VERIFICATION OF THE INTERNAL HOLD-DOWN MECHANISM FOR LUNA-27 PROSPECT DRILL COLUMN: DEDICATED GSE DEVELOPMENT CHALLENGES AND LESSONS LEARNED

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ABSTRACT

Internal Hold-Down Mechanism (IHDM) is one of two hold-down & release mechanisms developed by Astronika for PROSPECT mission as a Leonardo's subcontractor under ESA contract. Key functionality of the thermal knife actuator based mechanism is to, during flight, secure the Drill & Positioner (~1 m rods implemented in the PROSPECT's drill column).

Paper describes the development challenges encountered during verification programme of the IHDM breadboard refurbished to engineering model due to the successful nature of the test campaign outcomes. Verification activities hardware was subjected to cover: functional, preload measurement, generated shock measurement, vibration, thermal cycling and dust contamination test. Main focus of the paper is put on the development of vibration test Ground Support Equipment replicating the boundary conditions of the overall drill column as well as system level loads acting on the IHDM interface. As a result of these activities, when delivered to the system level testing, IHDM shall achieve TRL 6.

1. INTRODUCTION

Scope of the paper describing Internal Hold-Down Mechanism (IHDM) verification activities is divided into following sections:

- Mission & IHDM design description, highlighting key mechanism functionalities verified during test campaign,
- Engineering Model (EM) test activities,
- Lessons learned – key input for future Qualification (QM) & Flight Model development (FM),
- Conclusions.

1.1. Prospect mission description

IHDM is one of the key subsystems of the Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT). Mission is set to be launched in the 2023 on board of the Luna-27 lander (ROSCOSMOS). Astronika develops 2 subsystems in scope of PROSPECT:

- Internal Hold-Down Mechanism (IHDM) – responsible for holding the PROSPECT's Drill Rod & Drill Translation Screw in locked state during flight, releasing them upon activation,
- External Hold-Down Mechanism (EHDM) – 2 point Hold-Down Release Mechanism (HDRM) responsible for holding the PROSPECT's Drill Structure in locked state during flight, releasing it upon activation.

PROSPECT is developed by Leonardo under ESA contract.

Primary objective of the PROSPECT mission is to use its Drill (ProSEED) in order to gather samples from the Moon's south pole region, expected to contain ice and other chemicals that can become trapped at the extremely low temperatures (down to -200 °C). When obtained, samples shall be analysed in the on-board chemical laboratory subsystem (ProSPA), extracting trapped volatiles. Such mission will test processes that could be used in the future resource extraction activities.

1.2. Internal Hold-Down Mechanism design & design drivers description

Fig. 1 presents the overview of the PROSPECT system composing of IHDM, Upper and Lower EHDM as well as mechanical interfaces to the Drill Structure and Luna-27 Lander (interface plate shown in the figure). Based on the figure alone it can be identified that IHDM interfaces mechanically only with the Drill components, not being in direct contact with Lander. IHDM interfaces with (see Fig. 2):

- Mechanical & thermal interface:

    - Drill Structure (DS),
    - Drill Rod (drill translation),
    - Drill Translation Screw (sampling tool),
    - ProSEED Multi-Layered Insulation (MLI) – not visible in the figure, covering entirety PROSPECT components external surfaces,
- Electrical interface:
    - ProSEED Central Electrical Unit (CEU) – not visible in the figure, core electrical unit executing PROSPECT mission.

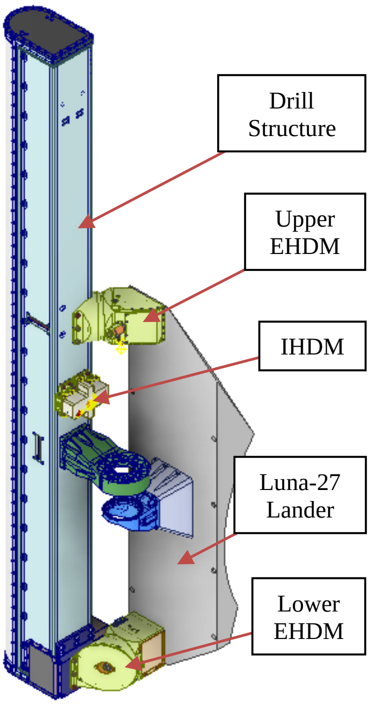

Figure 1. PROSPECT system overview

The direct mechanical interface to Drill Structure are 8 M4 steel inserts housed in the CFRP Drill Structure wall. The remaining 2 key interfaces are presented in the section view in Fig. 2: Drill Rod (DR; Al. 7075, hard anodised, thread outer diameter of 38 mm) & Drill Translation Screw (DTS; Al. 6082, black anodised, thread outer diameter of 24 mm).

