DEVELOPMENT OF A HIGH TEMPERATURE ANTENNA POINTING MECHANISMS FOR BEPICOLOMBO PLANETARY ORBITER

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ABSTRACT

BepiColombo is an ESA mission to Mercury its planetary orbiter (MPO) has two antenna pointing mechanism, High gain antenna pointing mechanism steers and points a large reflector which is integrated at system level by TAS-I Rome. Medium gain antenna (MGA) APM points a 1.5 m boom with a horn antenna. Both radiating elements exposed to sun fluxes as high as 10 solar constants without protections.

The pointing mechanism is a major challenge as high performances are required in a harsh environment. It has required the development of new technologies, and components specially dedicated for the mission needs. Some of the state of the art required for the mission was achieved during the preparatory technology development activities [1]. However the number of critical elements involved, and the difficulties of some areas have required the continuation of the developments, and new research activities had to be launched in CD phase. Some of the major concerns and related areas of development are:

- High temperature and long life requirements for the gearhead motors (up to 15500 equivalent APM revolutions, 19 million motor revolution)
- Low thermal distortion of the mechanical chain, being at the same time insulating from external environment and interfaces (55 arcsec pointing error)
- Low heat leak to the spacecraft (in the order of 50W per APM)
- High precision position control, low microvibration noise and error stability in motion (16 arcsec/s)
- High power radio frequency (18W in band Ka, 30 in X band) with phase stability for use in radio-science (3mm in Ka band, 5º in X band).
- Wide range of motion (full 360º with end-stops)

Currently HGA APM EQM azimuth and elevation stages are assembled and ready for test at actuator level.

1. INTRODUCTION

The possibility of operating a mechanism under 10 solar constant radiation coming from any direction, plus planetary infrared and albedo is a complex issue. But besides this other performances are required for the scope of the mission: Good pointing accuracy to achieve the downlink figures, radio frequency phase stability for radio science experiments, and long angular range life to keep the link through all mercury orbits in mission phase and cruise satellite spin compensation in the five years journey. These elements require some special features and unprecedented technologies.

The first step is to limit the temperature for the components and the gradient in the pointing mechanical chain. The mechanism has insulating interfaces to exposed elements like reflector and medium gain antenna boom, and it is covered by high temperature MLI. However once those barriers are trespassed the thermal system tries to couple and homogenize as much as possible to avoid gradients in each stage, and drains the heat dissipation and leaks to the MPO thermal system.

With these measures temperatures are are limited but in unusual range for space components (above 200ºC). Lubrications, solderings, coating, plastics, EEE and differential CTEs are the restrictive elements.

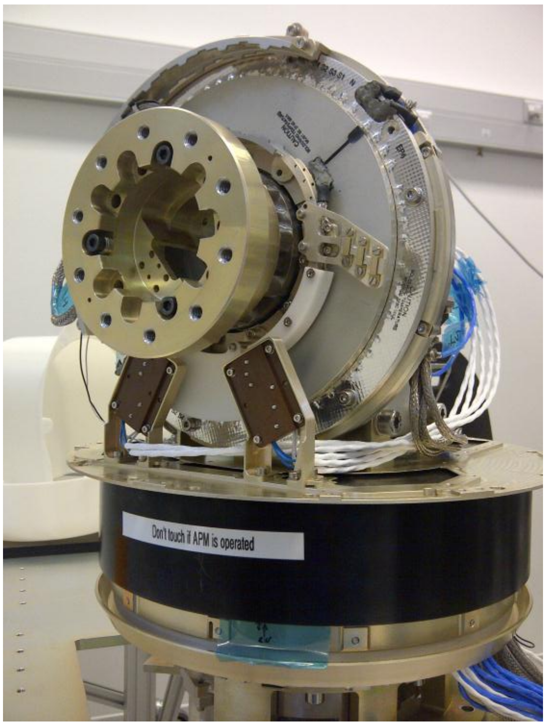

Figure 1 Breadboard APM

As positions sensor an Inductosyn® transducer is used. It already achieved the required adaptation to high

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temperatures during the technology development phase. Materials, foils, and soldering customization were successful.

