FRONT DOOR ASSEMBLY DEVELOPMENT FOR CORONAGRAPH INSTRUMENT ONBOARD ESA'S PROBA-3 MISSION

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ABSTRACT

The Front Door Assembly (FDA) is a subsystem of the ASPIICS Coronagraph instrument developed by CSL onboard ESA's Proba-3 mission which is devoted to the In Orbit Demonstration of precise formation flying technology which will enable two satellites to form a 144 m externally occulted coronagraph in orbit which will produce a nearly perfect eclipse of the Sun allowing to observe the corona closer to the rim than ever before.

The FDA is a mechanism designed to protect the telescope optics with the capability of opening/closing the entrance aperture on the ground and during operation by rotating a lid of 134 mm diameter.

This paper will describe the most important design and verification challenges along with lessons learned during first-time development of a complex ECSS compatible space mechanism by Serenum/VZLU.

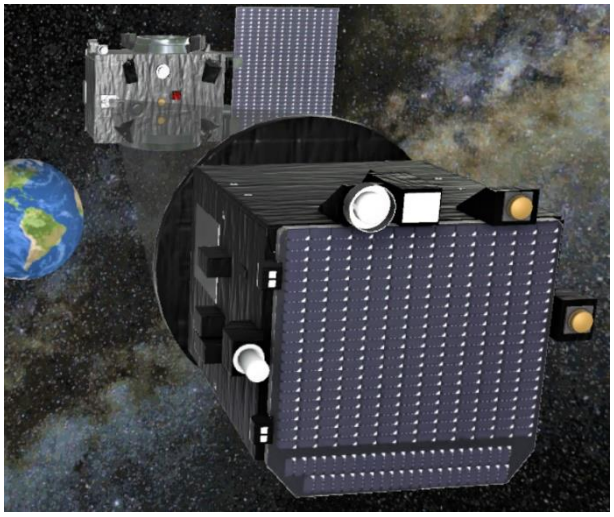

Figure 1: Proba-3 illustration - CSC (further) with FDA at the tip of the shadow cone cast by the OSC (closer)

INTRODUCTION

The main function of the FDA is to protect the coronagraph telescope optics from light and contamination during on-ground activities, launch and some flight operations. This is achieved by blocking the entrance to the Coronagraph Optical Box (COB) by the main moving part which is a lid of 134mm diameter with the ability to be opened in under 30 seconds when the coronagraph goes into operation. This happens only during a 6-hour apogee arc when the two satellites of the Proba-3 constellation are in formation and the telescope placed on the Coronagraph Satellite (CSC) is eclipsed by the disc on the Occulter Satellite (OSC). When the formation is broken the FDA lid is closed to prevent direct sunlight from thermally loading the inner parts of the coronagraph. Thus, the FDA is required to operate in the region of both eclipse and direct sun illumination.

There are three configurations of the FDA: locked, closed and opened. The lid is locked during launch while it is also preloaded to prevent rattling or any extensive movement of the lid during flight vibration. Closed FDA enables systems for optics calibration and formation flying control placed in the COB to see through the lid by total of nine windows, five of which contain a special filter. A wax actuator (pin-puller) is used to lock/release the lid and a stepper motor is used for rotation of the lid by 180º to the open position.

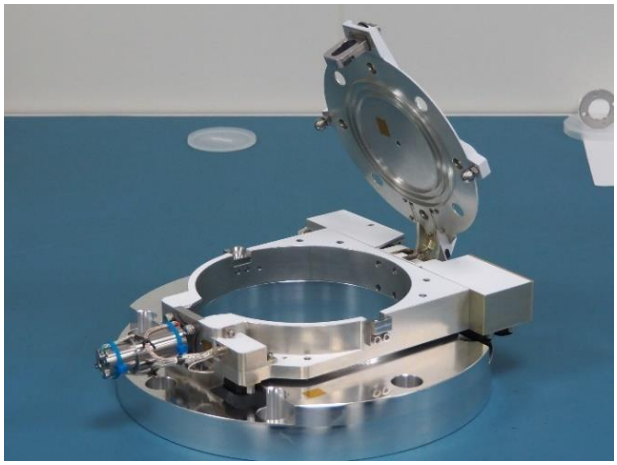

Figure 2: Partially opened FDA FM on a vibration jig

REQURIEMENTS

Below are listed some of the most important requirements governing the design and verification of the FDA:

