Qualifications challenges of a SADM using slipring technology

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***Abstract*— The SADM-200 (Solar Array Drive Mechanism for 200W) is a new mechanism developed at Comat in order to provide a solution for solar array rotation and power transfer for small satellite applications. This mechanism is designed to be as compact as possible while providing a reliable angular positioning and electrical power transfer from the solar array to the satellite. Robust mechanical guidance and high quality components selection allows an accurate positioning with low angular play while withstanding the tough mechanical and thermal environment faced during launch and in-orbit operations. The development focused on keeping the cost as low as possible through the use of COTS (Component Off the Shelf) while maintaining a high quality requirement. This paper describes the challenges faced by the development team during the qualification campaign that recently succeeded.**

Keywords—SADM, slip-ring, qualification

I. Introduction

Following a growing demand for affordable off-the-shelf SADM for small satellite applications, COMAT started the development of a new product with the support of the CNES, the French space agency. This paper presents the main development and qualification steps of this SADM-200 mechanism. The design started in 2020, the PDR was held in 2021 and the CDR was passed in 2022. Additional derisking tests were performed in 2023 and the qualification campaign was successfully performed in 2024. FM are being built for already planned flight missions, delivery set for 2025.

II. Design and Development

The design was kept as simple as possible, built around 3 main components:

- **Slip-ring**: allow the power transfer from the solar array to the satellite while rotating, with unlimited rotation angle.
- **Gearbox stepper motor**: drives a slow (up to 0.01 rad/s – 0.1 rpm in flight, 0.14 rad/s – 1.3rpm in qualification) and relatively accurate rotation (<3° angular backlash).
- **Bearings**: ensure a smooth, low friction rotation and withstand the deployment loads.

The design resulted in the following final configuration (see figure below), this is the version without the additional radiation protection cover:

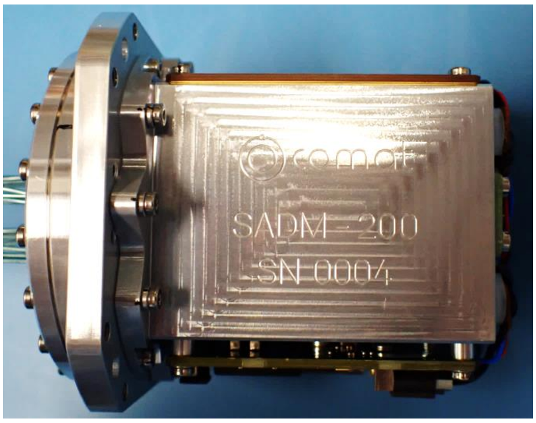

Figure 1: SADM-200 (QM1), side view, cover-less version

Comat designed the SADM-200 embedded motor control PCB, benefitting from the development of its reaction wheel product line. Hence an important portion of the EEE components (such as connectors or micro-controller) are reused, however a new embedded software was developed by Comat. The software includes different control modes depending on the required action: rotation at specific speed, rally to a target position, number of steps to perform. It also allows error handling (temperature, voltage, etc).

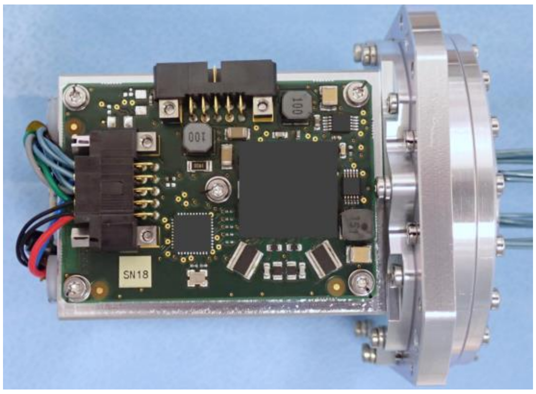

Figure 2: SADM-200 (QM1): control board view, cover-less version

The main performances of the SADM-200 are listed in the following table:

Parameter	Value
Volume	Ø80, length 85 mm (cover-less version)
Mass	<0.440 kg
Operational Temperature (satellite interface)	-20 ; +50 °C
Non-Operational Temperature (satellite interface)	-40 ; +60 °C
Solar array Voltage	Up to 28 V
Solar array Current	7.14 A (through 7 pairs of power lines)
Supply voltage	10 to 18V
Supply current	< 0.5 A
Dissipation	< 4 W
Rotation range	Unlimited
Angular resolution	0,03° (per motor step)
Angular accuracy	<+/-3° (gearbox and reed switches)
Nominal speed	0.01 rad/s (0.1 rpm)
Qualified speed	0.14 rad/s (1.3 rpm)
Actuation torque	Up to 0,350 Nm
Holding torque (unpowered)	Irreversible motion (gearbox), <0.5 Nm
Lifespan	100,000 full turns (qualification target)
FIT	<124 @80°C (embedded electronic)

Table 3: SADM-200 performance table

A. *Slip-ring*

The slip-ring is composed of 17 conductive rings stacked on the SADM rotor and 17 pairs of brushes on the stator side. To ensure an optimal electrical transfer during the entire lifetime of the product, we use a gold based, non-lubricated surface contact: gold plating on the tracks and gold alloy for the brushes. The brushes are two per track in order to ensure contact redundancy and they are qualified for 1,02A transfer (200W, 28V on 7 power pairs). The slip-ring does not require running-in, it is fully operational at cycle 1.

B. *Bearings*

The choice was made to use hybrid (stainless steel rings and ceramic balls) bearings: no strict need for lubrication, however the cage contains MoS2 particles which can improve the tribology of dry contacts.. The pair of angular contact bearing is mounted in "O" (back-to-back) configuration, axially preloaded with springs. In order to accommodate for the large environmental temperature range and axial parts' induced expansion/contraction, the outer ring of the external bearing is held through an axially flexible blade (radially stiff).

C. *Top-turn with reed switches*

Since the baseline mechanism does not include a position sensor for compactness reason, two top-turns are positioned 180° apart in order to regularly be able to adjust the software position indication. The reed switches are magnetically activated, normally open devices. They close when the magnet fixed on the rotor passes nearby.

Regarding the magnet selection and design, past issues with NdFeB corrosion, see [1], and their higher sensitivity to temperature led us to select Sm2Co17 magnets. Although being less common on supplier shelves than NdFeB, their high resistance to temperature and corrosion free material composition met our needs. They also show high magnetic performances with typical remnant induction around 1,1T compared to 1,3T for NdFeB.

The motor we are using is a 2 phases stepper, supplied with a current controlled driver. Owing to its compactness the magnetic circuit is relatively thin and there is an important part of non-canalized magnetic field. Hence the two reed switches are disrupted by the resultant motor magnetic field which overlaps the one generated by the switches magnet placed on the rotor. The most notable consequence is a repetition of on/off toggles on the reed when the magnet is angularly closing in while the motor is activated, as shown in the Figure 4, issued from measurement at nominal motor current and speed. This flickering should not be confused with the nominal bouncing behaviour, see [2], that occurs at higher frequency and for a very short duration (a few ms) compared to the effect we are noticing (a few seconds, depending on rotation speed).

Based on the measurements (Figure 3) with nominal current (360 mA), the reed can start to pull-in up to 5° before the final threshold angle (2° before in the figure), when the reed remains closed. Hence preventing accurate and repeatable position adjustment.

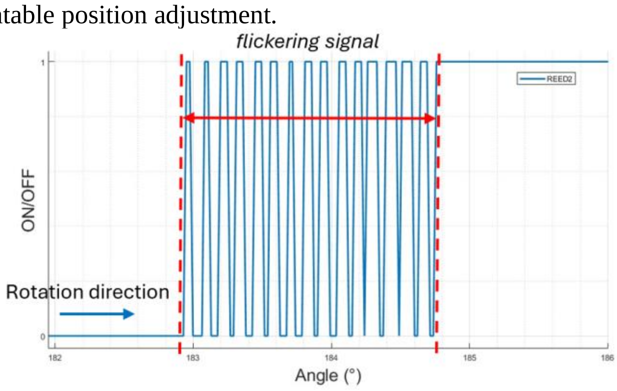

Figure 4: reed signal measurement plots vs rotor angular position – magnet closing in and inducing flickering – raw, unfiltered signal

In addition, the motor influence regarding the reed flickering is further established by testing with different phase current values. The resulting number of reed activation per rotation is indicated in the following figure:

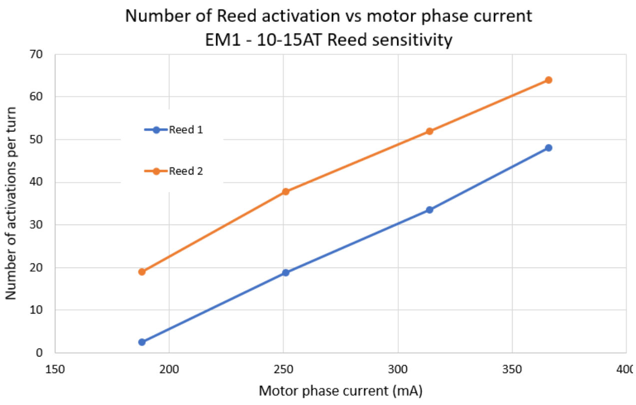

Figure 5: number of reed activation per turn vs motor phase current

As expected, the higher the motor current is, the higher its external magnetic field is, hence inducing reed flickering at earlier angular positions and for a higher total number of activation. The higher number of reed n°2 is due to a lower magnet induced field at its position (measurements performed) probably caused by a higher distance to the triggering magnet (within mechanical chain of dimension tolerances). With a lower magnet induced field at this location, the motor magnetic field then gets more relative impact on the reeds flickering range.

Mitigation options and selected solution

The reed activations number versus phase current relation is relatively linear and seems to reach 0 activations per turn at around 150mA. Reducing motor current would then be an option to cancel the flickering effect, however motorization margin would be affected. Magnetic shielding could also be possible to greatly reduce motor magnetic field but would add mass and require volume that is not easily available in this compact mechanism.

In the end, a software solution is preferred. Thanks to a built-in post-treatment algorithm, filtering out temporary reeds activations, these undesired activations are ignored and only one rising front per reed is considered. The final reed rising front positioning accuracy of the system is measured under 0.5° (3 sigma repeatability) which is well within the targeted 3° position uncertainty.

Consequences on reed lifetime

The other impact of this flickering effect is that it increases the total number of activation cycles proportionally to the mechanism's lifetime The required qualified number is 100 000 full revolutions, which is to be multiplied by the average number of reed activations per turn (50-60), leading to around 5 to 6 million. The reed sensor specification ensures a minimum of 10 million activations as a lifespan., which then allows a maximum number of activations per turn of 100, covering the SADM-200 measured number with margins.

D. Motorization

For the motorization we use an off-the-shelf gearbox combined with a stepper motor. Due to the very low speed of 0,1rpm in flight, a good angular resolution (<3° accuracy) and a required output torque of 0,35Nm, the selected gearbox is designed with reduction ratio close to 600.

To ensure 100 000 lifetime output rotations, the high gearbox ratio requires more than 50 000 000 rotations on the motor side, challenging the motor axis bearings, gearbox first stage teeth and space lubrication selection.

III. SADM-200 Mechanism qualification

The qualification sequence went through the typical path of testing under mechanical and thermal vacuum environments followed by a lifetime test under high vacuum and thermal operational conditions. Functional tests were regularly performed in order to monitor the good health and the evolution of the main performances of the SADM throughout the qualification campaign. Other important tests like magnetic moment measurement and EMC verifications were also performed.

A. Mechanical environments

The SADM was submitted to mechanical environment testing, with two accelerometers monitoring stator and rotor (on solar array interface plane) accelerations. In order to keep the ISO-7 cleanliness level and avoid the risk of bearings and slip-ring contamination, a dedicated cube tooling was designed. This cube-shape also ensures a stiff enough tooling to prevent modal amplifications. The SADM is mounted on its stator interface (link to satellite wall) and free on the rotor interface, with no added dummy mass : considered as a worst-case compared to the stowed configuration during launch, which is the rotor attached to the stator through the solar array.

