Development, Manufacturing, and Testing of the Ariel's Structural Model Prototype Flexure Hinges

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ABSTRACT

The Atmospheric Remote-Sensing Infrared Exoplanet Large Survey (Ariel) is the M4 mission adopted by ESA's "Cosmic Vision" program. Its launch is scheduled for 2029. The mission aims to study exoplanetary atmospheres on a target of ∼ 1000 exoplanets. Ariel's scientific payload consists of an off-axis, unobscured Cassegrain telescope. The light is directed towards a set of photometers and spectrometers with wavebands between 0.5 and 7.8 μm and operating at cryogenic temperatures. The Ariel Space Telescope consists of a primary parabolic mirror with an elliptical aperture of 1.1· 0.7 m, all bare aluminum. To date, aluminum mirrors the size of Ariel's primary have never been made. In fact, a disadvantage of making mirrors in this material is its low density, which facilitates deformation under thermal and mechanical stress of the optical surface, reducing the performance of the telescope. For this reason, studying each connection component between the primary mirror and the payload is essential.

This paper describes, in particular, the development, manufacturing, and testing of the Flexure Hinges to connect Ariel's primary Structural Model mirror and its optical bench.

The Flexure Hinges are components already widely used for space telescopes, but redesigning from scratch was a must in the case of Ariel, where the entire mirror and structures are made of aluminum. In fact, these flexures, as well as reducing the stress due to the connecting elements and the launch vibrations and maintaining the alignment of all the parts preventing plastic deformations, amplified for aluminum, must also have resonance frequencies different from those usually used, and must guarantee maximum contact (tolerance in the order of a micron) for the thermal conduction of heat. The entire work required approximately a year of work by the Ariel mechanical team in collaboration with the industry.

Keywords: space telescope, Ariel mission, aluminum mirror, flexure hinges, structural model, primary mirror.

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1. INTRODUCTION

Ariel, the fourth medium-sized mission of ESA's "Cosmic Vision" program, was officially adopted in 2020 to comprehensively survey the atmospheres of a large sample of known exoplanets [1,2]. This mission places significant importance on critical components such as the primary mirror (M1) and its associated Flexure Hinges (FHs). FHs are not just passive mechanical-structural devices but the lifeline of the primary mirror, designed to isolate it from the mechanical and thermal effects of the Ariel Telescope's Optical Bench (TOB), thereby safeguarding its optical quality. Mechanical effects include gravity, inertial, vibratory loadings, and potential stresses resulting from integrating the primary mirror to maintain proper alignment and ensure optimal optical performance during assembly on the satellite. In this study, we underscore the pivotal role of these flexure hinges in connecting M1 to the TOB, detailing the challenges in designing and fabricating this complex structural frame and highlighting the importance of maintaining the alignment of optomechanical elements under various loads.

2. MECHANICAL DESIGN

The primary function of the FHs is to minimize stress and distortion on the primary mirror while maintaining optimal alignment. This is crucial under the sinusoidal, random, and shock loads typical of the Ariane 6 launcher. To ensure a satellite-compatible dynamic response, the hinges must exhibit high stiffness, requiring the M1 mirror and hinges assembly to achieve a first resonant frequency above 130 Hz [3], but at the same time must be able to compensate the expected differential thermal shrinkage between M1 and the TOB during the transient cooling phase to reach the operative temperature of 50K.

Figure 1 shows an exploded view of the FHs mounted on M1 and their positioning. Both the mirror and the FHs are made of the same aluminum alloy, EN AW 6061 T651.

