical Hirth gear.

For the Euclid-CM, the Hirth gears, as well as the whole set of CM mechanical parts have been accurately machined by DMP company in Spain. The positioning capabilities of the CM are strongly coupled with the gears manufacturing precision and DMP succeeded in very thin teeth machining.
In order to build the seven models of CM that are required for the Euclid development program, ending by the flight spare model, CEA bought a unique set of 10 superduplex ball bearings from ADR. Each of the 10 ball bearings has been measured by ADR under nitrogen atmosphere before being delivered to CEA; the measurements include friction torques (average and peaks values) as well as the preload measurements. During ball bearings integration in the CM housing structure, the friction torques are measured at room temperature and then under cryogenic environment.
The lifetime requirement that applies on the CM for Euclid space mission is quite stringent. One of the wheels has to be operated for ~950000 motions (72° or 144°) in flight, preceded by ~6000 motions on ground for acceptance tests. When the ECSS coefficients are applied, the lifetime, including margins, results in 1,515,000 operations in the worst case. If such life-time seems not unfeasible for the ball bearings, it was never proved for the clutch gears that releases and engages once every motion. It has been decided to build a simplified model of the clutch assembly to demonstrate the life-time requirement is fulfilled.

Full CM tests.

The BBM will be the first operational cryomechanism built in the frame of Euclid-NISP development plan. This BBM aims to verify the tribological issues at bearings and clutch level. To achieve this, it is scheduled to perform a life-test including ECSS margins on the BBM (total 1 515 000 actuations). As this life test is expected to cover the qualification program, it will be preceded by thermal-vacuum and vibrations tests. To sum-up, the BBM pre-qualification program should cover:

- torque measurement at room temperature (RT) and operating temperature (OT),
- clutch peak/hold currents,
- functional tests at RT (repeated at each major stage of the test program),
- functional tests at OT (repeated at each major stage of the test program),
- motion profile measurements at RT and OT,
- repeatability measurements at RT and OT,
- exported torques measurements at RT,
- bake out,
- Thermal balance, thermal cycles,
- sine and random vibrations at qualification ,level
- life-test,
- EMI/EMC.

TEST RESULTS

This chapter will give the main results obtained during the test campaign performed on the BBM up to this paper edition. The test campaign is still on going and only followings tests results will be commented in this article:

- accelerated lifetime test for the clutch mock-up,
- ball bearings friction torque measurements,
- motion profile measurement,
- exported torques and forces measurements.

Accelerated lifetime-test.

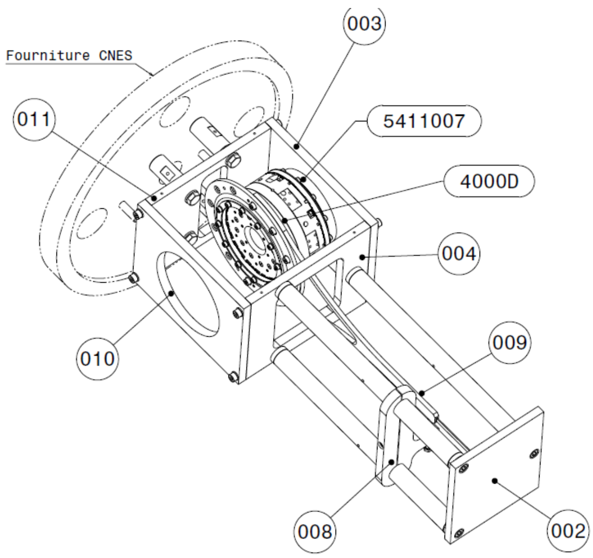

Figure 7: clutch accelerated life time test set-up.

A CM mock-up is created using the CM housing with a set of ball bearings from Kaydon and the whole clutch subsystem. This partially integrated CM is loaded with an unbalanced level arm creating a 0.1N.m constant torque at rotor level. The level arm motion amplitude is restricted by the help of hard stops such as the rotor cannot move more than one half degree when the clutch is released. The test consists in driving the clutch electromagnet to release the clutch, let the rotor move by half degree under gravity effect and then engage the clutch while the rotor clutch gear position is mis-aligned with respect to the stator clutch gear. When it engages, the clutch gears forces the rotor to come back at the original position.

The clutch has been operated for 1.5 million operations under vacuum (5.10^{-7}mbar), once every 2 seconds. At the end of the life-time test, the CM has been kept static under vacuum for 50 days, and then operated again for 10 times. This second batch of operations aimed to highlight potential cold welding effect. This didn't occur. After the 1.5 million motion completed, the clutch was dismounted for gears inspection. As shown on Fig.*Figure **8***, some dusts were visible in the internal volumes surrounding the gears zone. The dusts seem well encapsulated and didn't migrate outside the CM housing. It was quite difficult to state about direct metal to metal contacts, CNES material experts are going to make detailed inspection and dust analysis. Once again, the most important result is the capability of the clutch to survive 1.5 million operations without cold welding.

