HYDRAULIC ACTUATOR FOR THE LISA PATHFINDER CAGING MECHANISM: TECHNOLOGICAL CHALLENGES

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ABSTRACT

LISA Pathfinder is an ESA mission that will demonstrate the key technologies to be used in the future LISA mission. One of the most technologically challenging device of the LISA Technology Package to be flown on LISA Pathfinder is the so called Caging Mechanism (CM). This mechanism has mainly 2 functions:
1) to cage a Test Mass (TM) during the launch phase (applying a very high pre-load without damaging the TM surface);
2) to grab, position, centre and release the TM when the orbit position has been reached and whenever needed. The first function is performed by a hydraulic actuator named Caging Mechanism SubSystem (CMSS).
In this paper the technological challenges and the solutions implemented to realize the CMSS, will be shown.

1. Caging Mechanism description

The Caging Mechanism (CM) is composed by 2 identical mechanisms (one in +Z and the other in –Z axis). The CM +Z (as the –Z) envelope is a cylinder with height 200 mm and diameter 130 mm. The TM is made of a very pure gold-platinum alloy, and its envelope is a cube with side 46 mm and weight of 2 kg.
The CM has to perform mainly 2 functions:
1) to cage a Test Mass (TM) during the launch phase (applying a very high pre-load without damaging the TM surface).
2) to grab, position, centre and release the TM when the orbit position has been reached and whenever needed.
Two different sub-mechanisms allow the Caging Mechanism to perform these functions:
- a CMSS (Caging Mechanism SubSystem)
- a GPRM (Grabbing, Positioning and Release Mechanism)

While the CMSS is based on a hydraulic actuator, the GPRM is based on a piezo-actuator.

In CM+Z (as in CM-Z) a CMSS and a GPRM are integrated

2. Caging Mechanism SubSystem description

The CMSS of each Caging Mechanism is made of the following elements:

- 4 hydraulics actuators
- 2 hydraulics reservoirs
- 1 piezo-valve internally redundant
- 1 piezo-pump in 2 stages
- 4 not return valve
- end switches
- 2 pressure sensors
- hydraulic liquid

All these parts are connected to a Cover (where the hydraulics bellows are soldered) and to a Housing (to which the piezo-valve and piezo-pump are mounted).

In fig. 1, the hydraulic circuit is shown.

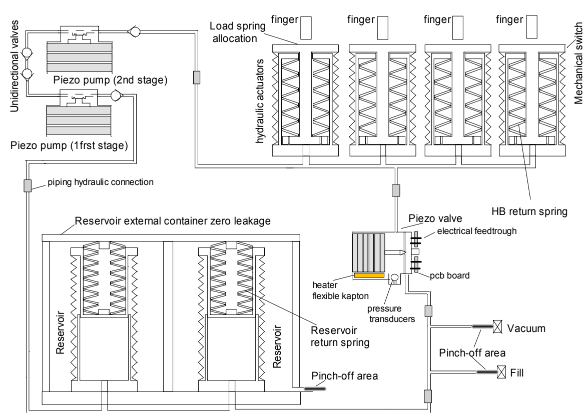

Figure 1. CMSS hydraulic circuit

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The CMSS is required to satisfy the following main demanding requirements:

- Apply a high pre-load to the TM during launch and AIV phase, varying from 300N (storage and test) to 3000N (launch), without damaging the TM surface;
- Perform the hand-over to GPRM in orbit, releasing the TM;
- Move the TM inside the Electrode Housing (EH) for a total travel range of 8mm about;
- Have very stringent out-gassing rate performance;
- Avoid use of any ferromagnetic material;
- Have a low mass while occupying a very small envelope;
- Allow for contact with the TM, avoiding high adhesion forces
- Survive and maintain in position the TM under a quasi static load of 75g enveloping all launch mechanical loads, to be tested under vacuum.

The CMSS will cage the TM using 8 "fingers" (4 on the CMSS+Z and 4 on CMSS-Z), interfacing with conical geometry (optimised for gold friction coefficient) the 8 corners of the TM. The contact area is approximately $8mm^2$ for each finger.

The hydraulic circuit is composed by high pressure side (hydraulic actuator, piezo pump, piezo valve) and low pressure side (reservoir bellows, vacuum and fill connection ports, hydraulic tube).