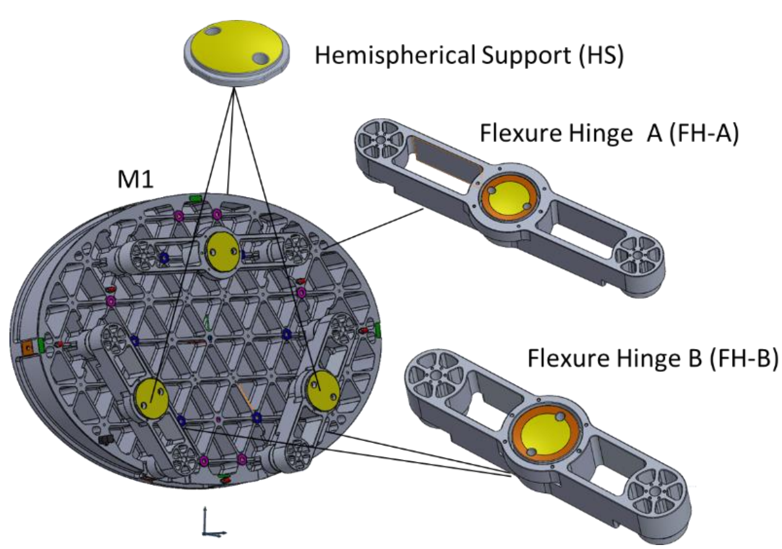

Figure 1. Explode view of M1 and Flexure Hinges.

Three flexible hinges support the M1 mirror, consisting of two types located on the back of M1, mounted to form a triangular configuration with the mirror's center of mass (see Figure 2). The implementation of this design allows to satisfy the thermo-mechanical requirements. In this context, the fabrication process of the FHs required careful attention to the techniques used. Based on these considerations, the manufacturing process must guarantee very tight dimensional and shape tolerances to minimize distortion of the optical surface when these elements are assembled between M1 and the TOB, and optical misalignment of M1 after launch.

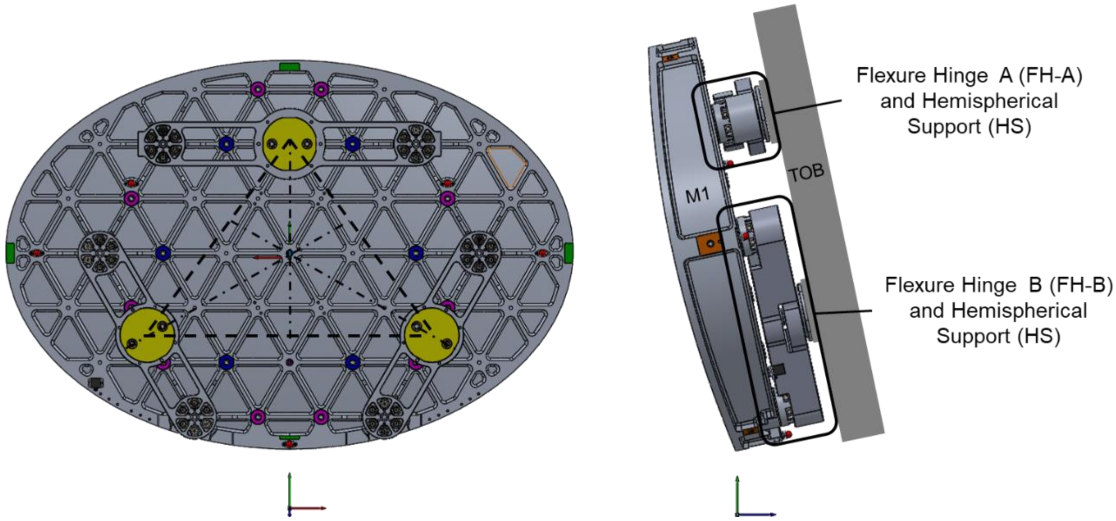

Figure 2. Assembly schema of FHs on M1 and TOB.

A particular aspect of the design of these elements is the hemispherical support (HS, see Figure 3) located between the FH and the TOB. This component achieves coupling with the FH through the interaction of a sphere and a conical-spherical housing surface and a plane-on-plane coupling with the TOB, freeing five degrees of freedom: two translations on the TOB plane and three rotations, making the mirror support system isostatic. The mirror positioning system's isostatic nature helps reduce any distortion and stresses generated by manufacturing errors.

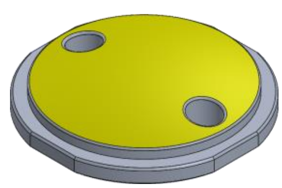
Figure 3. Hemispherical Support (HS) with a sphere R 195 mm.

Moreover, the shape of the concave interface surface (externally conical and spherical in the middle as visible in Figure 4) assures that during the mounting phase contact will occurs on the conical surface, reducing at the minimum possible distortional effects due to friction.

