A Coarse Pointing Assembly for Optical Communication

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Abstract

In the framework of a contract with the European Space Agency, RUAG Space are developing a Coarse Pointing Assembly for an Optical Communication Terminal with the goal to enable high-bandwidth data exchange between GEO and/or LEO satellites as well as to earth-bound ground stations. This paper describes some development and testing aspects of such a high precision opto-mechanical device, with emphasis on the influence of requirements on the final design, the usage of a Bearing Active Preload System, some of the lessons learned on the BAPS implementation, the selection of a flex print design as rotary harness and some aspects of functional and environmental testing.

Introduction

In the framework of the European Space Agency's (ESA) Artes V long-term technology development initiative, RUAG Space is developing a Coarse Pointing Assembly (CPA) for an Optical Communication Terminal.

The main requirements for the CPA can be summarized as follows:

- full hemispherical pointing range
- high absolute pointing accuracy: ± 270 µrad under TV conditions
- very low jitter: < 2 µrad RMS
- high reflectivity, minimal wave front distortion, as well as maximum stray light suppression of the optical components in the CPA
- challenging environmental requirements in the form of
  - high accelerations during take-off on various launchers
  - very large temperature ranges derived from a broad spectrum of thermal load cases
  - optics and electronics components sustaining a tough radiation environment during 15 years in-orbit life

Full hemispherical pointing is achieved by a two-axis azimuth/elevation design – a commonly encountered solution for such pointing devices. Arranged at a 90° angle to each other, each actuator stage carries a flat mirror mounted at 45° with respect to its axis of rotation. With this arrangement, each mirror deflects the optical beam by 90° effectively resulting in the required pointing range.

From the very beginning, it was clear that the jitter and pointing performance could only be realized by minimizing friction and stick-slip effects. Besides utilizing ultra-precision bearings and brushless DC motors operated in closed-loop control with a high-resolution optical encoder, the CPA's actuator stage performance was pivotally enhanced by integrating a Bearing Active Preload System (BAPS).

The BAPS offers on one hand a high and stiff preload state for launch, providing high tolerance to the above mentioned challenging launch loads. On the other hand, the BAPS can be actively transitioned to a low and soft bearing preload state for in-orbit operation, enabling smooth, low-jitter movements during beam tracking, as well as allowing for relatively large thermal gradients across the bearings, which is especially important for GEO applications, where the interior of the CPA might be exposed to the sun. Finally, minimization of friction was tackled by implementing the harness from the azimuth to the elevation

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axis as a flex print design rather than slip rings, roller rings, or conventional cable wraps. These elements brought together the mechanization aspects of the CPA design.

The mirror units were designed to exhibit minimum susceptibility towards thermo-mechanical disturbances. While being of pure Beryllium for weight reasons, the design solution eventually chosen was a highly optimized mirror shape on an innovative iso-static mounting construct.

The high structural loading capacity while maintaining a mass as low as possible was achieved by using AlBeMet or Titanium for all major structural parts.

In the subsequent sections, first, the main components of the CPA are introduced. Following the description how the ambitious requirements were successfully accommodated in the design of the CPA, some lessons learnt concerning the implementation of a BAPS and a flex print cable wrap are discussed before some of the tested achievements of the CPA are presented.

Background

A multi-purpose Optical Communication Laser Terminal is being developed by TESAT Spacecom, Backnang, Germany. The terminal – capable of simultaneous data transmission and reception – is intended for high-bandwidth data transfer between telecommunication satellites operating on different ranges of orbits. The envisaged links (GEO-GEO, GEO-LEO and LEO-LEO, and to ground stations) are foreseen to be established by laser beams. The entire terminal is a highly complex system consisting of tightly interacting subsystems involving mechanical, thermal, optical, and electro-optical elements. In this context, RUAG Space supplies the full chain of front end optics, i.e. CPA and telescope.

Origin of Design-Driving Requirements

The design-driving requirements for the CPA originated from the combination of the wide range of target applications, i.e. operating orbits, as well as the logical need for getting the terminal on the satellite to its in-orbit station. The following points illustrate the origin of the major CPA requirements.

