Development and qualification of the Feed-Select Mechanism for the Polarimetric and Helioseismic Imager on-board Solar Orbiter

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Abstract

The Solar Orbiter Polarimetric and Helioseismic Imager (SO/PHI) will provide maps of the magnetic vector and of the line-of-sight velocities in the solar photosphere. For reaching its science goals, SO/PHI is equipped with two telescopes: the high resolution channel (HRT) and the full disk channel (FDT). Since both optical channels are fed into a common path including the camera, the need arises for a highly precise mechanism, which selects only one telescope at a time: the Feed-Select Mechanism (FSM). The mechanism therefore needs to serve two purposes: (1) directing one channel towards the camera, (2) shutting the second channel to not disturb the measurement of the observing channel. In this paper we will describe the different design features, as well as the design verification and qualification of the mechanism.

Keywords Space instrumentation · Optical instrument · Space mechanism · High precision · Solar Orbiter · SO/PHI

1 Introduction

Solar Orbiter is the first medium-class mission of ESA's Cosmic Vision programme. The aim of the mission is to study, how the Sun does create and control the heliosphere [4, 5].

The mission profile is based on a highly eccentric orbit, during which the spacecraft approaches the Sun up to 0.28 AU. Over the nominal and especially during the extended mission phase, the spacecraft will leave the ecliptic and allow to study the enigmatic poles of the Sun from a heliographic latitude of up to 33°. One of the key aspects of the Solar Orbiter mission is the combination of remote-sensing instruments, observing the Sun's surface and atmosphere, with in-situ instruments performing particle, wave and field measurements in the vicinity of the S/C.

The Polarimetric and Helioseismic Imager (SO/PHI) will provide maps of the magnetic vector and of the line-of-sight velocities in the solar photosphere [1, 8]. It will thus probe the deepest layers of the Sun of all the instruments on-board Solar Orbiter. Since the magnetic field anchored at the solar surface produces most of the structures and energetic events

in the upper solar atmosphere and significantly influences the heliosphere, SO/PHI plays a key role in reaching the science goals of Solar Orbiter.

2 The SO/PHI instrument

2.1 Measurement principle

The measurement principle of SO/PHI is to scan the FeI 617.3 nm spectral line, for which the polarisation properties are depending on the magnetic field structure in the line-forming regions of the solar atmosphere (Zeeman Effect), with a tunable narrow-band Filtergraph and to thus obtain the spectral line profile of each point of the field-of-view. At each of the 6 spectral scan positions the full polarimetric properties of the incoming solar light will be measured. Thus, the primary observables of SO/PHI are intensity profiles of the solar absorption line at four dedicated polarisation states. In addition, the exact wavelength position of the spectral line is depending on the relative velocity of the observing target and the S/C (Doppler effect).

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2.2 The instrument

SO/PHI is a diffraction limited, wavelength tunable, quasi-monochromatic, polarisation-sensitive imager with two telescopes, which alternatively feed a common Filtergraph (FG) and a Focal Plane Assembly (FPA). The High Resolution Telescope (HRT, [2]) provides a restricted FOV of 16.8 arcmin squared and achieves a pixel size that, near the closest perihelion pass, will correspond to about 100 km on the Sun. The all-refractive Full Disk Telescope (FDT), with a FOV of about 2° in diameter and a pixel size corresponding to 725 km (at 0.28 AU), provides a complete view of the full solar disk during all orbital phases. To restrict the imaged information on the FPA to the selected optical channel, a mechanism is needed which (1) directs the desired feed towards the common optical path and (2) shuts the unselected feed to suppress unwanted straylight. This role is fulfilled by the Feed-Select Mechanism (FSM). Figure 1 provides an overview of the SO/PHI Optics Unit opto-mechanical design.