Unlike the interface to the Drill Structure, both DR and DTS are preloaded with IHDM clamps, assuming preload levels of 300 N obtained on DR and 250 N on DTS interfaces. Indicated forces ensure that both rods (overall length up to 0.92 m), clamped in their middle points are secured during flight with an IHDM minimum eigenfrequency in locked state of 50 Hz.

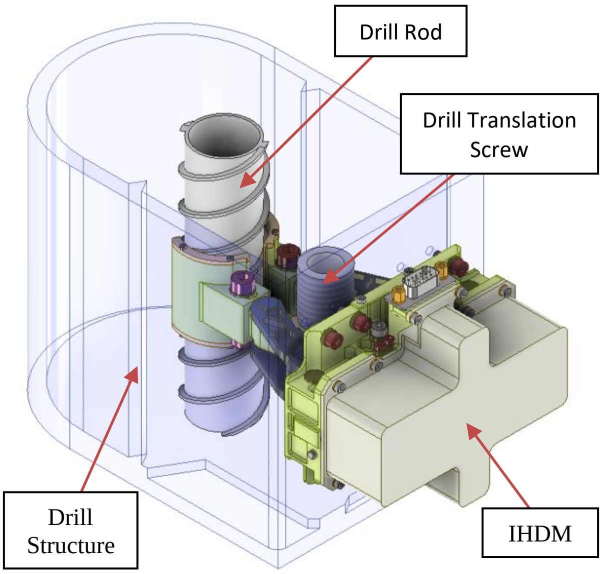

Figure 2. Drill Structure internal envelope

Based on the IHDM allocation and interfaces type following aspects of the mechanism were its design drivers:

- IHDM shall be a one-shot mechanism, based on the manually resettable actuator,
- While no explicit internal envelope is required in the IHDM locked state, in unlocked state IHDM shall fit the envelope presented in the Fig. 3, preventing clamping the entirety of DR circumference,
- When mounted to Drill Structure walls, only IHDM parts placed externally can be accessed – no direct access to DR and DTS interfaces is possible,
- Upon activation, IHDM shall be actuated using a feeding voltage of 27V to 32V PWM controlled. The maximum power consumption shall not exceed 20 W – deployment duration is not a design driver.
- IHDM shall be implemented with a redundant internal sensor providing confirmation of its proper deployment.

Except defining the internal envelope of DS unlocked state, IHDM cross section presented in the Fig. 3 reveals several key components. IHDM primary functionality (DR & DTS preloading) is realised with 3 stage leverage system, secured in locked state with dedicated IHDM actuator. When powered, actuator releases IHDM components after it melts the Vectran VB6 wire it is armed with. All leverage system stages are mounted on dedicated plain bearings, implemented with either torsion or flat springs (steel AISI 301, H) actuation, ensuring its travel to unlocked state envelope.

Entirety of IHDM key functional elements is symmetrical and redundant. This aspect of the design enforces a “symmetrical” preload application sequence, realised with dedicated screws (steel AISI 304, hard anodised) – by unscrewing the bolt (alternately each) mounted in the 2nd stage of leverage system; 1st stage, directly associated with the DR & DTS clamps, is preloaded. Distribution of the preload between each interface is realised with assuming correct position of the second preload application bolt type.

