LISA PATHFINDER CAGE AND VENT MECHANISM - DEVELOPMENT AND QUALIFICATION

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ABSTRACT

The Cage and Vent Mechanism (CVM) is one of the core devices of the LISA Technology Package to be flown on the LISA Pathfinder Mission, a technology demonstrator for a potential future mission formerly known as LISA. The Cage and Vent Mechanism as part of the Inertial Sensor System (ISS) shall cage and constrain a Test Mass (TM) during launch and later, hand-over the TM to the Grabbing, Positioning and Release Mechanism (GPRM). The GPRM is designed to release the TM into a perfect free-fall within the enclosing Electrode Housing (EH), which itself is used to control and measure the TM using electrostatic forces.

The development and qualification of the CVM is described in this paper. See [1] and [3] for further information on GPRM.

1 INTRODUCTION

One of the few challenging systems of the LISA Technology Package (LTP) is the Caging Mechanism (CM) with the purpose to cage the TM during launch and later release the TM into a perfect free-fall inside an enclosing Electrode Housing (EH).

To accomplish these two tasks the CM was split in two subsystems for each task. The initial solution for the caging function was the Caging Mechanism Sub-System (CMSS) [2] based on a piezo powered hydraulic system actuating 8 fingers to grasp the 8 corners of the TM. The second task is performed by a piezo actuated mechanical system called the Grabbing, Positioning and Release Mechanism (GPRM), which grasps the TM using 2 fingers on interfaces of the +/-Z faces. Both systems were designed to operate multiple times to offer maximum operational flexibility. The GPRM was developed by RUAG and Flight Models were delivered in 2009.

During the qualification process of the CM, technical and programmatic issues related to the CMSS were identified, leading to the request for an alternative solution for the caging function. Due to the criticality of this function and the schedule situation in the LISA Pathfinder project in general, an aggressive approach has been chosen to develop a replacement solution. One way forward was to develop a full replacement for the CMSS based on the same specification and using the same interfaces. This approach resulted in a piezo driven mechanical system called the Caging Mechanism Launch Locking Assembly (CMLA) [5]. The second way forward was to simplify the specification and realise a simple system capable for one single release operation.

Starting in May 2011 RUAG Space Zürich took over the responsibility for the second approach. The initial phase of this project had the goal to design and manufacture an Elegant Breadboard Model (EBB) and to perform a vibration test integrated in a partially assembled Inertial Sensor Head (ISH). The EBB was used to prove that the simplified design concept is able to cage the TM reliably when exposed to qualification level vibration loads. This phase was completed in just 4 months and concluded in the PDR.

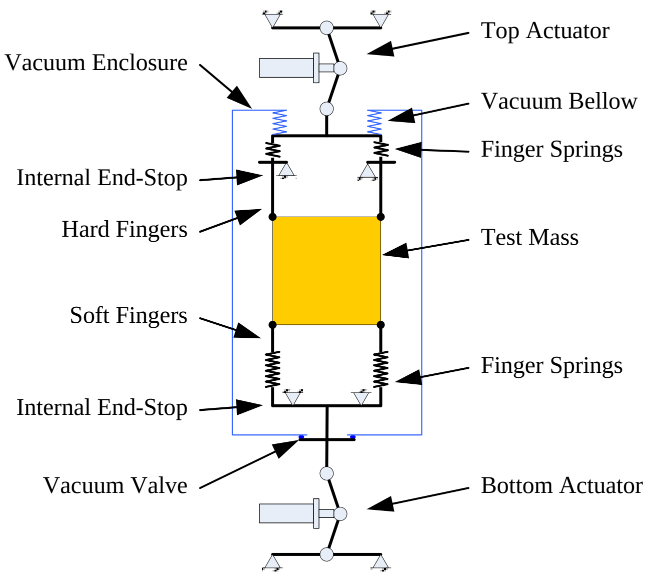

Figure 1. CVM Preload Concept

By end of 2011 the decision was taken by the LISA Pathfinder project to continue with the CVM approach and the detailed design phase for the CDR began in April 2012. Due to the highly compressed schedule, manufacturing of some parts was initiated before CDR

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and the first Engineering Qualification Model (EQM) components were delivered in June 2012. The last component of the EQM was delivered in February 2013. All parts for the Flight Models (FM) were manufactured together with the EQM parts which enabled delivery of the last FM in May 2013.

2 REQUIREMENTS AND DESIGN

2.1 Design Drivers

Besides some challenging requirements, the CVM had to comply with existing interfaces and reuse existing fingers for TM caging. The fingers have been made of molybdenum and iridium and remanufacturing was no option for schedule reasons.