3 The Feed-Select Mechanism

Being the junction point between the two optical feeds and the common optical path, the FSM is the key mechanism inside the SO/PHI instrument. To prevent a single point failure source, i.e., due to a motor failure during the mirror movement, which could result in a total loss of the instrument performance, a fail-safe functionality was required for the mechanism (see Sect. 4.6).

From a mission point of view, the FDT channel is of crucial importance, since it delivers context information for the other instruments on-board Solar Orbiter. The FDT position has therefore been defined as fail-safe position of the FSM.

In nominal operation mode, the mechanism needs to flip its mirror between the HRT and the FDT position with an

accuracy of $< 0.05^\circ$ (see Table 1). Section 4.5 explains in detail the design approach to achieve this high-precision positioning.

Although only two positions within the mechanism range are of interest, an absolute position encoder (see Sect. 4.4) is implemented to obtain complementary position information on top of the step counting and the information delivered by the end-switches when reaching the end of the travel range.

The main environmental and performance requirements driving the FSM design are listed in Table 1.

4 FSM detailed design

The FSM consists of a highly integrated and lightweighted structure made from aluminium alloy. Being manufactured in one piece, the structure provides the mounting provisions for sub-assemblies, bearings, etc. with high precision towards each other. This is especially important for the main bearings of the mirror rotation axis, which are spread over almost the full length of the mechanism. Any misalignment of the two bearings would directly impact the resistive torque and in the worst case, block the movement.

An overview of the FSM design is shown in Fig. 2. The major sub-assemblies are:

- the mirror assembly (Sect. 4.1),
- the worm gear assembly, comprising the worm gear and the mirror coupling and thus connecting the mirror with the drive train (Sect. 4.5)
- and the moving adapter, supporting the worm and key element of the fail-safe functionality (Sect. 4.6).

4.1 Mirror and mirror mount design

The Feed-Select Mechanism mirror (M3) is a plane mirror made from Suprasil® with a coating optimised for the science wavelength at 617 nm. To cope with the operational temperature range and the very low thermal expansion

Fig. 1 SOPHI optics unit

Table 1 FSM main design requirements

Parameter	Value
Fail-safe position	FDT
Number of flight operations	208
Movement range	50°
Position accuracy	$< 0.05^\circ$
WFE (peak-to-valley)	1.1λ
Operational temperature range	− 10 °C to + 70 °C
Non-operational temperature range	− 40 °C to + 70 °C
Design load	70 g (QSL)
Mass	< 0.50 kg

Fig. 2 Feed-select mechanism with its main components and sub-assemblies (cabeling and connector box are not displayed)

Fig. 3 Flight model of the FSM mirror holder with mounted mirror cell and glued mirror, seen from the rear side. The individual glue spots can be recognised through the ground glass surface

of the mirror material, the mirror is radially glued into a thin-walled mirror cell made from Invar[®]. The mirror cell is then mounted to the mirror holder, which includes the rotation axis.

To ensure a smooth running, the mirror holder needs to match the thermal expansion of the mechanism structure and is therefore made as well from aluminium alloy (see Fig. 3). With this approach, it is possible to handle the mismatch in coefficient of thermal expansion at a bolted metal-to-metal interface, while keeping the mirror's optical performance within its tolerances.

4.2 Kinematic chain and lubrication

The FSM uses a Phytron stepper-motor as the main actuator. The stepper-motor has a resolution of 200 steps per revolution. It drives the mirror rotation axis through a worm gear stage with a gear ratio of 70:1. This gives a theoretical mechanical resolution of 0.026° per step. To account for the stringent EMC requirements of the Solar Orbiter mission, the motor is optimised for a low magnetic flux leakage. This optimisation includes a special arrangement of the permanent magnets on the rotor.

The gear stage is composed of a steel worm (440C) and a worm gear made from TECASINT2391, a polyimid filled with MoS₂. The rotation axes of mirror, worm gear and worm are mounted through individual pairs of ball bearings.

