DEVELOPMENT AND SPACE QUALIFICATION OF CRYOGENIC ROTATING ACTUATOR.

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Abstract: On the basis of a "dog clutch" cryogenic rotating actuator developed for the ground based astronomical instrument VLT-VISIR in which 10 models have been running over 5 years without any reported failure, CEA-IRFU with the financial support of the French Space Agency (CNES) made the decision to adapt this actuator to space environment.
The cryogenic rotating actuator further called "Cryomechanism" has been designed to operate from room temperature to cryogenic environment (down to 4 Kelvin). Based on a step motor and a 360 positions dog clutch, this cryomechanism (CM) allows to reach any position with electronically controlled acceleration and speed by 1 degree steps with a repeatability below 50 µrad (10 arcsec). Due to the dog clutch mechanism, there is no power consumption once the actuator has stopped
The proposed paper will first describe the baseline requirements, the design principle highlighting the improvements from the ground based system to comply with space constraints, as well as the operation principle. Then, the qualification plan will be shown as well as the environment test results with respect to vibrations, thermal cycling and life testing campaigns carried out on a Qualification Model. Performance results will be addressed as well.
Relying on the success of this development, CEA-IRFU has undertaken further developments on smaller CM in the framework of the METIS project.

Key words: Cryogenic mechanism, space qualification, rotating actuator, stepper motor.

I INTRODUCTION

The astronomy division of CEA at Saclay (France) leads both ground based and space astronomical instruments. Some of these instruments are designed to study cold dusts in far space and use infrared detectors. As the emissivity of any good depends on its temperature, all infrared instruments are cooled down to cryogenic temperatures in order to reduce the background noise. As consequence, all items included in the instrument have to work at cryogenic temperatures, under vacuum.

In 1995, CEA started developments of so called "Cryomechanism" (CM): cryogenic actuators used to rotate optical filter wheels in instruments. Few years later, after different prototypes, VISIR was run in Chile with 10 CM inside. Over 6 years, all these actuators have been running daily with no reported failure.

In 2008, CEA-IRFU, with the financial support of the French space agency (CNES) decided to improve this actuator to adapt it to space environment [1].

II REQUIREMENTS, DESIGN

The general requirements for this cryogenic actuator are listed below:

- Functioning under vacuum (10^{-6}mbar) between 4K and room temperature with constant repeatability, in all orientation.
- Lock in exact position with high repeatability and accuracy.
- Zero dissipation in the locked state.
- 360 steady states/turn.
- High reliability (>100,000 movements).
- Ensure thermal connection between rotor and stator.

- Space allocation: diameter 100mm; thickness <50mm, center hole 35mm, mass<1300g.
- Low frictions, no reduction gear.
- Built-in high absolute accuracy rotor and stator mechanical interfaces.

According to these requirements, CEA-IRFU designed the CM based on the association of the following elements:

- Stepper motor: SAGEM space qualified motor.
- Enlarged KAYDON angular ball-bearings in "O" arrangement: increases stiffness.
- Dog clutch system with Hirth teeth gears: very stiff and accurate. 360 teeth.
- Monostable electromagnet+below: allows closing the clutch system without electrical consumption.

All these elements are mounted in stainless-steel frame, in order to keep homogenous coefficients of thermal expansion. Figure 1 illustrates the CM design.

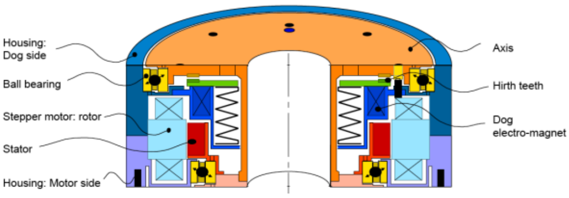

Figure 1: design of CM

The stepper motor is delivered as separated stator holding redundant coils, and permanent magnet rotor. This motor has a large diameter compared to its thickness. Its particular shape ensures 360 steps/turn with high holding torque: 0.6N.m @ 0.2A (12W at 300K). It is provided as a space qualified product: all components fulfill space requirements (low outgassing materials, vibrations, certified performances).

Bearings are class 6 precision (tolerances<5µm) angular ball bearings from KAYDON. They are made with AISI440C stainless-steel tracks and balls and brass ball separators. The bearings are maintained pre-stressed under the elastic deformation of a flange.

