Lessons Learned from Qualification of HDRM for Ultralight LP-PWI Boom for ESA JUICE Mission.

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Abstract

The paper presents the complications appearing during the qualification campaign of the Langmuir Probe – Plasma Wave Instrument (LP-PWI). The article focuses on one subsystem of LP-PWI: the Hold Down and Release Mechanism (HDRM). After the qualification vibration test, the HDRM was supposed to open to release the LP-PWI boom. However, the mechanism was blocked. The analysis presented reveals several root causes of this failure. The following root causes were identified: an optimistic functional analysis, incorrect integration processes, and neglected finishing of the parts. The second part of the paper shows the improvements implemented in the HDRM and the result of these changes. Finally, the lessons learned from the qualification process of the LP-PWI and HDRM failure are presented.

Introduction

The LP-PWI is one of the instruments within the Radio & Plasma Wave Investigation experiment on board ESA's JUICE (Jupiter Icy Moon Explorer) mission. The experiment consists of four identical LP-PWIs mounted on the edges of JUICE Spacecraft (S/C). The main objective of the instrument is to provide crucial information about the bulk plasma surrounding Jupiter's icy moons. The instrument is built in cooperation with the Swedish Institute of Space Physics in Uppsala under contract with ESA Prodex.

The article begins with a general description of the LP-PWI architecture and an introduction to the main environmental and technical requirements. The state-of-the-art section presents an overview of the boom with a short description of the main subsystems. The paragraph on system overview gives a detailed description of HDRM. The next chapters of the article focus on the qualification campaign and problems that appeared after the vibration test. The core of the article is the analysis of the HDRM's failure to open. The root causes of this failure and further solutions are described. As a summary, the paper presents all HDRM design and process improvements that helped overcome all the problems encountered with the opening of the HDRM. Final conclusions and lessons learned can be found in the last chapter.

State of the Art

The HDRM is a part of the bigger instrument - the LP-PWI (Figure 1). The LP-PWI is a two-section boom ended with Langmuir Probe (LP) [1]. The LP is a spherical sensor made of titanium and covered with TiAlN (Titanium Aluminum Nitride). The LP on board JUICE mission is 100 mm in diameter, which is two times larger than those on board Rosseta [2] and Cassini missions [3]. The two sections of the boom are made of CFRP (Carbon Fibers Reinforced Plastic) tubes ended with titanium interfaces and covered with Single Layer Insulation. The interfaces allowed to link the tubes with two hinges: Base and Central. Both are very similar. They are equipped with clock springs, which drive the boom, and a latching mechanism. The Central Hinge opens to 180 deg, while the Base Hinge opens to 135 deg. In a deployed configuration all LP-PWIs are positioned at an angle of 45 deg to the S/C longer edge.

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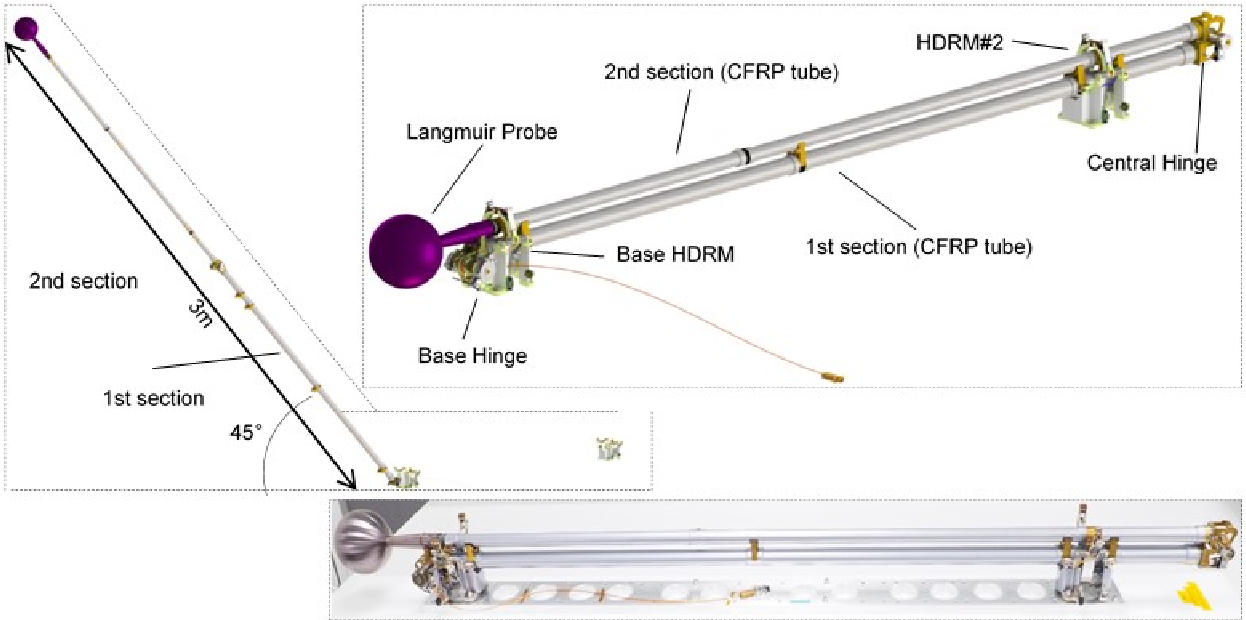

Figure 1. LP-PWI overview (CAD model deployed configuration – left; CAD model stowed configuration – right; as built model stowed configuration - bottom)

The boom has two HDRMs: Base HDRM and HDRM#2, which hold the CFRP tubes in a stowed configuration during the launch. The Base HDRM is placed close to the Langmuir probe while HDRM#2 is placed close to the Central Hinge. The position of HDRM#2 was optimized to maximize the first natural frequency of the boom. Both mechanisms are identical in terms of functionality; the difference between them lies in the structure: HDRM#2 is standalone while Base HDRM shares the structure with the Base Hinge.

In a stowed configuration the boom's length is under 1.6 m; it deploys to the length of 3 m. The LP-PWI's angular position must be kept within ±0.5 deg cone with a tip in Base Hinge. The length of the boom must be kept within the tolerance of ±5 mm. During the mission the LP-PWI will be exposed to highly demanding environmental conditions. There are four identical LP-PWI booms located on three different corners of the S/C. As consequence, the level of Sun illumination is different for each boom. The S/C trajectory comprises a close Sun approach with high Sun illumination, as well as long time spent in the shadow during Jovian Tour with Sun eclipse. This leads to a wide range of temperatures on the LP, ranging from -220°C up to 200°C. However, the main driver behind LP-PWI's architecture was a limited mass budget – in order to comply with requirements, each LP-PWI needed to have a mass under 1.3 kg.