The ball bearings are optimised for low friction, while sustaining the launch and qualification loads. As pointed out by [3, 7], it is of crucial importance to control potential gapping of the ball bearings during launch to secure the mechanism performance and lifetime. Therefore, special emphasis was put in tailoring the bearing stiffness such that resonances within the highly loaded frequency ranges during launch are preferably avoided.

To comply with the cleanliness requirements of the SO/PHI instrument, Braycote[®] 601EF micronic has been selected as lubricant. The bearing balls and races were made from 1.4108 stainless steel. To provide dry run capability to the bearing, the ball cages were made from Vespel[®] SP3.

Angular contact bearings were used for the mirror rotation axis. The mirror bearings are most demanding in terms of load capacity and compensation of thermo-elastic expansion, which reaches up to 0.015 mm between the two bearing points for a potential temperature difference between mirror holder and mechanism structure of $\Delta T = 10$ K. Therefore, it has been decided to use a pair of hard pre-loaded angular contact bearings in back-to-back configuration at the motor-driven side of the axis and for the second mounting point a soft pre-loaded angular contact bearing, ensuring a smooth running of the mirror rotation axis, even if temperature gradients are occurring. With this configuration, the first axial mode of the mirror system is pushed to about 1900 Hz, which is far outside the critical frequency range during random vibration. A potential gapping of the bearings is thus avoided and the Hertzian stress inside the bearing is kept below 3000 MPa. The friction torque of the bearing system is estimated with 4.3 mNm for cold and 0.4 mNm for the hot operational case.

The worm gear and worm axis bearings are less critical. Therefore, a pair of soft pre-loaded ball bearings is used for both cases. The bearings are arranged in face-to-face configuration for the worm axis and in back-to-back configuration for the worm gear axis. Both bearing systems have a first axial mode around 280 Hz, which is within the critical

frequency range during random vibration. However, for the given loads the bearings show sufficient margin against gapping. As for the mirror bearings, the Hertzian stress inside the bearings is kept below 3000 MPa. The friction torque of the bearings is estimated with 0.7 mNm (cold operational case) and 0.2 mNm (hot operational case).

After integration of all sub-assemblies and components, except for the motor, the mechanism's resistive torque was measured under cleanroom conditions to confirm the health state of the mechanism. The measurement showed a resistive torque of 1–2 mNm, which is in good accordance with the predicted bearing frictions for ambient conditions.

4.3 Shutter design

The *HRT shutter* is composed of two parts: a static (unsharp) field stop attached to the FSM structure and a moving plate, which is directly mounted to the rotating mirror (see Fig. 2). When the mirror is moved into the FDT position (see Fig. 4), the plate closes the field stop and catches the light coming from the HRT path.

The *FDT shutter* and the rotating mirror are directly coupled by a lever arm. The geometry of the moving plate is such that the FDT beam is only blocked, when the mirror has reached its final HRT position (see Fig. 5).

4.4 Position sensors

The mechanism has two types of position sensors, namely end switches and a potentiometer.

End switches are used to detect the mechanisms two operational positions. The inductive proximity switches employed for the FSM as end of travel switch provide a repetition accuracy of ± 0.01 mm, which translates together with the minimum distance to the mirror rotation axis to a rotational accuracy of $\pm 0.032^\circ$.

The *potentiometer* works as absolute position sensor and delivers redundant position information to the step counting. The sensor is directly flanged to the mirror rotation axis through a flexible coupling and provides thus a

Fig. 4 Feed-Select Mechanism in FDT position

Fig. 5 Feed-Select Mechanism in HRT position, showing FDT shutter

direct reading of the mirror movement. Read-out of the potentiometer is performed with a resolution of 12 bit. Taking into account the potentiometer non-linearity and some margin, this translates into a read-out performance of 0.035° . The potentiometer consists of an optimised compact design with a mass of 10 g and outer dimensions of $\varnothing 27$ mm $\times$ 13 mm. The most important design feature to obtain this compact design is the bearing configuration. The assembly consists only of one ball bearing. The second bearing point is provided by the flexible coupling, which is an integral part of the potentiometer's rotation axis (see Fig. 6). The flexible coupling allows a close tolerance connection to the mirror's rotation axis, while tolerating slight misalignments of the axis [6].