The dog clutch system is based on 2 Hirth teeth gears and an electromagnet. One gear is fixed to the rotor and is free to rotate. The other gear is attached to the stator trough a welded waves below. The below gives very high stiffness in rotation, medium stiffness in radial motions and is quite flexible in axial translations. The electromagnet is powered to open the clutch and to allow the rotor turning. When the coil is powered off, the below acts as a spring, pushes the gear and closes the clutch. This is illustrated on Figure 2.

When running, the CM can be considered as two motors mounted in series. The stepper motor performs a coarse positioning, rotating the rotor at any of the 360 positions with 2 arcmin of accuracy. Then the clutch closes, performing the fine positioning with few arcsec of accuracy.

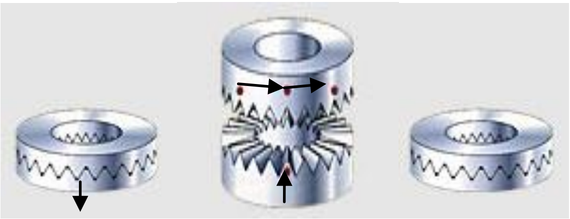

Figure 2: dog clutch operation principle

The typical sequence for a movement breaks down in 5 steps:

- Power the stepper motor ON.
- Open the clutch. A pulse current is send in the clutch coil (0.3A typically), then, a reduce current (0.03A) maintains the clutch open.
- Rotate the stepper motor.
- Close the clutch (power the coil OFF).
- Power the stepper motor OFF.

This design using a high torque stepper motor allows an open loop control with direct drive and fulfills ground based devices requirements.

III IMPROVEMENTS

With the design detailed in the previous sections, the CM is compatible with ground based cryogenic environments. To have the opportunity to run the CM in space conditions, some additional constraints have to be taken into account.

- Robustness to all life parts of a space project (ground testing, launch, space running). Reliability.
- Molecular contamination, cleanliness.
- Agreed materials and process: low outgassing materials.

The constraints of a real space project (JWST-MIRI) were applied to the CM to prove its robustness to space environment.

With the help of a product and quality assurance engineer, all the raw materials, glues, potting, copper insulations, coatings are listed to check their compatibility with space.

The ball bearings are upgraded by ESRT with a process agreed by European Space Agency (ESA). It consists on a very thin and controlled molybdenum bisulfide deposit on tracks, balls and balls separators which material is replaced by steel (instead of brass). With this coating, the ball bearings preloaded at the level of 600N have only few 10mN.m of friction torque. This torque does not change after 150000 revolutions [2].

In our case, the most difficult challenge for space application is the vibration capabilities. The CM is modeled under FEM software and its behavior is analyzed with respect to vibrations. Simulations show that the weak point of our system besides in the elastic flange which stresses the ball bearings.

The 3D model has been cross-checked with experimental tests on a vibration facility [3].

The design has been optimized in order to get higher axial stiffness and new parts have been machined.

Upgraded CM has been tested again to validate the mechanical changes.

When the design was theorically and experimentally compatible with space requirements, a new set of mechanical parts was machined and the construction of a qualification model started. After few weeks to achieve a complete integration, the CM was ready to start the qualification plan.

IV QUALIFICATION PLAN

The space qualification program consists in vibrations tests with the aim to simulate vibrations of the launcher, thermal cycles and life-test. Before starting, between each stage and at the end of the qualification program, performances are checked performing repeatability and bearing friction measurements.

A. Performances tests

Two dedicated test facilities have been set up for performance tests on CM. Both are cooled down using liquid nitrogen lines and allow test around 90K under vacuum (10^{-6}mbar) (see Figure 3).

The fist facility is equipped with dynamic torquemeter (range +/-1N.m) and is used to monitor ball bearings friction torque at room temperature, at 90K under atmospheric pressure or vacuum. The torque is acquired with a PC with data acquisition hardware at 100 readings/sec when rotor is turning at 0.25Hz (1 full turn every 4 sec). The acquisition is run over 40sec, while the rotor moves alternatively +2 turns, -2 turns, +2 turns, -2 turns. The results of these measurements are used to calculate motorization margins with respect to specific formulas given by ESA.

