ALTERNATIVE DESIGN APPROACH FOR THE LISA LTP LOCKING ASSEMBLY

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ABSTRACT

During the qualification process of the LISA Caging Mechanism S/S (CM SS) which forms part of the Inertial Sensor System (ISS) of the LISA Technology Program (LTP), technical and programmatic issues related to the already developed hydraulic Launch Lock Assembly were identified, leading to the request for an alternative Caging Mechanism Locking Assembly (CMLA).

Based on the extremely restricted schedule and the not less critical technical challenge, an Engineering Model (EM) of an alternative Caging Mechanism Locking Assembly (CMLA) was developed, built and functionally tested within the extremely short time frame of 5 months in order to provide to the LISA Technology Program (LTP) program a substitute for the existing hydraulic system included in the (CMSS).

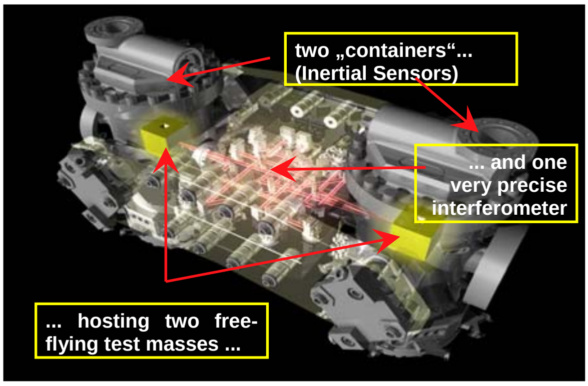

Fig 1. LISA LTP System

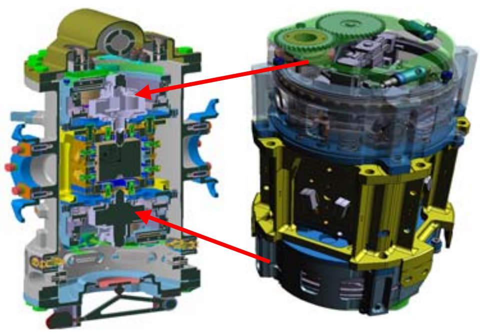

Fig 2. LTP Inertial Sensor and CMLA (2 Halves)

The CMLA task is to lock the Test Mass (TM) safely during launch within the vacuum enclosure of the Inertial Sensors and to release it in orbit.

Due to the critical mission requirements and the very restricted mechanism envelope, the mechanism design flexibility is extremely restricted.

1. INTRODUCTION

The development philosophy of the CMLA was to maintain already qualified elements of the existing CMSS, e.g. to maintain the qualified Grabbing Position and Release Mechanism (GPRM), and the locking fingers clamping the Test Mass during launch and their interfaces.

Consequently, the technical specification and specifically also the very challenging envelope constraints were adopted. Beside the fact that the available envelope within the vacuum enclosure is very restricted by definition, the situation became even more challenging due to the fact that within this given envelope a new mechanism design principle had to be realized which had to fit into the previously used envelope of the hydraulic system.

The key programmatic requirement was to not exceed a 5 to 6 months time frame from scratch to M AIT completion of an EM CMLA, including functional demonstration of the locking performance by test.

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2. KEY REQUIREMENTS

The technical challenge was to realize the alternative CMLA based on a pure mechanical design not using hydraulic components but within the available Envelope of the hydraulic system at respecting the geometric constraints of Vacuum Enclosure and GPRM and especially by maintaining the previous clamping concept of the test mass.

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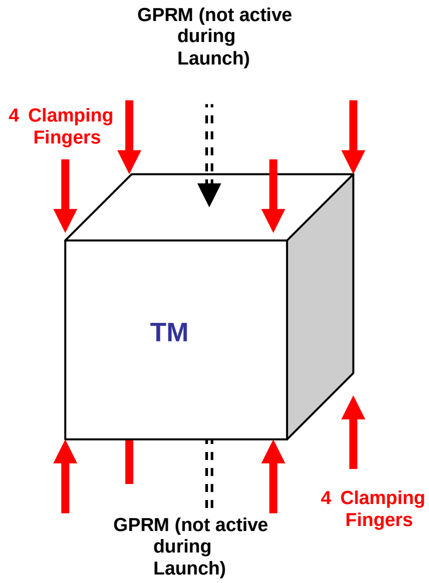