For each CMSS, four fingers connected with a hydraulic actuator are pushed by the hydraulic fluid pressurized by the piezo pump acting as the "active actuator".
The piezo valve provides the regulation of the liquid pressure transferring it from the hydraulic actuator to the reservoir.
During this phase the return springs integrated into each hydraulic actuator act as a ''passive actuator''.

Two reservoirs are necessary to compensate the actuators elongations, and allow to carry out the "baking test" (max 150°C) without opening the hydraulic circuit by means of the piezo valve ON when the pressure increases.

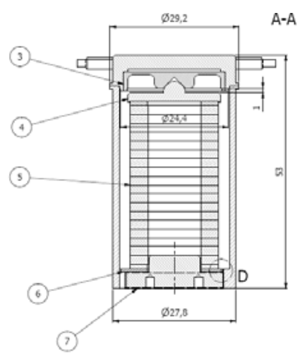
In each mechanism, two redundant functions have been considered:
- Piezo valve with two internal piezo stack actuators
- Pressure monitor with two pressure transducers in high pressure side
- Two stages Piezo pump to apply to TM the needed medium and high load; a Piezo-pump single stage is sufficient to move the TM up to EH opposite side.

The un-caging of the TM (to perform the hand-over to the GPRM), is performed by release springs integrated into the bellows. A piezo-valve (internally redundant piezo actuators) in series to the piezo-pump and normally closed, is able to decrease the pressure of the hydraulic liquid transferring it into suitable reservoirs based on metallic bellows as well.

In the following paragraphs the main parts of the CMSS will be described in particular considering the technologically aspects.

3. Piezo-pump

The Piezo-pump uses Piezo stacks as actuators and it is configured with stages in series. Each stage is connected (at input and output) to two unidirectional valves.
Each stage contains a piezo stack, which alternatively pushes and retracts a metallic membrane. This movement sucks the liquid from the reservoirs through the unidirectional valve and pushes it to the high pressure side of the hydraulic circuit extending the hydraulic bellows.
The first and second stage are connected together by titanium tube 1/16'' with titanium nipple RF brazing.
In fig. 2, a drawing of the Piezo-pump is shown.



POS	QTÀ	NUMERO PARTE	DESCRIZIONE
1	1	MEC700101981	BODY
2	1	cover-straight hole	COVER
3	1	MEC700101983	MEMBRANE
4	1	MEC700	SPHERICAL SUPPORT
5	18	piezo_	
6	1	MEC70	ANTISPIN
7	1	MEC7	PRELOAD REGULATOR

Figure 2. Piezo-pump section drawing

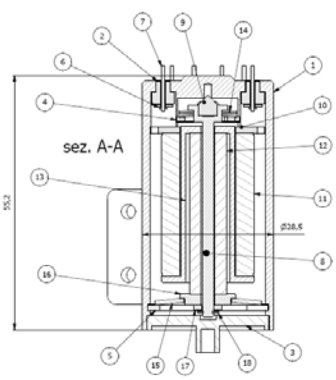
The choice of this configuration is due to the high pre-load value to be reached (3000 N) in order to keep in place the TM during the launch and, on other hand, to match the available volume inside the CM.
In order to achieve such strength, the working liquid has to reach at least 65bars.

Other constraints/parameters for piezo actuator design choice have been:
- Supply Voltage
- Blocking force of the piezo stack
- Free displacement
- Dimension
- Material allowed to be used
- Pressure of preload

The Piezo-pump is driven by a rectangular wave with a wave width/frequency sufficient to allow the membrane to open the unidirectional valves. Note that with a negative driving voltage the piezo stack decreases its length so that the total stroke increases. The two stages are driven in opposite phase.

4. Piezo-valve

The Piezo-valve has the aim to regulate the flow of the liquid from high to low pressure hydraulic circuit parts during the decreasing of load applied to the TM and during un-caging procedure.
For the PV technology/concept definition, Thales Alenia Space Italia choice use piezoelectric materials/actuators.