Fig. 6 FSM potentiometer design

4.5 Nominal mechanism operations

Although the mechanism provides a theoretical mechanical positioning accuracy of 0.026° , which would already be compliant to the required 0.05° (Table 1), the FSM design foresees additional means to ensure an accurate positioning of the mirror. To be independent from potential degradation effects over the mission lifetime, the positioning relies on the adjustment of the hard end stops. The hard end stops consist of an ultra fine thread, which enables an adjustment of the mirror position with an accuracy of (up to) 0.005° . This alignment step is performed during the FSM assembly and (if needed) repeated during the FSM integration into the SO/PHI Optics Unit.

As a design feature, the mirror rotation axis is not “hard” connected to mechanism’s drive train. The connection between drive train and mirror is established with the mirror coupling, which is formed by a dual flat spring.

To guarantee a well-aligned mirror and to increase the fault tolerance during mirror movement, the mirror is pushed with a predefined force against the hard end stop and thus pre-loaded. Figure 7 provides an overview of the mechanism’s nominal operation flow.

The pre-loading element is the mirror coupling between the drive shaft and the mirror rotation axis (Fig. 8). Until the mirror reaches one of the end-stops, the coupling is relaxed. As soon as the mirror reaches the hard stop, its rotational movement is blocked and a controlled overrunning of the end stop and thus a continued movement of the worm gear including mirror coupling is forced. Hence the corresponding flat spring is put under tension and creates the desired pre-load for the mirror.

Fig. 7 FSM nominal operations: **a** the mechanism is commanded in one of its operational positions (FDT or HRT); **b** the corresponding end switch triggers when reaching the desired end stop; **c** the motor executes additional steps to “overrun” the end stop and thus pre-loads the mirror; **d** the desired operational position is reached with a predefined pre-load

Fig. 8 FSM sectional view through the mirror rotation axis

4.6 Fail-safe mechanism operations

Primary purpose of the fail-safe functionality is to provide a second, independent actuator to direct the mirror into its fail-safe position (FDT). This role is fulfilled by a solenoid-based pin-puller, which was developed by Magnet-Schultz for the FSM. Similar to the whole mechanism, it has been optimised for low mass (60 g) and volume ($\varnothing 23.5 \text{ mm} \times 27 \text{ mm}$) and provides a pull force of about 20 N. The actuator is a manually resettable single shot device.

Figure 9 illustrates the sequence of the fail-safe mode. The mirror is assumed to be in arbitrary position within its travel range. To move it now into the fail-safe position, first the nominal drive train needs to be disconnected from the mirror. This is initiated through the pin-puller. While inactive, it holds the so-called moving adapter containing the worm engaged with the worm gear. After pull out of the pin,

Fig. 9 FSM fail-safe operation. **a** Nominal configuration with worm gear engaged and inactive pin-puller. **b** Nominal configuration with compressed push springs. **c** Pin-puller triggered and worm gear stage separated. **d** Push springs fully elongated and mirror pulled into FDT position

the moving adapter is pushed away from the worm gear by two push springs. The mirror would now be freely rotatable. To direct it into the FDT position, two pull springs connect the mirror coupling with the moving adapter. While being folded away, the rocker is thus pulling the mirror into the FDT position. As an add-on the two pull springs eliminate the mechanism's backlash during nominal operation.

5 FSM test and verification

For verification and qualification for the use in SO/PHI, the FSM underwent extensive functional and environmental testing. Since the environmental qualification tests (vibration, thermal cycling, and lifetime) are considered standard, this paper focuses on the mechanism's performance verification and provides only a short summary of the FSM qualification program (Sect. 5.4).