Fig 3. CMLA Clamping Principle

"Hard" key requirements are:

Requirement	Value	Comment
Caging Force per Finger	300 N	1200 N overall
Finger Stroke	4.62+0,5/-0,1 mm	CMLA design: Mechanism stroke: 5.6mm Finger stroke: 4.62 mm
Mass for upper and lower CMLA (w/o GPRM)	< 2750 g	Achieved: CMLA EM per two units: 2460 g (w/o harness, end s witches and GPRM)
Outgassing rate	40 x 10-9 Pa l/s	
Life (Caging / De-Caging Cycles)	78	Single Orbit rel ease + exp ected on Ground operations Incl. ECSS margins.

Table 1. Key CMLA Requirements .

"Soft" requirements are:

- Establish a sim ple and reliable design, **Non-magnetic, avoid lubricants**
- Maintain as much as po ssible proven and qualified elements
- Provide **ECSS motorisation margins**
- Retract and preload test mass w/o manual operation (**provide resettability**)
- Provide possibility for TM h and-over to GPRM (at reduced clamping force)
- **Fit to the available budgets** (mass, envelope) as for hydraulics
- **Minimize impact to higher level** also considering available Caging Control Unit (CCU) w.r.t. electrical, mechanical and software impact.

3. CONCEPT TRADE-OFF

At the beginning of the development phase, a conceptual trade-off was performed in order to identify the optimum concept satisfying the given set of requirements.

First analyses identified two major design drivers:

- Restricted envelope with the GPRM u nit in the center of the CMLA and the Vacuum Enclosure (diameter and hei ght) as t he outer limitation.
- Nominal Clamping force of 1200 N (300 N per finger)
- Required finger stroke
- Motorization factor according to ECSS.

It was very clear from the beginning that the relatively long finger stroke at high output force within the extremely restricted envel ope (allowing only for the accommodation of a very small motor) would require a high overall gear ratio in the range of 1:1000. This high gear ratio has therefore t o be provided over several linear or r otational gear stages, ending up in a l inear stroke of the clamping fingers. Due to t he fact that magnetic parts in the mechanism were not allowed, the selection of suitable motors was very restricted and was limited to the use of Piezo motors.

The trade off yielded two favorite concepts both based on rotary piezo motors. One concept was base d on a leverage system the other was based on a cam system, both translating the rotary motion of t he motor into a linear one of the fingers.

Basically both syste ms were feasible, however since the cam system was co mpletely fitting into the given envelope while the lever system was s uffering from motor accommodation issues withi n the envelope and provided a higher number of mating (tribologic) areas, the cam system was finally selected and built.

4. SELECTED CMLA DESIGN

Each CMLA unit is formed by overall 10 different key elements. All structural elements and the planetary gear box are manufactured from Titanium, all bearings are configured to be non-magnetic (hybrid or full ceramic bearings). Small supporting elements (e.g. bearing cages) will be manufactured out of Vespel® or similar material.

Lubrication is avoided wherever possible for contamination reasons (e.g. no lubrication is u sed on the planetary gear and in t he bearings, the gea r runs dry). This approach becomes possible due to the limited torque loads and low operation velocity at limited life (800 input revs correspond to 1 caging/de-caging sequence).
Due to procurement schedule reasons, the bearings on the EM are still manufactured from 440 C and will be substituted in the final flight configuration by the non-magnetic ones.

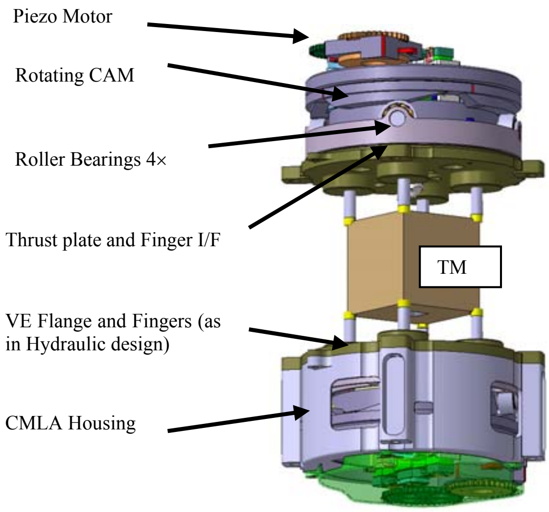

Fig 4. CMLA Overall Design (Both Units)