Pointing-Range:	For pure GEO-GEO link applications, a much simpler CPA design could be conceived (Ref. 1) where the required pointing range is much less, especially in elevation. However, if GEO-LEO or LEO-LEO link capability is required, high pointing range with relatively large rotation speeds and fast acquisition times become necessary.
Pointing Accuracy:	When initiating contact between two satellites, the beam is pointed towards the target terminal based on inertial navigation data provided from the satellite to the CPA drive electronics. In a GEO-GEO scenario the involved satellites may be as far as 60’000 km apart, hence directly requiring a high pointing accuracy. For GEO-LEO or LEO-LEO situations an absolute pointing knowledge is essential. The relative velocities of the involved communication terminals may be quite high. With mutual line of sight contact limited to as little as 20 minutes fast beam acquisition is crucial. This furthermore, dictates the need for a high-pointing accuracy even at moderately high-speeds.
Low Jitter:	Maximization of the transfer power is essential to maintaining high data throughput. Therefore, the optical beam has to be kept as stable as possible, hence directly dictating the need for “jitter as low as possible” at zero velocity as well as under constant movement. In fact, jitter must therefore be minimized both cross-axis and in plane

Thermal Stability:	During operation, the CPA may point in the direction of the sun or to deep space for quite long durations. The operational thermal range of the CPA poses a true challenge for material choice and component or design selection. Furthermore, thermo-mechanical stability throughout the operation at these temperature extremes must be guaranteed.
Radiation Hardness:	Telecom satellites operating in GEO orbits have generally a comparatively large life time, often 15 years or more. Thus, radiation hardness of the equipment must be very high, which reduces the number of choices for electronic components and surface coatings of mechanical or optical parts, or may even impose the need for shielding.
High Load Capability:	To enhance versatility and extend the scope of application, the quasi-static loads have been chosen accordingly.

CPA Design Overview

General Overview

Figure 1 shows the assembled CPA without the MLI thermal cover.

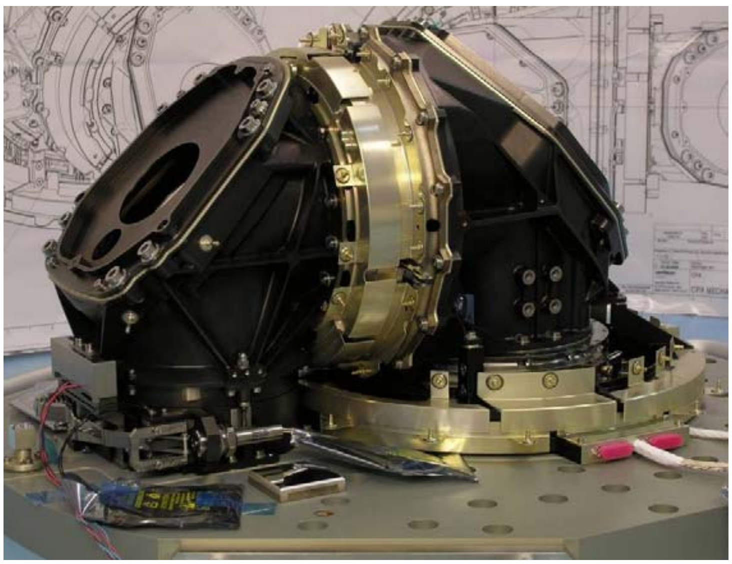

Figure 1. Assembled CPA without MLI protection

As shown in Figure 2, the CPA consists of the following main elements:

- Azimuth Actuator Assembly, containing a bearing set, a BAPS, a brushless DC motor and an optical encoder. This assembly is explained in more detail further on in the text.
- Azimuth Supporting Structure, an ultra light weighted AlBeMet structure that connects the Azimuth Actuator to the Elevation Actuator and supports the Azimuth Mirror Assembly
- Cable Wrap, for transmission of power and signals over one rotation axis to the next.
- Azimuth Mirror Assembly, which is composed of the Azimuth Beryllium Mirror with a high-reflectivity coating, its iso-static support and the Azimuth Mirror Support.
- Elevation Actuator Assembly, same concept as the Azimuth Actuator Assembly.
- Elevation Support Structure, same concept as the Azimuth Support Structure.
- Elevation Mirror Assembly, same concept as the Azimuth Mirror Assembly.
- Park Position Assembly (PPA) incl. Launch Lock, where the functions of the Launch Lock are to rotationally lock the CPA and to increase the first Eigenfrequency to the minimum required value.

Making use of significant synergies, the two Actuator Assemblies have been designed to be identical.