The low mass of the unit did not allow for using hold and release mechanisms available on the market due to the mass requirement. The HDRM also needed to be part of the boom structure. In the LP-PWI, the HDRMs are also the main support of the boom as well as the interface with the S/C. Each HDRM contains mechanical and electrical interfaces with the S/C.

The design concept of the HDRM was based on the Hold Down and Release Mechanism from MUPUS instrument on Rosseta mission [4]. A similar design was later also used in the DRAGON-8U Nanosatellite Orbital Deployer [5]. However, this specific application (for LP-PWI) forced a major tailoring of the mechanism.

HDRM System overview

The core of the HDRM is a Preload Jaw which provides the preload to the CFRP tubes and keeps them in the stowed configuration (Figure 2). The Preload Jaw consists of a stainless-steel V-shape spring with two Tension Clamps attached to each arm of the spring. The Tension Clamps press the Tube Interface, which is attached to the upper 2nd section of the boom. The upper section lays down on the separators, which are a part of the lower 1st section of the boom. The pressing on the Tube Interface is transferred through separators to the lower section and it holds both of the CFRP tubes. The Tube Interface is equipped with overlay made of Vespel SP1. The Tension Clamps are made of nitrided titanium, which is essential for further investigation in this article. The materials are a good and stable friction pair with friction coefficient 0.21-0.24 in vacuum, in room and low temperature (-80°C) [6]. Vespel SP1 also has high strength, which does not degrade significantly in the higher temperatures (tensile strength: 86.2 MPa at 25°C; 41.4 MPa at 260°C). These features make Vespel SP1 the best choice for this application.

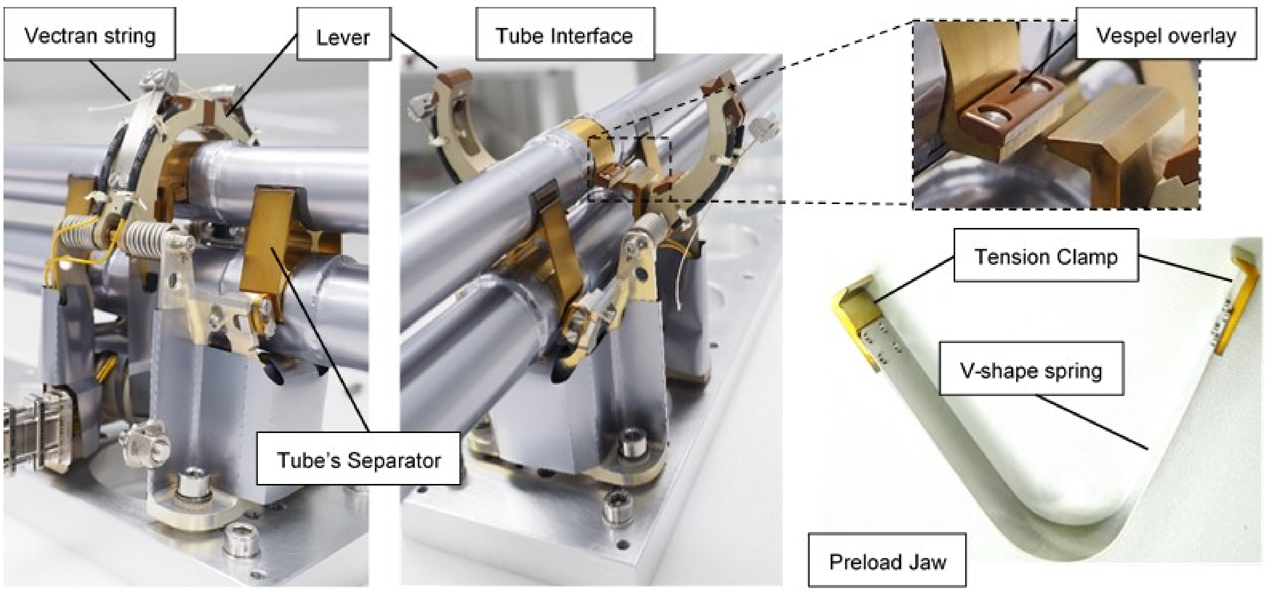

Figure 2. HDRM design

In a closed position of the HDRM, the Preload Jaw is bent and supported by two levers. The levers are connected to each other above the CFRP tubes with a Vectran string. The string is wrapped around the resistors placed in the lever. The resistors play a role of thermal knives that cut the Vectran string. In a single HDRM, there are two resistors (one on each lever): primary and redundant. The geometry of the lever combined with the inclination angle of the Tension Clamp (α) lowers the loads seen by Vectran string with a ratio 28.5.

The opening of the HDRM (Figure 3) is initiated by a weakening of the Vectran string by heat from deployment resistors. The levers are motorized by their own torsion springs and they are released after cutting of the Vectran string. The constrain resulting from the closed levers disappears, and the V-shape spring comes back to its open position. The Tension Clamps stop pressing the Tube Interface and the boom's sections are ready to be opened.

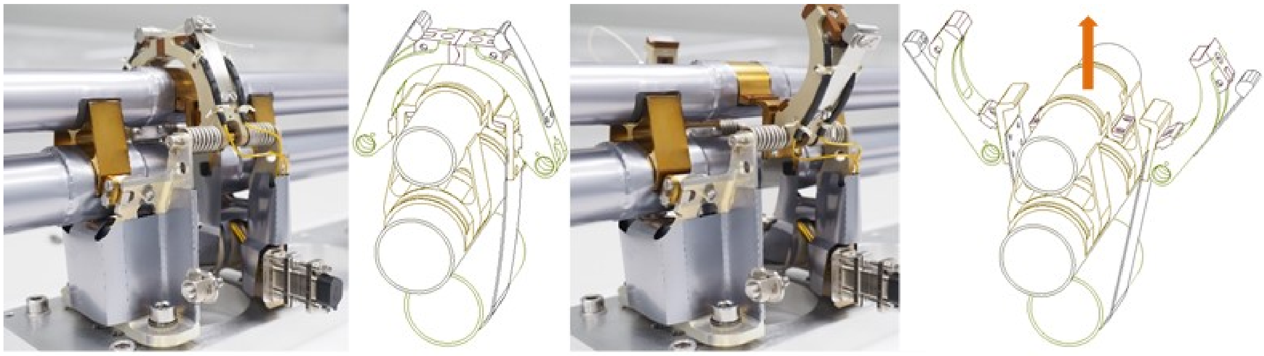

Figure 3. Closed HDRM #2 - left; Open HDRM #2 - right

<u>HDRM preloading</u>

The project entailed the delivery of 4 identical LP-PWIs, hence all of the eight HDRMs shall be similarly preloaded. The preload cannot be determined only by its hardware. The manufacturing tolerances did not allow for reaching the required repeatability in the preloading. Naturally, it cannot rely only on the hardware dimensioning and needs to be adjusted during integration process (Figure 4). The nominal preload for one HDRM was selected to a range of 160-170 N. A higher loading of HDRM could lead to the cumulation of too high a stress in the structure. The preload is applied to the Preload Jaw by the Tension Tube. During integration, the Tension Tube is loaded and tightens the V-shape spring when HDRM stays in a closed position. When all parts are preloaded, the tube is blocked by 6 blocking screws tightened to the HDRM walls. On the one hand, this solution releases the mechanism from manufacturing inaccuracy, but on the other the final preload depends on the correctness of the integration process.