POS	QTÀ	NUMERO PARTE	DESCRIZIONE
1	1	MEC700102379	BODY
2	10	MEC700102374	Ceramic feedthrough
3	1	MEC70010xxxx	Plug
4	1	UNI 7437 - 13	Anello elastico di arresto
5	1	UNI 7437 - 25	Anello elastico di arresto
6	10	MEC70010xxyy	Washer
7	10		Filo rame
8	1	MEC700102380	Plunger
9	1	MEC700102381	Conical shape
10	1	MEC70010xxxy	Ring support
11	1		Piezo actuator ø20
12	1		Piezo actuator ø8
13	1	MEC700102385	Piezo cup
14	3		Molle a tazza øe12.5
15	1		Molla a tazza øe23
16	1	MEC700102386	Piezo valve stopper
17	1	MEC700102387	Ring thickness
18	1	DIN 6799 1.4034	Anello elastico ø1.9
19	10	saldante 0.15	
20	10	saldante 0.15 piccolo	
21	10	saldante ø0.5	

Figure 3. Piezo-valve section drawing

The Piezo-valve has been conceived and developed taking into account the following guidelines:

- minimization of mass and external dimensions;
- intrinsic safety (normally closed)
- minimization of internal leakage; zero external leakage
- use, as far as possible, of space qualified materials
- reliability

The Piezo-valve exhibits the following main features:

- Operating with Liquid
- Analog operation
- Exit orifice opening regulated by an actuation mechanism based.
- Normally closed with high pressure isolation when de-energized (un-powered); in rest condition the shutter is forced against the orifice both by the spring strength and by the upstream pressure
- Operation - starting from a high pressure:
- Fast Time Response
- Zero external and low internal leakage
- Low mass, dimensions and power consumption

The main elements/parts composing the PV are:

- piezo ceramic actuator stack
- plunger spring
- conical shape
- orifice
- electric interface
- mechanical housing
- piezo actuator spring

The technological processes involved in the Piezo-valve integration are:

- Valve Cover brazing with feedtroughs and cooper pin
- Body and Plug sealing with Plasma welding

Ceramic feed trough is used for electrical connection.
The feedthrough is made of Alumina metallized without Nickel; it's assembled in the body with copper pins and titanium washers and brazed in oven using brazing alloy.

Pressure sensors (strain gage type) will be assembled inside Piezo-valve for high pressure monitor.

5. Hydraulic bellows

The CMSS foresees 2 different bellows:

- Reservoir Bellows (RB)
- Hydraulic Bellows (HB)

The RB have to compensate the liquid which flows from high to low hydraulic parts of the circuit as well as the liquid volume dilatation due to liquid CTE during baking.
Two RB are and four HB are integrated in each CMSS.
Reservoir and Hydraulics Bellows are TIG/arc-plasma welded on the Cover.
The reservoir schematic assembly drawing is show in the next fig. 4.

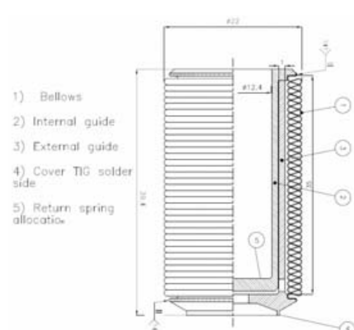


Figure 4. Reservoir bellows assembly in compressed position

The reservoir free position is few mm over the compressed position; in order to guarantee that the compressed position is reached, a dedicated external return spring is necessary.

The Hydraulic actuator and relative return spring schematic assembly is shown in the next fig. 5.

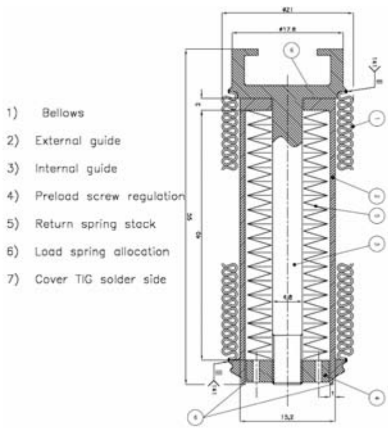


Figure 5. Hydraulic bellows and relative return spring assembly in compressed position

The HB is fixed on the Cover by TIG welding performed in the area shown in point 7 of the above figure. During this process the return spring must be installed. The screw regulation is used for bellows height calibration:
With bellows HB in 5mm over compressed position, the difference in height must be lower 70µm; with this requirement the CMSS can touch all TM corner with a lower force. When the calibration is reached, a local welding point will be performed around the screw regulation.