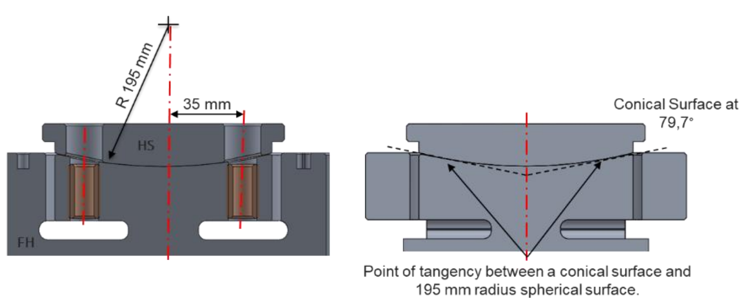

Figure 4. drawing of coupling between FH – HS.

Additionally, they must ensure optimal thermal conduction by maintaining a perfectly matched mechanical interface. When subjected to the load of the tightening screws, the minimal clearance on the spherical shape, achieved with exact machining, ensures the best possible thermal contact, as showed in Figure 5.

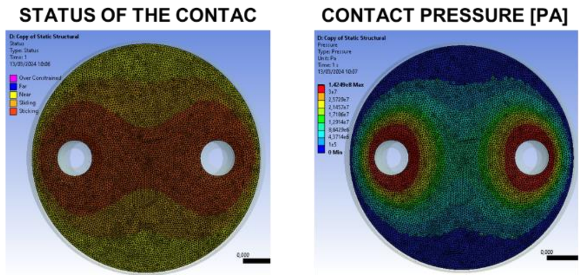

Figure 5. Contact simulation between the hemispherical support and FH due to the tightening of the screws.

3. MANUFACTURING

a. Flexure Hinges' functionality

The complexity of the flexure hinges arises from the need to provide multiple degrees of freedom (DOF) during installation (see Figure 6). The DOF compensates for manufacturing errors and accommodates various elastic parts capable of mitigating stresses due to vibration load levels during launch and thermal contraction during the satellite's cooling to 50K [3]. The more flexible parts of the FHs, known as flexors, are crucial for mitigating stresses at the interface with M1 and TOB.

The overall stiffness in all directions of the FH components is essential [4]. The cylindrical elastic part under the HS functions as an elastic spherical hinge to compensate for the stick-slip due to cone-sphere contact during assembly and absorb distortions of the TOB during vibrational loads. The stiffness corresponding to the parallel guide flexors allows the central cylindrical body (connected to the TOB) to translate and rotate, compensating for differential contractions due to the thermal gradient between TOB and M1 during the satellite's cooling.

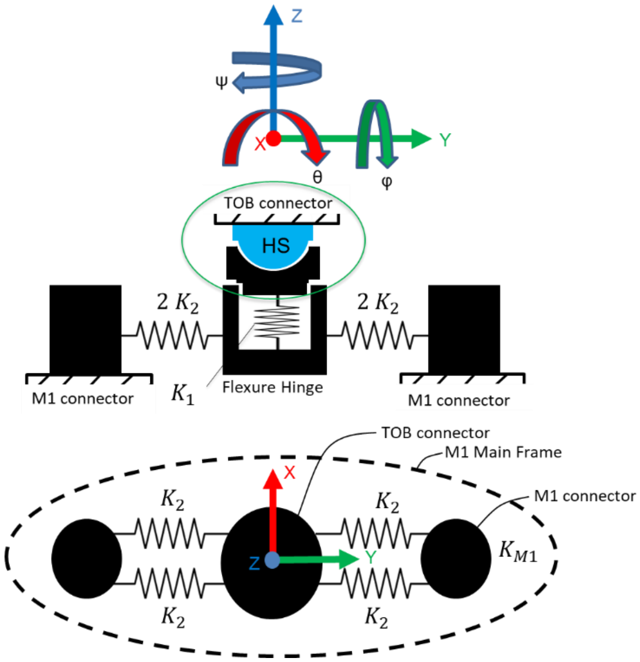

Figure 6. general FH schema, K_1 cylindrical spring and K_2 parallel spring guide.

b. Modal and thermo-structural analysis

A modal analysis was set up in Ansys on the FH-A to evaluate the prototype's modes and natural frequencies in free-free conditions. For this purpose, a detailed solid model of the FH-A prototype, including flanges, holes, and fillets, was imported as the finite element analysis (FEA) geometry.