- When the lid is closed there is no direct light path left except through the High Density Diffuser (HDD) windows.
- One full opening or closing cycle shall be achieved in less than 30 seconds.
- The overall flight configuration mass shall not exceed 1.5 kg.
- The FDA shall be bolted to the COB by eight M4 bolts.
- Upon final assembly the mounting bots shall be locked by self-locking mechanism .
- The COB interface is a tube of 135 mm diameter.
- The sine vibrations go up to 30 g.
- The random loads originally up to 41.6 gRMS (reduced during project to 16.5 gRMS).
- The FDA shall be able to endure, without deterioration, at least 1000 operating cycles in orbit.
- The FDA shall have its first natural frequency above 400 Hz.
- Spacecraft side conductive thermal environment: -14.6 to 77.3 ºC.
- Radiative thermal environment: -100 to 150 ºC.

The design and verification consequences of these requirements will be addressed throughout the paper.

DESIGN

The FDA consists of the following main structural subassemblies shown in Figure 3 – the Flange (1), the Lid (2), the Motor bed (3), the Connector bed (4), the Hinge (5), and the Pin-puller (6). Most of the structure is manufactured from Aluminium 6082 except parts with friction and contact regions. These regions are where the Lid is in contact with the rest of the structure. There is a steel shaft in a VESPEL (SP-3) bush bearing, Titanium Pin-puller pin in a steel nose lubricated with Dicronite, and Titanium touchdowns in steel cup-cones. There is no liquid lubrication used in the design outside the purchased parts such as the motor and the Pin-puller. The self-lubricating properties of the VESPEL bearing are enough for good motorization [3].

<u>The Flange and the Pin-puller</u>

The Flange is the main structural part which holds other parts and subassemblies, and which is connected to the COB via eight M4 bolts with composite washers for better thermal insulation of the FDA from the rest of the satellite. The interface bolts were problematic throughout the development and are discussed later.

The Pin-puller is a SP-5025 wax actuator from SNC with a pin which goes to the steel nose (may be seen up on the Lid in Figure 2) which is used for locking and preloading the Lid. During commissioning the pin will be retracted and the Lid will be unlocked and free to be operated.

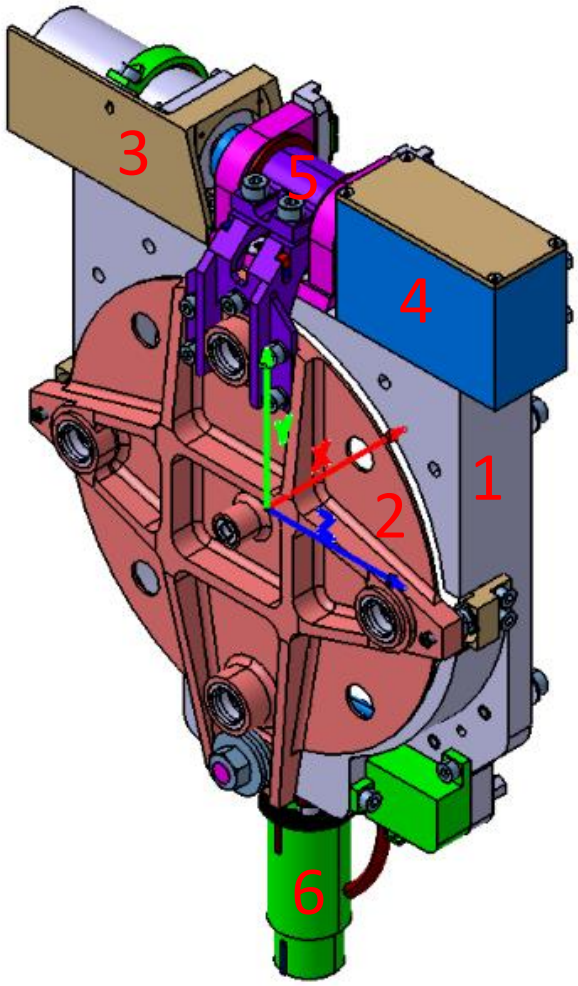

Figure 3: FDA CAD model

<u>The Lid assembly</u>

The Lid is the main moving part of the FDA which opens and closes the telescope aperture. There are multiple important design features on the Lid assembly.