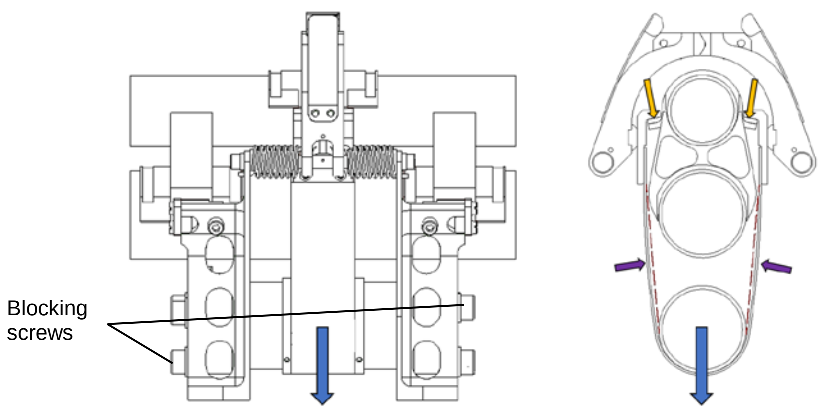

Figure 4. Application of the preload in HDRM

Qualification Campaign – Failure to Open after the Vibration Test

<u>Qualification campaign overview</u>

The full qualification model (QM-1) of the LP-PWI was subjected to several functional and environmental tests during the qualification test campaign. The functional tests were focused on the deployment reliability. The boom was designed to be deployed in micro-gravity. On ground, the LP-PWI can only be opened in a horizontal position. For the deployment test, the boom requires a 3x4 m flat table and ball supports attached to the CFRP tubes. During the deployment, the ball supports move on the table and offload the boom from gravity force. The dynamic opening of the boom excluded any other offloading methods. Due to the necessity of opening on a large ground support, the deployment following the environmental test was replaced with a limited release. The limited release was restricted to the opening of the HDRMs in vertical position without opening the hinges.

The environmental test included the thermal-vacuum (TVAC) cycling, shock and vibration tests. The TVAC test was performed on a reduced qualification model (QM-2), which was limited to one hinge, one HDRM, and shorter CFRP tubes with a dummy mass. The unit passed the thermal cycling in the range of -180°C and 100°C, and was successfully deployed in cold conditions (-50°C). After the test, the QM-2 parts were used in a full model QM-1.

The QM-1 was subjected to vibration and shock tests. The vibration test included resonance search, sine and random vibrations, and was performed on qualification level. The boom was subjected to vibrations in all 3 axes (Figure 5). The model passed the vibrations, but the limited release after the test was not fully successful.

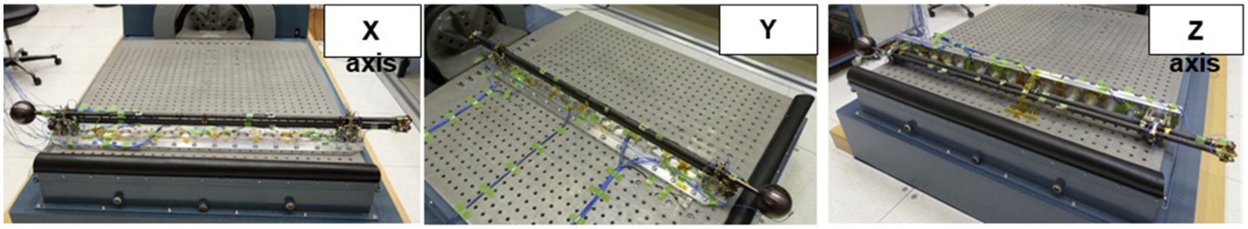

Figure 5. Configuration of LP-PWI on the shaker

It is worth mentioning that the qualification test campaign was preceded by a test campaign of the engineering model in Phase B. The design of the HDRM had not been modified significantly as compared to the previous phase. The Breadboard (Engineering) Model (BBM) passed over 50 deployments and random vibrations at acceptance level (-3 dB from qualification level). The HDRM was considered well tested on BBM level and the failure on QM came very unexpected.

<u>HDRM opening failure</u>

After the vibration test on QM-1 (in all 3 axes) followed by limited deployment test, the Base HDRM did not open. The Clamp got stuck on the Tube Interface after the opening of the levers (Figure 6) - the Clamps were blocked. In order to release them, several finger taps onto the V-shape spring were needed. At the same time HDRM#2 opened without any problems.

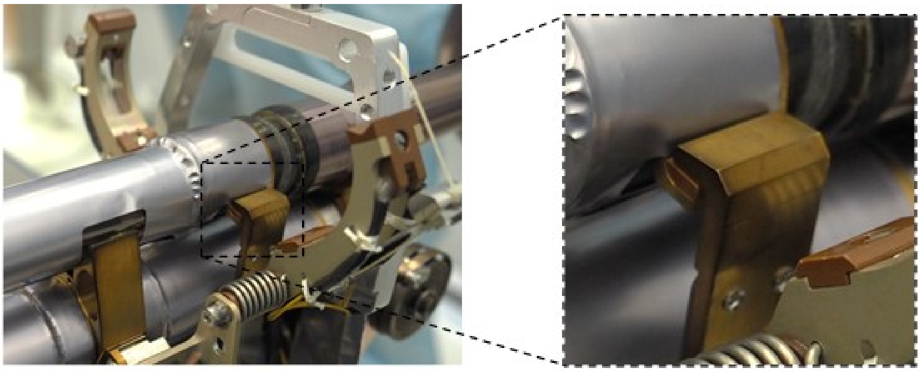

Figure 6. Failure to open of HDRM

Even before the issue with the actual deployment, the first sign indicating that something changed in the Base HDRM was the modal response recorded by an accelerometer placed on the levers (Figure 7). The resonance searches in Z axis before and after random vibration show large differences between these stages. These response changes could not be linked with the behavior of the remaining subsystems of the boom. The first mode was (at 500 Hz) increased by over 200 Hz. The mode around 1700 Hz moved close to 2000 Hz. Main mode recorded at 1200 Hz totally changed its shape. Generally, for the higher frequencies (above 800 Hz) the modal responses start to highly deviate from each other.