However the use of Inductosyn implied several issues to the general design of the APM and APM electronics (APME). To obtain extra accuracy from high frequency weak signals a double electric and magnetic shielding is used in the harness. It protects the signal from internal cross-talk and from fast control motor signals. The resulting harness complexity and total number of lines to route through the 360º range of motion azimuth stage required the development of a special twist capsule.

The number of operational cycles during cruise and orbital mission are a challenge for dry lubrication systems used for the motor gearhead and bearings. The use of combination of MoS2 and PGM cages for bearings in the frame of this project and others have shown capacity for the level of tens of millions of motor revolutions when low contact stress conditions are guaranteed [2 and 3]. For gears however the information and durability is more limited [6]. Several life tests, inspections and redesign activities were conducted to achieve required life figures in the planetary gearhead.

Prior to qualification test campaign, some other models have been manufactured and tested. Thermal model for solar simulation test, MGA assembly structural model for mechanical tests at assembly and spacecraft level, one axis APM breadboard for performance test, one axis APM lifemodel for microvibration and several lifetests, a two axis fully functional electrical breadboard, several APME electronics enginery models and twist capsule life models for azimuth and elevation stages.

Qualification campaigns and material research were conducted for high temperature use of radiofrequency plating on titanium, reed-switches and cables.

2. DESIGN OVERVIEW

2.1. Mechanical thermal design

The pointing mechanism for both antennas is an elevation over azimuth dual pointing. The structure of the mechanisms is titanium to create the required insulation of the structural path. While an ancillary aluminium structure provides the required coupling to maintain the components within their operational temperature.

The output shaft to the reflector for high gain and boom for the medium gain is made of titanium in order to limit the heat flux to the APM and to be thermally compatible with the rotary joints, reflector and boom.

Once inside the APM the beryllium disk of the inductosyn transducer rotor on the elevation output shaft is used as a radiator towards the thermal envelope of the APM. The internal side of the shield and the inductosyn surfaces are black anodized to improve their thermal coupling. Shield external side is white alodized to reduce coupling to the MLI around. Several thermal test have proof these processes to be stable thermo-optically when applied in good conditions and the correct standards. The external part of the shield is covered with high temperature MLI.

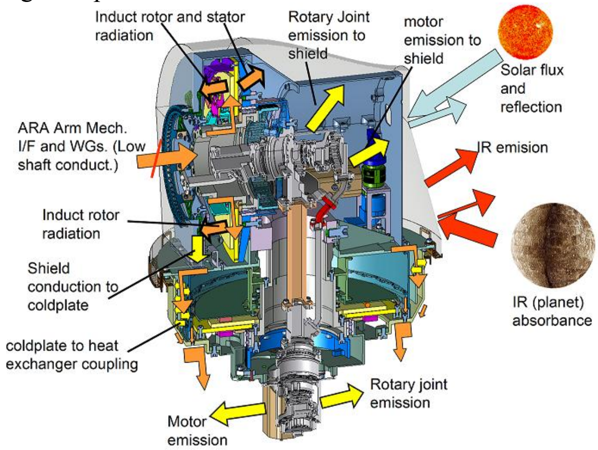

Figure 2 Thermal system schematics

The radiating shield homogenizes the temperatures of the sensors and components within the shield to avoid gradient causing distortion or friction. Gearhead motors are attached to dedicated radiators in order to evacuate their heat dissipation to this envelope.

The shield which rotates with azimuth stage is later coupled by radiation to the fixed part through cylindrical aluminium heat exchangers. This coupling guarantees good heat drain in hot conditions to control the temperature, while little coupling in cold cases to minimize the thermal control system power consumption during the cruise phases. Finally the fixed part of the heat exchanger is attached to the thermal control system heat pipes which will direct the heat to the MPO main radiator. The MPO main radiator is the only side of the spacecraft that is not directly illuminated by the sun. That radiator is equipped with fins to avoid planetary infrared and albedo. Thermal model solar simulation test with the MPO supported the thermal concept to maintain the components temperatures in the required radiation environment.