5.1 Positioning accuracy and repeatability

Mechanism alignment and alignment check were start and end point of each test campaign. The alignment of the mirror was measured through a triangulation setup using two theodolites (Fig. 10). With the use of this setup, the operational positions of the mechanism were aligned to an accuracy of 0.002° (HRT) and 0.001° (FDT) for the FSM lifetime model (LTM).

To assess the positioning repeatability, the mirror orientation was recorded for ten operational cycles, thus ten times each operational position was reached. It could be demonstrated, that also after going through its full test campaign, the FSM provides a positioning repeatability of at least 0.004° (Table 2). Combining the results of both measurements, an effective positioning accuracy of better than 0.01° can be determined for the FSM.

Fig. 10 FSM triangulation setup for alignment check

Table 2 Representative FSM positioning repeatability as measured for the FSM FM

	HRT	FDT
Minimal deviation	0.0030°	0.0013°
Maximal deviation	0.0036°	0.0009°
Standard deviation	0.0021°	0.0006°

5.2 Positioning accuracy under thermal vacuum conditions

During the thermal cycling test, functional tests have been performed on each of the temperature plateaus (hot-op and cold-op). The aim of the functional tests was to check the mechanism's torque characteristics and to verify the mirror positioning accuracy over the full operational temperature range.

The torque characteristic has been verified through careful ramping up of the motor drive current, until a movement of the mechanism was detected. It turned out that the mechanism's resistive torque remained even during lifetime testing at such a low level that it was possible to operate it with a phase current of < 100 mA (nominal phase current of the motor is 300 mA). No degradation of the mechanism's torque characteristic could be observed.

The optical setup of the functional test is depicted in Fig. 11. It enables a direct view of the theodolite on the mirror in FDT configuration and uses a plane folding mirror to measure the orientation of the mirror in HRT position. With this setup, it is possible to assess the relative change of the delta angle between both operational positions. Assuming stable operational positions of the mechanism over the full temperature range, this delta angle should remain similar over the full temperature range.

Although several disturbances as chamber vibration, low light level for the detection of the HRT position and slight deformation of the setup under temperature complicated the measurements, it was possible to confirm the stability of the operational positions.

The analysis of the test results showed a scattering of the measurements on each temperature level with respect to the delta angle of 0.01° – 0.02° , which is well in accordance with the expected measurement accuracy. A summary of the measurements for the FSM lifetime model thermal vacuum test is given in Fig. 12. The deviation from the reference value measured at ambient conditions is between 0.03° and 0.04° for the hot and cold operational case. These values represent a worst case for the mechanism's positioning accuracy over the operational temperature range, since contributions due to deformations of the test setup are already included in the measurement. Together with the static alignment error introduced in Sect. 5.1, the mechanism fulfills its required

Fig. 11 FSM TV test setup. **a** Functional test configuration for FDT position; **b** functional test configuration for HRT position; **c** functional test setup in TV chamber

Fig. 12 Results of functional tests performed during FSM LTM thermal vacuum test (summary of 36 functional tests distributed over 8 operational temperature cycles)

positioning performance, which could as well be confirmed during the system (instrument) level thermal vacuum test and calibration campaign.

5.3 Wavefront error (WFE)

Besides the mechanism's alignment performance, the optical quality of the mirror is a key performance parameter.

Table 3 FSM wavefront error budget

Contribution	WFE (ptv)	WFE (rms)
Mirror substrate	0.199λ	0.045λ
Mirror glued	0.324λ	0.075λ
Mirror holder mounted	0.324λ	0.070λ
Mirror spring loaded	0.929λ	0.198λ

Fig. 13 FSM mirror WFE vs. pre-load (0% = no deflection of the spring, 100% = full deflection of the spring). Green line: WFE with piston, tilt, focus and astigmatism terms removed; orange line: WFE with piston, tilt and focus removed; blue line: WFE with piston and tilt removed

This quality is described by the wavefront error (WFE) produced by the mirror. The wavefront is closely monitored throughout the whole FSM integration and test campaign.