The increase and the major change of modal responses turned out to be the first symptom that something was blocked in the HDRM. After the unsuccessful HDRM opening it became clear that the blocked Clamp transfers the loads from the CFRP tubes to the levers differently. This caused the change in the modal response.

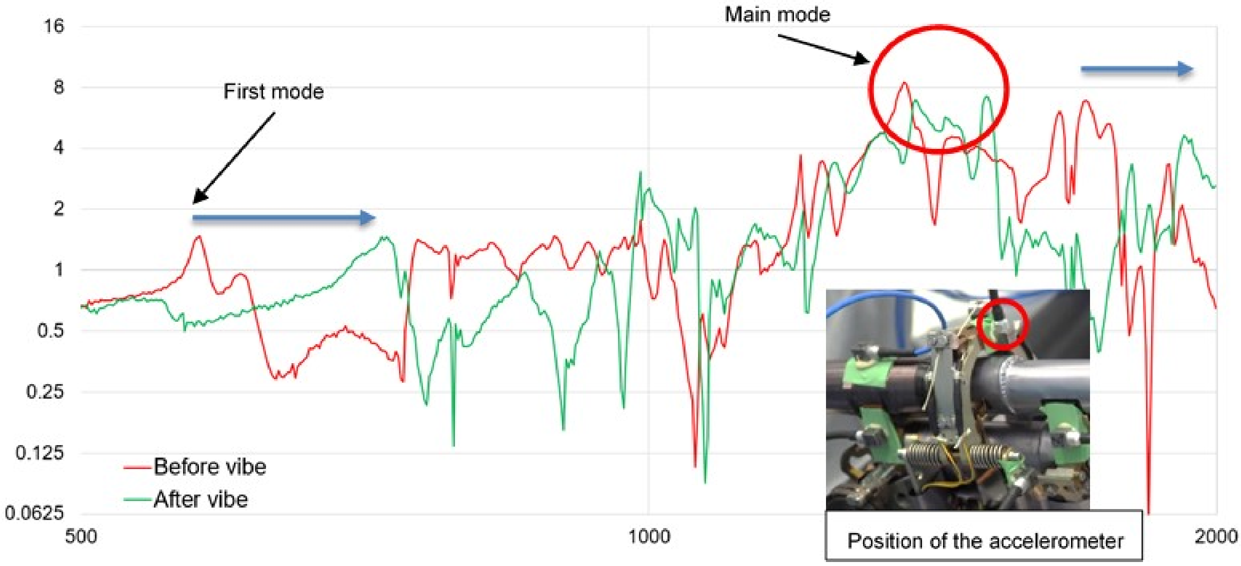

Figure 7. Resonance response of the lever in Base HDRM in Z-axis before and after vibration of QM-1

Root Cause of the Failure

After the failure of the Base HDRM the most critical task was to find the root cause of the problem. At the beginning, blocking of the Tension Clamp seemed very unlikely. The design of the HDRM was well known and had been used in two others flight instruments. However, a deeper analysis revealed 4 potential root causes of this failure. All of them affect each other, therefore it is impossible to clearly identify which problem was the most critical for the system.

<u>Preload change during vibration</u>
As mentioned above, the QM-1 was not the first model that was tested. The qualification phase was proceeded by the breadboard (engineering model) testing phase. The HDRMs in BBM and in QM-1 were practically identical in terms of the Preload Jaw design. The BBM passed similar tests during the breadboard test campaign. However, the BBM was subjected to random vibrations with a level reduced to -3 dB (from qualification level) due to the limitations of the available shaker. Hence, the BBM had never seen full qualification loads before the QM vibe test.

The preload in LP-PWI was between 160 N and 170 N. This value was established by scaling the preload form the MUPUS instrument. The vibration loads in the Preload Jaw were estimated at 1120 N. It was clear that the preload was not high enough to avoid gapping during vibrations. Unfortunately, a higher preload could not be applied due to the strength limitation of the HDRM structure. Strengthening the structure would affect the mass budget and therefore could not be applied. There was also a strong conviction that if the BBM survived the vibrations, then the QM-1 should also pass the test. However, the qualification level of random vibrations appeared to be critical. The gapping between the Tension Clamp and the Tube Interface caused micro movement of the Clamps (Figure 8), which led to a higher tension of the V-shape spring and leveraged the preload.

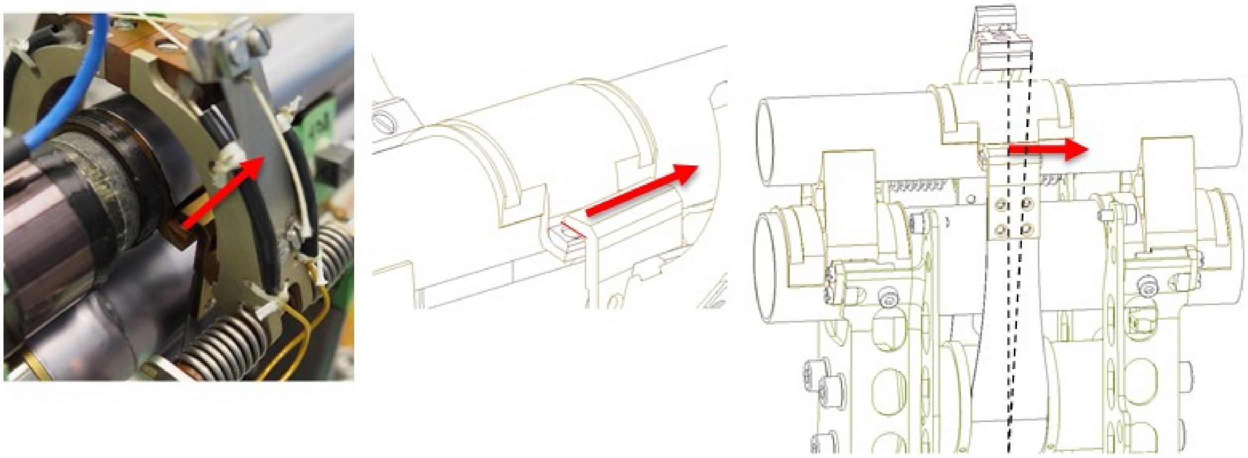

Figure 8. Position change of Tension Clamp on Vespel overlay

<u>Stacking in the softer material</u>
The design of the HDRM assumed the protruding of the Tube Interface from the Tension Clamp. The edges of the harder Clamp touch the relatively soft interface surface. In case of gapping during the vibration, the Tension Clamp moved and started to press one edge into the Vespel SP1 surface (Figure 8). This led to an uncontrolled increase of contact pressure between the parts. As a consequence, the Clamp was blocked on the Vespel SP1 overlay.