Further elements that are not shown in the figures are the Multi-Layer-Insulation and thin film heaters, which enable the thermal control of the CPA.

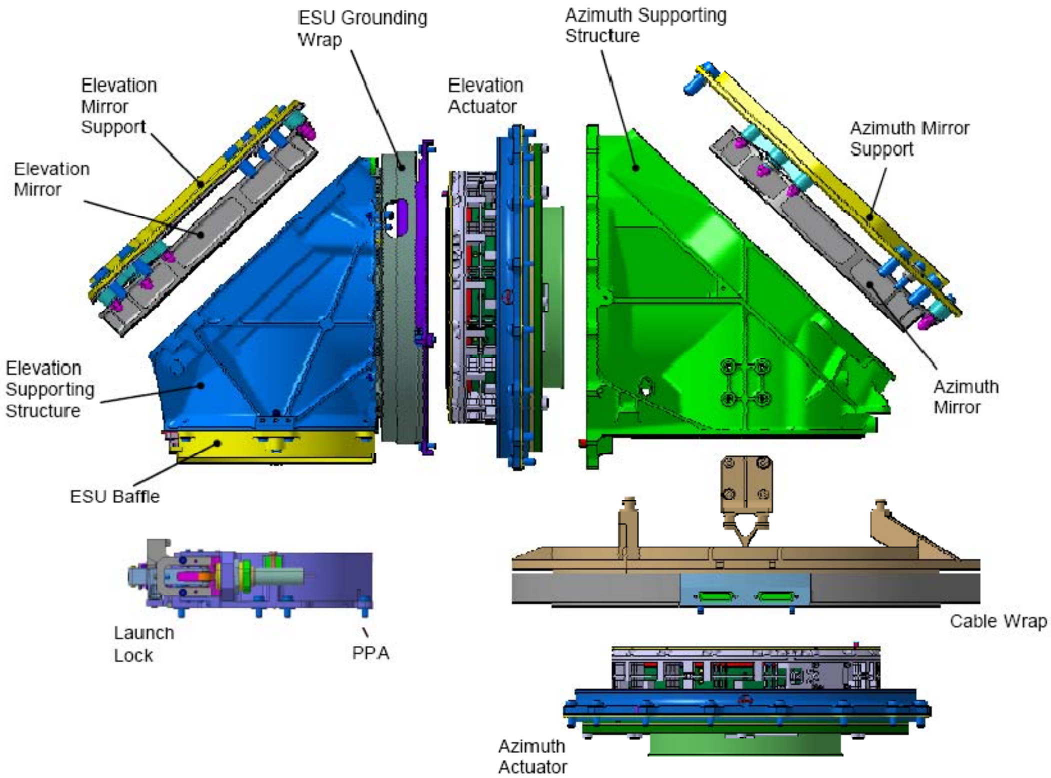

Figure 2. CPA exploded view

Actuator Units

The CPA mechanism core components are the two Actuator Assemblies. The requirements to these assemblies can be summarized as follows:

- Provide the rotation possibility with a bearing system that has:
- a minimum of resistance torque
- very low torque noise
- a long life in terms of time duration as well as number of cycles
- a high tolerance of quite large temperature gradients across the bearings, which is especially important for the GEO applications
- Allow the optical beam to pass through the centre of the CPA.
- Include the brushless DC motor
- Include the 24-bit resolution optical encoder
- Withstand the challenging launch loads.

Typically, the first point can be reached through a soft and low preloaded bearing system (see Ref. 1). However, this is in contradiction to the last point, which generally asks for stiff, highly preloaded systems preventing too much gapping in the bearings. Together with ESR Technologies, the solution to this challenge was found by using an evolution of their original Bearing Active Preload System (BAPS) QM (see Ref. 2). The BAPS can be considered a bearing housing consisting of a monolithic titanium structure of three coaxial rings which are joined by pairs of thin, blade-like flex-struts as shown in Fig. 3. The upper and lower rings are interfaced to the bearings to be preloaded whereas the middle ‘synchro-ring’ can be rotated through a small angle (typically ~10-15mrad), thus deforming the flex-struts and axially displacing the upper ring with respect to the lower (typically by 30-100 µm) so changing preload whilst retaining tight control of the bearing ring planarity.

