SHUTTER MECHANISM FOR THE PLEIADES HIGH RESOLUTION INSTRUMENT

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ABSTRACT

SENER has developed and produced the two models of the Pleiades Shutter Mechanism. The mechanism is integrated in the Pleiades High Resolution Instrument, for which, Thales Alenia Space is the responsible.

The paper describes the requirements driving the conceptual design of the mechanism, the detailed design and the main performances achieved.

An anomaly was detected during the assembly of the first model of the mechanism. The description of the design modification implemented and the extensive testing performed to verify the suitability of the selected design is also part of the paper.

1. INTRODUCTION

The Pleiades Shutter Mechanism is mounted after the opening of the M1 mirror and the diaphragm slotted hole of the Pleiades High Resolution Instrument. The main function is to prevent, in case of emergency, the sun light to heat sensible components of the instrument

The mechanism has to open and close the diaphragm slotted hole within a maximum time delay and be stable without electrical power in these two positions.

The final design of the mechanism has been driven by the requirements, the most relevant of which are depicted together with the description of the design area affected.

2. DESIGN DRIVERS

The following paragraphs outline the most relevant design requirements applicable to the Pleiades Shutter Mechanism and which are driving the mechanism design.

The size of the hole to be closed and the allowable volume envelope for placing the mechanism in both positions, open and close, prevented from using a simple mechanism consisting of one single plate for covering the hole and one rotation axis to move from one to another position. Instead, a configuration compliant with the requirements was found by covering the hole with two plates, each covering half of he total hole area and being supported by one rotating shaft.

One of the main requirements to be considered at the time of the conceptual design was that the use of any holding and release mechanism is forbidden. In addition, the mechanism has to be shut during the launch phase and this position will be maintained without any electrical power.

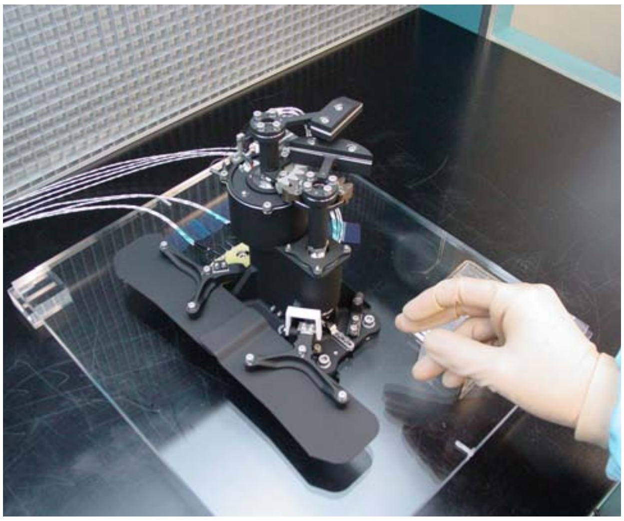

Figure 1. Pleiades Shutter Mechanism

The first implication is that each of the two rotation shaft has to be mass balanced in order to avoid undesirable opening of the mechanism due to the high accelerations generated during the launch. Counterweights have to be added to achieve this purpose. However, even a small unbalance could affect to the stability of the close position, and therefore the position is maintained with the force of one spring which pulls the mechanism against an end stop.

In orbit, the mechanism can be in the open or the close positions, but any of these configurations needs to be stable without the use of electrical power. This is the reason why, during half of the complete angular range, the tension spring pulls the mechanism to the closest stable position.

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The mechanism is driven by one stepper motor. There is a requirement to check the mechanism robustness with respect to any spurious command. In the worst case the mechanism must keep functional after two successive “open” or “close” commands in already open or close position (when the mechanism is on a mechanical end stop).

Dynamic simulations of the mechanism motion, using a voltage supply full step command law, demonstrated that in certain conditions it could happen that an “open” command when the mechanism is in open position could generate the opposite action, that is to close the mechanism. The following different command laws were simulated:

- Voltage supply/two phases on/full step
- Voltage supply/half step
- Current supply/one phase on/full step

The correct behaviour of the mechanism was found with the voltage supply in half step which was taken as the command law to be implemented in the mechanism drive electronics.