<u>Mechanical analysis – low margin.</u>
The mechanical analysis of the HDRM's performance is relatively complex. The behavior of the Preload Jaw is very hard to model. The V-shape spring is bent and preloaded at the same time. At first, the motorization margin was not calculated for the Preload Jaw, due to the Clamp rotation theory described above: the preload force pulls the Tension Clamp at a certain distance from the contact area with the Tube Interface. This creates the torque that rotates the Clamp. The rotated Clamp loses contact with the Tube Interface, hence the friction between them can be neglected. The mechanism was considered safe from being blocked. The previous experience from BBM (over 50 successful deployments) seemed to confirm this theory. The movement of the Clamps during the opening is very dynamic and it was very difficult to observe the behavior of the mechanism in real time.

Finally, the QM-1 vibration tests showed that the Preload Jaw can be blocked on the Tube Interface. This situation was later repeated manually in a lab. The failure of the HDRM opening sparked a reconsideration of the mathematical model and the behavior of the V-shape springs. The approach was changed - if a more accurate model cannot be built then the most conservative one should be used. The new mathematical model excludes the rotation of the Clamp during the opening. Now the Clamp slides from the interface and maintains the contact with the Tube Interface.

The Preload Jaw is fully symmetrical, so the model is presented only for one Clamp. Figure 9 presents the forces acting on the Clamp after the release of the levers. All forces' values are presented for one Clamp.

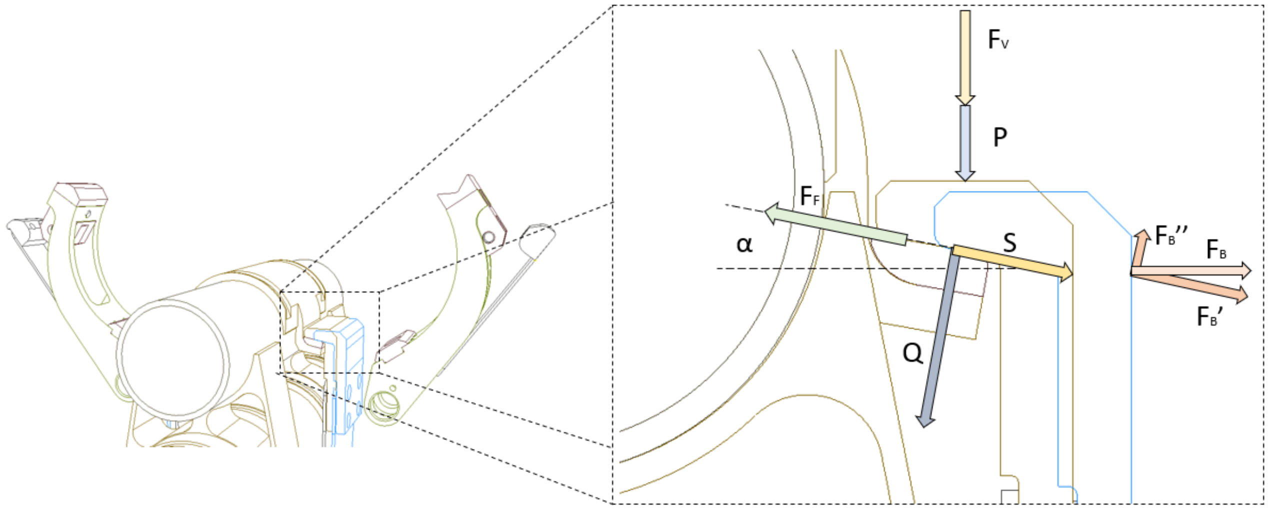

Figure 9. Force relation in Tension Clamp

The Clamp slides down from the interface driven by an opening force. The opening force is a summary of the force from V-shape spring's bending (F_B) and the sliding force (S). The sliding force is a result of the initial preload (P) and its change introduced by residual force after vibrations (F_V). The contact force (Q) is also a result of the residual vibration force and the preload force. The contact force is additionally reduced by a part of the bending force (F_B'). The friction force (F_F) simply results from the contact force lowered by a part of the bending force (F_B'') and multiplied by the friction coefficient (μ) between the Clamp and Tube Interface. The success criteria for the HDRM opening was presented in Eq.1. The opening force must be higher than the friction force. The Eq. 2 presents the dependences between the forces and the angle of the Clamp (α).

$$(Q - F_B'')\mu < F_B' + S \quad \text{Equation 1}$$

$$((P + F_V)cos\alpha - F_B sin\alpha)\mu < F_B cos\alpha + (P + \mathrm{F_v})sin\alpha \quad \text{Equation 2}$$

The QM design was confronted with the new mathematical model. The calculation showed that the QM had a barely positive motorization. The nominal working point of the HDRM was located below but still very close to the motorization line (Figure 10). The change of the preload combined with a slight increase of the friction coefficient could block the HDRM, presented by the movement of the working point into the red area on the plot. The conclusion was that the margin of safety for the HDRM working point was too low to be accepted.

The friction coefficient can increase when the contact surface is worn out or when the parts were not properly finished. There is no possibility to check the friction coefficient on the unit itself. The contact force can be locally increased by a wedging of the Clamp into the interface. Both effects lead to the increase of the friction force and blocking of the mechanism.