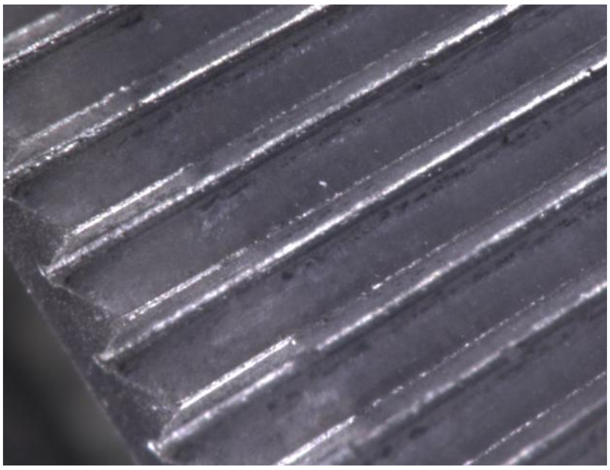

Figure 8: zoom on the clutch gears after the 1.5 millions cycles completion.

Ball-bearings friction torque measurement.

During CM integration process, the ball-bearings are mounted before the stepper motor and the clutch sub-system. The integration is then interrupted to make the ball bearings friction torque measurement in vacuum conditions, at room temperature and at 110K.

The test facility is equipped with an in-line dynamic torque meter that is located outside the vacuum vessel and measures the torque of bearings that are placed inside the vacuum vessel. The measurement device is linked to its load by a transmission shaft and a hermetic feedthrough. With this set-up, the data are the sum of the load friction and the feedthrough friction.

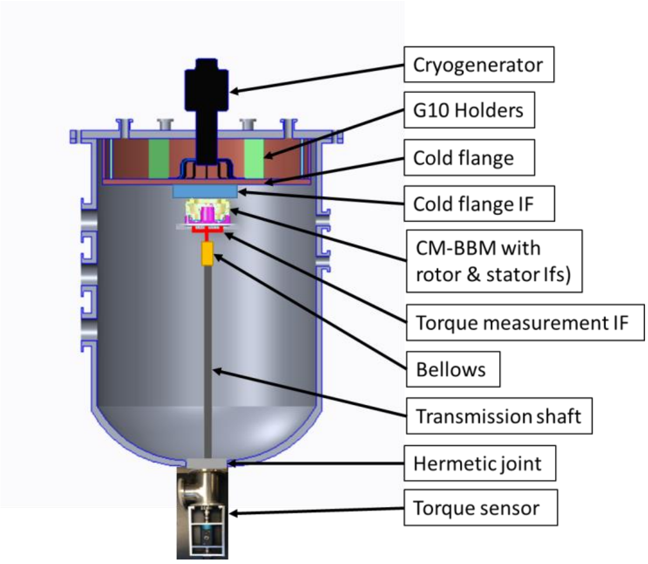

Figure 9: ball bearings friction torque measurement set-up.

The ADR ball-bearings, dry-lubricated with molybdenum disulphide, have been measured at room temperature under nitrogen atmosphere (same condition than ADR measurements). The average friction torques measurements show very similar values than what ADR got in their facility. When the nitrogen is pumped and the bearings are under vacuum, the results don't change. Both average and peak values are in line with ADR ones.

At cryogenic conditions, some unexpected friction torque appeared. From 50mN.m average friction, the cryogenic friction torques were measured at around 75mN.m. As the CM body is made of the same steel than the ball bearings themselves, it was expected that thermo-mechanics don't affect the bearings behavior.

Today, two allegations were set to explain the friction torque increase.

The first one is some additional stress on the ball bearings coming from residual stress after machining. It seems that the stress relief heat treatment (one cycle from room temperature down to 77K by liquid nitrogen immersion and back to room temperature under natural exchanges) that was applied on the mechanical parts was not efficient enough to stabilize the steel before final grinding. For future models, materials will be set such as the stress on ball-bearings will decrease at cryogenic condition with respect to room temperature. In addition, a special care will be put on the material thermal stabilization.

The second possible cause is that the tolerances on mechanical parts are such as the bearings clamping force strongly increases as the temperature lowers. Action has been taken on the design for better control on the mounting tolerances.