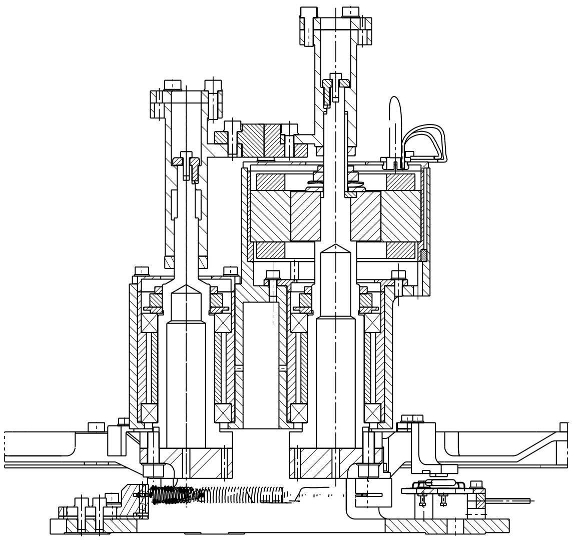

Figure 2. SM cross-section

3. DESIGN DESCRIPTION

3.1 General description

The Shutter Mechanism (SM) design consists of two flat plates which cover the diaphragm slotted hole of the Pleiades High Resolution instrument. Each plate rotates around one axis. Both rotating shafts are parallel among them and perpendicular to the plane of the hole.

Each shaft is supported on one pair of ball bearings. One shaft is driven by a stepper motor and the rotary motion is transferred from this to the other shaft through a spur gear connection.

Counterweights are mounted on each shaft for mass balancing.

The nominal angular range of motion, between the close and the open positions, is 90 degrees. These positions are determined by mechanical end stops.

The open and the closed positions are monitored by the signal provided by redundant reed switches.

3.2 Support structure

The support structure is a monolithic part made of aluminium alloy for housing the different static parts of the mechanism. Internally accommodates the outer spacer of the ball bearings and the motor stator. Externally provides attachment for the mechanical end stops, reed switches PCB and fixed part of the spring.

It is manufactured to very tight tolerances to maintain both shafts aligned.

3.3 Flat plates

There are two flat plates to cover the diaphragm hole, each one covering approximately half of its area. The flap plates provides minimum overlapping of 5 mm with respect to the hole border.

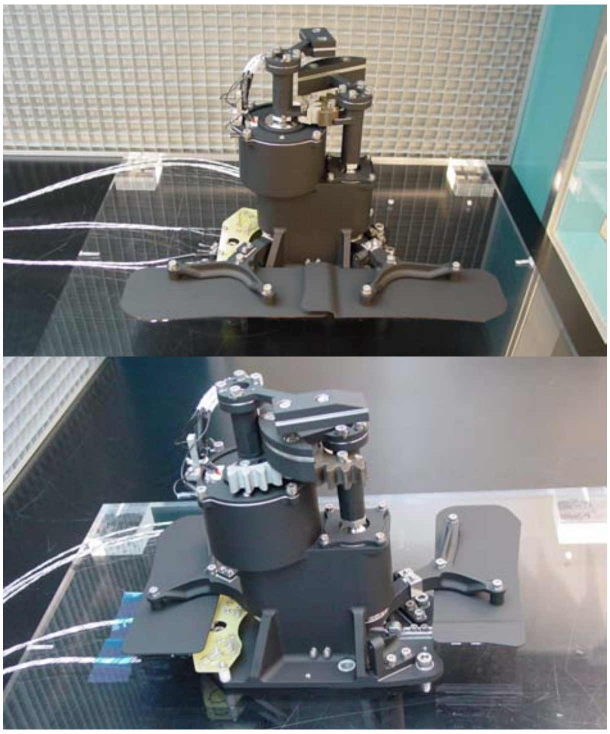

Figure 3. Shutter Mechanism in close and in open positions

The centre of gravity of each plate is located far from the rotation axis. Therefore it is essential to reduce its mass to the minimum possible in order to save also mass in the corresponding counterweights.