The Reservoir Bellows hydraulic connection with Piezo-valve and unidirectional valve are realized in titanium tube RF brazed on the hydraulic circuit using a very small copper coil; the connection between each reservoir is realized directly in the Cover as well as HB hydraulic connection.

Inside each Hydraulic Bellow a set of Return Spring is integrated as sketched in fig. 5. The Return Spring force is determined by two points: the Hydraulic Bellow "zero" position and the maximum elongation (8mm) of bellows.

Load Springs are positioned between the Hydraulic Actuator and the finger; they are directly guided by actuator shape and finger.
Purpose of this Load Spring is to control the pressure when the fingers are in contact with the test mass and the high load is applied and compensate the liquid elongation during launch temperature range. Load Springs are sketched in fig. 6.

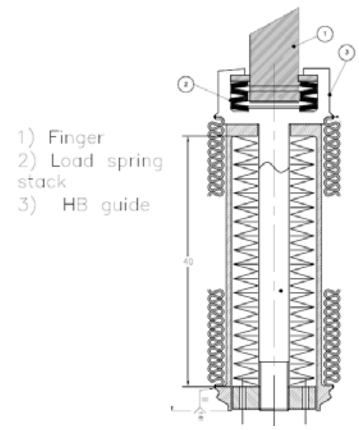


Figure 6. Load Springs inside the Hydraulic Actuator

6. Hydraulic liquid

The hydraulic liquid is a mixture of water and ethylene glycol. This mixture has been optimised taking into account the liquid thermal expansion during baking and under launch temperature range.
The idea is to exploit the low CTE of water adjusting its composition in order to decrease the freezing point and increase its boiling point to fulfil the requirements (baking at 150°C).

To avoid corrosion problems arising from saline solutions, we choose ethylene glycol: this choice is based on chemical considerations concerning the minimum amount of CTE increase adding ethylene glycol to water with respect to the addition of other possible glycols.

7. Vacuum Enclosure I/F Flange

The Vacuum Enclosure I/F Flange (in Titanium) provides the connections of the CM to the structure of the Inertial Sensor Head Vacuum Enclosure.
It guarantees also the alignment of the caging fingers with the TM Corners.
In fig. 7 a sketch of the VE I/F Flange with the fingers and the TM is reported.

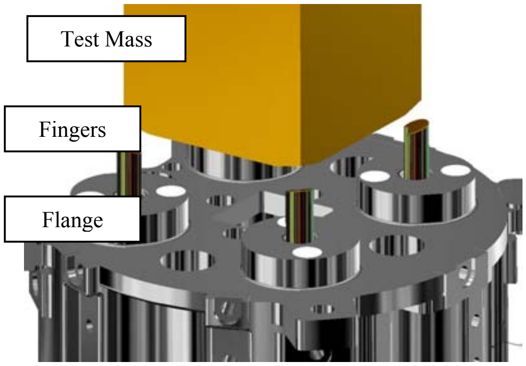


Figure 7. VE I/F Flange

8. Housing

The Housing connects the VE I/F flange to the Cover.
It also provides connections to Piezo-pump and Piezo-valve.
It provides the windows for harness routing.
Housing material: Titanium.
Housing is sketched in fig. 8

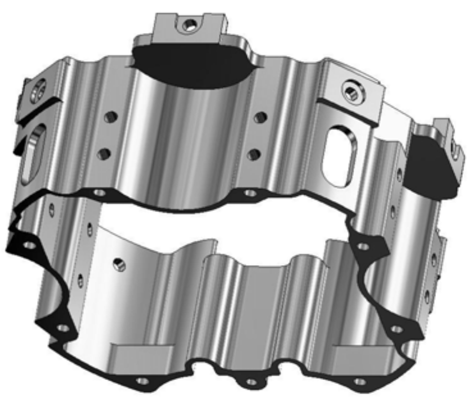


Figure 8. Housing

9. Cover

The Cover is the I/F to which the CMSS parts are connected. In particular the bellows actuator and the reservoirs are welded to the Cover.
The Cover provides the access both to adjust the GPRM grabbing finger and the reference surfaces (optical cube) for alignment purposes
The material of the Cover is Titanium.
Cover is sketched in fig. 9.