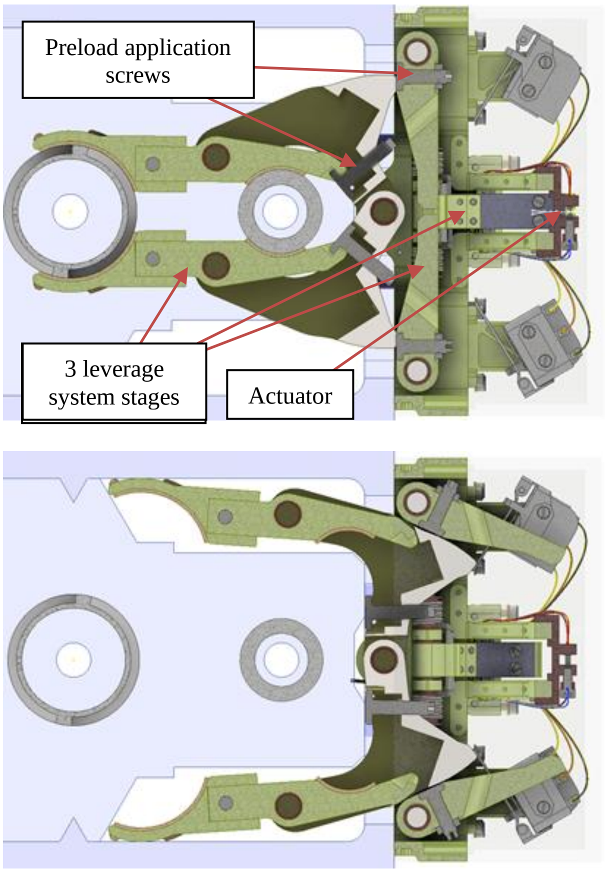

Figure 3. IHDM in locked (upper figure) & unlocked states (lower figure); section view

1.3. Development activities overview

IHDM development activities assumed developing BB model prior to Preliminary Design Review (PDR) as well as EM, QM and FM in frame of the CD phases of the project. Due to the key functionalities being impossible to isolate without replicating the whole hardware, it was decided that BB model shall be developed as a unit fully representative of the FM with lower standard of electrical components, materials and processes to be used. Additionally, while majority of environmental tests were planned to be executed using BB model, it was assumed that if all AIT (Assembly Integration & Testing) activities are considered as successful with no major NCs (nonconformances) identified, BB model shall be refurbished to EM and delivered to Leonardo for system level testing using Drill & Positioner EM assembly. Such approach was concluded successfully, ensuring IHDM TRL 5 (TRL 6 when EM system level testing are concluded).

2. INTERNAL HOLD-DOWN MECHANISM, ENGINEERING MODEL VERIFICATION ACTIVITIES

Based on the approach briefly described in the chapter 1.3, following flow chart summarises the AIT activities leading to IHDM EM validation in relevant environment (corresponding reviews are omitted):

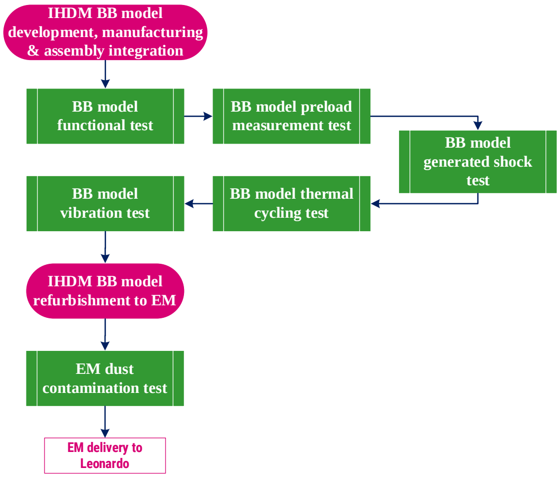

Figure 4. IHDM EM AIT activities flow chart

It must be highlighted at this point that while IHDM hardware was subjected to several test activities, the major emphasis was put on the vibration test due to the necessity of replicating the representative test configuration with no DS EM available at the time.

1.4. Assembly integration & functional test

IHDM BB model was manufactured and assembled without major NCs identified. Hardware functionality testing can be divided in 2 main aspects:

- IHDM functional deployments,
- IHDM preload application sequence determination (preload measurement test).

First point was quite straightforward – IHDM was deployed several times using test configuration composed of the sections of DS, DR and DTS (Fig. 5). Due to mechanism being fully resettable by the operator in ~15 min (replacement of the Vectran VB6 wire & preload application) no limitation of number of deployments was present. During IHDM BB model testing 60 deployments were registered – deployments in scope of functional test as well as prior and post each environmental test. When including deployments associated strictly with EM, overall number of 69 deployments were performed. Tab. 1 summarises the average data obtained from the BB model functional tests. Main and redundant resistors resistance is indicated in the table due to the actuator components being sensitive to resistance degradation – allowable IHDM limit equals (75.6, 105) Ω when powered for no longer than 12 s (initial values: main resistor 75.6 Ω, red. Resistor 76.4 Ω). Switches indication in all steps were successful.