Those thin aluminium plates are connected to the shaft via an arm and rotate around an axis perpendicular to the hole plane, one of them clockwise and the other one counterclockwise. As the gears ratio is 1, both plates rotate the same angle.

3.4 Ball bearings

The rotation of each shaft relies on one pair of ball bearings. In the absence of an off-loading device, they have to withstand the loads generated by the launch phase accelerations.

The ball bearing pair is mounted in back to back configuration, spacers separate 30 mm one each other to increase the bending stiffness, and is hard preloaded.

Figure 4. Ball bearing system

Lubrication is a combination of the raceways coated with ion-plated lead and lead-bronze cage. This lubrication is appropriate for a mechanism which is placed in the instrument optical cavity.

The design of the ball bearings was exactly taken from other mechanism that SENER had produced for a previous space application. This heritage was an advantage in order to reduce the risk associated to the development of a new ball bearing system specifically for this program.

The decision was taken after checking that the performances expected for the ball bearings in the Pleiades Shutter Mechanism were covered or exceeded by the previous application. The main aspects considered were the thermal environment, the type of motion, the maximum speed, the on-ground and in-orbit lifetime and the load capability.

3.5 End stops

Mechanical end stops are used to avoid that the mechanism surpass the end positions (open and close). Therefore, these end stops shall be able to absorb the kinetic energy when the open/closed configurations are performed.

Each end stop is the combination of a part fixed to the baseplate of the support structure and a part located on the rotating arm. Different materials, titanium alloy and stainless steel, and different geometrical shapes of the contact surfaces, sphere against plane, have been used in each part.

The thickness of the flat part can be adjusted to determine the flaps position.

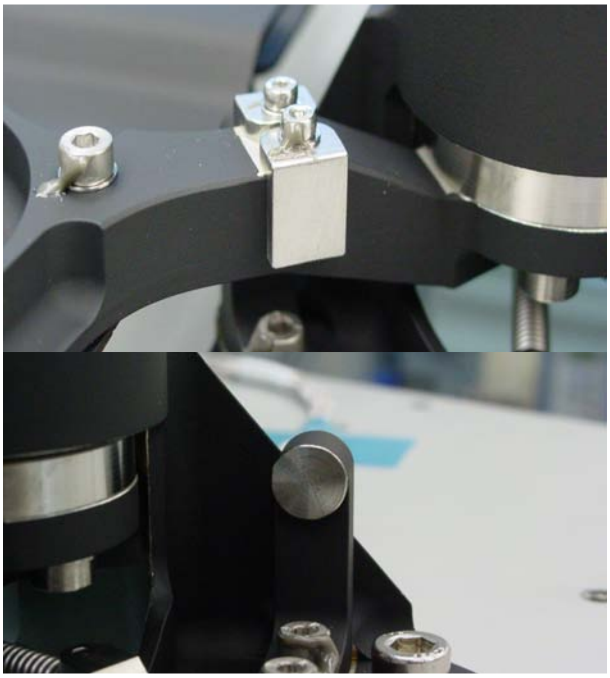

Figure 5. Mechanical end stops

The end stops also provide stiffness against rotation of moving parts to support loads during launch phase. In order to maintain the mechanism preloaded against the end-stops, one tension spring is introduced in the mechanism.

3.6 Motor

The selected motor is a two phases hybrid stepper motor of 1.8 ° step size with redundant windings. The motor is supplied in frameless configuration, stator and rotor separately, and accommodated in the mechanism housing and shaft respectively. Keys are used to lock the rotation of the motor stator with respect to the housing and the motor rotor with respect to the shaft. This configuration permits to obtain a compact design.

3.7 Gears

A pair of spur gears is provided to transmit the rotation from the motor shaft to the other one. The driving parameter for selecting the material, surface treatment, and lubrication of the gears is to minimize the possibility of contamination to the mirrors of the optical cavity.

