ABSTRACT
The Sentinel-3 mission is encompassed in the Copernicus programme and its main objective is to measure sea-surface topography, sea and land surface temperature and ocean and land surface colour with high-end accuracy and reliability.

SENER is contractor for the delivery of the Flip Mirror Subsystem (FMS) for the Sea and Land Surface Temperature Radiometer (SLSTR) and it is composed by a mechanism, the Flip Mirror Device (FMD), and its control electronics called Flip Mirror Control (FMC).

1. INTRODUCTION
The FMD is a single d.o.f. mechanism, its rotation axis is defined by two flexural pivots (FP), connected to an angular position sensor (absolute optical encoder), a mirror and an actuator (Limited angle torque motor). The main general function of the FMD is to periodically flip a mirror (± 9.4°) to combine the two SLSTR views. In order to minimize friction sources, no sliding surfaces are used. In fact, flexural elements (FP’s) are used for the rotational axis. Fig. 1 shows a photograph of the FMD Flight Model 2 (FM2).

The FMD is driven by the FMC by means of control logic able to fulfil the required performances.

2. FMD DESIGN OVERVIEW
2.1 FMD Main components
Fig.2 shows a cut of the FMD and its main components.

- Encoder
The position sensor is an absolute optical encoder with a resolution of 19 bits (equivalent to 2.5 arcsec). Due to envelope constrains, part of the electronics is located in delocalized PCBs, with dedicated provisions in the mechanism to fulfil EMC requirements.
- **Motor**

The motor is a redundant (two windings) Limited Angle Motor (LAT) with 4 poles. No-load position is located at the intermediate point between two working positions of the mechanism. Motor was developed and improved from EM model to optimize torque linearity.

- **Flexural Pivots**

The FP are composed of a fixed part and a moving part joint by means of three blades. The blades have been designed for infinite life, so the blades are 50 µm thick. The main drawback of this thickness is that the load capability is very low (12 N in radial direction). Fig. 5 shows a photograph of a FP during the incoming inspection with microscope.

The moving part of the FP is joined to the shaft, while the fixed part is joined to the stator of the mechanism through a flexible diaphragm that avoids loading the pivot over its limit.

- **End Stops**

Three different end stops are implemented (two radial, one axial and one rotational). The gaps are dimensioned to limit the loads on the FP due to vibration and shock loads thanks to the flexibility of the diaphragms.

- **Mirror and mirror fixation**

The active area of the mirror is approximately a 14x14mm² square. The mirror is bonded onto a support frame that guarantees tight positioning wrt the shaft, i.e. wrt rotation axis. Mirror bonding detail design was optimized to minimize thermal distortion within operational temperatures, including a dedicated test campaign.

3. DESIGN REQUIREMENTS

3.1 **Performance Requirements**

- Transition time below 34 ms
- Stability better than +/-15 arcsec
- Repeatability better than 4.9 arcsec
- Knowledge better than 15 arcsec
- Life: 1E9 cycles

These requirements are the design drivers of the mechanism (see performance test results below).

3.1 **Environmental Requirements**

- **Vibration Loads**

The sine qualification vibration loads are up to 38.4g OOP and up to 16g IP. Random qualification levels are 18.7grms OOP and 12.1grms IP. Acceptance levels are 1.25 times lower.

- **Shock Loads**

The required shock loads are shown in Tab.1.

<p>| All axis | | |</p>
<table>
<thead>
<tr>
<th>Freq (Hz)</th>
<th>Level (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>2000</td>
<td>1500</td>
</tr>
<tr>
<td>10000</td>
<td>1500</td>
</tr>
</tbody>
</table>
Operational Temperature Range

The operational temperature range for the FMD is from 0ºC (30ºC on ground) to -35ºC.

Life

The FMD required life during the complete duration of the mission is around 750M cycles. A factor of 4 has been considered for the FPs.

4. FMS PERFORMANCES

FMD performances have been verified at Thermal Vacuum conditions at operational temperature with qualification margins (+/-10 ºC). The test was performed at INTA (Spain) Fig.7 shows the test configuration for the FMD FM2.