The nose with a tightening nut serves for locking of the Lid by the Pin-puller and for soft preloading the Lid by tightening the nut. The preliminary design at the time of Pin-puller procurement did not include preload, when the need was identified to achieve a more linear structural response the preload was incorporated in a way allowing use of the existing Pin-puller. The amount of preload is measured by a gap between the Lid and the Flange. The relationship between the gap and the preload force was calibrated using a special custom-made tool. The lesson learned during the calibration was to mount the Flange to appropriately rigid structure. At first, the Flange seemed

much stiffer than the Lid, but it was found it bends significantly during the preload and needs to be properly fixed to yield the right gap-preload correlation.

The contact points are half-sphere titanium parts fitting in steel cup-cones which ensures the right position of the Lid when closed. This is important because the Lid itself can move a lot when in-between extreme positions, but it needs to be very well positioned when closed because of the next important feature.

The labyrinth (may be seen on the bottom side of the Lid in Figure 2) is there to provide good light and particle tightness as required, and without touching the counterpart which is under the Lid. The labyrinth was difficult to design because the counterpart was developed elsewhere (INAF), and it was important to balance the tightness with the tolerances. It was also critical to properly design the windows on the Lid to enable the systems inside to see through when the Lid is closed.

The Motor bed and the Hinge

The stepper motor (bottom right in Figure 4) is a GN6 from CDA with 0,8 Nm geared pull in torque at room temperature was selected for rotating the Lid. It was chosen mainly based on the dimensions, torque, and mechanical loads. The vibration input loads were already quite high at the time of the motor selection and unfortunately were later significantly amplified at the motor location by the design. This caused many challenges along the way as discussed later. The lesson learned is to account for possible high dynamic amplifications. On the other hand, it should be said that the design changed significantly after the motor selection, and it would have been probably very difficult to find a much more suitable motor.

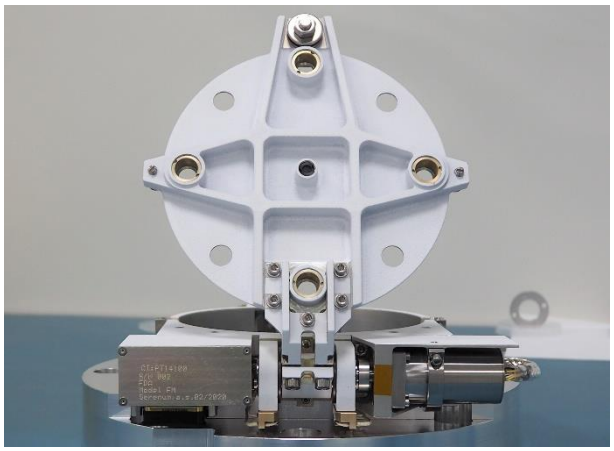

Figure 4: FDA FM – partially opened Lid and the Connector bed, the Hinge, and the Motor bed below (left to right)

The torque from the motor was originally planned to be transferred to the Lid by direct mounting, however during the analysis campaign it was found that this would exceed the max radial load at the motor shaft. Thus, coupling was re-designed to transfer the toque through a motor shaft with a key which goes inside a hollow Lid shaft with a clearance fit (Figure 5).

The Lid shaft is placed inside two friction bearings made of VESPEL press-fitted in the Hinge. There are clearances both between the motor shaft and the Lid shaft as well as between the VESPEL bearings and the Lid shaft. The clearances at the bearing are present because the Lid can be exposed to both direct sunlight and shadow from the OSC, so to help maintain the coronagraph at a stable temperature the Lid is thermally isolated by the clearance bushes, and this causes a large thermal difference of up to 130 °C. The clearances are also governed by the different materials used, in this case steel, aluminium and VESPEL were implemented for their different properties. The clearances at the motor shaft are present for mechanical decoupling of the motor from the Lid. The Lid and the motor shafts are not in contact while the FDA is locked and thus the extensive vibration of the Lid assembly does not transfer directly to the motor through the shaft.