The preferred solution for dry lubrication at low loads is a self-lubricating polymer versus a steel or light alloy gear. The selected materials are Vespel SP3 (polyimide with MoS_2) versus hard anodised aluminium (to reduce the mass). The mode of operation is a film of material which is transferred from the plastic to the metal gear.

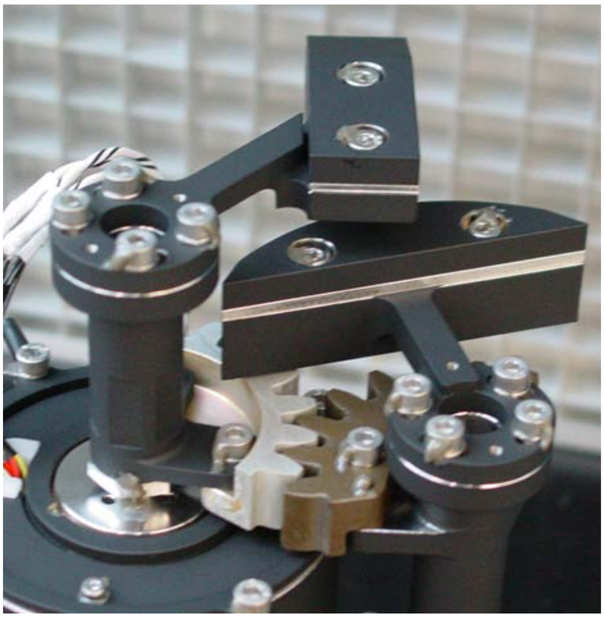

Figure 6. Gears and counterweights

3.8 Counterweights

The counterweights are the masses required to compensate the static moment of the rotating elements with respect to the axis of rotation. Each counterweight has been designed to compensate a static unbalance (mass x distance) trying to optimize the mass. The shape of the counterweights has been optimised, bearing in mind the following facts:

- the distance to the axis is maximized
- must be inside the allowed volume
- no interference with the shafts or the other counterweight during opening and closing strokes
- no interference with the optical ray in open position

Adjustment capability of the counterweights has been foreseen, in order to equilibrate rotating parts after assembly, with two approaches: rotating the counterweight with respect to the axis (with slotted holes), and modifying the mass with adjustable shims. With this approach the maximum mass unbalance per shaft is 0.12 kg·mm.

Being the mechanism mass balanced the functional performances of the SM can be tested in any position.

3.9 Spring

In order to maintain position accuracy in open and close configurations and also to avoid undesirable movement during the launch environment, a tension spring has been included in the mechanism.

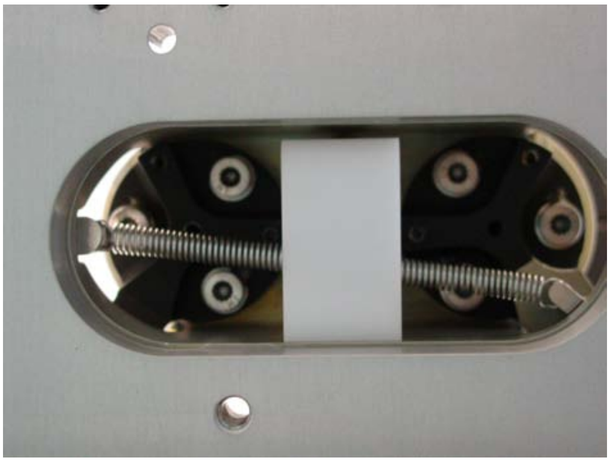

Figure 7. Spring

The spring connects one rotating shaft to the support structure. The spring is installed in such a way, that it creates a torque, which tends to move the flat plates towards the close position, whenever the flap is between this position and half way between open and close configuration. On the contrary, when the flap is between this mid point and open position, the spring provides a torque that tends to move it towards the open position.