![Figure 7. FMD FM2 mounted inside the TV Chamber](image)

A measurement of the required current to reach to the working positions (NA and OB) was done at each test point, this test is a quasi-static test meaning that the position is stabilized. Fig.8 shows the curves obtained during the test.

![Figure 8. Motor current (mA) vs. position (º)](image)

The required current to reach working positions is around a 10% higher at cold temperature due to the winding resistance variation.

Functional performances are verified at each test temperature measuring the transition time, stability and repeatability. Fig. 9 shows a typical position measurement, while Tab. 2 shows the measured value at different temperatures for transitions from OB to NA with nominal unit.

To fulfil the tight performances requirements, the use of no sliding rotating elements (Flex Pivots) avoiding friction is required. Also, a dedicated control strategy had to be developed, combining open loop for fast transitions and closed loop control based on accurate position measurement to guarantee stability. Both open loop and closed loop control parameters are commandable and automatically tunnable in order to accommodate model-to-model differences as well as to provide stability against aging and temperature variation effects.

![Table 2 FMD FM2 performances on TV test](image)

<table>
<thead>
<tr>
<th>Temp (ºC)</th>
<th>Trans. Unit</th>
<th>Stability (arcsec)</th>
<th>Repeat. (arcsec)</th>
<th>Transition time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>NA Nom</td>
<td>5</td>
<td>1</td>
<td>27.3</td>
</tr>
<tr>
<td>30</td>
<td>NA Nom</td>
<td>7.4</td>
<td>1</td>
<td>27.4</td>
</tr>
<tr>
<td>-45</td>
<td>NA Nom</td>
<td>5</td>
<td>1</td>
<td>28.1</td>
</tr>
<tr>
<td>30</td>
<td>NA Nom</td>
<td>10</td>
<td>1</td>
<td>28.1</td>
</tr>
<tr>
<td>-45</td>
<td>NA Nom</td>
<td>10</td>
<td>1</td>
<td>28.3</td>
</tr>
<tr>
<td>20</td>
<td>NA Nom</td>
<td>7.4</td>
<td>1</td>
<td>28.8</td>
</tr>
</tbody>
</table>

Req +/-15 +/-4.9 <35

In order to verify the knowledge of the mirror position, optical measurements were performed by means of a theodolite comparing the FMD mirror angle with a reference mirror.
Fig. 10 shows the deviation of the mirror orientation at different temperatures for the rotation axis for nominal encoder at NA position, the light box delimits the real operational temperature range while the dark lines are the measurements.

Figure 10. Angular deviation (arcsec) vs. Temperature (ºC).

Tab. 3 shows the results for Nominal and redundant units, at NA and OB position and around rotation axis (X) and the other out of plane axis (Y).

Table 3 Pointing deviation (arcsec) at NA/OB position at operational temperatures

<table>
<thead>
<tr>
<th>Dev. (arcsec)</th>
<th>Temp (ºC)</th>
<th>p-p</th>
<th>Req</th>
</tr>
</thead>
<tbody>
<tr>
<td>θx Main NA</td>
<td>-5</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>θx Main OB</td>
<td>0</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>θx Red NA</td>
<td>6</td>
<td>18</td>
<td>30</td>
</tr>
<tr>
<td>θx Red OB</td>
<td>-8</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>θy Main NA</td>
<td>3</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>θy Main OB</td>
<td>3</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>θy Red NA</td>
<td>4</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>θy Red OB</td>
<td>2</td>
<td>8</td>
<td>30</td>
</tr>
</tbody>
</table>

The fulfilment of this tight requirement has been achieved by optimizing the design of the mirror gluing to the support frame.

5. ENVIRONMENTAL TESTING

The FMD Qualification Model (QM) has been submitted to the qualification test levels and the Flights Models to acceptance levels. Before and after each run of the tests, a health check of the FP is performed by verifying its natural flipping frequency.