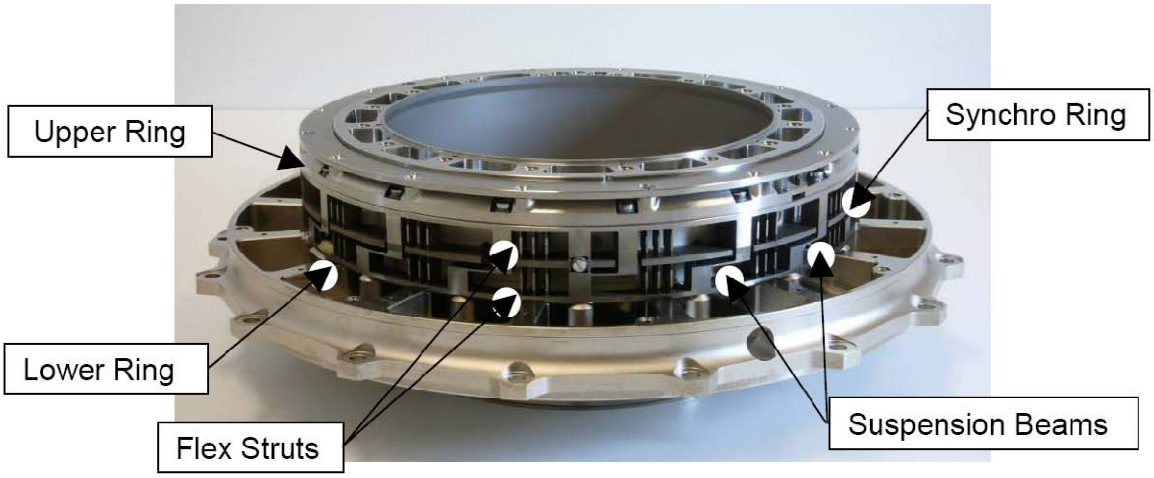

Figure 3. Actuator Unit with BAPS

In the high preload state for launch the flex-struts are slightly deformed from the nominal as-manufactured fully straight 'Top Dead Centre' (TDC) position as shown in Fig 4. In order to actuate the device a torque or tangential force is applied to the synchro-ring causing its rotational displacement past the straight strut position "Top Dead Centre" (TDC) initially to low-preload balance point (which is optimally low preload stiffness since the synchro-ring is un-restrained) at which point the residual preload in the bearing system is balanced by the elasticity of the flex-struts in bending.

The BAPS structure is inherently stiff and stable in the high preload state for launch when the flex-struts are relatively lightly stressed even by launch vibration loads. The struts also serve to synchronize the motion so that the parallelism of the axial motion of the upper and lower bearing housing is extremely high.

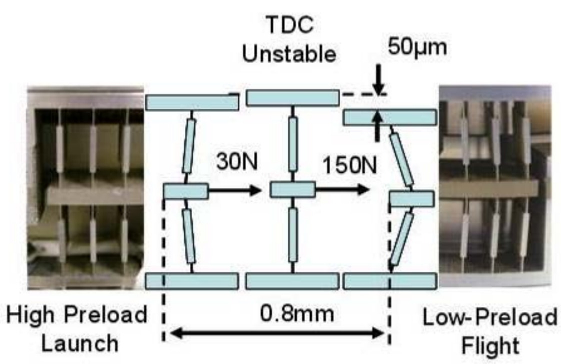

Figure 4. Preload States of BAPS

Thus, the BAPS provides an ideal solution for the application, and eliminates the compromise required with a passive system. In the high-preload state, it provides high stiffness for launch in order to prevent bearing gapping, a concern for bearings of the highest surface finish quality, and in order to protect the close clearance between the rotating and static discs of the high precision encoders from touching. On-orbit, the BAPS is switched to low preload and low stiffness in order to provide very low inherent sensitivity to thermal strains, and low torque noise in absolute terms.

The specified design load parameters to the BAPS are shown in Table 1.

Table 1. Specified Design Load Parameters of the BAPS

Parameter	Value
Maximum High Preload	~ 4000N
Min Low Preload	~ 350N
Quasi-Static Launch Loads	5650N
Quasi-Static Bending Moments	770Nm
Quasi-Static Angular accelerations around rot. axis	2500 rad/s^2

The actuation of the BAPS from high to low preload is achieved by a bi-directional Shape Memory Alloy (SMA) actuator, which engages into the synchro ring with an SMA contact. The SMA actuator activates upon introduction of heat into the heater plate. When power is switched off, the SMA contact returns to its original position and leaves the synchro-ring free, such that the BAPS is in a minimum energy balance preload condition. The resetting of the BAPS is done manually.