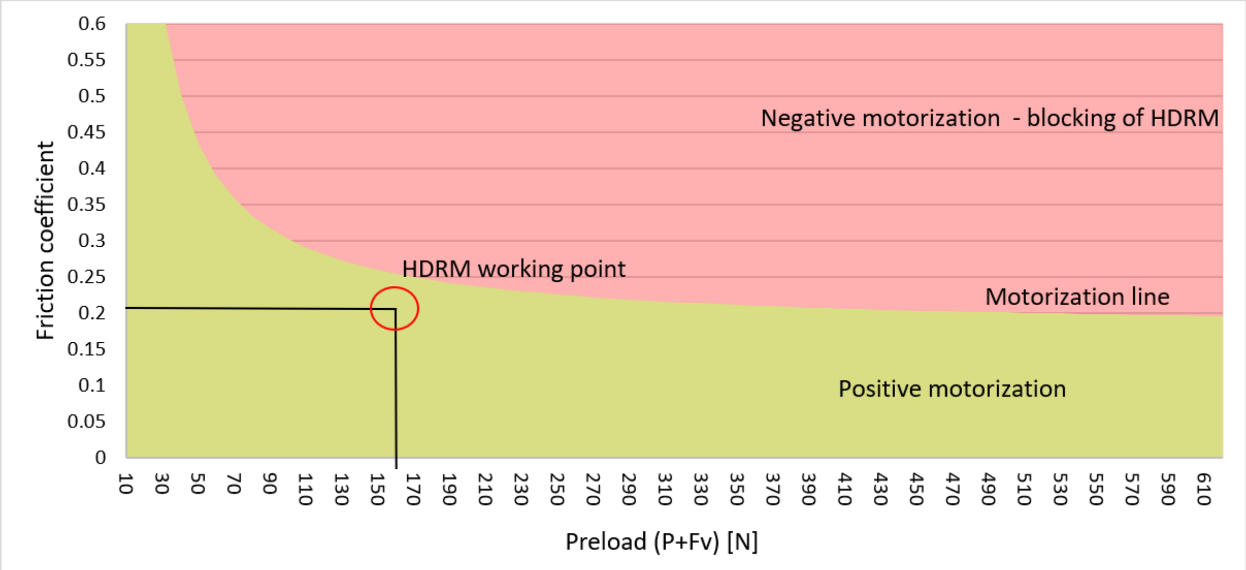

Figure 10. Motorization of Preload Jaw – QM-1 (α=10deg; F_B=6N; μ=0.22)

<u>Preload application</u>

Another cause of the preload change following the vibration test could be a wrong method of its application. The lower preload causes a higher gaping than it was expected. Generally, the preload is adjusted during the integration process by the loading and movement of the tension tube (Figure 4). In BBM the preload was applied in a vertically positioned boom. The Tension Tube was loaded with an adjusted mass. In QM-1 the method was modified. The preload was applied through the force meter with a stiff hook attached to the tension tube. The HDRMs walls were constrained and could not move due to the horizontal positioning of the boom. In this configuration, the wedging of the tube between the walls was highly possible (Figure 11). The force meter indicated the correct value of the preload, but this force was not necessary fully transferred to the Preload Jaw. It could have been consumed by the blocking of Tension Tube between the HDRM walls. This way of the preload adjusting did not allow for the full control of the preload in HDRM. As a consequence, the final preload could have been randomly lower, which led to a higher gapping during the vibration test. The final position of the tube as well as its tilting were not measured. Additionally, the tilted tube tightened the Preload Jaw asymmetrically. The asymmetrical position of the V-shape spring causes higher pressure of one side of the Clamps, which increases the tendency of pressing the edge into the soft Vespel SP1 overlay. The modification between the BBM and the QM-1, which was intended to be an improvement, introduced an additional uncertainty to the mechanism.

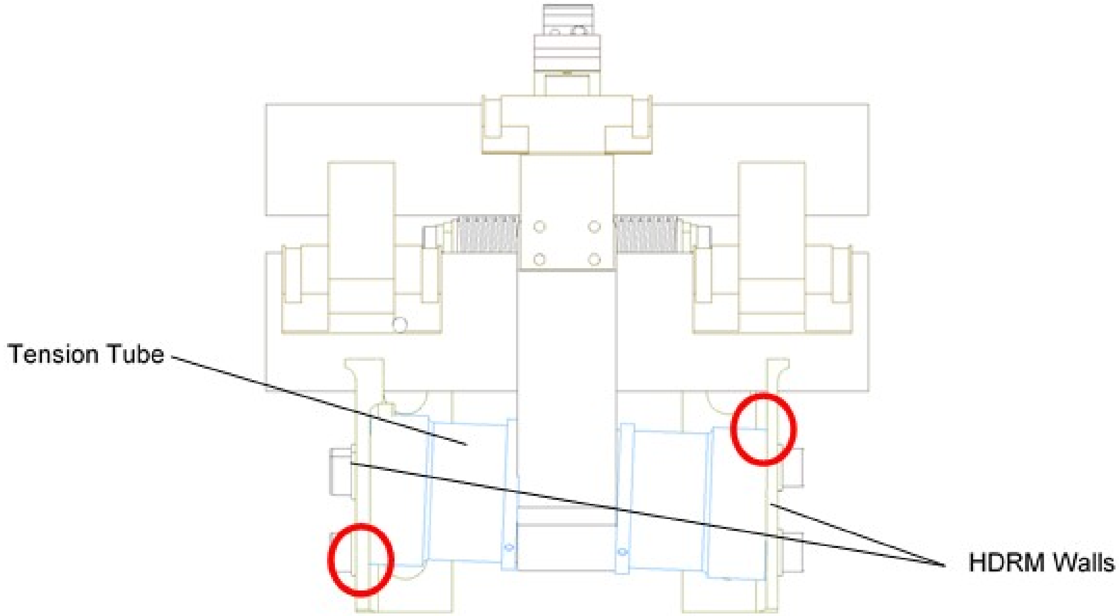

Figure 11. Tilted and blocked Tension Tube.

Design and process improvements

The blocked Preload Jaw in the HDRM was a critical and unexpected failure. The problem was on the critical path of the project. The design needed to be improved and the test campaign had to be continued. The design changes could not be too deep in order not to affect the design of the rest of the boom: the LP-PWI was in the midst of a qualification test campaign, and any major changes could challenge the validity of the previous QM tests. Additionally, most of the flight parts had already been manufactured, hence the quantity of the modified parts had to remain as few as possible.
The improvements focused on:

- Controlling the friction coefficient between the Tension Clamp and the Tube Interface.
- Lowering the risk of remaining the residual vibration loads in the Preload Jaw.
- Improving the relation of motorization margin to the preload force.
- Better control of the preload adjustment.

The LP-PWI qualification model QM-1 with the following modifications is called QM-bis in the next chapters.

<u>Design changes</u>
As mentioned above, the modification had to be conservative and affect as few parts as possible. First, the Tension Clamps were redesigned (Figure 12). They were widened to protrude from the Tube Interface and the edges were manually rounded. More attention was put on the surface finish. The inclination angle was increased to 15 deg. Applying a higher angle was not possible as it resulted in too high loads on the levers and could have led to an inadvertent opening during vibration.

The V-shape spring was also widened. The previous spring's model was optimized to withstand the preload and keep a low mass. The modified spring increased the bending force at the expense of the mass budget.