1) VE Flange and Linear Guidance
2) Return Springs
3) Thrust Plate
4) Roller Bearings
5) CAM
6) Thrust Bearing
7) Housing
8) Planetary Gear Box
9) Piezo Motor
10) Cover

Fig 5. CMLA, Exploded View of one Unit

5. FUNCTIONAL PPRINCIPLE

A rotary piezo motor mounted on top of the CMLA actuates via a spur gea r a planetary gear box with a ratio of i= 245. The output of the gear box is equipped with a sp ur pinion acting to the Cam, supported by a ball bearing (thrust bearing).
By rotation of the progressive cam by means of the gear output pinion, 4 ball bearings integrated into the thrust plate are pushed in a xial direction together with the thrust plate, thus moving the clamping fingers towards the loaded (clamped) position on the Test Mass I/F.

For de-caging, the operation direction is reversed and while the cam is moving to its o riginal starting position, eight CuBe release sp rings push the thrust plate respectively the clamping fingers back.

6. TECHNOLOGY ISSUES TO BE SOLVED

Especially the requirements for non magnetic materials and for extremely low residual gas load within the vacuum enclosure in combination with minimised particle contamination led as a conse quence to the requirement to avoid lubricants. This caused the need for technology work on component level in view of material choice, especially for the un-lubricated condition of bearings which strongly influence the torque/ force budget and component life.

For development risk mitigation purposes some early component tests were per formed in parallel to the development work and back-up solutions for potentially critical elements were identified:

6.1. Early Risk Mitigation Activities

<u>Torque Force Budget</u>
In parallel to the design activities early to rque/force budget analyses were carried out in order to identify the motorization margins. While the first analysis was purely based on ass umptions, the analysis was m ore and more refined by including real measured friction values into the analysis.

<u>Structural Analysis</u>
A complete FE model of the CMLA was b uilt up in order to verify the dynamic behavior and to identify critical local stress levels in the mechanism.

<u>Piezo Motor torque and Life</u>
In order to verify that the output torque and life of the selected piezo motor is sufficient for the application, an early life test under UHV condition was carried out.

<u>Piezo motor bake-out</u>
A 96 hours bake-out of the selected piezo motor was carried out in th e thermal chamber at 130 deg C in order to verify that the piezo did not degrade due to this thermal load.

<u>Bearing Friction and Gear efficiency</u>
Early friction tests unde r realistic conditions on all bearings and efficiency tests on the planetary gear and on the spur gears were carried out under realistic load conditions in order to obtain reliable inputs for the force/torque budget analysis.

6.2. Piezo Motor Selection

Since the Piezo motor is a key element of the CMLA, alternative motor concepts were investigated in order to select the favorite candidate but also to generate a potential back-up solution. Overall three Piezo Motors were identified as potential candidates:

<u>Linear Piezo motor from PI (Germany).</u>
A design for transfer of t he linear to a rotary motion was realized in the CMLA

Advantage
- ➢ high output torque

Drawback:
- ➢ does not fit to the given envelope height.
- ➢ redundancy not on motor level (to be generated by specific motor arrangement).
- ➢ Linear output to be transferred to rotational one by specific I/F design.

Rotary Piezo Motor from PiezoMotor (Sweden)

Advantage:
- ➢ high output torque
- ➢ fits into given envelope

Drawback: Vacuum life issues were identified
- ➢ Not redundant (however fail safe in case one piezo would fail)

Rotary Piezo Motor from Attocube (Germany)

Advantage:
- ➢ Fits into given envelope
- ➢ Provides cold redundancy

Drawback:
- ➢ lowest output torque

7. COMPONENT TEST / BACKUP SOLUTIONS

At the beginning of the development phase a component test plan was defined for technology critical items and the necessary test rigs were built. During the development phase the tests were carried out in parallel to the mechanism design for early development risk mitigation.

Component tests were not only carried out on the components included into the baseline design, but also on components which might be used as an alternative, in order to generate and have available suitable fall-back solutions for critical components.