This approach ensures that the flap is always in contact with one of the mechanical end stops when the motor is not energised. In addition, the torque provided by the spring in the closed position maintains the flap without moving, even if a torque is generated during the launch environment.

The fixation of the spring is by means of two sets of pin plus titanium attachment which are screwed to the mechanism baseplate and to the motor rotating shaft respectively. The fixed attachment part provides an elongated hole which allows to modify slightly the length of the spring, and consequently adjust the tension and the torque generated.

The local eigenfrequency of the spring falls within the sine vibration frequency range (up to 150 Hz) with an input amplitude requirement of 20 g. A plastic part was included around the middle of the spring in order to limit its maximum displacement possible.

3.10 Position switches

Shutter Mechanism end-position monitoring is implemented with reed switches. Two reed switches are located at each position. Main and redundant switches are located in such a way that they are activated almost at the same time. The reed switches are mounted on a GFRP printed circuit board.

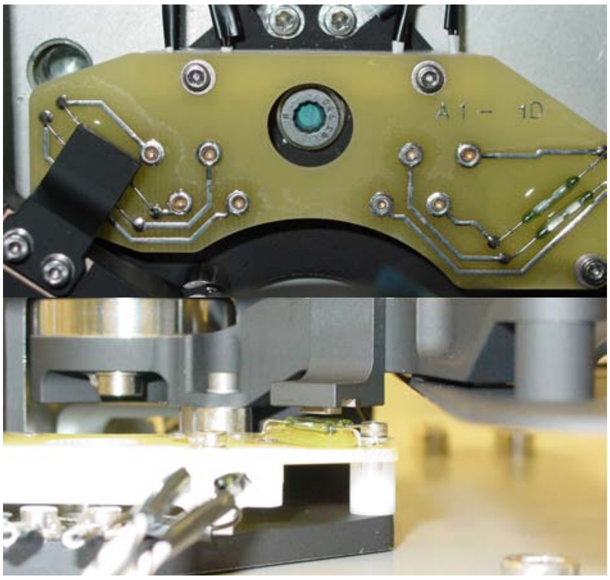

Figure 8. Reed switches PCB

Reed switches are activated by a magnet which is mounted to one of the rotating arms. The magnet is bonded on one slot of an aluminium part. The distance between the magnet and the reed switches can be adjusted by changing the thickness of a shim inserted between the aluminium part and the arm. The material used for the magnet is ALNICO.

4. DESIGN MODIFICATION

During the assembly of the first model of the mechanism and after the integration of the motor rotor once the motor stator was mounted, it was realized that the air-gap between rotor and stator was not uniform but close to zero in one area.

An investigation was carried out to explain the anomaly detected. It involved the review of the acceptance data package of the different components (ball bearing system and motor) and machined parts (housing and shaft), the stiffness and tolerance analysis and also the testing of the assembled hardware to measure the actual force-displacement characteristic of the system. Two causes were identify as the origin to this anomaly:

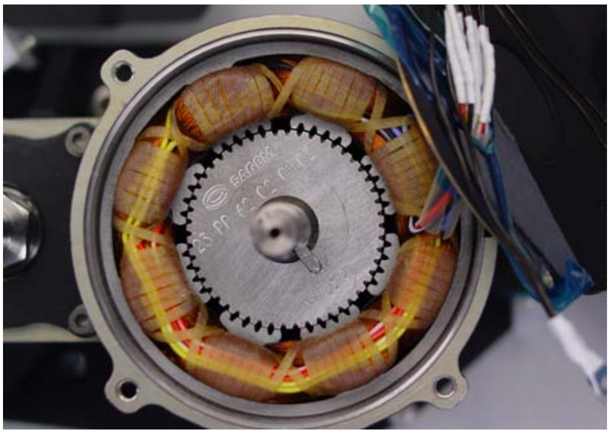

Figure 9. Motor rotor and stator

- On one side the way the rotor was supported (in cantilever mode) provided less stiffness than calculated. The use in the calculation of the stiffness values of the ball bearing contact, disregarding the effect (flexibility) of other parts involved in the ball bearing preloading system (rings, outer and inner spacers). The result is that the system was not stiff enough to guarantee the mounting conditions recommended by the motor supplier in order to ensure the required airgap.
- On the other side, the plays found in the fits between the different parts (housings-spacers-bushings-ball bearings-shafts) and the errors created by the geometrical tolerances during manufacturing and the assembly of the parts helped also to reduce the airgap.