Table 1. IHDM BB model & EM functional deployments summary

IHDM model	Total depl. no.	Avg. depl. duration [s]	Final main (red.) resistor resistance [Ω]
BB & EM	69	3.44	84.5 (84.4)

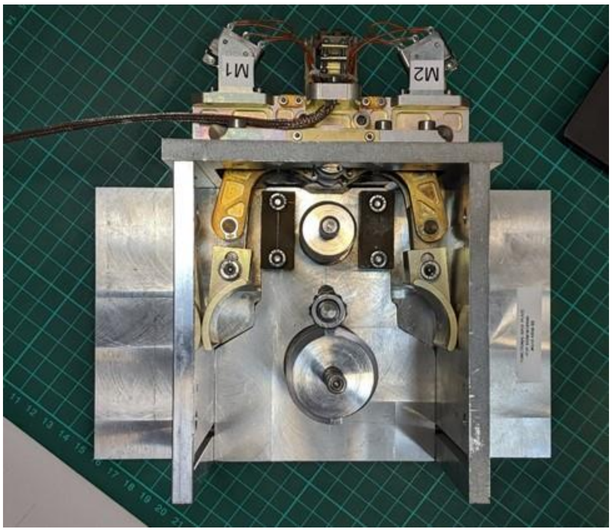

Figure 5. IHDM functional test configuration

1.5. Preload measurement test

Second point is related to the symmetrical preload application procedure briefly mentioned in the chapter 1.2. In order to determine what is the sequence in which preload application bolts shall be rotated and for what angle, test configuration equipped with DR & DTS sections (representative interfaces) and force sensors, allowing the operator to directly measure preload applied to the DR & DTS interfaces.

1.6. Generated shock test

Functional test configuration was additionally used in the measurement of the shock level generated by the IHDM deployment. Main source of shock results from IHDM clamps hitting the internal parts of the DS with no dampers implemented in the design. While all the interfaces were replicated in the test, GSE's Drill Structure walls were manufactured from Al. 6061 (not CFRP) so the obtained shock values were assumed as conservative. Fig. 6 presents the shock response spectra obtained from the triaxial sensor placed near the clamps impact point (expected worst-case) which proves the spectra is below required values at all times.

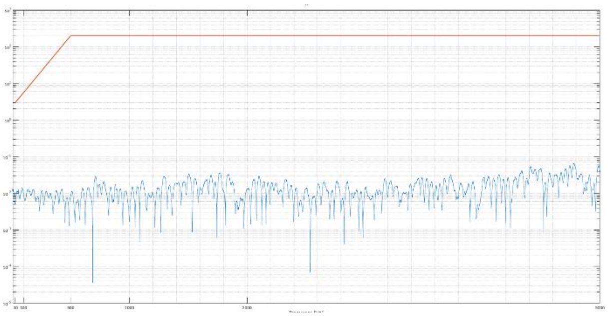

Figure 6. IHDM generated shock levels

1.7. Vibration test

Development of the vibration test approach was the most significant part of the BB/EM verification activities due to the fact that apart from external loads applied to the IHDM-DS mechanical interface, the majority of the load results from the reaction of the Drill Rod & Drill Translation Screw to system level external loads. In order to replicate these reactions without the use of Drill Structure hardware (not available at the time), Astronika along with Leonardo and ESA supervision developed test configuration replicating following DS design aspects:

- Key IHDM resonant frequencies replication without introducing additional GSE responses,
- Replication of worst-case scenario interface forces (resulting from system level structural analysis) in all axes directions,
- Replication of boundary conditions of both DR & DTS allowing rotation along their axes while preventing all other movements,
- Possibility of stiffness regulation of both side jigs (DR & DTS ends mounting points) in the excitation direction,
- Possibility of limiting the configuration movement only to the shaker excitation direction and its reconfiguration using the same GSE.

Based on these assumptions, test configuration presented in the Fig. 7 was developed. VTS (Vibration Test Stand) composed of:

- IHDM
- VTS central jig:
    - Implemented with DS mechanical interface,
    - Ensuring representative distances from DR & DTS dummies allowing IHDM to be properly mounted,
    - With no major modal frequencies below 2000 Hz,
- 2 VTS side jigs:
    - Implemented with housings for both DR & DTS allowing rotation along their axis while blocking all other movements,
    - Allowing 90 ° rotation of the DR &

    DTS dummies housing in order to test the configuration in Y axis direction (Z axis direction possible to be tested with either configuration – 8 additional bolts required to block the housing linear movement in excitation direction, avoiding shear loads acting on the bearings),
  - Implemented with the set of compression springs connected in parallel and linear bearings ensuring first modal frequency of the DR & DTS housing at 100 Hz (2 springs set rigidity of 780000N/mm, oscillating mass of 2100 g),
  - With no other major modal frequencies below 2000 Hz,
- DR & DTS dummies – representative section geometry, length, materials and mass (allocated evenly across their length using dedicated rings; DR mass: 835 g, DTS mass: 1680 g).