Main elements submitted to component test and optimization:

- Piezo Motor life and torque output optimization
- Planetary gear stage selection and efficiency optimisation under load
- Efficiency of spur gears
- Linear guidance friction under load
- Bearing friction torque under representative loads

7.1. Linear Piezo Motor from PI

One candidate motor for the application was the hypersonic Linear Piezo Motor from PI, type U-164. In standard applications the output motion of the motor is acting to linearly guided systems. In the CMLA case the required rotary motion is generated by including an Al2O3 friction wheel into the design to which the motor acts as an input to the planetary gear. A Breadboard model of the PI motor acting to the rotor was built for torque performance measurement purposes.

Fig 6. Ultra Sonic Motor

Though the motor does not fit completely into the restricted envelope height, it was however considered as a back-up (precondition: waiver to be granted for envelope height requirement excursion by 20 mm).

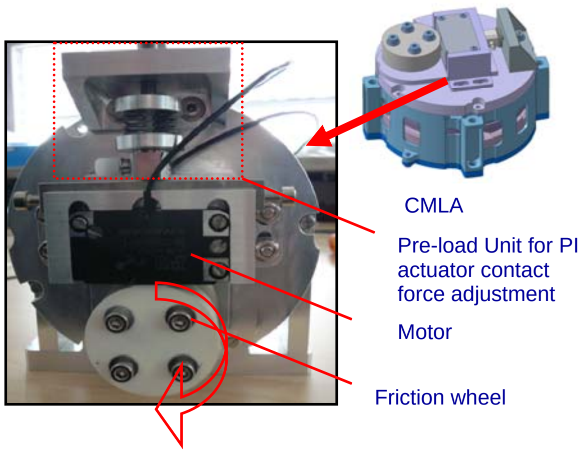

Fig 7. Ultra Sonic Motor B/B

7.2. Rotary Piezo Motor from PiezoMotor

The motor acts according to the "Piezo-leg" principle. The motor fits in to the CMLA design envelope and was therefore considered as a potential alternative. The motor was procured and comparably high output torque values (range 10 Ncm) were measured.

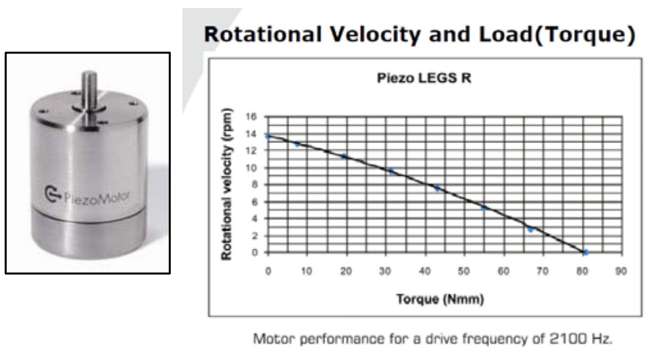

Fig 8. Piezo Legs Motor

The motor worked well in a life test at ambient, however a subsequent test in vacuum revealed a life issue. The motor jammed after several thousand revolutions under vacuum conditions. This failure was quite unexpected and was considered to be somehow linked to a change of the tribological properties in vacuum between the Al2O3 contact Interfaces in the motor. A final investigation of the root cause was however not yet performed.

7.3. Rotary Piezo Motor from Attocube

The selected motor for the CMLA application is the Attocube ANR 200, based on the inertia principle. In this concept the rotor is clamped to the stator by friction forces. At slow rotation of the flexible stator due to the piezo forces, the stator is moved accordingly, while at fast retraction of the stator, the CuBe rotor maintains its position due to its own inertial forces, overcoming the friction forces between rotor and stator. By consequent application of this saw tooth like command profile an output motion in cw or alternatively in ccw direction is generated.