The modal analysis of the model, under unconstrained conditions, allowed us to determine the resonance frequencies and natural modes assumed by the FH-A prototype. This analysis highlights that the first mode is lateral bending along the Z-axis and translation along the X-axis due to the flexibility of the parallel spring guides on the mirror plane. The second mode involves rotation around the X-axis and translation along the Z-axis, which could result in rotational deformation of the mirror around its principal axes. The third mode is rotation around the Y-axis. These first three resonance modes, illustrated in Figure 7, originate from the three natural frequencies of the parallel spring guides. The modes generated by the central cylindrical spring appear above 1000 Hz, demonstrating high bending and torsional stiffness.

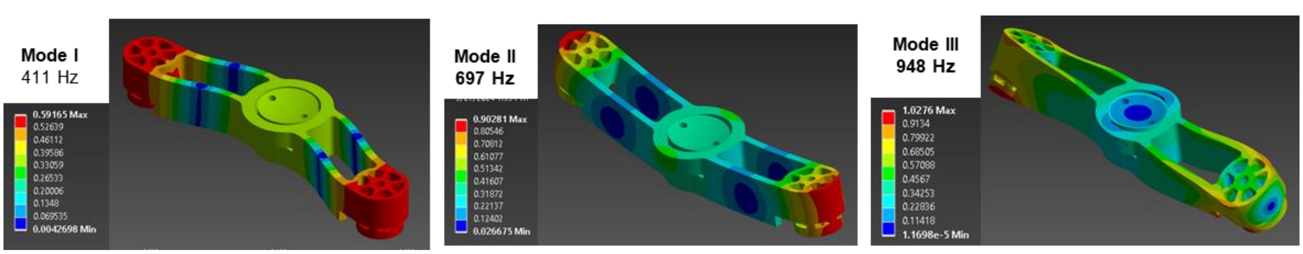

Figure 7. Modal analysis of FH-A prototype.

The above-mentioned design allowed to meet the tight dynamics requirement of the M1plus FHs subsystem, as showed in Figure 8, guaranteeing at the same time enough flexibility in the back plane of the mirror to compensate the different thermal shrinkage between M1 and TOB during the cooling phase, reducing the stresses at the interface as show in Figure 9.

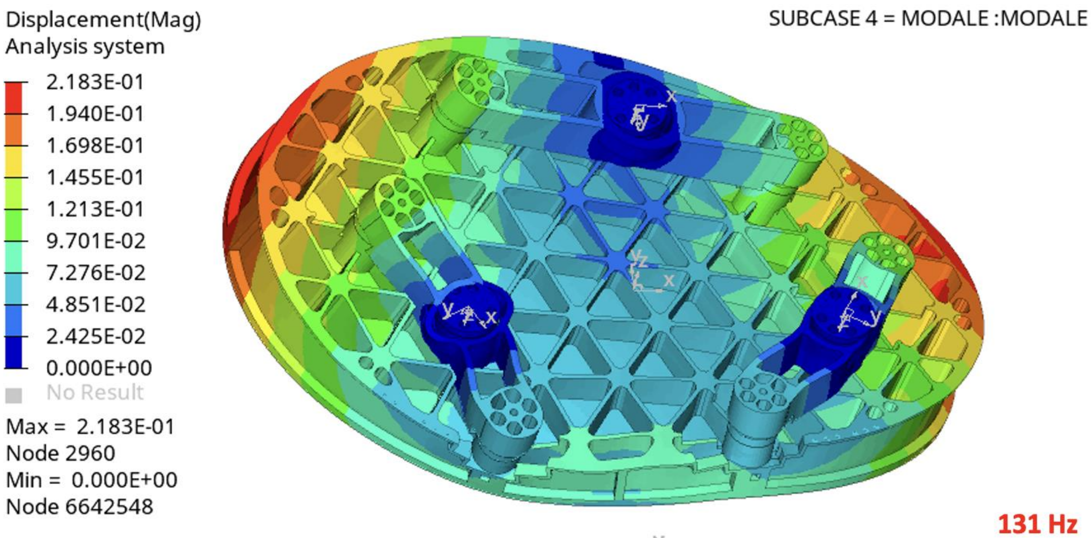

Figure 8. First modal shape of M1+ FHs subsystem rigidly constrained at the interfaces with TOB.