Motion profile measurements, exported torques

In the Euclid-NISP configuration, the CM is loaded with “heavy” wheel which inertia is much greater than the stepper rotor inertia. As consequence, the wheel motion is affected by a natural mode which frequency is driven by the wheel inertia and the motor angular stiffness ratio. Applied with FWA and GWA inertia, this mode is expected at around 3Hz.

Both motion profiles measurements and exported torques measurements were operated on the CM. In the first case (motions), the CM is loaded with an invar disc, supporting an optical encoder on its periphery. The wheel assembly is then fixed onto the cold flange of the cryogenic tests facility. The optical encoder readout is sampled at 100Hz while the CM is driven according to different motion profiles. The test is operated at room temperature, under vacuum, and then repeated at cryogenic conditions.

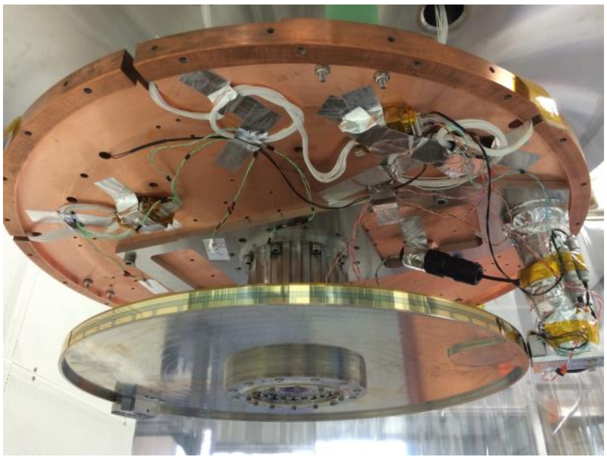

Figure 10: CM equipped with the encoder wheel, in the motion profile measurement configuration

The tests results show that the 3Hz mode was higher than expected, especially at cold temperatures. The main reason for that is linked to the ball bearings friction increase at cryogenic temperatures. When the motor currents are driven to start the motion, the wheel stay static until the motor torque is greater than the bearings starting torque. As soon as the torque provided by the motor exceeds the starting friction, the wheel motion starts suddenly. This phenomenon initiates the 3Hz oscillations that are not damped until the end of the motion.

Moreover, it was proven that the motion profile has a great impact on the 3Hz mode behaviour. Typically, if the speed profile is very smooth, the electrical signal that are driven into the motor coils excite the 3Hz mode and makes the oscillations larger. When the motion duration is shortened, the 3Hz mode is crossed quicker and the 3Hz oscillations are divider by factor 2.This is illustrated on *Figure 11* and *Figure 13*, where a motion of 72° is performed within 8 seconds and 4 seconds respectively, according to a sine velocity profile. For future tests, improvements of the 3Hz mode behaviour will be focused on the motions profile parameters

These motion profile measurements results were confirmed by exported torques measurements performed on a Kistler table at CNES-Toulouse facility. In this test set-up, the CM and its wheel are mounted on the top of the measuring table. The CM is driven to perform 72° and 144° motions according to different motion profiles. The reaction forces on the table are measured by the help of 8 piezo sensors which data are recombined to provide exported forces and torques in an orthonormal frame.

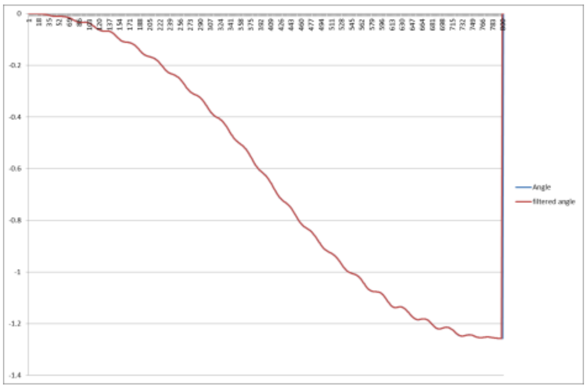

Figure 11: angular position measured during one 72° in 8 sec wheel motion.

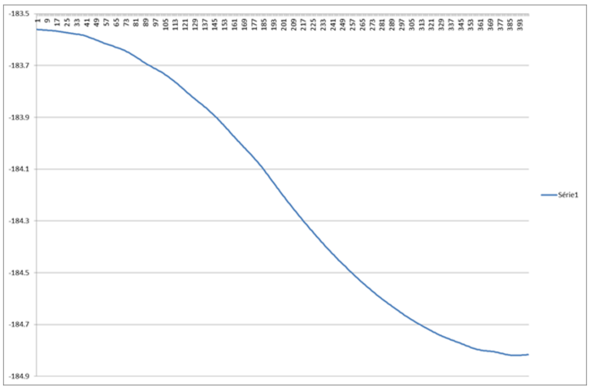

Figure 12: angular position measured during one 72° in 4 sec wheel motion.