Fig 9. Piezo Motor

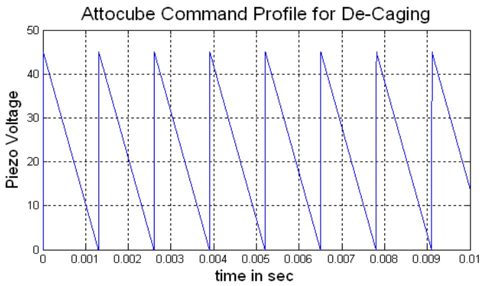

Fig 10. Piezo Motor, Command Profile

Since the motor was originally designed for motion of small appendages (mirrors) about a precise rotation axis but not for maximum output torque, the I/F between the CuBe stator clamped to the rotor by defined clamping forces was found to be not optimal for the application and subsequently generated a life issue at the required output torque level during the first life test under UHV conditions.

In the CMLA application the key requirements are output torque and lifetime, therefore the I/F area between the rotor and stator was changed for the sake of improved lifetime at maximum output torque in UHV conditions.

A second life test in UHV conditions at a minimum output torque of 3 Ncm was successfully carried out for 45000 motor revs (The test was interrupted, because the H/W was needed for integration into the CMLA).

During test the motor was loaded with a sinusoidal torque profile with 3 Nm torque amplitude.

Though the motor provides the lowest output torque of all three investigated motors, it was selected as a baseline since it provides the best compromise between output torque, life, UHV compatibility, non-magnetic requirement and redundancy, while fitting into the given envelope.

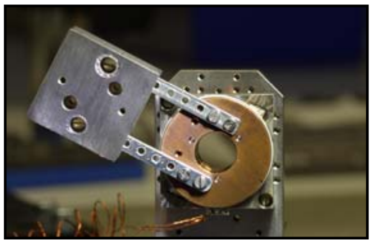

Fig 11. Piezo Motor during torque/life test

7.4. Gear Stage

A planetary gear with a ratio of i=245 was selected as baseline. In order to comply with the given requirement for non magnetic materials, the available standard Stainless Steel product was manufactured completely from Titanium (housing and wheels). In order to cope with the potential issue of high friction at reduced life in a pure Ti to Ti combination in the un-lubricated condition, additionally Bronze planetary wheels were produced. Indeed, after the first gear efficiency tests it was found that high friction occurred in the loaded (sliding) contact area between the planetary wheels and the planet carrier pin in the TI version. This effect was improved by using the bronze planets, however the issue was only finally solved after including Vespel® SP1 bushings into the planet bores in order to separate the planet carrier pins from the rotating planets. During test it was also observed under load (and un-lubricated condition) that the individual stages of the gear tend to move in axial direction towards the first (input) stage, thus producing un-acceptable friction in this torque sensitive stage in which no parasitic torques are allowable.

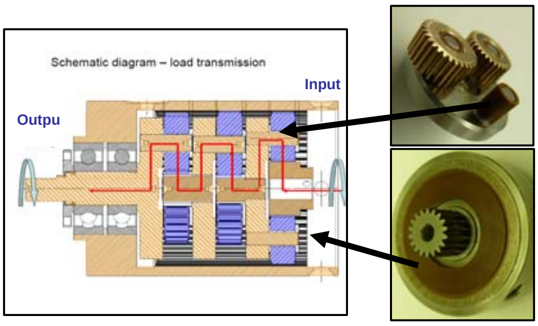

Fig 12. Ti Gear equipped with Bronze Planets and Vespel® bushings/spacer

Therefore an additional Vespe®l spacer was mounted into the Interface between the first stage planets and the planet carrier plate to reduce friction to a minimum in this sensitive are. In this configuration the expected gear efficiency of about 50 % was achieved over life in un-lubricated condition.

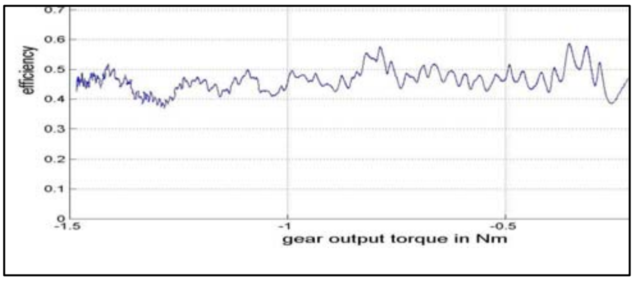

Fig 13. Planetary Gear Efficiency

7.5. Bearings

For schedule reasons non magnetic hybrid or full ceramic bearings could not be included into the CMLA engineering model, however form, fit and functionally identical steel bearings were included into the design, procured and tested in un-lubricated condition for friction under realistic operational loads in order to obtain realistic inputs for the CMLA torque budget analysis.