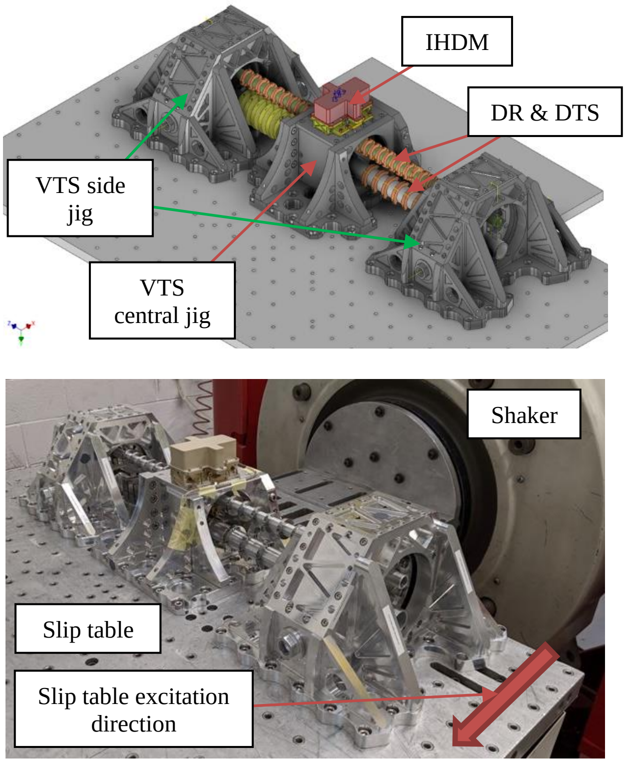

Figure 7. IHDM vibration test configuration (X axis direction)

Listed functionalities of the VTS side jig are realised with the elements indicated in the Fig. 8 section view. The key idea behind such design of side jigs was to simulate the reactions DR & DTS have on the IHDM resulting from the system level structural analysis. When regulating the springs rigidity in the excitation direction, first modal frequency associated with both rods would guarantee representative forces visible at the DR & DTS interfaces with IHDM – such relation was iterated upon using dedicated FEM.

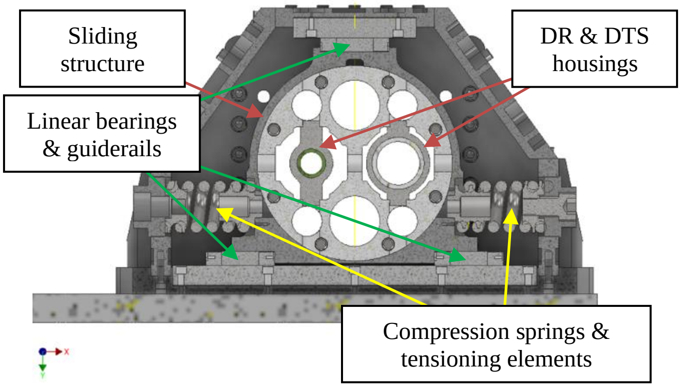

Figure 8. IHDM VTS side jig (section view)

In order to ensure full representativity of the DR & DTS boundary conditions, proper IHDM interface forces achieved with both rods' ends being excited at 100 Hz and preserving all VTS representativity (reconfiguration for shaker excitation in all axes direction), dedicated FEM was developed assuming replicating interface loads resulting from the system level structural analyses. GSE parameters possible to regulate the resultant interface loads received by IHDM cover:

- Regulation of the rods length (final length – 0.8 m),
- Modification of rods' added weights centre of mass,
- Regulation of target random (worst-case) excitation profile level (for Y axis direction -2 dB target level was assumed as a baseline; other directions assumed 0 dB),
- Regulation of the parallelly connected compression springs set rigidity.

By iterating on these conditions representative system level loads were visible on the IHDM interface with DR & DTS.

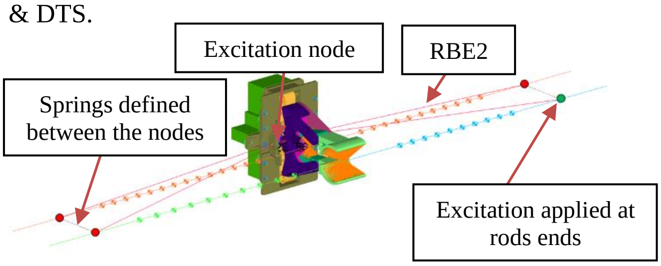

Figure 9. VTS FEM boundary conditions

Remaining FE related activities covered verification whether central jig is not excited below 2000 Hz. Similarly, side jigs did follow this assumption except replicating a single 100 Hz mode of the structure mounted on linear bearings, housing both rods ends. VTS side jig verification did assume 1 % local damping level applied to the linear bearings.