VIBRATION CAPABILITIES

The CM was designed to withstand static accelerations up to 35g and ball bearings have loading capabilities up to 4.5kN axially and 8.9kN radially. Finite element computations were run to check about the CM vibrations behaviour when it is coupled to the large Euclid wheels.

The CM+wheel assembly first mode is at 134Hz and is linked to the momentum stiffness of the ball bearings. In that case, the wheel oscillates perpendicularly to the rotation axis. The relative associated mass is 74% in Rx and Ry. The system symmetry makes the mode twined in X and Y direction.

It is interesting to note that during vibrations tests performed on the Structural and Thermal model (STM), the 134Hz was visible neither on sinus nor on random vibrations. If the wheel is well balanced, this mode is not excited when the system is mounted on a shaker table that oscillates only on pure X, Y or Z translations.
The second modes (180Hz) is a pure axial mode (Z direction) and is linked to a pure wheel mode (refer to *Figure 13* and *Figure 14*). In this case, the associated mass is 43% on Z axis. The others contributors for X and Y axis is the 464Hz mode (twinned by symmetry), when the wheel deforms according to *Figure 15*. Relative associated masses are 73% on X and Y and 23% on Rx, Ry.

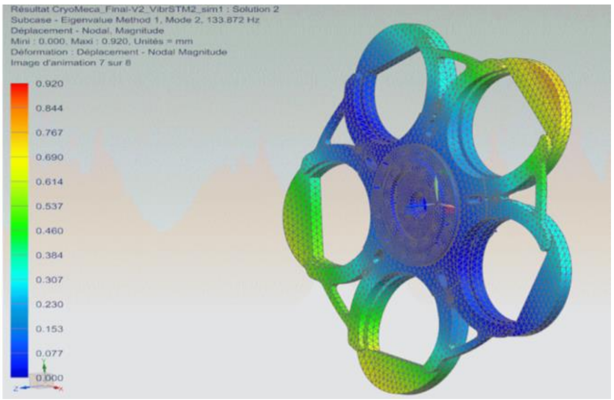

Figure 13: deformation of CM+wheel at 134Hz.

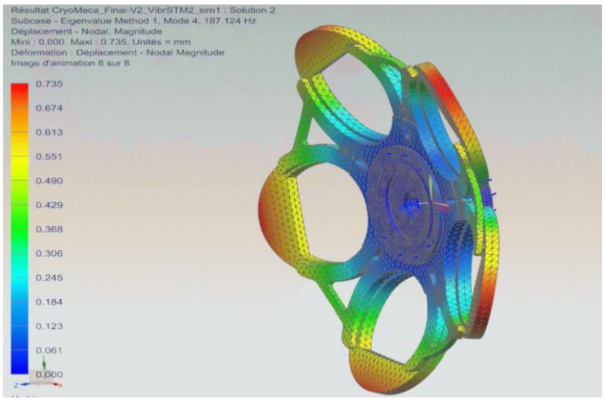

Figure 14: deformation of CM+wheel at 180Hz

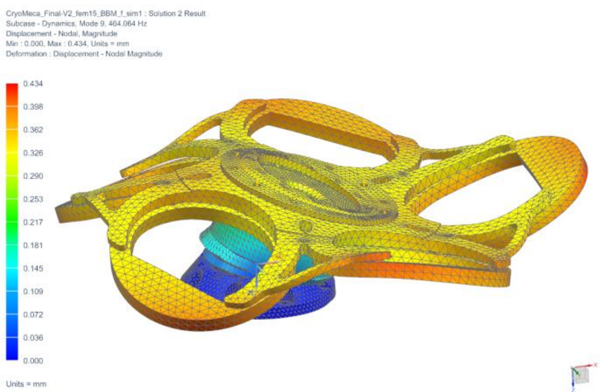

Figure 15: deformation of CM+wheel at 464Hz

The finite element analysis induces some notches definition such as the hertz pressure at ball bearings level is kept under 3300MPa.

CONCLUSION

At this stage, the CM has been built in a bread board model that goes through the test program. The preliminary design review has been passed and the critical design review is scheduled in the coming months. After the clutch subsystem removal decision has been formalized, the CM design is almost frozen. Vibrations tests are expected in the coming months but vibration results performed with the Structural and Thermal Model and the results of simulations show that our CM is compatible with the Euclid qualification vibration levels.
The motions parameter will be optimize to minimize the 3Hz natural mode.

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