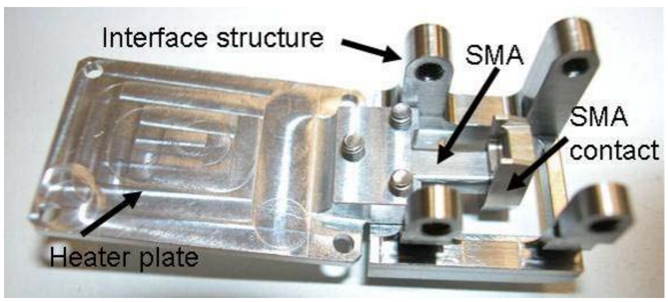

Figure 5. BAPS SMA Actuator

In order to allow for a large optical beam in the center of the mechanism in combination with low torque noise, the previous experience (see Ref. 1) has been recalled and thin section angular contact ball bearings are utilized in back-to-back configuration. Ceramic load carrying balls are used with undersized steel spacer balls. The bearings are lubricated with Fomblin Z25.

As mentioned above, the motion is enabled by a brushless DC torque motor. The motor has dual windings for redundancy reasons. A frameless design has been selected in order to minimize mass. It has to be noted, that the volume constraints are very stringent. In order to minimize the length and diameter of the system, the motor is placed between the central Hollow Shaft and the BAPS structure.

Finally, the actuator units are equipped with 24-bit Optical Encoders from Codechamp, which allow for a very smooth control and hence contribute to the achievement of the jitter requirements in motion direction.

Cable Wrap

A major challenge for many multi-axis motion systems, especially with large angular motion ranges, is the transmission of power and signals over one rotation axis to the next. In order to keep the design simple and close to previous heritage, a flex print design has been utilized in Omega configuration (see also Ref. 1). However, the number of transferred lines is much larger than used in Ref. 1 and the EMC shielding requirements are more complex. Hence, a flex print consisting of three ribbons has been implemented. One advantage of this design is that the power lines and the sensitive encoder signals can be routed over different ribbons, providing naturally better protection from interference. Again, for redundancy reasons, the flex print exists in primary and redundant configuration in the CPA.

Launch Lock

When utilizing a BAPS, a launch lock system in the classical sense of a launch protection system or a bearing off-load system is not required. The reasons for implementing a launch lock into the CPA nonetheless are the following:

- The COG of the rotating parts, especially around azimuth axis, is out of center. Hence, lateral accelerations can cause rotational movements, which need to be prevented.
- With the introduction of a pure rotational lock, the required minimum Eigenfrequency of the CPA could not be met, mainly due to the nodding and bending modes across to the azimuth axis.
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For the launch lock design key design drivers were minimizing the required volume and the particular location of the CPA with respect to the terminal's support structure. The CPA is placed with its azimuth axis onto the centre of this support structure and in launch configuration the elevation axis points to one of the supported corners of the plate.

In summary, the requirements to the implemented launch lock are:

- Provide a rotational lock to both axes
- Increase the Eigenfrequency of the CPA above the min. required
- Do not bypass loads of the support structure via the CPA bearings
- Only use one actuator that can be reset and reused during ground testing
- Minimize the overall used volume

The final implementation is shown in Figure 6. The rotation locking is achieved by a latch that engages with a lock on the moveable part of the ESU structure. In addition, the latch positively preloads the Elevation structure into the flex supported contacts on either side, which thus stop rotational motion around the Elevation Axis. The preloading is achieved by a lock spring. The release of the system is performed by a HOP actuator and monitored by micro-switches. With this design, all of the above mentioned requirements are met.