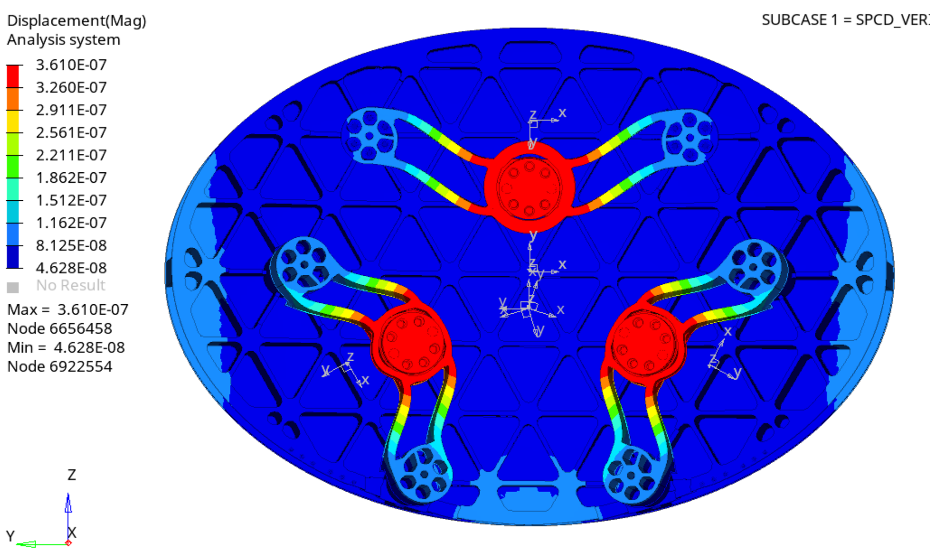

Figure 9. Deformation of the FHs during the cooling phase.

c. Manufacturing technique

The feasibility of manufacturing, determined by the results of the required functionalities and the modal and thermo-structural analysis, is a crucial step for the successful completion of the project. Prototyping the flexure hinges (FH) aimed to verify machining feasibility and compliance with the project's stringent dimensional and shape tolerances. Additionally, the construction of the FH-A prototype allowed for verification of its functionality once mounted on the M1 SM mirror, which is used for structural tests but has optical properties. An essential step in manufacturing the FH-A prototype was producing the cylindrical spring, which, after the milling phase with a 3-axis machine (see Figure 10), required a plunge Electrical Discharge Machining (EDM) process (see Figure 11).

Figure 10. rough milling of the part, Left) Rough milling of the outer profile, right) Semi-finishing milling of the cylindrical spring.

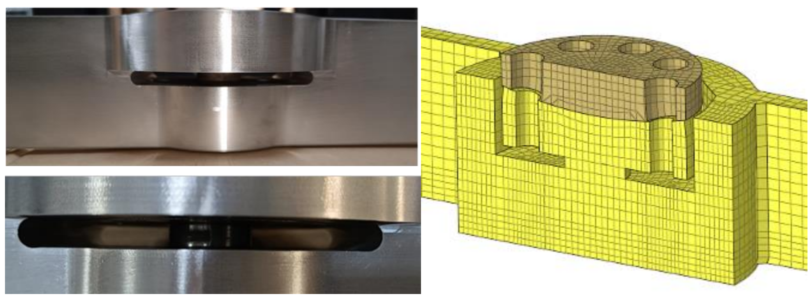

Figure 11. Frontal view of the central cylindrical flexor, obtained through a combination of semi-finishing milling and EDM techniques.

The Single-Point Diamond Turning (SPDT) was performed using a Nanotech 650 FG V2 machine, which was essential for achieving the project's required flatness and shape precision. Critical to the success of the machining process was the careful positioning of the components relative to the machine spindle, as shown in Figure 12.