2.2. Motion system

The APM uses a high temperature permanent magnet stepper gearhead motor (120:1 ratio) coupled to a gear wheel (10:1 ratio) to point the output shaft. The output interface of the gearhead motor is an anti-backlash pinion which mates to the main gearwheel minimizing the backlash. The anti-backlash pinion is a spur gear formed by two parts linked through a torsion spring which preloads the pinion to the mating main wheel. The pinion half that is coupled through the torsional spring is also aligned with an additional bearing pair in the tip of the actuator which helps reducing the total backlash figure. The rear part of the motor has a thermal interface to transfer the heat dissipated in the windings.

Figure 3 Gearhead motor by CDA Intercorp

The use of planetary stages in the gearhead motor implies a certain backlash as some clearance is required between the planetary stage gears. The total APM backlash is basically that of the final planetary stage. The clearance is a compromise between pointing performance and adequate clearance to avoid abnormal wear in the gears. Other types of reducers with less or zero backlash would not be suitable to be used with solid lubrication. The final figures of backlash were set to 18 to 24 arc min at gearhead level after harmonization of the risks and performance needs.

Through the gearheadmotor has a high stiffness by itself (above 850 Nm/rad would provide 85000Nm/Rad) the deflection of cantilevered gearhead output pinion under torque by the circumferential load is the major driver of the stiffness. Moreover the stiffness only starts to be effective after the backlash is overcome. In the dead-band area in between the stiffness is virtually zero, in this case the stiffness concept itself has to be re-defined depending on the application and working mode.

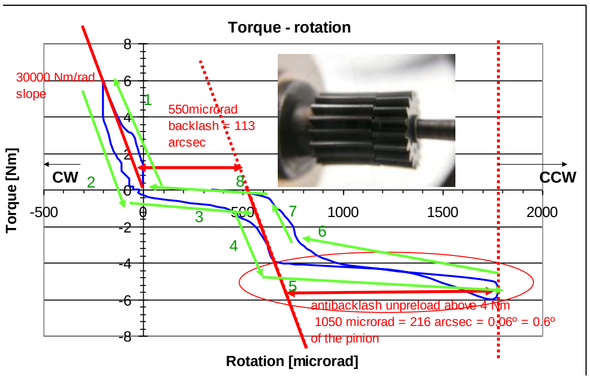

Figure 4 Torque angle behaviour of an actuator

The torque angle plot shows the following areas:

- Stiff area (30000 Nm/rad) driven by the deflection of the gearhead pinion cantilever rotation
- 550 microradians backlash dead area
- Offloading of the antibacklash pinion around 5Nm (designed for 0.5Nm preload at the gearhead)

During effective steering in microvibration test with inertia the effective stiffness is obtained to be around 5000Nm/rad, depending on the inertia and level of perturbations.

2.3. End stops

The range of travel is limited in both azimuth and elevation stages of MGA and HGA.

There are three types of end stops, fixed stops, latches and oscillating end stops. Fixed ones block the mechanism in one position. Latches allow deploying in one direction (elevation in HGA, azimuth in MGA) but do not allow moving back to the stowage area. Oscillating end stop allow a range of motion of 360º.

Latches are performed with CuBe elements that bend and allow the pass of the end stop paddle in the main gear, they are manually resettable in ground for integration and testing with incorporated threads to allow re-stowing the antenna systems without blockage.