5.1 Vibration test

The vibration test was carried out at SENER facilities in Madrid (Spain). Fig. 11 shows the FMD QM mounted onto the shaker, it is protected by a plastic bag fluxed by nitrogen to maintain cleanliness conditions.

Figure 11. FMD QM mounted onto vibrator.

After the complete vibration test, the FMD performances are verified.

5.2 Shock test

The shock test was performed at ETS facilities in ESTEC (The Netherlands). The shock environment has been one of the main design drivers of FMD (see dedicated sections to dynamic response and damper configuration below). After significant design optimization FMD, shock limits were found. It was agreed to test FMD QM assembled on its upper level subassembly, to have more representative boundary conditions and less conservative input load. In addition to this, required shock levels were relaxed via RfW. Modified levels can be seen in Tab.4 (which can be compared with original levels in Tab.1).

Fig. 12 shows the FMD QM mounted onto the test table.

Table 4 Modified FMD Shock Level

<table>
<thead>
<tr>
<th>X axis</th>
<th>Y axis</th>
<th>Z axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq (Hz)</td>
<td>Level (g)</td>
<td>Freq (Hz)</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>800</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>10000</td>
<td>400</td>
<td>10000</td>
</tr>
</tbody>
</table>
5.2 Life test

The Life test was performed on the FMD QM after vibration and shock tests at SENER facilities in Bilbao (Spain). The test was carried out inside a climatic chamber with controlled environment by nitrogen, as half of the cycles were done at minimum operational temperature (-35°C) and the other half at the maximum (0°C). Fig. 16 shows the temperature profile including the intermediate health checks.

The nominal life of the FMD during the seven years of mission is 750 million of cycles. A margin of 4 was considered leading to a total number of cycles to be tested of 3000 million.

Considering the nominal duty cycle of the FMD (2 cycles every 600 ms) and the required margin, the nominal test duration would be of 28 years. In order to reduce its duration, two measures were taken.

Firstly, the duty cycle was reduced to minimize the time between the transitions, as in nominal operation the stabilized time is around 500 ms while the transitions last 100 ms per duty cycle of 600 ms. An external control was developed with a wave generator to avoid stabilization times. Fig. 17 compares the nominal transition (yellow and blue lines) with a transition generated by the wave generator (green line).
On the other hand, the number of cycles was reduced based on Wholer theory of equivalent damage: lower number of cycles at higher stress level. In order to reduce the test duration to 10 million cycles, the deflection angle was increased from real 9.4° to 11.8° in life test.

Figure 18. Definition of test angle with Wholer curve

The performances of the FMD were successfully verified after the life cycling test. The selection of the proper FP thickness has been a key factor to fulfil the life requirement.

6. LESSON LEARNED: DYNAMIC RESPONSE OF THE FMD

Due to the fact that the shaft is linked to the housing by the flexible diaphragms that limit the load of the pivots, the dynamic behaviour at the shaft is decoupled from the stator, leading to relative displacements of both parts. This relative displacement is limited within the gap at the end stops, in both radial and axial directions.

Due to the difficulty of modelling the non-linear behaviour resulting from elastic displacements plus contacts at end stops, a test-based approach was followed. SENER tested FMD structural models, representative in mass and stiffness, with an accelerometer on the shaft. This was not possible for QM or FM models as the mirrors needs to be installed. Fig. 19 shows the accelerometer location.

Depending on the input level, the frequency of the shaft varies due to the non-linearity of the contact when the end stops are reached. The higher is the level, the higher is the eigenfrequency.

This behaviour can be seen in the following test results. Fig.20 shows a LLSS run, with a response amplified at around 350 Hz, Fig.21 shows the response during a random at qualification level with amplification at around 500 Hz and Fig.22 shows the response to a shock that has the amplification at 800 Hz.

Figure 19. Structural model, accelerometer location.

Figure 20. FMD shaft response to a LLSS.

Figure 21. FMD shaft response to a random vibration.