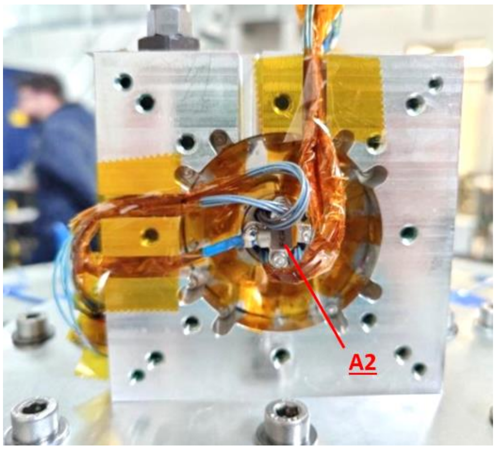

Figure 6: location of the 2 accelerometers on the SADM-200 for the vibration tests (left: stator, right: on the rotor)

For each axis, the test flow consists of a low frequency sine sweep (25g to 100Hz) followed by the random vibrations (20,8grms during 2min). A low level sine sweep is performed for resonant frequency search before and after each tests (3 per axis) in order to detect any modal spectrum variation.

Axis	Frequency (Hz)	Level
X, Y, Z	20 – 50	+6 dB/octave
	50 – 400	0,5 g²/Hz
	400 – 2000	-4 dB/octave
	Global	**20.80 g_{RMS}**

Figure 7: specified random vibrations PSD

The measured modal landscape revealed that the first structural mode (rotor swinging mode) is slightly lower than expected from the design analysis. The investigation allowed to identify the deviation sources: added mass on the rotor, lower bearing stiffness and additional stiffness not taken into account in the model. The FEM was adjusted and refined accordingly to better fit the actual mechanism behaviour.

The mechanical environment also revealed some frequency shifts above the ECSS limits (5% in frequency and 20% in amplitude), detected from the low level frequency search performed before and after each random vibration run. Only 2 modes at relatively high frequency (1110 and 2070Hz) are affected over the first 10 modes identified, the other 8 are remaining within the ECSS targets. This kind of modal shift has already been detected and accepted in other mechanisms (with flight heritage) with similar flexible bearing preload.

For vibrations test on incoming qualification models it has been decided to perform a preliminary random vibration run at reduced levels (-3dB) in order for parts to set in place before performing the random vibrations test at full qualification level. Acceptance run for flight models is not affected.

In conclusion the vibration tests went well, the SADM-200 withstood the mechanical environments without damage. All post-test visual and functional verifications were conclusive so the mechanical environment qualification sequence was deemed successful.

B. Magnetic moment

A first SADM-200 magnetic moment measurement performed in 2023 on the EM1 revealed a value exceeding the 20mAm² target, caused by the use of slightly ferromagnetic 15-5PH steel (see more details in [3]). After a fast delta-design iteration, the material was replaced by a non-ferromagnetic stainless steel for the final QM-FM configuration. For this qualification, a new magnetic moment measurement was performed at the CNES BIOT laboratory.

Figure 8: magnetic moment measurement in BIOT lab (CNES)

Different SADM-200 operational configurations were tested, especially the modes OFF, IDLE (embedded software switched on but motor off) and ON (motor activated at nominal speed and current). All measurements are performed without power transfer through the slip-ring since its magnetic moment cancels out with proper power wiring (alternating positive and negative current in the tracks).

The SADM magnetic moment while the motor is activated is performed through the maintain mode (static position, no coil current inversion). Doing that the measurement which takes around a minute can be performed without having an alternating magnetic field. The moment value while the motor is activated is at 20,5mAm², slightly above the target of 20mAm² but considered acceptable since the motor usually never remains activated for long periods before switching back to the idle mode.

The new measurement revealed a significant decrease in the magnetic moment value, from 60mA.m² on the EM1 to less than 10mA.m² on the QM (see Figure 9), confirming the positive effect of the 15-5PH replacement.