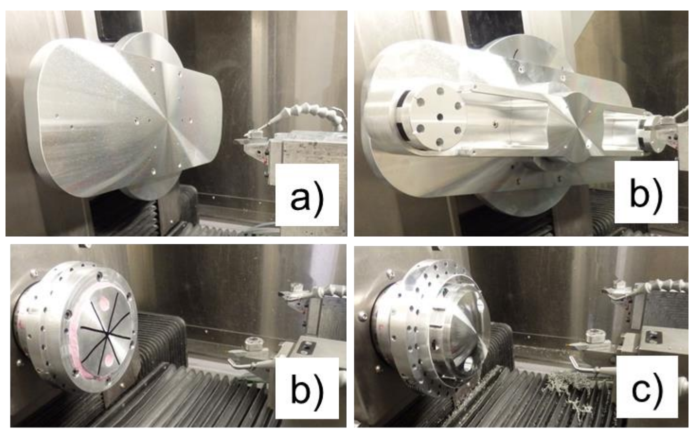

Figure 12. Phase of SPDT a) is the interface between the FH and the Lathe spindle b) the FH-A mounted on the Lathe C) is the interface between HS and the Lathe spindle d) the HS mounted on the Lathe.

The two pads of the FH were machined SPDT process, which achieved a flatness of less than 2 μm while maintaining the design specifications (see Figure 13).

Figure 13. Prototype of Flexor Hinges (FH) A: Images a) and b) show the surface quality achieved on the pads.

The tight tolerance of ±4 µm on the fitting dimensions between the FH housing and the HS was respected (see Figure 14).

Figure 14. Prototype of hemispherical support (HS): Image a) shows the quality of the spherical-conical surface of the HS housing made on the FH, b) shows the quality of the spherical surface of the HS, and c) shows the quality of the flat surface of the HS.

4. RESULTS

The performance of the M1 SM mirror was evaluated by installing a prototype of the Flexure Hinge type A (FH-A) and measuring the surface form error (SFE) before and after assembly. This test aimed to assess the distortion effect of the FH installation on the mirror.

The measurement setup involves mounting the mirror on a balanced support system with four contact points on the lower edge (see Figure 15). The FH was mounted under a condition where gravity and the semi-kinematic system's contact points induced a mirror deformation. In this configuration, the FH, which has its stiffness added to that of the M1, results in the mirror's shape being the sum of a random combination of geometric errors in flatness at the interface, the tightening of the fastener elements, and the mirror's reaction to the assumed geometry in its specific position. The geometry assumed as the counter-reaction of M1 in its natural position under the effect of gravity determines the shape of the mirror that results from the sum of the stiffnesses of M1 and FH-A.

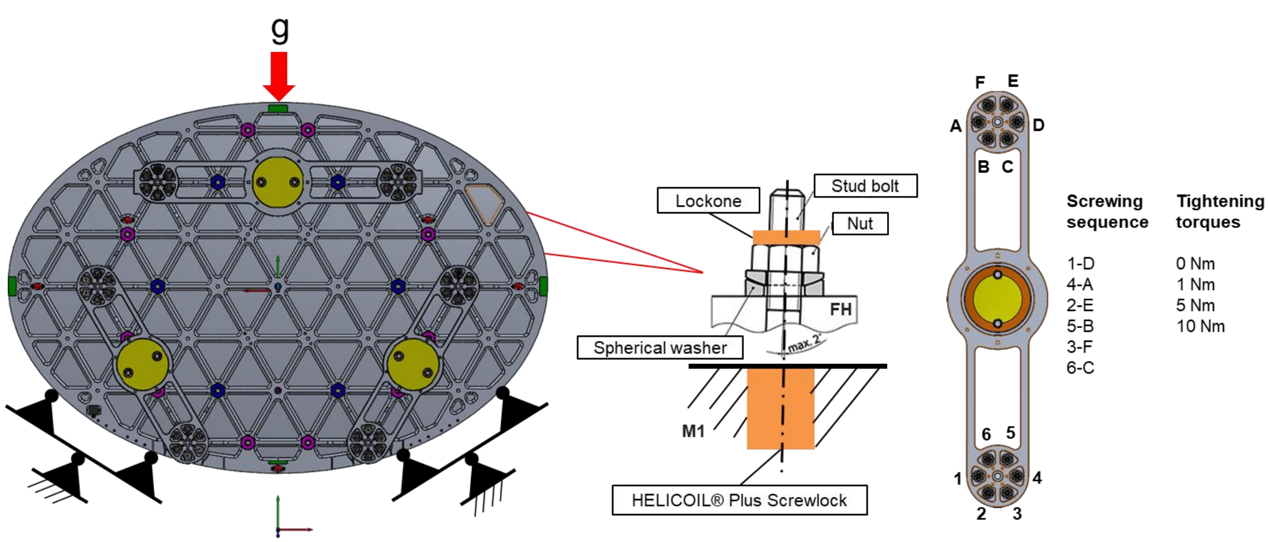

Figure 15. Mounting scheme of the FH on M1.