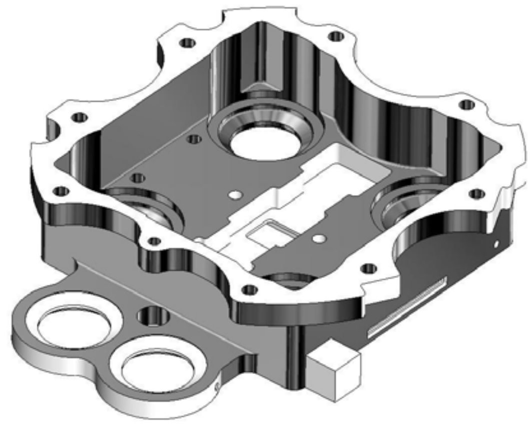


Figure 9. Cover

10. TM - fingers interfaces

The interface between the CMSS fingers and the TM is based on friction. The stability of the contact is guaranteed by the static friction between the preloaded contacting surfaces. The geometry of the contact has been designed in order to minimize the contact pressure under operating loads and to avoid the contact sliding during launch vibrations.
Dedicated FE model have been developed to verify these aspects (fig. 10).

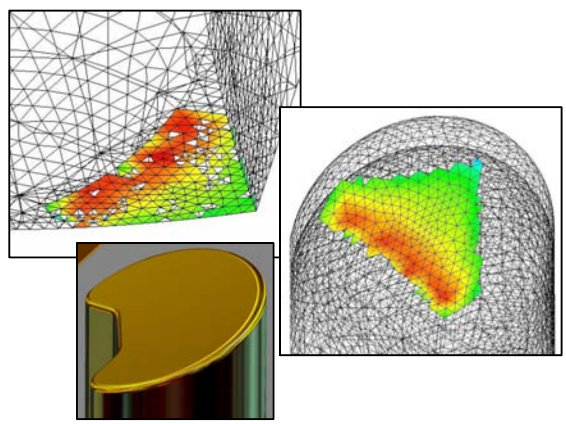


Figure 10. Finite Elements Models

The static friction coefficient, used for the design of the contact, has been measured at ESTL (Warrington, UK) in a vacuum tribometer (fig. 11). Pin on disc tests have been devised to simulate the interface between the CMSS fingers and the curved corners of the cubic TM.
Pins (simulating the TM corners) were made from titanium sputter coated with pure gold and a pure titanium interlayer intended to improve adhesion. Discs (simulating the fingers) were made from Molybdenum

with different thicknesses (1 and 10 μm) of gold sputter coatings.

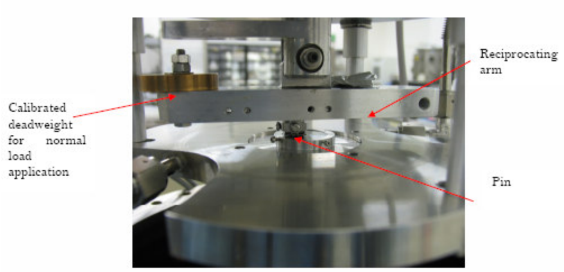


Figure 11.Pin-on-disc mechanism in vacuum tribometer

11. EBB test campaign results

A test campaign on Elegant Breadboard (EBB) has been performed in order to verify the capability to maintain the TM in position under launch vibration loads and to release the TM measuring the adhesion force between TM and fingers.