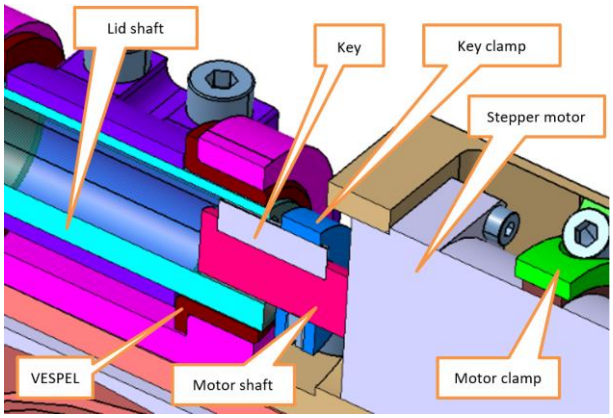

Figure 5: Cross-section of the torque transfer design

On top of the bearing, the Hinge bracket holds other important components such as plungers and position sensors. The plungers have a nominal force of only 14 N, but they will help define the extreme positions of the Lid in the microgravity environment and add some slight torque when the Lid is about to leave those positions. Reed-switches are used as position sensors and there are nominal and redundant for both the open and the closed position. The design allows some amount of adjustment of the switches, but it was still quite difficult to find the right configuration for good reading of the open/close position. The main problems were the required tolerances for the positions, the clearances which allowed movement of the Lid based on gravitation and thermal loads distorting the sensors and the structure.

DESIGN MODEL VIBRATION TEST

The vibration test of the DM was performed in February 2019 in ESTEC facilities. The main goal was to test and assess whether the design is capable of withstanding, at that time very high, qualification random vibration spectra going up to 41.6 gRMS. Secondary goal was to try different values of the preload to help correlate the analysis and find the value sufficient to prevent any rattling or movement of the Lid. The test had three important conclusions:

1) There is some amount of settling of the mechanism with any viable preload value especially after the Lid is opened and closed which makes sense as it needs to find the right position again. It was decided to use the highest preload from preselected values while keeping a good margin for yielding of the Lid and whilst staying within the capabilities of the Pin-puller. This preload does not allow for any gapping and rattling, but it can allow for some settling at some point during the random vibration.

2) High mass and location of the motor resulted in very high resonance at 870 Hz with amplification factor of 80 (dashed line in Figure 6) which would most certainly lead to damage during test. This resulted in additional coupled loads analysis with the instrument prime (CSL), notching of the spectra and redesign of the motor mounting by adding more screws between the Motor bed and the Flange, and adding a clamp to a stiff location (Motor clamp in Figure 5). These changes moved this resonance up, into an area with lower input, and reduced the height of the peak significantly as may be seen in Figure 6. Additionally, a model correlation and the additional coupled loads analysis allowed for lowering the input levels.

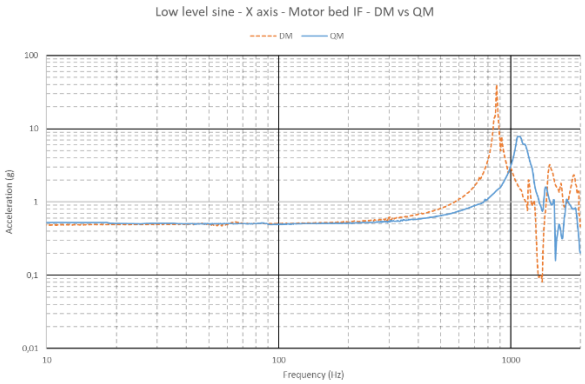

Figure 6: Motor IF resonances before and after the redesign

3) The final conclusion, which also led to a design change, came from a failure of a key on the motor shaft during the last run of the test. The key fell out of the motor keyhole and the Lid could not be opened by the motor. To prevent this from ever happening again a clamp was designed to hold the key in place and still allow it to turn the shaft (Key clamp in Figure 5).

QUALIFICATION VIBRATION TEST

The vibration test of the QM was conducted in October 2019 in ESTEC and CSL vibration facilities. Along with typical qualification requirements, acceleration limits were specified for the stepper motor and Pin-puller to prevent damage. After each reduced level random run the measured responses were used for prediction at full level random load. During the out-of-plane (X-axis) runs it was predicted that the responses would exceed the limits and notches had to be addressed.