Due to the variety of variables included in the iteration process, the overall development time of the correct VTS design approach has proven to be quite extensive. Additionally, since the central and side jigs integrated several moving parts and functional features (instead of typical vibration GSE approach of developing rigid structure with equipped with bolted connections to the mechanism and shaker) the overall cost of manufactured GSE was significantly increased.

Using described test configuration, test was performed in Centrotecnica facility (Italy) using V895-440T shaker equipped with 2 configurations of the slip table (1200x600 for X, Y axes tests and 600x1200 Z axis test). During the test 4 sensors were identified as most critical for interpreting the test results:

- Triaxial sensor mounted near the IHDM-DS mechanical interface,
- Triaxial sensor mounted near the IHDM's DR/DTS dummies clamping area,
- 2 monoaxial accelerometers mounted on the moving components of the VTS MGSE side jigs (control of the GSE springs first resonant frequency).

Test sequence presented in the Tab. 2 was realised during the test for each axis direction - prior to target test verification of the VTS side jig natural frequencies (first freq. at 100 Hz) was performed:

Table 2. IHDM vibration test sequence

No.	Excitation type	Excitation level	Duration
0	Resonance search (VTS side jig)	0.5g/5-2000Hz	2 Oct/min
1	Resonance search	0.5g/5-2000Hz	2 Oct/min
2	Sine vibration	Axial: 15 g Lateral: 7.5 g Frequency: 25 Hz	5 min/axis
3	Resonance search	0.5g/5-2000Hz	2 Oct/min
4	Random vibration	-12 dB	30 sec./axis
5	Resonance search	0.5g/5-2000Hz	2 Oct/min
6	Random vibration	-6 dB	30 sec./axis
7	Resonance search	0.5g/5-2000Hz	2 Oct/min
8	Random vibration	-3 dB (-2 dB for Y axis)	30 sec./axis
9	Resonance search	0.5g/5-2000Hz	2 Oct/min
10	Random vibration	0 dB (Not performed for Y axis)	2 min/axis
11	Resonance search	0.5g/5-2000Hz	2 Oct/min

Verification of the VTS jigs resulted in almost ideal representativity with the prepared predictions, obtaining first modal frequency at 100 Hz for X, Y axes direction configuration and no other major frequencies (no major frequencies identified in Z axis direction as expected).

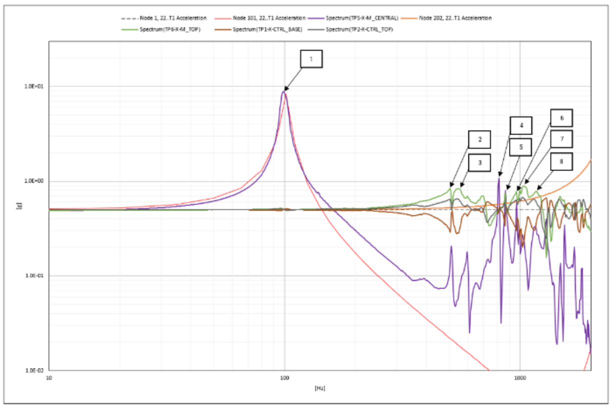

Figure 10. VTS side jig resonance search results

Based on the ECSS success criteria applicable to the assessment of vibration test results, when comparing initial and final resonance searches less than 5 % in frequency shift and less than 20 % in amplitude shift (for modes with an effective mass greater than 10 %) shall be visible. Based on those assumptions only for Y axis direction (recognised as worst-case during predictions preparation – nominal excitation level limited to -2 dB) major shifts is both frequency and amplitude were visible. During the visual inspection of the test configuration it was identified that the elements tensioning the VTS side jigs' compression springs were loosened, breaking the adhesive securing them. Such major shifts were not visible post -6 dB level random vibration test step.

Vibration test was concluded with the deployment of IHDM performed after mechanism being subjected to vibration loads in all 3 axes directions. Deployment was considered successful with a deployment duration of ~4 s, similarly to the avg. deployment duration observed across all IHDM deployments.

Visual inspection of the IHDM hardware performed after its deployments revealed an issue which was later on recognised as major NC, necessary to be corrected in scope of the BB model refurbishment to EM. Due to being subjected to vibration testing, extensive wear was identified on both the IHDM clamps and DR & DTS dummies external surfaces – Fig. 11. No other components were identified as damaged. Since both, the correct preload and resultant interface forces were implemented during the test, a modification to the interface surface material was recognised as necessary preventing any risk of damaging the DR & DTS components, possibly leading to loosing functionality of the Drill & Positioner. While all IHDM components were manufactured in representative standard, the DR & DTS dummies were not additionally treated with hard adonisation.