8. CMLA ENGINEERING MODEL

In the following pictures the final CMLA configuration with mounted clamping fingers is shown. In the left hand H/W picture the 8 return springs for the 4 clamping fingers are shown, while in the right hand picture the complete CMLA half is depicted in the fully integrated status, ready for mounting it into the Vacuum enclosure.

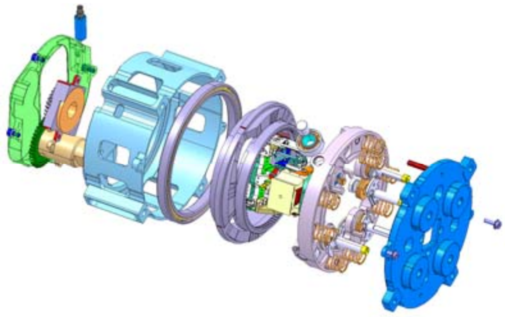

Fig 14. CMLA Final Design, Exploded View

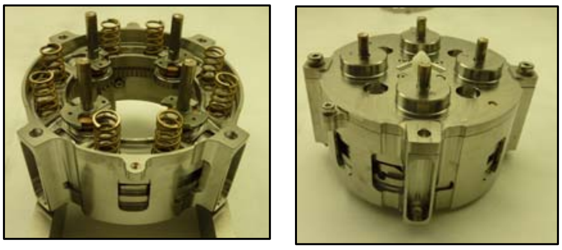

Fig 15. CMLA during Integration and Integrated

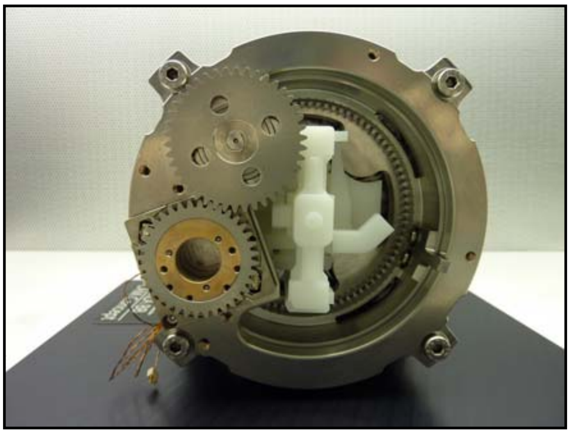

Fig 16. CMLA Integrated, top view, with GPRM dummy in the centre (white element)

9. CMLA FUNCTIONAL TESTING

During and after the development phase, functional tests were performed on component and on unit level in order to verify the correct component/mechanism function, to provide inputs to the torque budget analysis and to confirm the torque budget analysis by test results. Beside the caging and de-caging torque measurements and the finger force measurements on the integrated mechanism, the efficiency tests on the planetary and spur gears and the friction tests on the individual bearing units in un-lubricated condition and under realistic loads yielded important test results.

The efficiency tests were performed by a test setup using a gear motor as input torque generator, a Kistler torque sensor followed by the test item (planetary gear or spur gear). To the gear output a realistic external load was applied, measured by another torque sensor attached between the gear output and the external load. By this test setup the efficiency could be measured as the ratio between output and input torque both detected by the individual sensors.

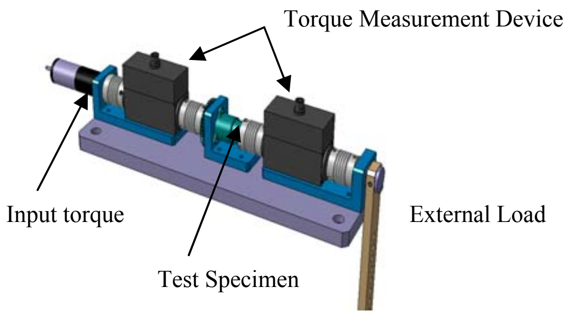

Fig 17. Gear efficiency Test Setup

The bearing friction was measured by applying representative loads to the individual bearings and then measuring the (worst case) starting torque under load. For Clamping Finger force measurement, four force sensors were used to measure the individual finger forces over time during the caging and de-caging process.