Figure 22. FMD shaft response to shock.
7. LESSON LEARNED: DAMPER CONFIGURATION DEVELOPMENT

During FMD development and qualification tests it was found that there was a need of adding additional damping to shaft displacement wrt the stator. One reason was to avoid motion control exciting shaft natural frequency causing over-oscillation. This cross-effect was observed on EM under certain environmental conditions. The other reason was to limit shaft displacement in order to safeguard the encoder, due to the tight gap between encoder rotor disc and its stator.

Potential damper materials were traded-off and low outgassing polymer was eventually selected. Dampers were designed to act on the diaphragms that join the Flex Pivots to the stator. Their disposition adds damping to both radial and axial displacement.

In order to obtain additional information of the FMD dynamic response, a test campaign of Structural Models was developed. An accelerometer located in the shaft, as shown in Fig. 19, provided information to the dynamic response of the shaft during vibration and shock tests.

Four different aspects were analysed during the campaign:

- Encoder rotor displacement was analytically calculated from measured shaft accelerations. Tab.5 shows the effect of implementing an axial damper on the FMD, STM1.5 did not carried the axial damper whereas the STM1.7 did. Fig. 23 shows the calculated total displacement depending on the shock level.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Level [freq [g]]</th>
<th>Displc. [um]</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM1.5 X Axis</td>
<td>1000/2000</td>
<td>311</td>
<td>25%</td>
</tr>
<tr>
<td>STM1.7 X Axis</td>
<td>1000/4000</td>
<td>231</td>
<td></td>
</tr>
<tr>
<td>STM1.5 Z Axis</td>
<td>1000/2000</td>
<td>189</td>
<td>13%</td>
</tr>
<tr>
<td>STM1.7 Z Axis</td>
<td>1000/5000</td>
<td>154</td>
<td></td>
</tr>
</tbody>
</table>

Figure 23. Calculation of shaft displacements depending on shock level.

- SRS of the shaft to evaluate the stress and load level of the FPs by means of a dedicated FEM model, shown in Fig.24

![Figure 24. FP FEM model](image)

- Influence of the damper configuration and damper preload on the dynamic response, by testing different alternatives.

- Maximum admissible shock level before reaching the FP or encoder strength limit, by testing the structural models increasing the shock level until detecting a damage in the FPs.

In addition, a damper verification Model (DVM) was developed with different damper configuration to verify the shaft tilting due to thermal excursions depending on the dampers preload. Fig. 25 shows the shaft tilting at different temperatures for the DVM4, which carried asymmetrical and highly preloaded dampers. These results can be compared to the ones for the FM2 presented in Fig.10.

Figure 25. DVM4 shaft tilting due to thermal excursions.

The outcome of each one of the analysed factors were taken into account to define the required encoder gap, the damper configuration, damper preload and the maximum admissible shock load.
As a result of this investigation, a RfW was issued for a reduced shock level. This level was agreed by the consortium. On the other hand, the final FMD configuration was defined with a very low preload below 1 N to limit the residual load during nominal working of the FMD but acting when dynamic loads are applied. Finally, the complete test campaign was performed on the FMD QM and the design has been qualified.

8. CONCLUSION

The FMD is capable to fulfill the demanding performance requirements, withstanding the specified loads. Tight performances (10arcsec pointing stability with averaged 1arcsec repeatability and transition times below 30ms) and extensive life (equivalent to 3000 million cycles) have been demonstrated. These requirements lead to a detriment of the load capability of the FMD, which required precise design optimization against environmental loads, in particular dynamic: vibration and shock.

The achievement of this optimum point where both objectives meet has been possible thanks to the combination of an extensive development phase of the different configurations, analysis of the mechanical loads and correlation with test campaigns and a very controlled assembly process.

As main lesson learned, the need of extensive test support to validate the design with significant non-linear behaviour together with demanding dynamic environment.

ACKNOWLEDGMENTS

The authors want to thank Jena-Optronik, Selex ES and ESA/ESTEC team members for their support and excellent ideas that led to the successful Sentinel-3 SLSTR FMS qualification.

We also would like to thank the LINES team at INTA who carried optical measurements in thermal-vacuum environment and ETS team at Noordwijk who supported shock test investigation, for their contribution to the success of the project.