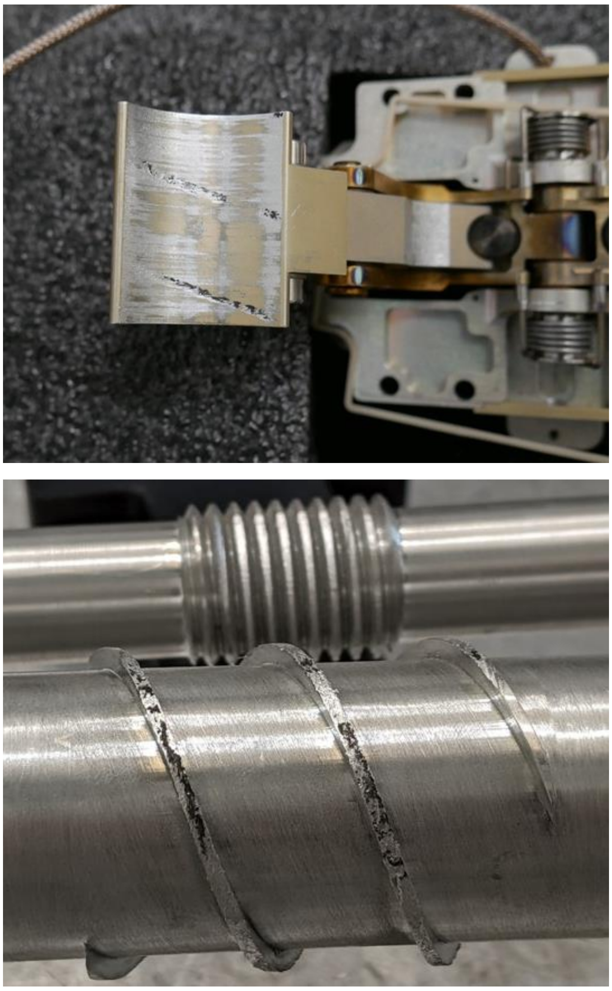

Figure 11. IHDM post-vibration test visual inspection findings

1.8. Thermal cycling test

Test configuration used during functional test was subjected to the thermal cycling in dedicated climate chamber. Thermal range of +60/-105 °C was verified. At the end of the dwell time associated with each hot-/cold-case IHDM was deployed and reset after removing it from the chamber in ambient temperature. 6 full cycles were conducted (temp. change rate: up to 5 °C/min, dwell time: 1 h, stabilisation criteria: 1 °C/h). 3 full cycles were performed with nominal preload applied to IHDM. In the remaining cases, preload was decreased by 15 % in cold-case and increased by 15 % in hot-case in order to test more conservative worst-cases.

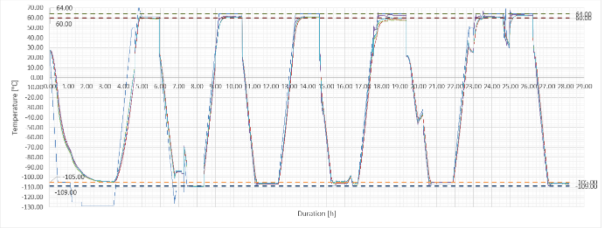

Figure 12. IHDM thermal cycling

All performed deployments were successful. Expected deployment duration in cold-cases occurred and equalled 6.36 s (2.93 s increase in relation to the avg. depl. duration). During hot-case deployments average deployment duration equalled 2.58 s (0.85 s decrease in relation to the avg. depl. duration).

1.9. Refurbishment activities

A single refurbishment activity identified as major, required to recognise EM as representative of the flight configuration, was a replacement of elements being in contact with DR & DTS components. In order to prevent potential damage to system level hardware following design modifications were implemented:

- Introduction of TECAPEEK Drill & Screw Inserts mounted directly on the pre-existing Al. 7075 clamps – more susceptible material is expected to eliminate potential damage risk or guarantee the damage is visible on IHDM components instead of Drill & Positioner, potentially preventing their full functionality,
- Modification (re-manufacturing) of IHDM clamps ensuring that after inserts implementation, mechanism’s kinematics are not changed – thickness of the element with implemented inserts must remain the same.