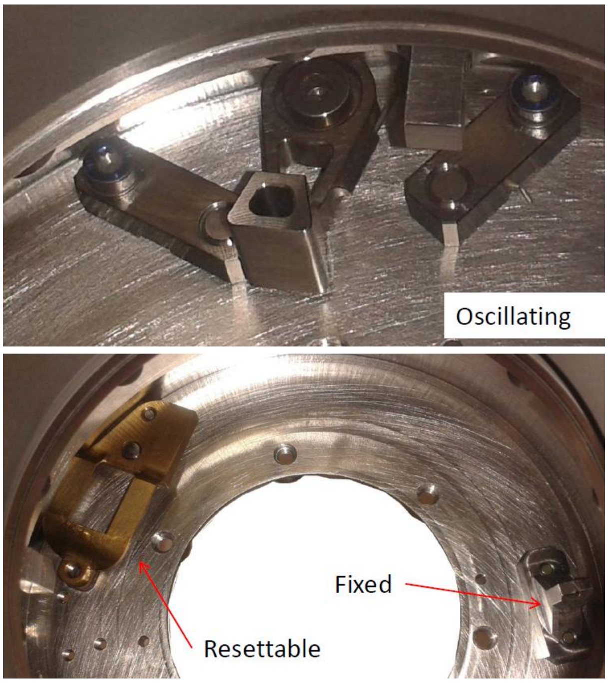

Figure 5 End stops

Oscillating end stops are paddles dangling from a pivoting point up to contact to fixed end stops to which they transfer the contact pressure relieving the pivoting point. The pivoting point is achieved through a Vespel® bushing and a torsion spring that preloads the oscillating element against a stop to avoid hammering in vibrations or in orbit.

2.4. Position sensor

The position feedback is provided by a beryllium Inductosyn transducer which was developed during the Technology development activities led by ESA and Kongsberg with Farrand controls to ensure the materials and processes suitable for high temperature use. The transducer has to operate at temperatures close to 250ºC. The mismatch of beryllium with titanium housing is compensated with radially flexible attachment.

In the APME a new inductosyn pre-amplifier (IPA) was developed to provide two tightly matched voltage amplifier channels to amplify the very low sine and cosine voltage signal from transducer stators. Also an automatic gain control (AGC) was implemented in order to stabilize the amplitude drift of the sine/cosine feedback due to temperature varation. Additionally and automatic phase control (APC) circuit was required to compensate inductosyn phase shift between the excitation and the output signals.

Due to transducer size limitation for the accuracy required the number of patterns are limited to 4 (twice sine and cosine) , so either the sensor is used as absolute without redundancy, or semi-absolute with redundancy, or is used as absolute with cross-strapping of APME.

The reliability suggested to use the transducer as semi-absolute (absolute within 2.8 mechanical degs) and thus for operability it is required a synchronization element and a position search strategy to retrieve the position.

Reed switches are used to provide that synchronization signal and end of travel alarms. Reed switches are used in combination with Sm-Co magnets suitable for high temperatures. Hamlin reed switches were qualified for high temperature through a dedicated campaign.

Initial test on standard PCB showed that they are not compatible with high temperatures. Vespel holders with copper plates were developed to support the switches and connect them to the cables (see Fig 1.).

Another difficulty inherent to the use of inductosyn sensors is the need to have both electric and magnetic shielding. While the electric shielding is based on the shield of the high temperature twisted shield pair cables, the magnetic shielding is achieved through the use of mu-metal alloy. This element provides the impedance to insulate the high frequency signal used.

This double shield and the external braided termination of the mu-metal magnetic shield are difficulties for the development of a twist capsule.

2.5. Twist Capsule (TWC)

There is a long number of electrical connection needs through the twist capsule as the elevation stage has many components and also the azimuth stage has the inductosyn rotor as movable part. Thus up to 96 lines of electrical connections must be routed through the 360º azimuth stage configured as twisted pairs and some of the double shielded pairs as mentioned in paragraph 2.4. Also due to a connected rotor the elevation stage rotor requires an elevation twist capsule.

The high temperatures and hollow design for rotary joint prevents the use of slip rings.

The options were traded off following size and configuration needs [5]. Two major configurations were evaluated:

- Spiral configuration
- Goose neck configuration

Main limitations for spiral configuration are the length required that leads to a high weight and the possibility of blockages. There is not a suitable wrapping material with good flexibility and life in the required temperature range to prevent the friction between moving coils with mu-metal braids and attachments.