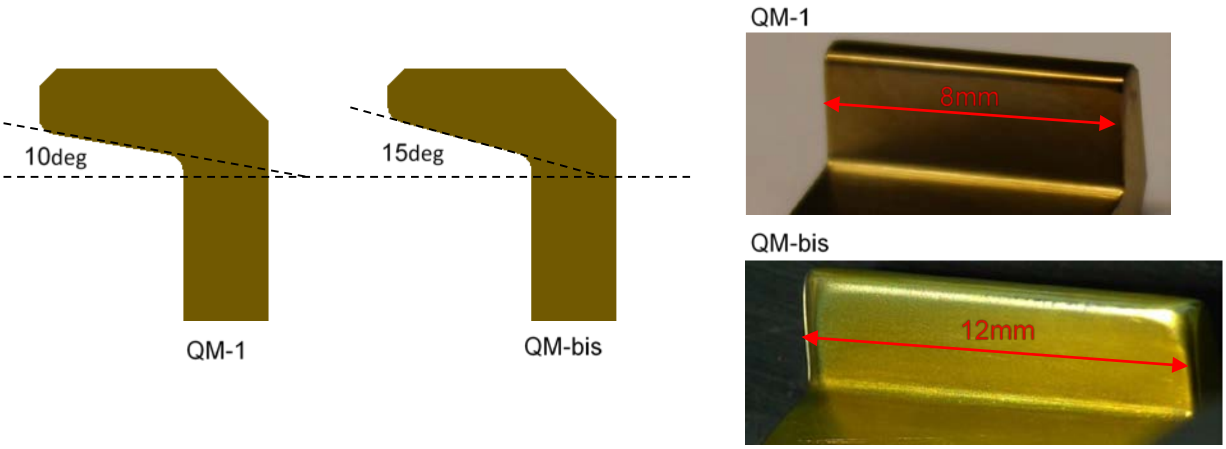

Figure 12. Tension Clamp design changes

The change of the Tension Clamp led to the modification of the Tube Interface. The titanium part of the interface was already attached to the CFRP tube and replacing them was not possible. Only the Vespel SP1 overlay could have been replaced. Because the Clamp angle had been changed, the overlay needed to be adjusted as well. The simplest solution was to round the contact surface of the overlay and create a linear contact with the Tension Clamp (Figure 13). This solution also had other benefits. In the previous design, the contact area between the Clamp and the Tube Interface was random. The manufacturing tolerances of the parts did not allow for perfect surface-to-surface contact. As a consequence, the Clamp pressed the overlay in random points under not necessarily a correct angle. Rounding of the overlay improved the control over the contact area and inclination angle. The disadvantage of this solution included higher Hertzian stresses of the linear contact, but it remained within accepted range. As a plastic material, Vespel SP1 can be easily deformed under pressure without risk of breaking. In this case, after exceeding the Hertzian stresses, the overlay simply adjusts its shape to the Tension Clamp and creates the sufficient surface to surface contact area.

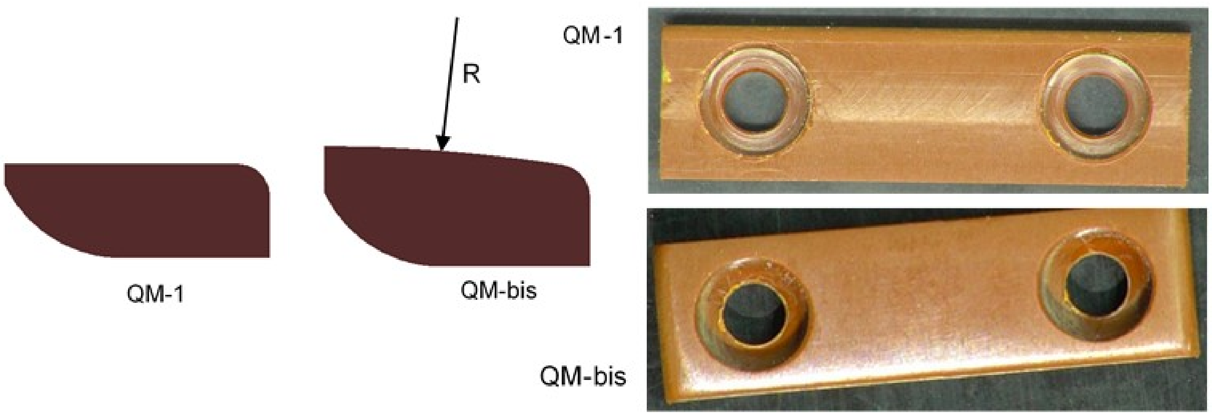

Figure 13. Vespel SP1 overlays modification

<u>Change of the preload application process</u>
The process of preload adjustment in the HDRM was also improved. The load was applied with a mass attached to the tension tube, similarly as in the BBM. During the process the boom was put in a vertical position, hence the HDRM's walls did not have to be screwed to the integration plate. Thanks to this, the HDRM walls were not rigidly fixed and a clearance remained between them and the Tension Tube. The tube was able to move freely without the risk of tilting and blocking. The position of the Tension Tube was observed from the beginning of preloading to the blocking by the screws. A lot of effort was put to ensure

that the final position of the tension tube is parallel. After constraining the tube in HDRM, its exact position was measured with the accuracy of 0.01 mm. The measurements were taken on both sides of the Tension Spring. All deviations of readings higher than 0.05 mm meant it was necessary to reapply the preload. This inspection assured that the tube was not tilted by more than 0.15 deg.

Test Campaign Continuation

All design changes were focused on improving the motorization margin of the Preload Jaw. Figure 14 presents the comparison between the motorization of the Preload Jaw in QM-1 and in QM-bis. The increase of the Tension Clamp's inclination angle and the modification of the V-shape spring made the HDRM much more independent from the preload and friction coefficient changes. The widening of the Tension Clamp and rounding of its edges excluded the possibility of the titanium edge sticking into the Vespel SP1. A well-finished surface of the overlays and the Clamps assured as low friction coefficient as possible. The margin of safety for the HDRM working point was significantly increased.