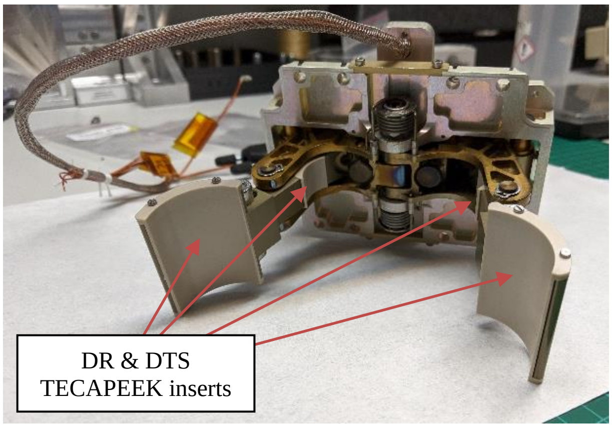

Figure 13. IHDM EM post BB model refurbishment activities

1.10. Dust contamination test

Last remaining test identified as necessary to be included in the early stages of verification programme was the dust contamination test. Test was following functional test procedure (test configuration inserted in the transparent container included with air compressor outlet) but with NU-LHT-2M lunar dust simulant application (samples sprayed inside the test container with a short air burst). Overall number of 9 steps of the dust contamination test was performed, each concluded with IHDM deployment. Following stages of the test can be identified (samples were not cleaned between each step):

- Dust screen implemented in the test

configuration, assuring the lunar dust simulant samples targeted mainly thermal knife actuator (resistors) and microswitches – applied samples: 0.15 g, 0.5 g, 1 g, 1 g, 2 g.

- Dust sample applied directly on the targeted components: thermal knife actuator, microswitches (without spraying) – applied sample: 2 g (Fig. 14),
- No dust screen (leverage system components targeted as well); dust sample applied via dedicated tube with a short air burst – applied samples 2 g, 5 g, 5 g.

All deployments were considered successful (results included in the Tab, 1). The only observed effect lunar dust had on IHDM was related to the 2nd step of the test. In this step deployment duration raised to 4.19 s (~0.5 s increase in relation to the avg. depl. duration) – effect assessed as negligible, especially in terms of occurrence probability – applied 2 g sample exceeds the target lunar dust density calculated based on the associated requirement ~33 times. In all other cases deployment duration was similar to the avg. one and equalled 3.54 s.

Figure 14. IHDM EM dust contamination test samples application

3. LESSONS LEARNED

Based on the presented verification activities results following lessons applicable to future qualification campaign were concluded:

- Development of vibration test GSE simulating system level conditions has proven to be a significantly complex and costly process – while concluded with a successful test results, replicating several moving parts and functionalities not related to the tested unit but GSE itself should always be avoided if not necessary since it would not be an easy task of tracking the cause of potential failure during unsuccessful test (most likely not connected to the tested unit but complex GSE),
- High complexity of the GSE reconfiguration for testing in different axes directions, while executed correctly, required detailed procedures and significant timeslots reserved during test execution,
- When developing the VTS side jigs the most important parameter (which was proven to be assumed correctly) for replicating linear bearings was damping level,
- Extensive DR & DTS interface surface wear observed after vibration test execution must be tracked as potential risk for QM AIT activities, observing if applied TECAPEEK insert shall negate the intensity of the issue at least on DR & DTS elements,
- IHDM equipped with several stages of leverage system and 2 point preload application sequence was proven to be sensitive to the defined preload application sequence which shall be verified for all future hardware using preload measurement GSE,
- As expected, activating IHDM thermal knife actuator equipped with redundant resistors in representative thermal environment results in modified activation durations. Duration was below assumed 12 s feeding voltage provision limit, however, the full scope of the effect must be tracked at QM thermal vacuum testing,
- IHDM actuation in significantly more critical lunar dust contamination density conditions (up to 300 times when cumulating all samples) is not affected. When targeting the thermal knife resistors specifically a minor 0.5 s deployment duration increase was observed. No negative effect was observed for microswitches functionality.

4. CONCLUSIONS

IHDM BB model & EM related verification activities results were considered successful with the sole major flight standard design modification being the implementation of DR & DTS interface inserts. Full scope of performed tests shall be applied to QM during hardware qualification with the exception of dust contamination test which was proven to be not a critical issue for IHDM key components. Thermal vacuum, shock and lifetime test shall be applied to QM as well. With the conclusion of these activities IHDM reached TRL 6, proving both the thermal knife actuator and overall HDRM provides full functionality for flight standard hardware. No major design modifications were implemented, preventing the use of already developed GSE in addition to system level testing.