The following requirements for the CVM were identified to be significant design drivers:

- Reliably clamp the TM and sustain the launch vibrations
- No use of magnetic or ferromagnetic materials
- Cleanliness level compatible for optical instruments and no use of liquid lubricants inside the ISH
- Extremely low exported shock during release operation (<200 g SRS)

The requirements to not use any magnetic materials and the low exported shock reduced the possible design solutions quickly down to a very few.

The clamping of the cubic shaped TM with 4 fingers from top and 4 fingers from bottom forms an over-constrained structural system. This makes it challenging to ensure an equal distribution of the preload force to all 8 TM corners and at the same time to achieve a high stiffness to keep vibration response at the TM as low as possible.

2.2 PDR Phase

The short phase up to the PDR had the main goal to prove the feasibility to clamp the TM using the existing fingers and the simplified CVM caging concept (see Fig. 1). The key feature of this concept is to place the actuating elements outside of the hermetically sealed Vacuum Enclosure (VE) while the CMSS and CMLA would have been placed completely inside the VE. This split into internal and external elements offered the advantage to reduce risk in the ISH schedule in case the more complex external actuator is delayed. In case of problems, the actuator would have been temporarily replaced by a simple hand-actuated device, allowing at least limited testing at ISH level by the customer.

During the PDR the CVM elements inside the VE have been designed and manufactured to establish an EBB. One of the EBB elements is the Transmission Stage (TS), comprising the finger units and other parts to support the fingers and to distribute the preload force among all fingers. A further element also realised in this phase is the GPRM flange which has the purpose to guide the lower part of the fingers and to support the GPRM.

The original fingers proved to be difficult to hold in place during the CMSS qualification, mainly due to the short length, but had to be reused for CVM. The solution was to extend the length of the fingers, enabling an accurate and stiff guidance. In addition each finger is equipped with strain gauges to individually measure the preload force.

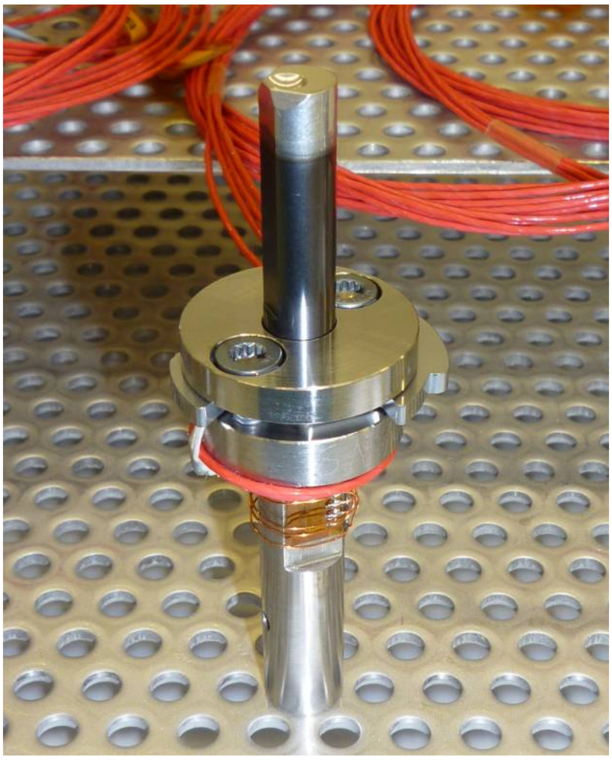

Figure 2. Finger Unit

The primary preload force is provided by Actuator Blocks (AB) installed on the outside of the ISH. The force is transferred to the inside the VE and distributed to each finger. With this logic, many elements coming from different suppliers are involved in the preload force loop and a stable preloading would be difficult to achieve. To decouple the multiple elements the force loop has been cut in several sub-loops by introducing intermediate end-stops. With this concept the individual finger force is less dependent from the preload force generated by the AB on the outside of the ISH and less sensitive to adjustment inaccuracies, thermal effects, etc.

While in lateral direction the fingers are guided precisely and rigidly, the fixation in longitudinal required some additonal engineering effort. For an equal force distribution a low finger stiffness would be advantageous. To keep the vibration response in an acceptable level the stiffness would have to be very low and large differential movements would occur during vibration, which is no option due to risk of interface wear. High finger stiffness on the other hand makes it difficult to achieve an equal force distribution as the 8 fingers form an over-constrained structural system. To keep the resonant frequency of the TM sufficiently high, a finger stiffness of ~5000 N/mm is needed which requires adjustment of finger length in the micron range. The solution for these contradicting needs was to design a high finger stiffness on one side of the TM and a low stiffness for the opposite fingers. This still requires a micron range finger length adjustment but just for 4 fingers in one plane to each other. The 4 opposite soft fingers feature a stiffness of ~150 N/mm each and are therefore much less sensitive for preload variations.