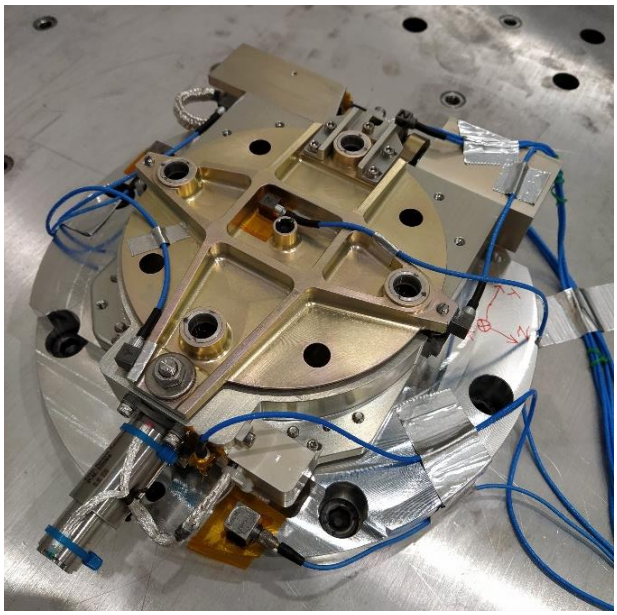

Figure 7: FDA QM during vibration test

Similar to DM vibration testing, some small settling almost always occurred after the Lid was opened and closed but this usually happened only during the low-level or intermediate-level random and stabilized. Other small frequency (<7%) and amplitude shifts happened during the in-plane runs, specifically Y -3dB run and Z 0db run which both correspond approximately to an input of 12 gRMS. Any frequency shift above 5 % was followed by another low-level random run and resonance search showing no further settling. It was concluded, that at that energy level the Lid can probably change its position between two relatively stable positions. Repetition of these runs always showed stability.

The vibration qualification was successful with no detected damage, successful functional tests, and first natural frequency at 770 Hz.

INTERFACE BOLTS

Some concerns about the tightening torque of the bolts connecting the whole FDA to the COB tube arose during the qualification at the instrument level which, after appropriate NRBs, led to use of different bolts for the FM.

After revisiting the bolts margins calculation, it was discovered that a higher torque should be applied to prevent any possible gapping or slipping negative margins. The biggest issues resulting in the low margins for those failure modes are the big difference between the possible maximum and minimum bolt preload force considered by the calculation, the static forces coming from preload of the structure and the prevailing torque of the self-locking helicoils used.

Uncertainties in the threaded fasteners margins calculations according to ECSS-E-HB-32-23 causes a big difference between the maximum and minimum possible preload force, which can cause problems while trying to find a tightening torque which would leave all the margins positive. These uncertainties are mainly in the friction coefficient range and torque wrench uncertainties. A more thorough investigation of those factors made it possible to make the range of bolt preload smaller.

Another important factor in the fasteners analysis are static forces coming from the preload of the Lid. These forces produce significant axial and lateral loads of the fasteners which with combination with the loads coming from random vibration decrease the gapping and slipping margins considerably.

The third problem was coming from the locking of the FDA interface bolts which was required. The self-locking helicoils were chosen to simplify assembly with the COB Tube and caused big problems as a significant portion of the applied torque is lost in the prevailing torque and therefore not contributing to the preload force and to preventing slipping and gapping.

After many computations with different parameters the problems were resolved for the FM by using special custom-made hight-strength lubricated bolts and not using the self-locking helicoils.

THERMAL VACUUM AND LIFETIME TEST

The FDA was life tested in thermal vacuum (TVAC) to verify the capability to function in the operational environment over the course of the mission. To achieve the qualification temperature extremes the unit was mounted within a custom adapter in the chamber, with the Lid facing down as shown in Figure 9.

This configuration made it possible to achieve the necessary temperatures but meant the FDA had to be capable of operating against gravity under all thermal conditions.

The planned test profile included completion of 4114 open/close cycles spread over 8 thermal cycles (shown in Figure 8), as well as Pin-puller activation in hot and in cold conditions. Another 90 activations followed during the lifetime test outside the TV chamber. During the testing, the start-up current and number of steps between activation of the reed switches was monitored.