Figure 10. Force-displacement test set-up

Several solutions were identified and traded-off taking into account technical and programmatic aspects.

The design solution selected consisted of installing an additional ball bearing system in the upper part of the motor. This ball bearing is identical to the ones used in the other pairs and it was available. This fact reduced significantly the impact on the delivery time of the mechanism. The upper ball bearing guarantees that the air gap between the motor rotor and stator is within the requirements taking into account worst cases of manufacturing tolerances, thermal environment and launch loads.

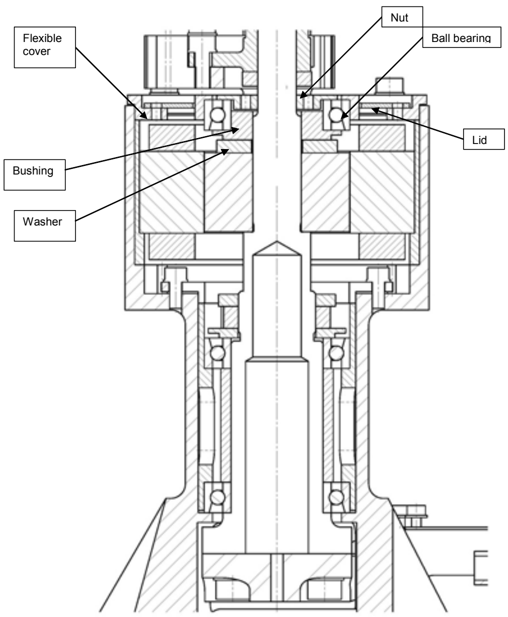

Figure 11. Design modification

The system comprises one ball bearing spring loaded by means of a flexible cover. The flexible cover is a part made of titanium alloy Ti 6Al4V composed by two rings connected by means of four flexible blades 0.4 mm thickness.

Figure 12. Upper ball bearing system

5. QUALIFICATION TEST CAMPAIGN

The qualification of the Shutter Mechanism was performed on the Proto Flight Model (PFM) and included an extensive test campaign to verify the correct behaviour of the mechanism throughout the expected lifetime.

Initially, during the assembly process of the shutter mechanism, the resistive torques of the different elements were measured in the order of the assembly:

- Ball bearings pair of each shaft independently.
- Ball bearing pair plus motor parasitic torque and upper ball bearing system.
- All the ball bearings plus motor parasitic torque and gear.

The last measurement was repeated at different steps of the test campaign in order to check its evolution.

The detail of the PFM test sequence is:

- Resistive torque measurement
- Initial functional performance test
- Sine and random vibration test
- Reduced functional test
- Thermal vacuum test with thermal cycling, functional performance at qualification temperatures and in-orbit lifetime test
- Resistive torque measurement
- On-ground (ambient conditions) lifetime test
- Resistive torque measurement
- Final functional performance test

5.1 Functional performance test

The functional performance test includes the following verifications:

- Open and close operations with different voltage conditions to check the evolution of the position versus time
- Actuation angular range of the position reed switches
- Motorization margin derivation through the threshold voltage for operation completion
- Robustness. This is a complete set of tests to check the correct behaviour of the mechanism after any spurious command is given.