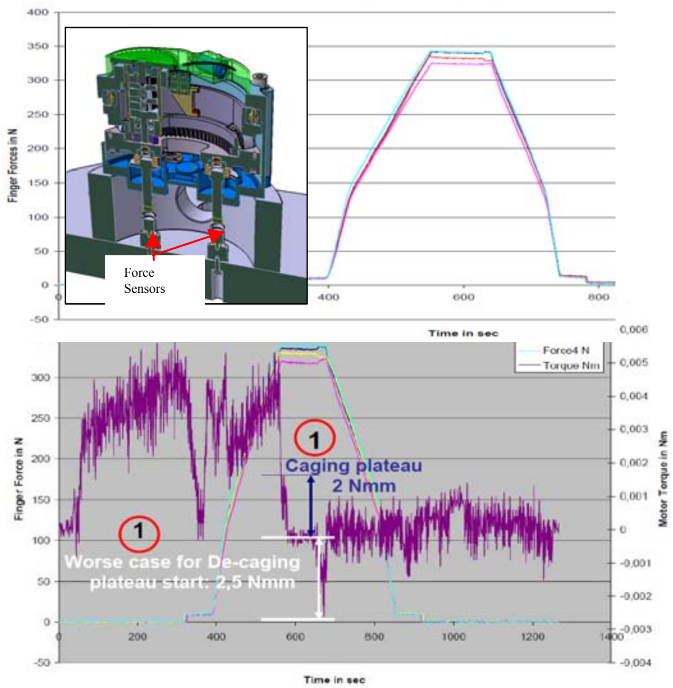

Fig 18. CMLA Caging/De-Caging Torque (NM) vs. caging forces

The torque values for caging and de- caging were identified with a similar test setup as used for gear efficiency measurement and the results corresponded very well to the nominal values achieved by the torque analysis (setting all resistances to 1, nominal values should correspond to the measurements). This confirmed the correctness of the analysis.

For measuring the CMLA torque required for caging/ de-caging the Piezo motor was detached from the CMLA and a test motor was attached, equipped with a torque sensor. This allowed measurement of the real input torque into the mechanism needed for caging and for de-caging.

Comparison of Analysis and Measurement	Required Motor Torque for De-Caging	Required Motor Torque for Caging
EM CMLA Analysis All resistives acc. To ECSS set to 1	2,6 Nmm	6,3 Nmm
EM CMLA Measurement	2,5 Nmm	6.3 Nmm

Tab.2. CMLA Caging/De-Caging Torque calculated vs. measurement. Note: De-caging is the orbit operational case

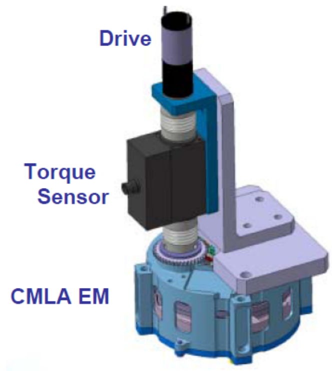

Fig 19. CMLA Torque measurement set up

10. LESSONS LEARNED

Motor:

After optimisation of the selected piezo motor for increased torque performance, a significant life without degradation could be achieved under vacuum conditions. After a bake out test lasting for 96 hours at 130 deg C, the piezo motor showed no degradation.

An optimised motor concept does not mean to choose the motor with the highest output torque, but the one providing a performance which satisfies all technical and programmatic requirements in a compliant manner.

Planetary gear box:

For the required application a Ti Planetary gear equipped with bronze planets and Vespel® spacer allows achievement of gear efficiencies in the range of 0.5 in un-lubricated condition. About 8000 gear input revolutions under external output load of 1.5 Nm were performed without degradation (test interrupted after 8000 revs due to schedule limitation). Inspection of the gear yielded no mentionable degradation.

General:

It was demonstrated that within a small and independent team a complex mechanism can be development within an extremely short time frame and with limited development risk by early consideration of adequate backup solutions and comprehensive component testing carried through in parallel to the development phase.

The work performed provides a good basis for the identification of residual technical and programmatic risks which can be judged with high reliability due to the fact that early contacts to potential component suppliers are built up and their performance and schedule compliance could be checked well in advance.