In a separated facility, repeatability measurements are performed. The CM is equipped with a mirror mounted on the rotor. A laser autocollimator, standing outside the cryostat, measures angle deviations of the mirror. The repeatability test consists in moving rotor from measurement position to random position and back and acquiring data from autocollimator. A second mirror, mounted on stator, allows subtracting common deviation due to thermal effects on the setup (cryostat or autocollimator).

Figure 3: test facilities

B. Vibrations

As written before, the most critical point is the behavior with respect to vibrations. To qualify the CM, JWST-MIRIM spectrum was used. This spectrum is given in Figure 4. It represents an average value of 13.6g rms in a bandwidth from 20 Hz to 2 kHz, over 2 minutes.

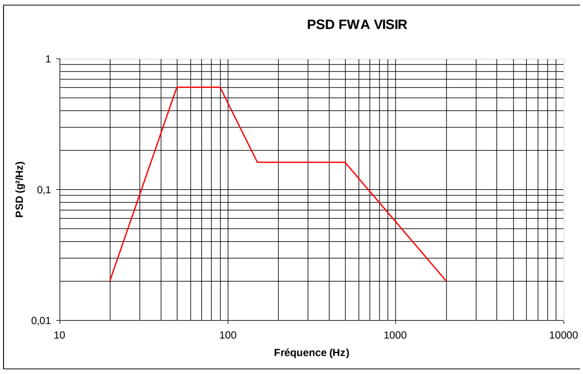

Figure 4: Power spectral density of MIRIM injection spectrum: 13.6g rms.

The CM was mounted in the MIRIM filter wheel assembly configuration: foot, kinetic interface plate (KIP), CM, KIP and filter wheel were assembled for vibration testing. This set up was instrumented with 2 three axis accelerators, and 2 single axis sensors. The complete set up is illustrated on Figure 5.

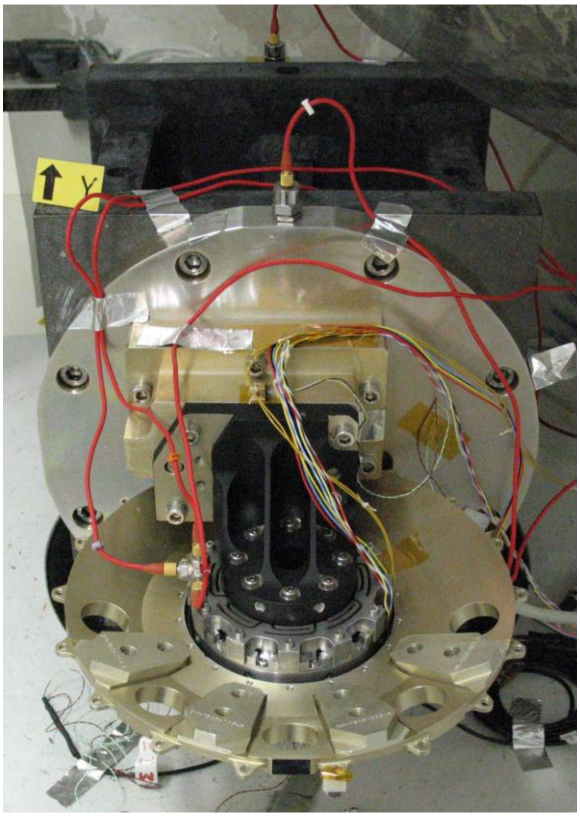

Figure 5: CM mounted in MIRIM-filter wheel assembly configuration and equipped with accelerometers for vibrations tests.

The following sequence was applied for vibrations tests; it was repeated for X, Y and Z axis:

- Functional test.
- Low level sine scanning: 5Hz-2kHz, 0.5g, 2oct/min (see Figure 6).
- Random vibrations, real spectrum -6dB.
- Low level sine scanning, functional test.
- Random vibrations, real spectrum -3dB.
- Low level sine scanning, functional test.
- Random vibrations, real spectrum 0dB (see Figure 7).
- Low level sine scanning, functional test.

The functional test consisted in driving the CM for a movement of +90° then coming back to zero position, then checking that everything was correct (visual checkpoint).