The SFE of the mirror was measured in two phases: first without FH-A and then with FH-A installed. The FH-A was mounted using a precise tightening sequence up to 10 Nm. The graph shows a geometric aberration of approximately 40 nm RMS between the seventh and eighth orders of Zernike polynomials (see Figure 16) caused by the installation of the FH-A. This aberration is a shape deformation of the surface mirror resulting from the combined stiffness of M1 and FH-A under the influence of gravity and the flatness of the interface pads.

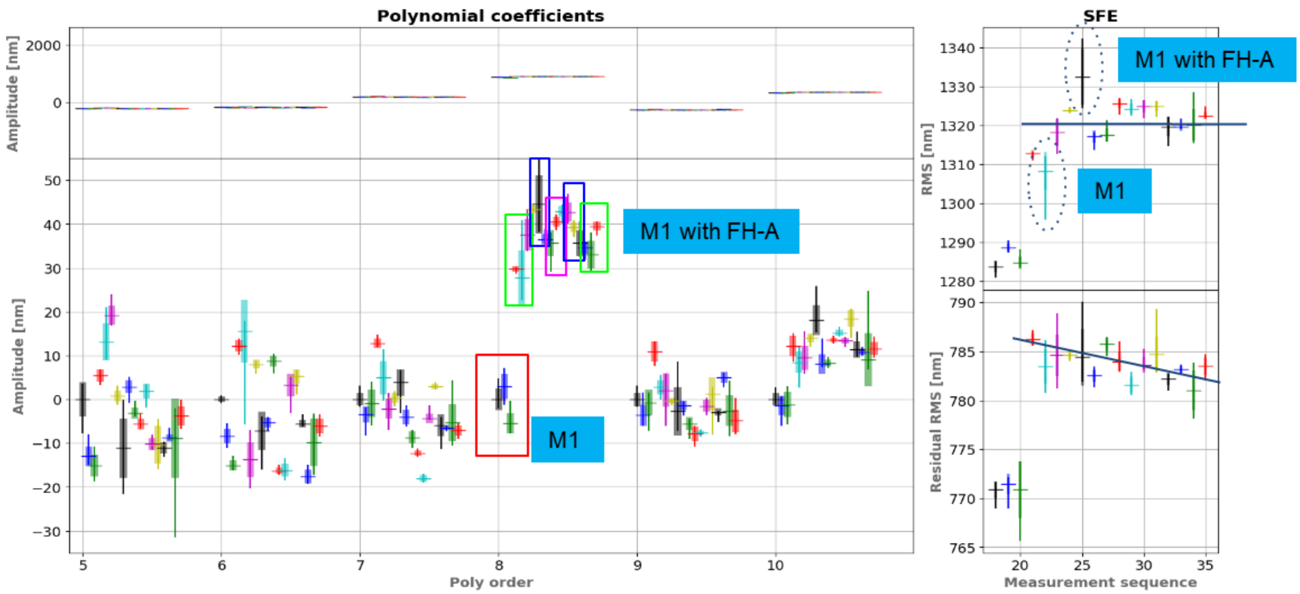

Figure 16. SFE graph without and with the FH-A mounted on M1.

The Zernike polynomials from Z5 to Z8 shown in Figure 17 highlight that the surface aberrations of the M1 mirror are primarily coma (from Z5 to Z6) and trefoil (from Z7 to Z8) due to the combination of the balanced support system used for M1 positioning and the subsequent mounting of the FH-A prototype. Coma occurs because of the non-uniform distribution of M1's mass on the four support points, while trefoil occurs due to an asymmetric distortion of the support points. In summary, the balanced support system of M1, the material used for the actuators placed to support the mirror, and the aluminum side surface of the mirror on which it is positioned randomly during the phase of alignment, can strongly influence the shape and SFE value, leading to a variety of optical aberrations including coma and trefoil.