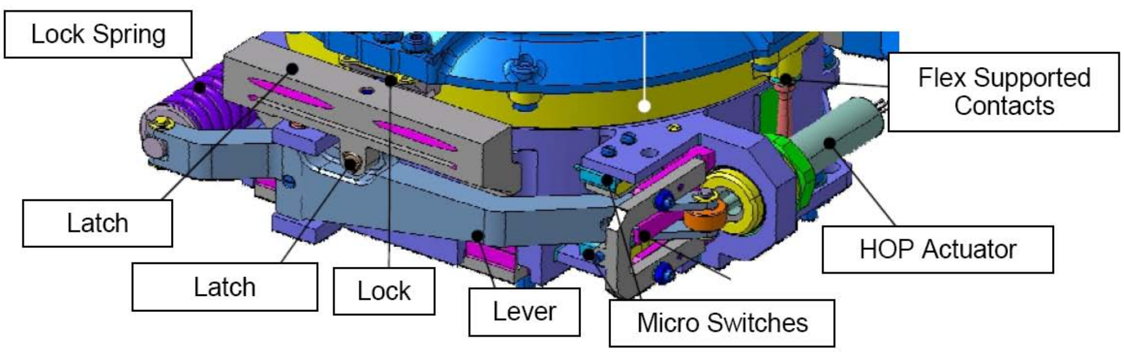

Figure 6. Launch Lock

Optical Elements

Along with the mechanization units, the performance of the mirrors is of critical importance. Figure 7 depicts the azimuth mirror assembly in its holding jig ready for integration on the CPA. The core of the mirrors is of pure Beryllium coated with Nickel. The Nickel is then polished to the required surface quality of around 10 nm RMS and later covered with a protective silver coating. The key performance characteristics of the optical coating are high reflectivity in the target frequency band (>99.5%) and polarization efficiency (>0.99). One particularly noteworthy aspect of the mirror units is the iso-static mounting concept. While providing the necessary stability, stiffness, and strength for the high launch loads, the mounting concept also provides thermal decoupling and by this means high tolerance towards thermo-mechanical influences.

Maximized stray light suppression is achieved by blackening all elements in the optical path. Thereby, the establishment of stable processes for black Titanium and black Nickel on AlBeMet proved to be veritable challenges. Eventually, both key processes were successfully space qualified.

Figure 7. The azimuth mirror unit ready for integration on the CPA.

Achieved CPA Major Performance Characteristics

The CPA is currently under testing. Based on analyses and tests performed so far the following performance data can be reported:

Pointing Range:	±175° (azimuth), -20/+200° (elevation)
Pointing Accuracy:	± 270 µrad, under TV conditions
Jitter performance:	≤ 2 µrad RMS
Mass:	< 15.2 kg including MLI and cables
1st Eigenfrequency:	> 180Hz
Max. power consumption:	< 5W
The following environmental conditions are covered:	
Quasi-static Launch loads:	70 g
Vertical Random Inputs:	15.2 g RMS
Lateral Random Inputs:	9.6 g RMS
Operational Temperature Range:	-30°C to +45°C at interface
Non-Operational Temperature Range:	-30°C to + 55°C at interface
Operation Temperature Tolerance:	Geo-Geo continuous operation, direct view of the sun; cold operation in earth shadow, view of deep space.
Max. thermal gradients across bearings:	-11°C to +11°C
Operational life time:	> 15 years

Various sub-unit level tests have been performed so far, among which the most interesting is the torque and torque noise test. Figure 8 shows that the bearing system, running at low preload, has a mean resistive torque of < 0.04 Nm and that the torque at high preload is ~ 0.2 Nm (i.e., factor of 5). It also can be seen, that the torque noise is in the order of 0.01 Nm peak to peak or 0.003 Nm RMS.