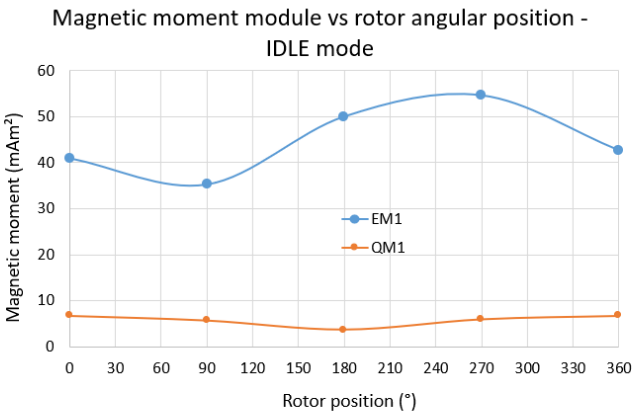

Figure 9: magnetic moment module evolution with rotor angular position – SADM OFF – comparison between EM1 and QM1 results

C. Thermal vacuum cycling

The thermal vacuum cycling (TVAC) is performed in a CNES high vacuum chamber. Due to technical and planning restrictions, only one SADM interface is thermally controlled: the satellite wall interface on the stator (- 30°C/+60°C OP qualification, -50/+80°C NOP qualification). Since functional tests must be performed during the TVAC the SADM rotor will be rotating, hence the technical complexity to control the rotor interface temperature independently.

The use of a control camera placed inside the chamber allowed to easily monitor the SADM rotation. The rotor had to be carefully watched since a thermocouple was placed on this rotating interface, limiting the excursion range to slightly more than a full revolution.

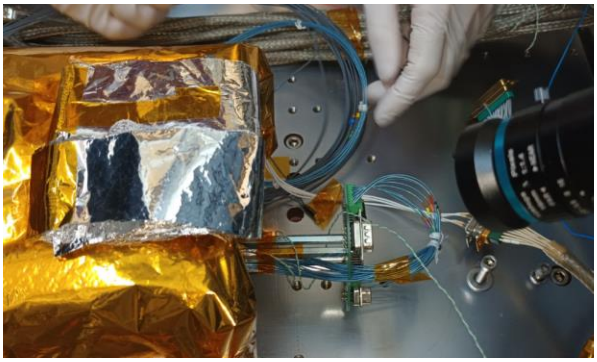

Figure 10: TVAC setup with thermal cover/MLI and view on the SADM rotor tracks interconnection

As per usual, a mix of operational and non-operational temperature cycles is followed in order to explore as much flight conditions as possible, according to this profile:

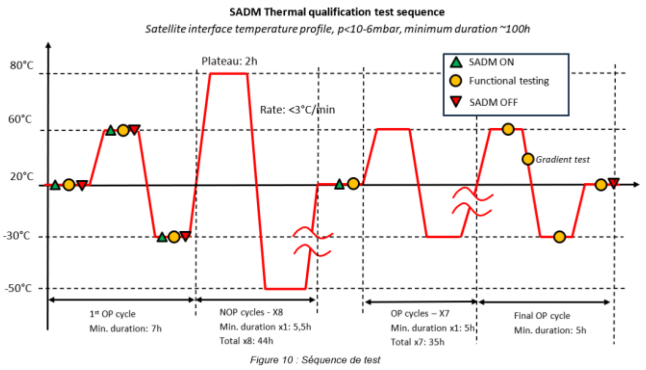

Figure 11: Qualification TVAC full profile

The tests performed during the cycling consist of track resistance and noise measurement, motorization margin evaluation and control board electrical verifications (min/max voltage, power consumption). All the tests performed during the TVAC ended up successful, with the expected characteristics evolutions (more power lines ohmic resistance and power consumption in hot OP, slightly less motorization margin in cold OP).

One key point to monitor was the motor self-heating during nominal operations. Due to volume limitation the SADM-200 embedded thermistor is not directly placed on the motor body but is located as a proxy at the nearest point on the aluminum structure.

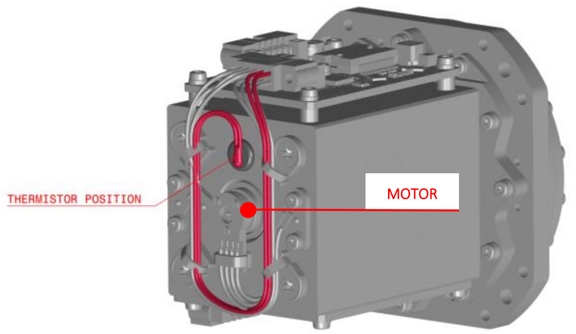

Figure 12: motor body vs thermistor position

For the TVAC we managed to place a thermocouple in direct contact with the motor. The results and comparison for the 3 tested temperature cases are shown in the following table:

	Cold	Ambient	Hot
SADM S/L measured interface temperature [°C]	-23	22	53
Motor body temperature (thermocouple measurement) [°C]	27.9	56.6	79.3
SADM embedded thermistor measurement [°C]	-16.7	28.5	60.4
Temperature difference [°C]	44.6	28.1	18.9

Figure 13: motor temperature measurement in TVAC

As it was expected from thermal models it is measured a noticeable temperature difference between the actual motor body temperature and the embedded thermistor, which reach its highest (44,6°C) in cold OP conditions. This difference decreases to 28,1°C at ambient and 18,9°C in hot OP and has to be taken into account to set the temperature upper limit control. The SADM control software sends an error for motor temperature, stopping current operations, when the embedded thermistor goes above the maximum temperature thresholds.

D. Lifetime test

For the flight representative lifespan a total of 101630 full SADM rotations were performed under ultra-high vacuum over 1308 hour test duration, distributed at 3 thermal operational plateau of +50°C, -20°C and +20°C. The 14 slip-ring power lines were constantly supplied with a 1,02A DC nominal flight electrical current.

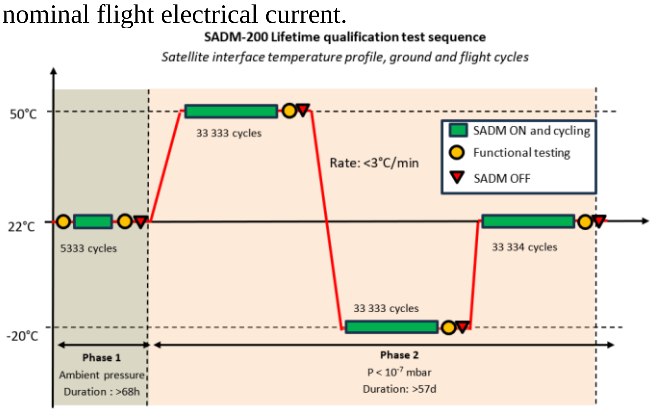

Figure 14: lifetime test full profile including phase 1 (ground representative cycling) and phase 2 (flight representative lifetime)

Overall, the lifetime test went well, with the SADM keeping good functional results and electrical parameters evolution within anticipated range. However, an issue was detected regarding the top-turns, with some occurrence of false "negative" detections which consist of the reed bouncing near the end of the activation range, inducing an incorrect front edge.

When it occured, this second front edge located about 25 d° away from the nominal top-turn location induced a noticeable error in the current estimated position in the embedded software, degrading the average system accuracy. A total of 3390 false negative triggers were detected (mainly occurring during the -20°C plateau counter clockwise rotation sequence) so it was about 1,8% of the 203260 total reed switch activations during the flight lifetime test. No clear root cause could be found, the issue could not be re-created on demand, it occurred at all temperatures.

In order to avoid this kind of phenomenon and solve this issue, it was decided to improve the software reed filter and reinforce it with the addition of a falling edge filter and a stricter variation criteria.

E. Final disassembly and inspections

At the end of the qualification, the QM was disassembled and inspected. Regarding the bearings, no wear were evidenced on the track and ball. On the ball cage some glass fibre extrusions were noticed but nothing functionally worrying. For the slip-ring, the gold based surface contacts showed the typical wear topology with 2 friction tracks on the rings and brushes (one for each contact path) surrounded by small wear particles stacks on each sides.

Figure 15: ring friction tracks wearing on the gold based surface

The gold based surface treatment thickness was only slightly reduced by the wear and could withstand a lot more revolutions.

IV. Conclusions

The development and qualification of a new SADM for small satellite demands is described in this paper. The constraint to design an affordable, compact and reliable mechanism led to some challenging issues that were solved in the development phase. The magnetic moment issue detected on the EM led to an important design iteration toward the final QM/FM configuration. This design evolution was successfully validated during the qualification. The 100 000 full rotations lifetime test proved that the SADM critical components (bearings, gearbox motor, slip-ring contacts) can withstand the required number of cycles. The next step is the delivery of a first batch of FM in 2025 and starting up the serial production phase in 2026.

The authors would like to thank CNES Toulouse and COMAT teams for their support in this mechanism development.

V. References

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