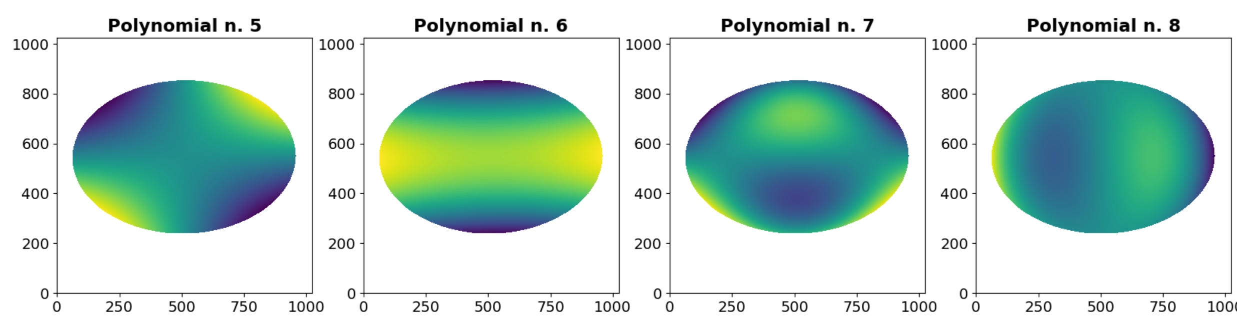

Figure 17. SFE maps aberrations of the M1 mirror starting from the Zernike polynomial from 5 to 8 with FH-A mounted.

To minimize these effects, a new support system, theoretically able to reduce its impact on the measured Wave front Error (WFE), and nominally to eliminate the influence of gravity, has been developed (see Figure 18) and is currently under test in the INAF Arcetri Observatory.

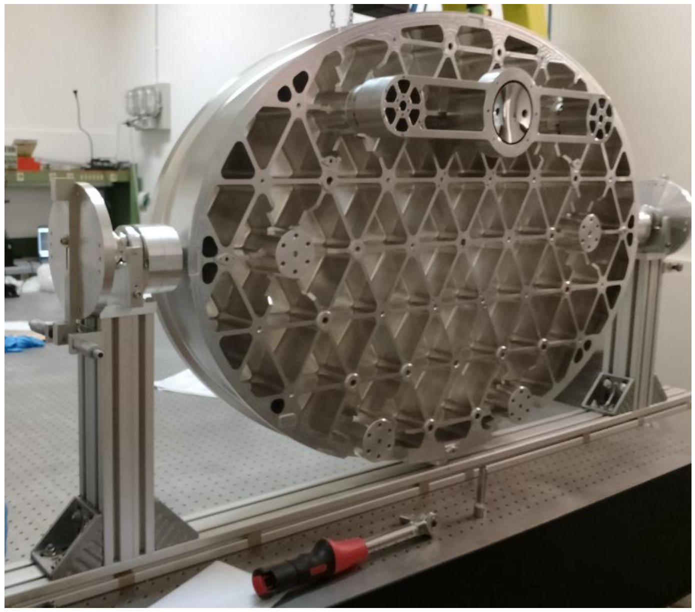

Figure 18. A new support system, such as the fork support, centered on the M1 CoG.

5. CONCLUSION

Flexure hinges are crucial passive mechanical components for the functionality of the Ariel telescope's primary mirror. They contribute significantly to its performance by minimizing stress and distortion, ensuring high stiffness, and achieving micrometric tolerances.
In the measurement configuration used for this test, gravity acts on the mirror and the support points, inducing deformation. The mirror bends or deforms according to its intrinsic rigidity and the support geometry. When the FH-A with its stiffness is mounted on the mirror, the assembly assumes a shape that combines the stiffnesses of both components. The resulting shape is then fixed in these conditions, representing a sum of the deformations, the combined stiffnesses and the fastening forces. The process leads to a final geometric configuration that includes all these factors, determining the mirror's surface form error (SFE), which results affected by gravity and deformations induced by the support system that could lead to erroneous interpretation of measured data. A new support system theoretically able to reduce at minimum its influences on the measured SFE and to eliminate the influence of gravity on the measured data has been designed and it is currently being tested under the supervision of INAF (Arcetri and Palermo), UNIFI and La Sapienza University.

Future activities will aim to formulate the best procedure for integrating the manufacturing and assembly phases of M1 and FHs, further mitigating the effects above and improving surface precision and structural stability.

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