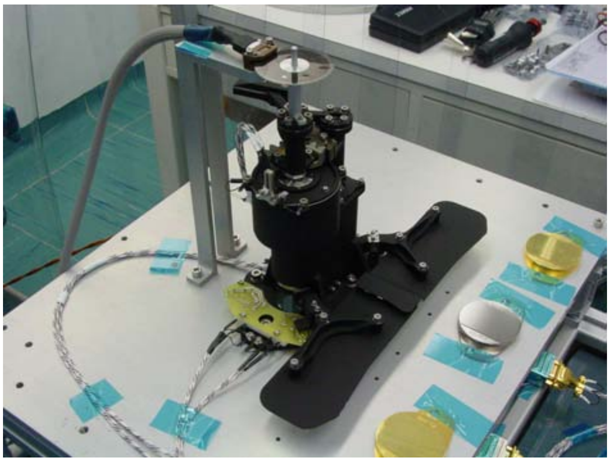

Figure 13. Test set-up for functional test

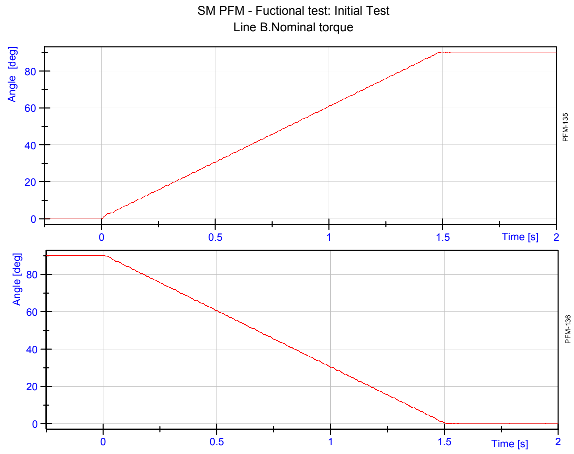

Figure 14. Position vs time open and close operations

5.2 Vibration test

Sine and random vibration are performed on each of the three axis. The lowest eigenfrequency measured was 221 Hz, therefore higher than the requirement of 170 Hz.

During the different runs of the vibration test, the signal of the position switches is recorded in order to verify that the mechanism does not open. In the sine vibration the signal status of the switches does not change. However, during the random vibration at qualification level, in the lateral axes X and Y, the signal of one of the two reed switches of the closed position changed several times during the run, indicating that the switch opens and closes. The other switch did not change its status, therefore defining a limit angle which was not exceeded by the rotation of the mechanism.

Concluding, the optical hole is covered with the flaps during the vibration tests, except for small periods of time (less than 40 ms duration) during random qualification vibration in X and Y axes, when the flaps opens less than 8.1°.

A detailed visual inspection was performed after each vibration axis. The inspection of the end stops showed no marks on the contact surfaces. The inspection of the gears revealed the apparition of straight dark lines on the aluminium gear after vibration, due to the transference of material from the Vespel gear to the aluminium one when gears are rotating because of the small rebounds against the end stop during random vibration test.

To check the risk of pollution coming from the tracks on the gear, they were rubbed with a dry cleanroom wiper, after rubbing, there were no particles on the wiper. There is no evidence of cracking or flaking on none of the gears.

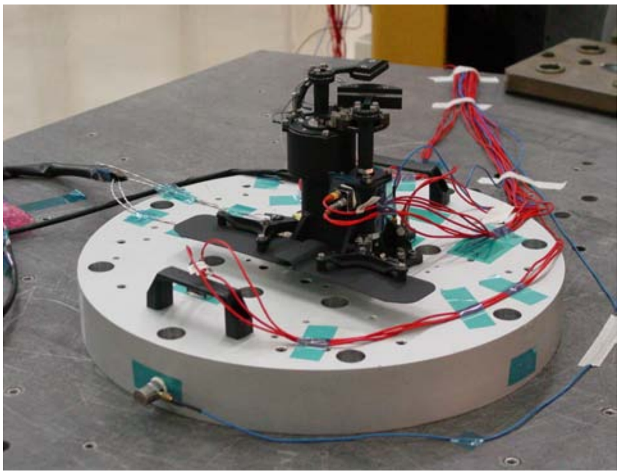

Figure 15. Test set-up for vibration test

5.3 Lifetime test

Lifetime test was performed in two parts:

- In-orbit lifetime test. The expected number of cycles (open and close operations) in-orbit is 30. When lifetime safety factors are applied, a total of 180 cycles have to be performed on the mechanism. The test is performed in vacuum conditions and half of the cycles are done at hot temperature (+43°C) and half at low temperature (+3°C).
- On-ground lifetime test. The expected number of cycles (open and close operations) on ground is 172. When lifetime safety factors are applied, a total of 688 cycles have to be performed on the mechanism. The test was carried out at ambient temperature and pressure.