The EBB is made of a couple of Flight-like CMSS, except for the piezo-pump (which is hydraulic connected to the mechanism but not integrated on it) and the piezo-valve, replaced by a manual valve.
The materials for the structural parts, the hydraulic circuit (Hydraulic bellows), the fingers and the technological process (gold coating, brazing, welding etc.) are the ones to be used for QM and FM.
A pressure sensor in the hydraulic circuit gave the pressure of the 2 CMSS separately.
A set of eddy current position sensors gave the relative measurement of the TM position before and under vibration. The vibration test has been performed under vacuum. A Vacuum cover (visible in fig. 11) assured a vacuum of less than 1mbar, maintained during all the vibration run time.
A Test Equipment let to monitor, in real time, for each CMSS, hydraulic pressure, position sensors output and load cell signals.
The main test activities were:
- CM EBB integration test
- Caging at high pre-load (3000N) and de-caging with adhesion measurement (performed using load cell positioned between Flange and TM).
- Random vibration and correlation of the Finite Element Model of the CM w.r.t. the test result. At the end of each vibration run at different level, an adhesion measurement has been performed. The Vibration has been performed on 3 axes. Notching at 25grms (as required) has been applied.
- Sinus vibration
In fig. 9 the TM (for the test the TM bulk material was Tungsten Copper) the CMSS fingers (gold coated) and the sensors (load cells, position sensors and accelerometers) integrated into the vibration fixture are shown.

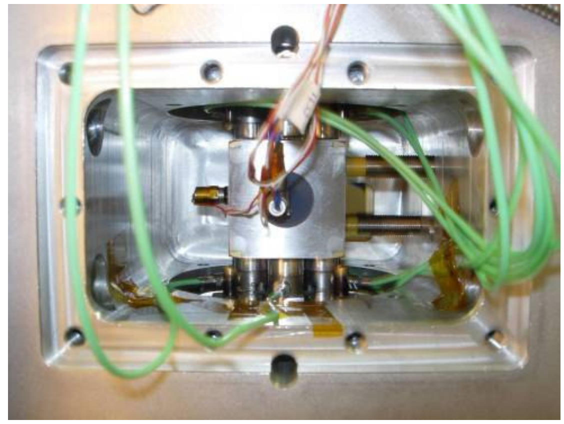


Figure 12. TM and CM integrated into the vibration fixture with sensors for acceleration, position and adhesion force measurements

Figure 13. CM caging TM integrated into the vibration fixture. The Vacuum Cover is removed.

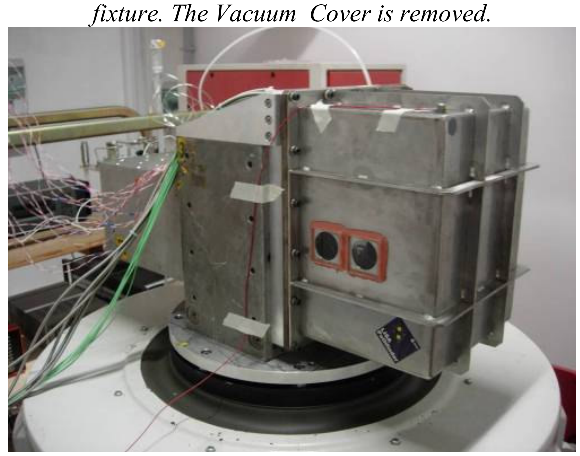


Figure 14. CM caging TM inside vibration fixture. It is visible the cover assuring the vacuum level during vibration runs.

EBB activities have been conceived with the aim to verify:

- Conceptual validity of the design
- Structural integrity after vibration at full qualification level
- Adhesion force measurement (Fretting of the I/F surfaces and Cold Welding)
- EBB Mechanism performances
- Movements of the TM during vibrations
- Gold Coating at the I/F between the fingers and the TM

Conceptual validity of the design

The mechanism well meets the stiffness requirement (first frequency above 400 Hz for all axes) and it does not allow any TM movement at low frequencies (liquid acts as a very stiff spring).
The TM can be caged with 3000 N (at 75 bars) and it can be moved up and down for about 2 mm working with the hydraulic pressure by means of the pump and the release valves.
The load applied to the TM can be regulated from about 0 N (32 bars) up to 4000 N (90 bars).

Structural integrity after vibration at full qualification level

Comparison between resonance search tests, before and after random vibrations at full level, demonstrates that the structural design is good and that the EBB mechanism can survive the launch very well.
Fingers are well dimensioned in shape and material.
As foreseen, sine vibrations, even at qualification level, were not critical at all.

Adhesion force measurement (Fretting of the I/F surfaces and Cold Welding)

Adhesion force has been measured, in air, several times during dry run, and in vacuum (about 0.3 mbar) before and after random vibration at -3dB and at full level; every time adhesion force was below 7 N (< 1%) and no Cold Welding happened. (see fig. 15).