The Transmission Stage and the GPRM flange were manufactured and integrated into a partially assembled ISH and a vibration test was performed. The results of the vibration test correlated very well with the analysis predictions and no degradation at the fingers or TM was found.

Figure 3. Transmission Stage Flight Model

In parallel to the hardware oriented activities on the TS, a preliminary design of the AB was established. This preliminary design and the successful test results of the TS were taken to the PDR.

2.3 Detailed design

2.3.1 Transmission Stage

With the performance demonstrated in the first phase no need for redesign of the TS was apparent. Only minor design modifications were implemented. As the existing EBB parts were manufactured from flight quality materials it was possible to refurbish and reuse them to build up the TS EQM. This approach helped significantly to deliver the first EQM hardware just a few weeks after the CDR.

Attached to the top and bottom TS are the elements to feed the mechanical force from the inside of the ISH to the AB on the outside. On the top side of the ISH a flexible vacuum tight bellow is used for this purpose. On the bottom side a vacuum valve is integrated, providing the venting function of the CVM. The vacuum valve is opened at the same time when the bottom fingers are retracted. The idea of the vent valve is that the ISH can be baked and sealed on ground to achieve a known cleanliness level. After launch the ISH is vented to free space by opening the vacuum valve.

2.3.2 Actuator Block

As the initial design concept was a compromise between achievable motorisation margin for finger retraction and shock generation, some considerable engineering effort had to be invested to comply with both contradicting requirements. A high motorisation margin required stronger springs and higher stored energy creating a stronger shock. Several completely different concepts were evaluated but at the end the original concept offered the best trade-off between performance, technical and programmatic risk.

The initial concept of the AB was based on a crank to translate the linear finger movement in a rotary movement, and a friction brake to control the rotary movement in order to dissipate the preload energy. An actuator was used to lift the brake in a controlled manner and to avoid shock generation.

As in the vicinity of the TM no magnetic materials are allowed, it was not possible to use classical electrical motors, magnetic pin pullers or similar elements. RUAG Space has used piezo-electric actuators for the GPRM and piezo elements were envisaged for the CMSS and CMLA as well. With the experience gained in the GPRM programme the development effort for a piezo based solution was assessed to be incompatible with the schedule constraints of CVM.

A different subsystem realised by RUAG Space for LISA Pathfinder, the Lid Opening Mechansim (LOM) [4], made use of a paraffin actuator, offering slow high force movement by design. With the very compressed schedule and the experience gained with this actuator it was an attractive element to be used for CVM. The major limitation was that the nominal force and stroke capabilities of the actuator type used for LOM, did not allow a direct use without an intermediate linkage. The initial concept based on a crank was developed specifically to circumvent this limitation, but did not succeed to achieve sufficient motorisation and to avoid shock with the same design.

Figure 4. Actuator Block Flight Model

A detailed mechanical analysis was established for the preliminary design of the actuator block to further optimise the design. It became apparent that the release of the finger preload force and the finger retraction motion were taking place in very different force regimes. During the unloading of the preload force, a push force of up to 2500 N had to be reduced to 0 N and for retraction just low friction forces in the range of a few Newtons in the pull direction had to be overcome.

The original crank design offered little flexibility to optimise the ratio between linear and rotary movement. A spiral cam with nonlinear variable stroke was implemented instead. The spiral shape could be optimised in a very flexible manner for the two operation phases. The final design features a spiral curve based on a 4^{th} order polynomial function, offering the best possible force to stroke ratio over the whole motion range.