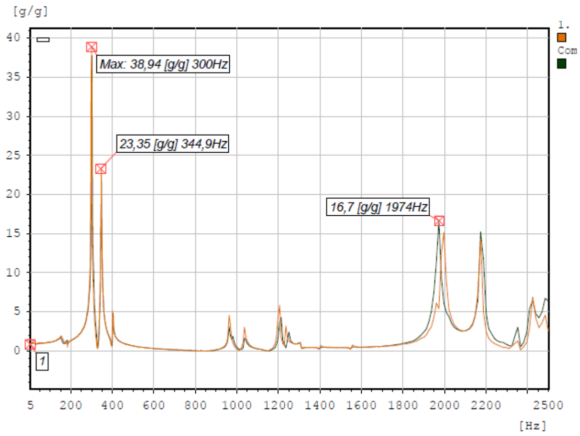

Figure 6: low level sine scanning in Y direction. Main Eigen modes are 300Hz, 344Hz, 950Hz, 1050Hz, 1200Hz, 1974Hz.

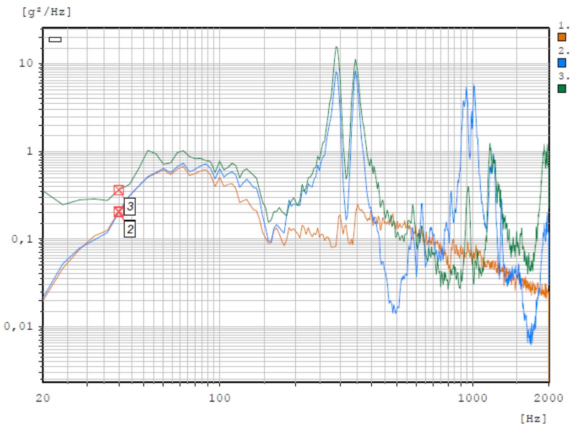

Figure 7: random vibrations at 0dB in Y direction. Peaks appear at 300Hz, 350Hz and around 1000Hz.

C. *Thermal cycles*

Astronomical devices are operating in very stable conditions. Before their scientist observing mode, instruments support many cooling down and warming-up periods. In space projects, thermal cycles are needed to prove the robustness of a design to thermal changes.

The typical cycle was defined starting from 293K, cooling down to 100K and warming up to 293K. The slope for temperatures changes was set at an average value of 15K/h. Taking account of cycles performed during performance tests, the CM went through 15 thermal cycles without performances evolutions. We only noticed very small cracks at the interface between potting and iron part (see Figure 8). This trouble is pointed out as an open Non Conformance Report (NCR). Solutions are foreseen and will be studied in the coming months.

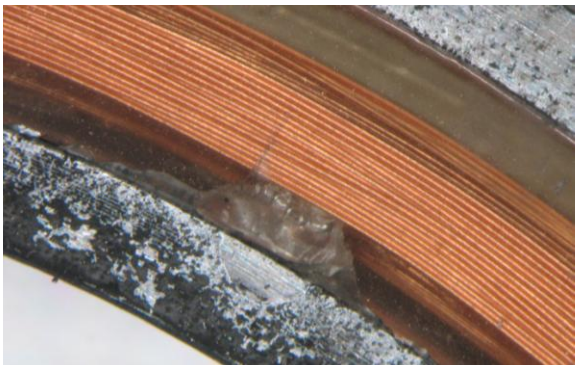

Figure 8: cracks in the potting after thermal cycles. The picture field is 8 mm wide.

D. *Life-test.*

In JWST-MIRIM space project, the lifetime for rotating actuator is estimated around 50000 movements, taking into account ground tests and experimental run. A safety margin factor of 3 is applied to the CM, so the life test is performed over 150000 movements. The CM is loaded with steel cylindrical piece of ~4kg and 120 mm in diameter. The inertia momentum of this part is quite comparable to MIRIM optical wheel: $7.5*10^{-3}$Kg.m². The overall test was 30 repetitions of following sequence:

- Set of 300 cycles to measure repeatability
- 5000 randomized movements.

The test had run over 40 days, meaning the average periodicity was 1 movement every 23 seconds. This was driven by the need to keep the motor cold. With these settings, the temperature raise, due to quasi continuous run, was below 10°C. In normal condition, the average duty cycle is 1 movement per hour.

V RESULTS

Some of the space requirements are fulfilled by design. Outgassing properties can be taken into account in the preliminary design phase as well as compatibility with cryogenic environment. Subcontracting the ball bearings preparation to ESA agreed firm ensures a space qualified process.