As described in Sect. 4.1, mirror cell and mount are optimised to balance the difference in thermal expansion between mirror material and FSM structure. It therefore includes flexures, which are already effective during the mounting process of the mirror. Glue shrinkage and manufacturing tolerances increase the WFE by only 0.13λ (peak-to-valley, Table 3).

The biggest contributor with respect to the WFE is the pre-loading of the mirror (Sect. 4.5). In fact, the induced WFE is the dimensioning factor for the amount of pre-load set for the mirror. Figure 13 shows the WFE as a function of the applied pre-load. While the adjustment terms (piston, tilt and focus) remain almost constant, a linear increase of the astigmatism with increasing pre-load is obvious. As a compromise between optical performance and achieved pre-load, it has therefore been decided to set the mirror pre-load during nominal operations to 30%.

Figure 14 shows the comparison between the pre-loaded and the unconstrained mirror.

Fig. 14 FSM M3 Mirror WFE (piston and tilt removed, colour scale is individually adjusted for each measurement) measured for the configuration **a** substrate only **b** mirror glued **c** mirror holder mounted **d** mirror spring loaded

Table 4 Summary of sine and random vibration qualification test levels conducted during the FSM lifetime test campaign

	Sine	Random
X axis	21.0 g	20.97 grms
Y axis	13.0 g	19.08 grms
Z axis	13.0 g	24.92 grms
Duration	2 oct/min	120 s

The test duration is only given for the final qualification levels

5.4 Lifetime model qualification test campaign

Following the ECSS standards, the lifetime test campaign comprised several environmental tests, between which the functional and performance characteristics of the mechanism have been checked to exclude any degradation, before continuing with the test campaign.

As first step within the environmental qualification test campaign, the FSM was exposed to sine and random vibration (Table 4), which was concluded without significant change in the mechanism's modal characteristics concerning frequency and amplitude.

A summary of the subsequent following thermal cycling and lifecycle test is given in Table 5. Regular current drop tests indicated no increase of the resistive moment, and thus degradation within the drivetrain over the full test campaign.

As concluding step, a strip-down inspection has been performed on the lifetime test model. Similar to the prior performed tests and checks, the inspection did not reveal any significant degradation of the mechanism. Figure 15 shows exemplary pictures of two of the inspected parts.

Table 5 Summary of temperature cycles, total nominal and fail-safe operational cycles conducted during the FSM lifetime test campaign

Environment	Thermal	Nominal	Fail-safe
+21 °C, ambient	–	340	4
–40 °C, vac (Non-Op)	1	–	–
+70 °C, vac (Non-Op)	1	–	–
+21 °C, vac	–	60	4
–30 °C, vac (Op)	8	409	3
+70 °C, vac (Op)	8	667	3

Fig. 15 Exemplary laser scan microscope pictures of lifetime model parts after strip-down inspection. **a**, **c** Show the engaged section of the lubricated polyimide worm gear. The pictures show the continuously lubricated teeth, without indication of any degradation. **b** Shows the spring guidance, over which the pull springs are sliding during mechanism movement. Also here, no wear effects or other degradation in the coating of the part can be identified

6 Conclusions

The SO/PHI Feed-Select Mechanism is a compact and highly precise flip-mirror mechanism. In addition to its precise mirror pointing capability, it moves shutters, such that only the light from the desired viewing direction is reflected. Besides its nominal operations, it provides a fail-safe functionality relying on an auxiliary actuator to avoid a full instrument loss even in the event of failure in the primary drive train. The mechanism's performance has been confirmed for the required environment through several laboratory and environmental tests throughout the mechanism development and AIT cycle. It is therefore well prepared to work as part of the SO/PHI instrument on-board Solar Orbiter.

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