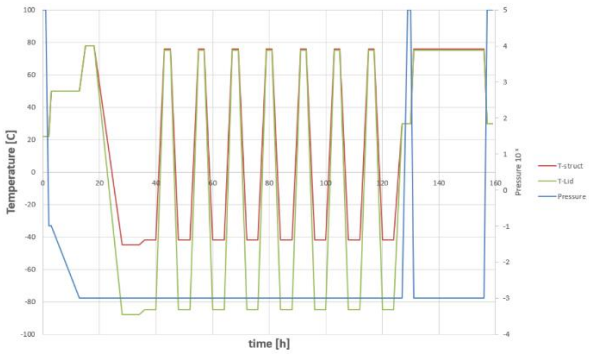

Figure 8: TVAC temperature and pressure profile

Several challenges were experienced during the TVAC campaign, the first was related to achieving the cold plateau temperatures of approximately -100 °C on the Lid and -50 °C on the Flange. These temperature predictions were for the operational configuration where the Lid was not preloaded, significant effort was initially spent trying to cool the set-up but the lowest Lid temperature achieved was warmer than -70°C. Once the Pin-puller was released the absence of preload allowed temperatures of below -85°C to be achieved whilst the Lid remained closed.

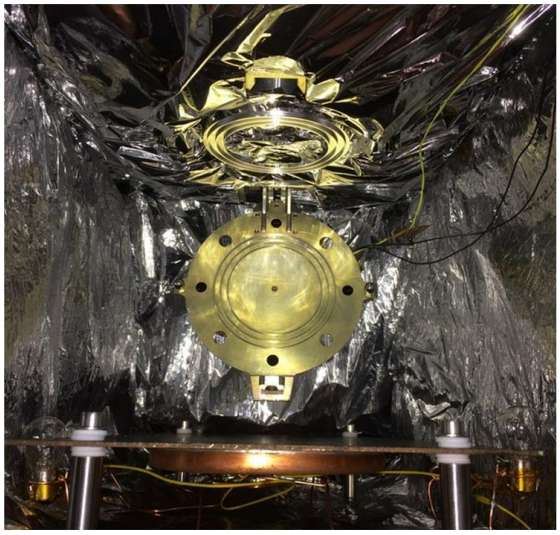

Figure 9: TVAC FDA Lid down configuration

The second challenge was related to high temperatures. To complete the necessary cycles on schedule a high duty cycle of opening and closing the Lid was planned, however during the testing this led to an increase in the motor temperature and an increase in the start-up current. Fortunately, a thermal sensor was implemented on the motor, and this could be identified and the period between open/close cycles increased to ensure the motor temperature did not become artificially high during the test.

Another issue experienced during the lifetime test was related to the resetting of the pre-load. During the release testing the nut which was used to apply the preload jammed due to the multiple uses, this is not a wearing part in flight, but the investigation and resolution without impacting the rest of the test configuration did cause delays. A fix was identified for the QM and the importance of planning spares for such parts for the FM identified.

LESSONS LEARNED

- Self-locking helicoils can have a significant prevailing torque which limits the ability of the bolt to prevent slipping or gapping.
- Static preload of the structure can lead to major forces in the bolts (and other parts) which can lead to problems in margins.
- During preload calibration the structure should be properly mounted to represent the proper forces distribution.
- Press fitted key should be secured in some way.
- When buying a component such as the stepper motor, attention should be given to the possible dynamic amplifications of the vibration loads early. However, it can be very hard to predict as the requirements may evolve, the design may change, and such complex components are very expensive and can have significant lead time.
- Designs avoiding direct coupling of the motor to the inertia to be moved can permit more separation between the motor selection and the system mechanical design.
- Where extreme cold temperatures are required across mechanism moving parts careful correlation of the TVAC test case with the applicable preload is important, as well as the application of thermal sensors to all key parts to avoid losing time during key tests.

CONCLUSION

The FDA was designed, developed, and tested as summarized herein. The FDA was for Serenum/VZLU a first complex space mechanism in full accordance with ECSS, and although many challenges and delays occurred along the way the development was successful. The qualification verified the robust design and at the time of submission of this paper the FDA has been successfully integrated and tested at the instrument (ASPIICS) level. Following is the instrumentation and testing at the satellite level and launch planned for year 2023. The work was financially supported by the Czech Republic participation in ESA-PRODEX Program.

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