Vibrations tests have been performed at the MIRIM qualifications levels. Low level sine vibrations, sign CM Eigen modes: 300Hz, 344Hz, 950Hz, 1050Hz, 1200Hz and 1974Hz. These patterns do not change after vibrations at 13.6 g rms in X, Y and Z directions: no change in frequency modes (<10% different), no change in amplification factors. When the CM was dismounted after vibration tests, there was no broken or deteriorated element in the CM structure. Some dusts were noticed at mechanical interfaces between KIPs and wheel. This was pointed out as NCR but doesn't concern CM itself.

As it is written before, the thermal cycles do not affect the CM functionalities. From mechanical point of view, cycles between room temperature and 90K are significant for lower temperatures, down to 20K. The cracks appeared in the potting are due to large differences in thermal coefficients of expansion between the potting and the iron of the electromagnet. The tests showed that no particle gets off from the coil potting.

The CM has been run over 150000 movements (open the clutch, moving the stepper motor and closing the clutch). The performances tests run before and after the life-test showed similar performances. Chemical analysis showed that dusts came from the teeth and from the electromagnet iron. Some work is undertaken to solve this trouble.

By and large, the CM has following performances:

- Motor torque: 0,6N.m; friction torque: 0,07N.m (Figure 9). With respect to ESA requirements [4], considering the CM has to rotate a wheel of 1kg, 20 cm of diameter, with accelerations of 0,42 rad/s², the system has motorization margin of 0,18N.m.[5]

Figure 9: torque measurement (mN.m) vs time (sec). This graph plots gross results, CM friction torque is calculated from these data.

- The repeatability of positioning in rotations is 50µrad peak to peak [6]. This angle value can also be given as mechanical jitter of 5 µm for optics mounted on a wheel, at a radius of 10cm (Figure 10).

- Due to clutch system, heat dissipation is completely null in steady states. The energy for 5 sec movement is 64J at 300K (60 J in the motor, 1.5 J for clutch opening, 2.3 J for clutch maintain) and 3.2J at cryogenic temperatures (3J in the motor, 0.1 J for clutch opening and 0.1 J for clutch maintain).

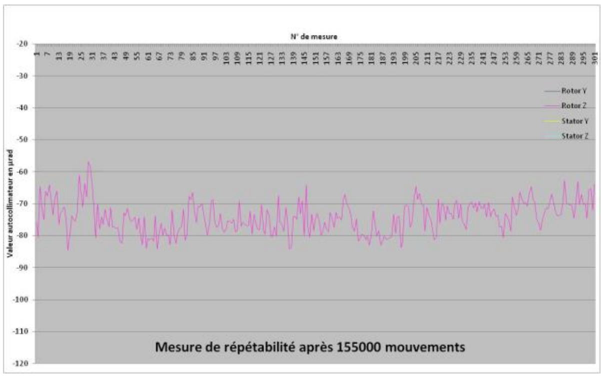

Figure 10: repeatability test. Measurement of rotor miror deviation (µrad) vs n° of measurement (time equivalent).

VI Conclusion

The cryomechnism developped by CEA passed over space qualification with success. The monitoring of performances made all along the qualification process shows that the behavior of this motorization system is not affected by vibrations. Non conformance reports will be treated soon. After the qualification model, CEA-team is going to start the construction of a flight model.

CEA leads further developments around cryogenic actuators. The association of teeth-clutch with stepper motor is successful and has been applied to extend the range of CM to 3 models. A smaller CM is going to be build, based on the SAGEM 21PP motor (200 steps/turn). The SAGEM 57PP motor will be integrated in a future 150mm of diameter CM, with 1000 steps/turns. Double clutch systems are foreseen, with very high resolution (1 million steps/turn). These developments could result in a large contribution of CEA into ELT-METIS, an infrared instrument mounted on the future Extra-Large-Telescope, in which 30 mechanisms have to be set.

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Glossary

CEA: Commissariat à l'Energie Atomique et aux Energies Alternatives.

CNES : Centre National d'Etudes Spatiales.

ELT : Extra Large Telescope.

ESA: European Space Agency.

FEM: Finite Element Model.

IRFU : Institut de Recherche sur les lois Fondamentales de l'Univers.

JWST : James Webb Space Telescope.

METIS : Mid infra-red ElT Imager and Spectrometer.

MIRI: Mid Infra Red Instrument.

MIRIM: MIRI iMager.

VISIR: - VLT Imager and Spectrometer in the mid-Infra-Red.

VLT: Very Large Telescope.