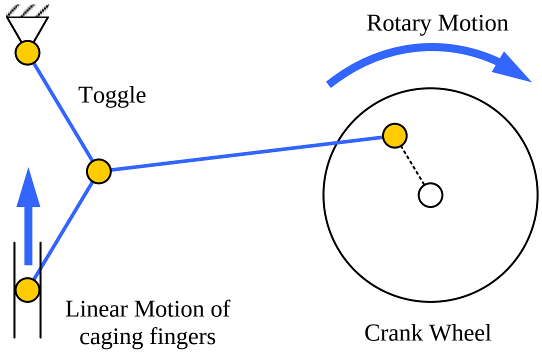

Figure 5. Crank Principle

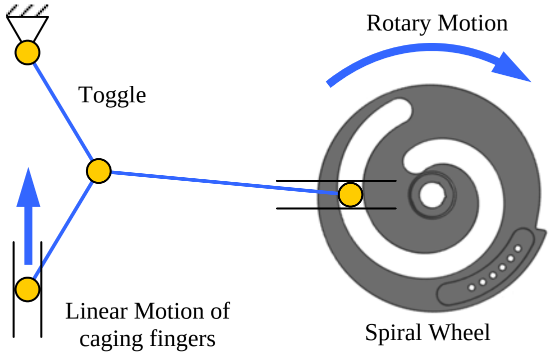

Figure 6. Spiral Cam Principle

The purpose of the friction brake is to control the rotary motion to prevent shock generation when the mechanism reaches the end-position. To ensure a controlled motion the brake needs to be stronger than all driving forces at any time. As with this configuration no motion would be possible, the paraffin actuator is used to reduce the brake force. At some point the brake force is equal to the driving forces and the motion will start. To keep the motion controlled, the brake acts on a surface with variable radius, which re-increases the brake force while the rotating wheel is moving. With all effects running at the same time the brake force and the driving force are kept in equilibrium by the force generated by the paraffin actuator, resulting in a slow and controlled motion.

An additional feature of the brake is that the brake force does not act perpendicular to the brake motion but in an inclined direction. This configuration further increases the available brake force with the help of the driving forces.

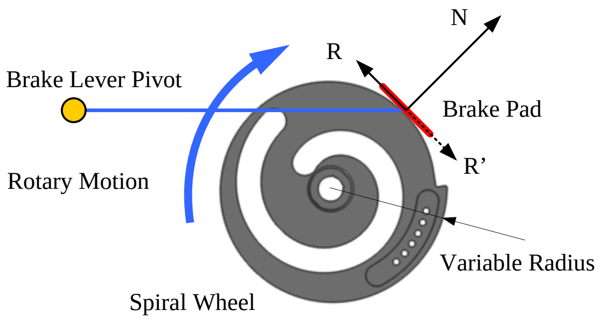

Figure 7. Brake Principle

With the above mentioned design optimisations it was finally possible to ensure a controlled uncaging with the intended paraffin actuator and to guarantee motorisation margin for the complete retraction motion.

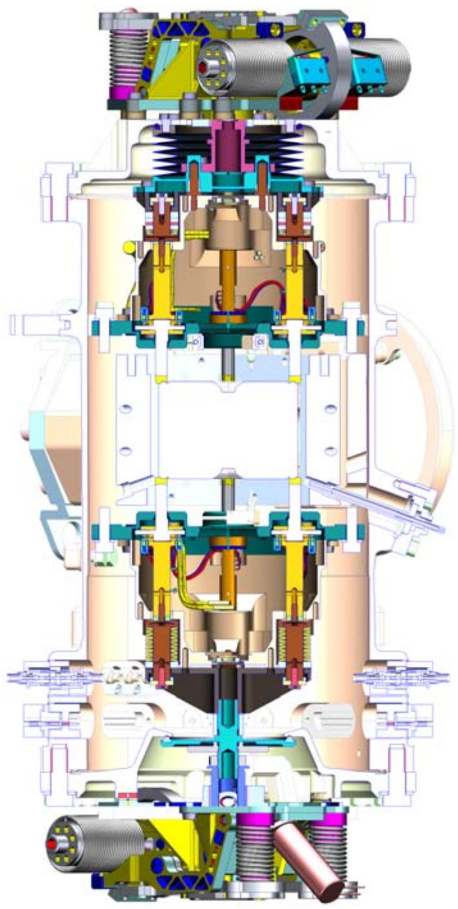

Figure 8. CVM integrated in ISH

3 TESTING

3.1 Breadboarding

After PDR all critical features of the AB were identified and simplified breadboard test setups were realised to proof the feasibility of basic AB concept and to gather preliminary data as input for mechanical analysis, e.g. friction data.

The breadboard testing was an important means to reduce technical and programmatic risk due to the high schedule compression. Most design and engineering uncertainties could be resolved within very short time

One of most critical breadboard tests was targeted to identify suitable material for the friction brake. The goal was to find a material combination with a friction coefficient >0.3 in air and in vacuum and without significant wear generation. A broad range of material combinations have been subjected to a screening test in air and later a few selected combinations also in vacuum.

3.2 Qualification Testing

The advantage of having to CVM split into the TS and the AB as rather independent sub-elements was the basis for the test plan. Testing was split in 3 main phases:

- Transmission Stage Testing
- Actuator Block Testing
- Testing of complete CVM integrated in ISH at customer level

This approach offered maximum flexibility in the planning as independent AIV could be assigned to the two sub-systems. The main risk of this approach is that a full functional test on the complete CVM is only possible at customer level after integration in the ISH. As this fact was well considered in the design of both TS and AB the associated risk severity level could be reduced to an acceptable level.