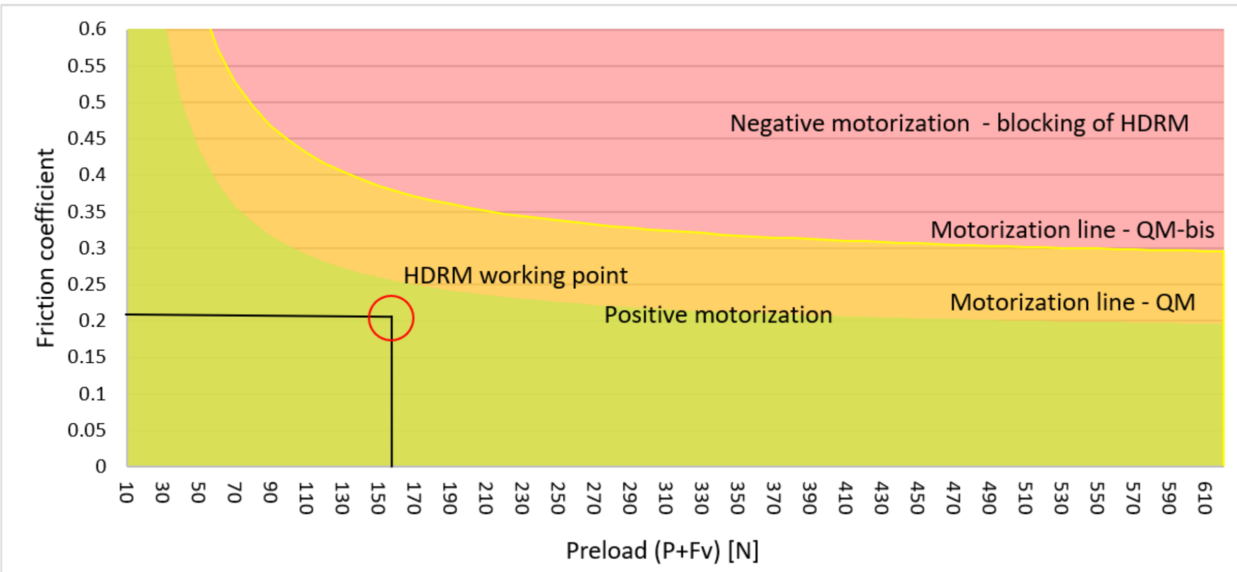

Figure 14. Motorization of Preload Jaw – QM-bis (α=15 deg; F_B=8 N; μ=0.22)

The modified qualification model (QM-bis) was vibrated once again in accordance with the same test specification. During the vibrations, it was apparent that the applied changes improved the mechanism. The comparison of modal responses (performed before and after the nominal random vibration test) from the accelerometer placed on the lever was more accurate than it was in the QM-1 (Figure 15). Previously, a major increase of the modes' frequencies and a great difference of the modes at frequencies above 800 Hz were observed. In the QM-bis the first mode decreases its frequency after the test. It can be explained by the initial setting of the mechanism. For higher frequencies the resonance characteristics remained similar before and after random vibration. Any major shift was not observed, and the main mode is almost identical.

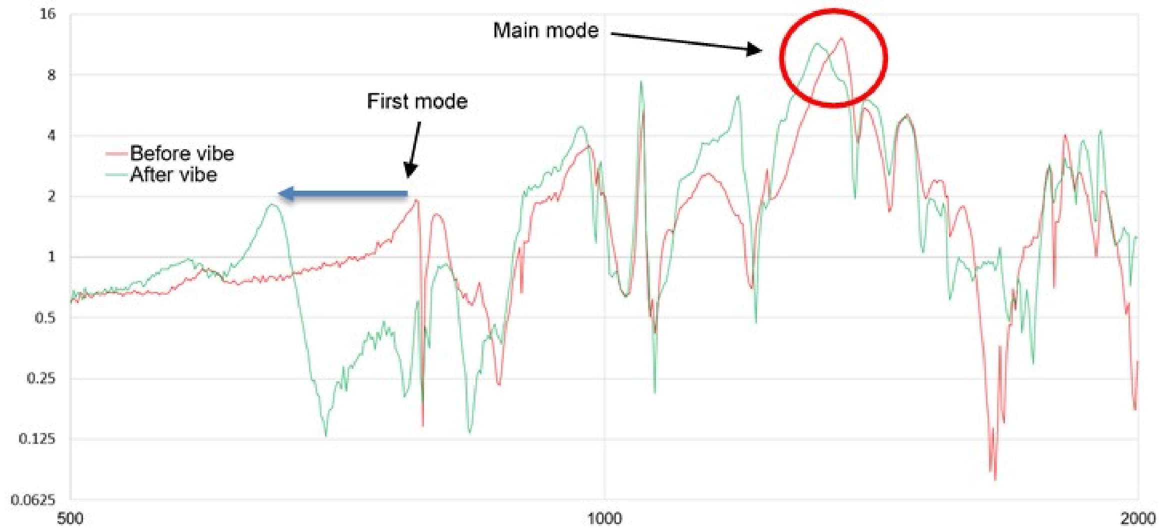

Figure 15. Resonance response of the lever in Base HDRM before vibration and after in Z-axis for QM-bis

The QM-bis passed the vibration test – the modal responses were very similar. For most of the parts it was the second vibration with the qualification level which additionally proved the endurance of the boom. The limited release just after the vibrations was successful as well - both HDRMs were opened. The qualification campaign could resume. All other tests, including full deployments and shocks, were completed successfully. The LP-PWI was fully deployed over 50 times during the qualification test campaign (QM-1: 8 deployments; QM-bis: 49 deployments). In the end, the LP-PWI reached TRL7.

Conclusions and Lessons Learned

The experience from the qualification campaign of LP-PWI is essential and can be used for other projects. Several lessons learned were extracted:

Great heritage and successful breadboarding does not guarantee reliability of the mechanism.
Several issues were neglected at the beginning of the project. The first motorization model of the Preload Jaw was too optimistic. The preload value was simply scaled from another instrument without confronting it with the real loads acting on the unit. These steps were taken due to the lack of a good analysis in the early phase of the project, but also due to strong faith in the reliability of the mechanism. The good heritage of HDRM and successful breadboard campaign discouraged implementation of any improvements.

In simulations and mathematical models, the most conservative approach should be considered as the baseline.
The analysis of the behavior of the Preload Jaw was neglected in the project. The inability to build a detailed mathematical model was replaced with an optimistic approach. The mechanism was considered unlikely to block. If a sufficiently detailed mathematical model is too complicated to achieve, the most conservative approach should always be used. In addition, in the early design process, the mechanism shall demonstrate clearly defined constraints and parameters that are verifiable and controllable during the manufacturing, assembly and testing process. When the project constraints appear, the design compromises are embedded and sufficient level of risk awareness needs to be tracked and not forgotten.

The harder material should always protrude from a softer one.
One of the basic mistakes in the design was the decision to make the Tube holders wider than the Tension Clamp. In consequence, the edges of the Clamp could wedge into the tube holders' overlays. The overlays made of Vespel SP1 are much softer than the nitride titanium Clamp. The wedged edge of the Clamp generates much higher Hertzian stresses and deforms the overlay. In the connections where one material is much softer than the other one, a contact of the hardest edges shall be avoided.

Parts inspection

The inspection and rejection of the parts with questionable quality at an early stage is critical. The project was under high time pressure. The risk of using several parts with surface or shape defects was underestimated. Not enough attention was put on the surface finishing and rounding of the parts' edges. The accepted parts were not in a bad condition and they passed the standard acceptance criteria, however, the standard inspection did not consider their specific application. In some cases, the parts were not properly finished. The elements that are part of the interface or a component of the friction pair should always have excellent surface finish and the inspection shall assume their future function. In addition, if the quality of the critical parts raises any question, the risk of accepting them may lead to costs much higher than those resulting from the delays or production of new ones.

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