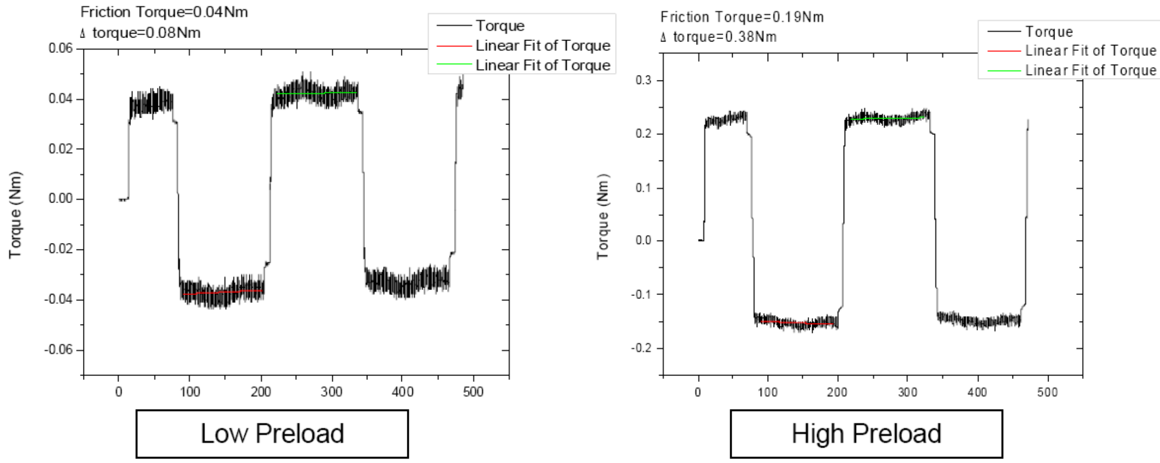

Figure 8. Torque and Torque noise measurements

Figure 9 shows the achieved in plane and out of plane random vibration input levels:

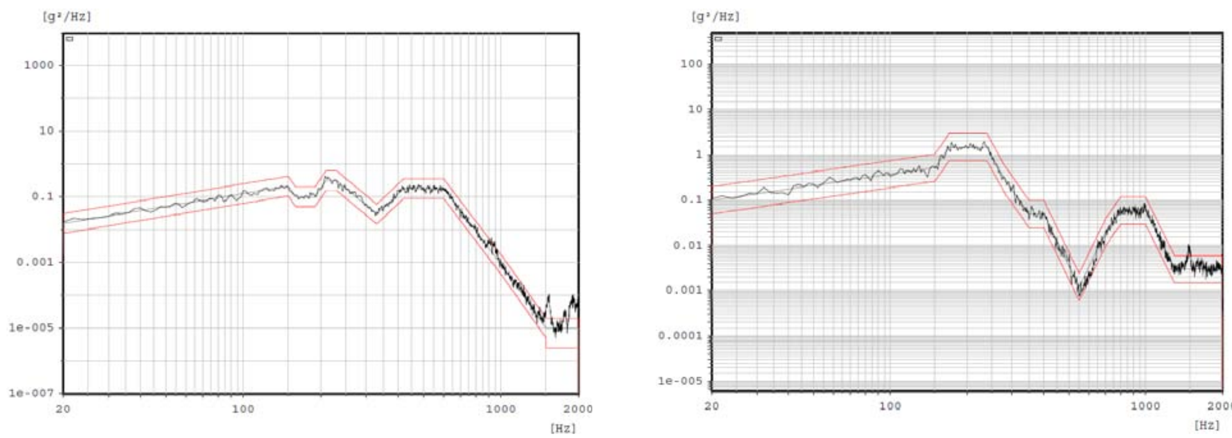

Figure 9. Random vibration tests: achieved inputs in plane (left side) and out of plane (right side)

Lessons Learned

During previous phases, RUAG has achieved considerable success in optimizing and further developing existing designs to meet the above discussed tight requirements. Some examples are discussed in the subsequent sections.

Flex Prints for Rotary Power / Signal Transfer

As mentioned above, the cable wrap of the CPA is made of flex prints. This solution was chosen based on heritage with the previously developed CPA (see Ref. 1). For this CPA, three ribbons are staggered on either side and connected to the same connector. This led to the situation that initially manufactured prints formed bumps and buckles and their roll-down had impacts on the torque noise of the global system, which would reduce the smoothness and thus the accuracy of the CPA. Therefore, RUAG Space improved the design together with the manufacturer. Subsequently the optimal shape of the flex prints was found.

Bearing Active Preload System (BAPS)

Many of the lessons learned on the BAPS, especially the ones concerning manufacturing and assembly are presented in Ref. 2 and will not be repeated here. However, there are some major lessons from the usage of such a BAPS that will be discussed below.

For the CPA application with the very high requirements on torque noise, life, jitter etc. the BAPS is an ideal solution. The measurements done so far can only confirm and justify its implementation.

One major challenge turned out to be the used SMA actuator. This actuator type was chosen due to very tight volumetric/geometric constraints. Several optimization loops were performed and a specific screening process has been introduced in order to obtain a qualified solution.

Conclusions

The CPA currently under testing at RUAG Space has been presented in this paper. It has been shown, that the very tight requirements can be met by a highly optimized design providing multi-purpose usability. The main performance characteristics have been reported among which the low torque noise and the sustainability of high launch loads shall be pointed out.

For future “coarse” pointing mechanisms it is recommended to use a BAPS (Ref. 2).

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