For the TS the test sequence was kept short as only little technical risks remained apparent after the EBB phase before PDR. The testing on the TS focussed on the following topics:

- Finger force distribution
- Retraction force
- Finger alignment precision
- Electrical properties
- Physical properties

On the TS no thermal vacuum, life or vibration testing has been performed before delivery to the customer. These tests would be representative only with the TS integrated in the ISH and have therefore deferred to the test program at customer level.

The AB was subjected to a more conventional test program:

- Full functional testing
- Motorisation Margin testing
- Random Vibration
- Exported Shock measurement
- Thermal Vacuum Cycling
- Life Testing
- Electrical properties
- Physical properties

Due to the very short and fast design phase it was anticipated that testing will reveal problems. The most difficult problem appeared during motorisation margin measurement. For motorisation margin verification it was foreseen to determine the friction torque by moving the rotating spiral wheel using an electrical motor equipped with a torque gauge in CW and CCW direction. Friction torque would then be half of the difference between the measured forward and reverse torque. For this measurement the brake is not engaged as in worst case the paraffin actuator just lifts of the brake completely.

From the first measurements it became apparent that the friction in forward and reverse direction is not symmetric. In theory this is the case for single element mechanism only, but is not correct if several mechanical elements are linked together. With this insight only the forward torque was considered and friction torque was agreed to be the difference to the theoretical torque from the mechanical analysis with friction set to zero.

The friction torque determined with the revised approach was still higher by about 50% compared to the mechanical analysis. As all mechanical elements have been tested using the various breadboards, the friction uncertainty factor was reduced to 1.5 for all elements already during the design phase. The additional friction leaded to reduction of the motorisation margin to a value bellow 2 for some parts of the initial phase of the release motion.

During the initial phase the preload force in the fingers is decreased and this preload acts as driving force. At the same time this rather high driving force also creates some friction in the moving elements of the AB. The higher this friction is, the lower is the counteracting force to be provided by the brake. From functional point of view the increased friction is therefore no problem as lower friction would just be compensated by higher brake friction. From formal point of view this could not be accepted as strictly seen the motorisation margin is less than 2.

In order to identify the source of the higher friction the AB was disassembled starting from the rotating spiral wheel side and all intermediate forces were measured and compared to the mechanical analysis.

All joints of the AB were equipped with sliding bearings with a sintered bronze and PTFE coating. This type of bearing was used also in the GPRM project [3]. During the breadboard testing a friction coefficient of 0.05 has been determined, which was confirming the experience from GPRM. While for breadboarding bearings with 4 mm shaft diameter were used, one bearing in the final AB design an identical type but with 3 mm shaft diameter. It turned out that the 3 mm bearings seem do be more difficult to manufacture and do no offer the same quality of the sliding surface. The 3 mm bearings installed in the EQM AB had friction coefficients of 0.11. This single 3 mm bearing was used for the roller of the spiral cam which is nominally causing ~40% of the total friction. The increase of the overall friction could therefore be addressed to this single bearing.

The problem was solved by doing a selection of the best bearings and by replacing the torque springs driving the spiral wheel by stronger ones offering more torque. The selected 3 mm bearings finally achieved a friction coefficient of about 0.07.

A remarkable result of the qualification testing program was the measurement of the exported shock. The shock was measured by installing the AB on a stiff support plate which was equipped with accelerometers and was soft supported using flexible ropes. The only substantial shock event was caused by the release of the launch lock which prevents rotation of the spiral wheel. The measured Shock Response Spectrum (SRS) was ~20 g and therefore a factor 10 bellow the required value.

The qualification test program has been successfully completed for both TS and AB EQM. Acceptance testing is completed as well for all FMs. The qualification program at ISH level has been initiated. Currently the full functional test and vibration testing has been completed successfully and life testing is in progress.

4 SUMMARY AND CONCLUSIONS

The Cage and Vent Mechanism has been developed, manufactured and successfully qualified within approximately 2 years, including delivery of all flight models. This was made possible by strictly aligning all aspects of the design and the relevant processes towards the goal of fulfilling the schedule. A key factor to achieve this goal was the very tight collaboration within the project team based on an open communication without hierarchical limitations.

The same approach was applied for collaboration with all external partners. The cooperative and solution oriented attitude of all involved partners was essential for the success of the project and was a very positive experience for the team members.

The following points were identified as lessons learned:

- Perform early breadboarding to verify initial assumptions and to generate input data for analysis
- Breadboards shall be representative
- Friction uncertainty factors shall be kept at 3 as long as no full representative test is performed.

5 REFERENCES

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