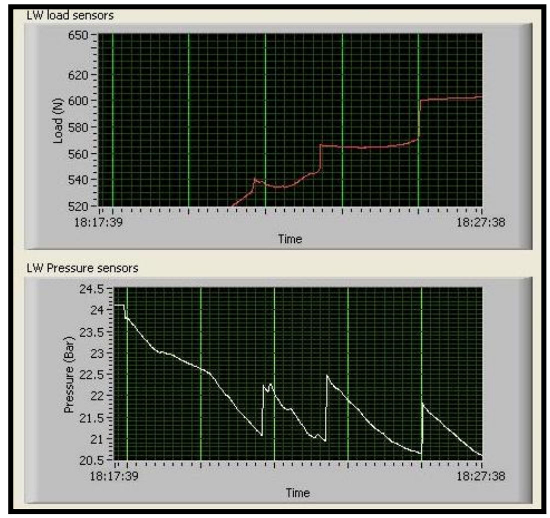


Figure 15. In the upper part the load variation on the load cell due to adhesion force is revealed; correspondently, in the lower part, the pressure into the hydraulic circuit suddenly increases.

EBB Mechanism performances

During dry run tests and during adhesion force measurements before and after vibrations the TM has been always de-caged without any problem.
This means that the return springs have been dimensioned correctly and that they are stiff enough to allow the de-caging of the TM and the finger to return in home position.
After several tests with high pressure (proof test at 90 bars) and difficulties in handling and transportation, hydraulic circuit and components (bellows, pumps, reservoir, piping, etc) do not present any leakage demonstrating, in particular, the goodness of design, manufacturing and welding processes of the bellows (considered one of the most critical components).

Movements of the TM during vibrations

As foreseen, the TM, at the beginning of random test runs, settles in the fingers.
This is more evident during the random test at full level along X axis where the movement detected by a position sensor was about 100 μm. (see fig. 16)

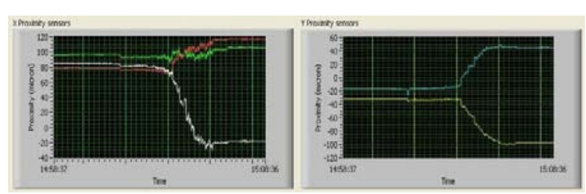


Figure 16. TM rotation during full level vibration run.

Once the TM has settled in the fingers, the residual movements were in the order of few microns.
This can be seen looking at the plots of position sensors during the same random test, but along the other two axes (Y and Z).
Friction coefficient, as predicted, is high enough to avoid evident fretting.
If some fretting has occurred, it was inside the uncertainty of the position sensors (± 1 μm), and much smaller than the electronic noise of shakers and their electronics.

Gold Coating at the I/F between the fingers and the TM

The sequence of inspections made on the TM and on the fingers, by means of a microscope and an endoscope, let us make the following considerations.
The prints of the finger on the TM are not centred; this effect can be caused by a not perfectly alignment of TM with the fingers and by a not nominal I/F spherical surface of fingers and TM.
The most of the Gold Coating damages have been produced during the adhesion test before vibrations. Vibrations increased them progressively. The main reason of these damages was probably the unbalancing of hydraulic actuators stiffness, far from the central position, during the movement of the TM up and down at high pressure.
Although damaged, finger surfaces present a compressed Gold Coating (10 μm at the beginning), while few TM corners (1 μm) seem without coating at the boundary of the print area.
In order to reduce surface damages, some design improvements will be evaluated.

12. Conclusion

The design of the CMSS hydraulic actuator has been shown. The main parts have been described and the EBB test showed that the conceptual design is valid, while some design improvements have to be considered for the TM – finger I/F.

13. Acknowledgement

The CMSS is developed by Thales Alenia Space Italy under Astrium contract, the GPRM is developed by RUAG Aerospace Wallisellen (RAW) as a Subcontractor of Thales Alenia Space Italy.
Thales Alenia Space Italy are also in charge of the AIV of the whole CM subsystem, along with the development of the relevant control electronics (HW and SW).