Reduced functional testing was performed after each lifetime test showing correct performance of the mechanism. The resistive torque measurement also demonstrated no degradation on the ball bearings.

Detailed visual inspection has been performed before and after lifetime tests with no degradation observed on the gears or the end stops.

5.4 Resistive torque measurement

In order to have observable parameters to detect a potential degradation in the behaviour of the ball bearings, the resistive torque of the complete mechanism, without the spring, has been measured at different steps of the test campaign, before the initial functional test, after environmental test (vibration and TV plus in-orbit lifetime test), and after on-ground lifetime test.

Resistive torque measurement is performed within the allowable angular range (90°) of the mechanism in the two directions of rotations. The result, for the three measurements, is shown in the next figure.

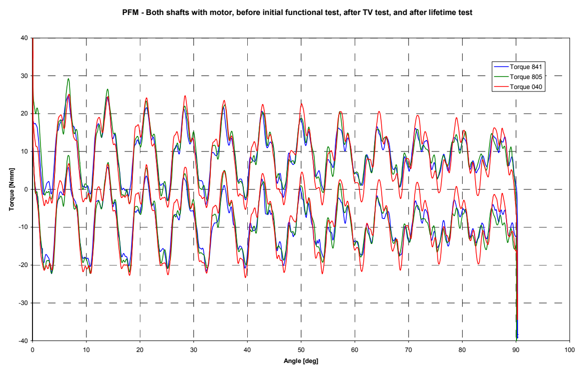

Figure 16. Resistive torque measurements

An analysis was carried out to obtain separately the friction component (ball bearings, gears and motor hysteresis) and the elastic (mainly motor) contribution.

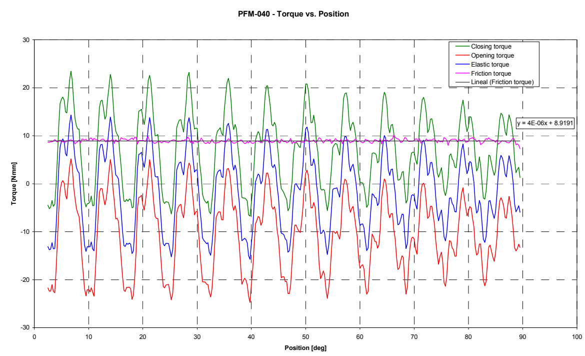

Figure 17. Resistive torque, friction and elastic contributions

Another analysis consisted of applying the Fast Fourier Transform to the resistive torque vs. angle data to obtain the angular frequency components of the torque. Five peaks appear in the plots, corresponding to the harmonics of the motor.

From this analysis, it was concluded that the value of the total friction was maintained almost constant within all the test campaign, showing no degradation on the ball bearings.

6. CONCLUSIONS

The Pleiades Shutter mechanism presents a very compact design and the capability of providing the shutter required functions without any holding and release mechanism.

A lesson was learned about the criticality of the way the motor rotor needs to be supported. The addition of the upper ball bearing, closer to the motor rotor, guarantees that the air gap between the motor rotor and stator is within the requirements taking into account worst cases of manufacturing tolerances, thermal environment and launch loads.

A re-design in the area of the motor shaft was required, in a later stage of the development, to implement the design change in the flight models.

The mechanism was submitted to an exhaustive qualification test campaign to confirm the validity of the developed concept to fulfil the mission requirements. Intermediate tests were carried to verify that there was no degradation of the ball bearings throughout the lifetime.

The test results showed the suitability of the shutter mechanism design, included the design modification.

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