Regarding the goose neck configuration, two options were discarded: The use of flexible circuit because of the high temperatures for the adhesives and the flat cable because of the need of development for the shielding. In addition there was already a qualification campaign for high temperature nickel coated copper with high strength toughened fluorpolymer (HSTF) for high radiation dose for twisted shield pairs.

After quite a lot of designs, analysis, and mock-ups, the only suitable architecture found is a goose neck configuration twist capsule constructed with the physical cable and its braids. This is solved by means of a stainless steel support flexible foil with geared slots in its upper and lower end which mesh to rotor and stator teeth profiles. Due to the small volume available the cables are attached to the foil in both sides. Mu-metal braided ones in the internal side and twisted shielded pairs in the external side.

When moving counter-clockwise the foil and attached wires are wrapped in the rotor. When moving clockwise the foil and its attached cables unwrap from the rotor gear and lay along the outer fixed gear. In the later movement is when the geared profile plays a major role helping to push the cable which otherwise would slide with respect to the rotor. The foil stiffness preloads the meshing area to the inner and outer gears at both ends of the bending area.

In a first design metallic tye-raps were used to attach the cables to the cables to the foil. The attachment was tight disregarding the mismatch of lengths between cables and foils as the coil wraps. Even if it found the way to slide, during the azimuth stage gearheadmotor life testing the high friction experienced wrinkled and cut the metallic braid resulting in contamination with debris and final blockage of the mechanism. Also the twisted shielded pairs without mumetal braids showed heavy wear caused by the metallic tye-wraps.

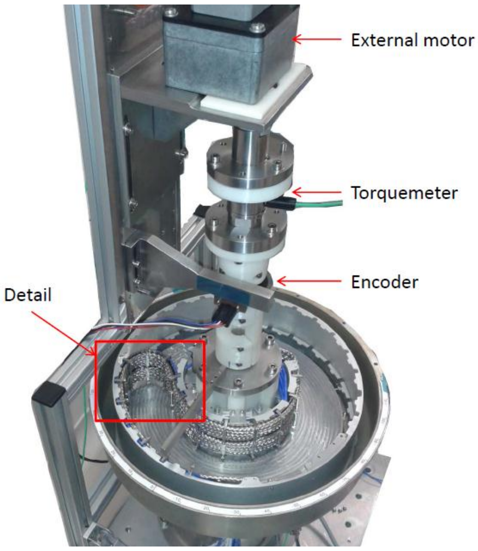

Figure 6 TWC test assembly

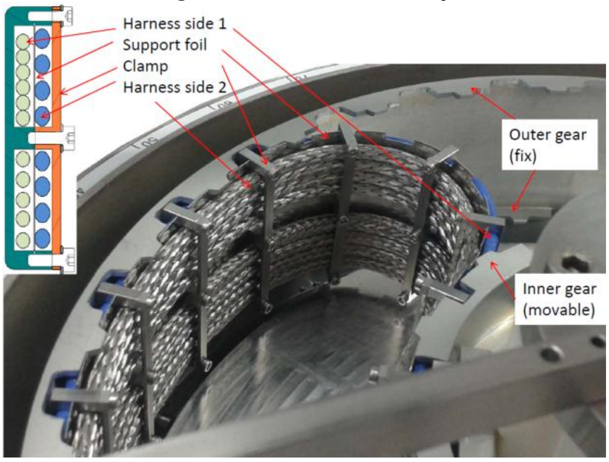

Figure 7 TWC detail

Figure 8 Problems of the first TWC during gearhead motor lifetest

The redesign of the retainers (see Fig 7) and mu-metal braids diameter reduction allowed the relative motion of the mu-metal braid. The design was successfully tested via a dedicated azimuth twist capsule life test were the twist capsule has performed correctly a number of cycles and degrees representative of the factored extended life of the mission (21700 cycles).

2.6. Rotary joint

The mechanism also has to be compatible with a two axis rotary joint in X band for the Medium Gain Antenna, and dual X and Ka band for the High gain antenna. The rotary joints have been developed by Cobham, and both have similar configuration.

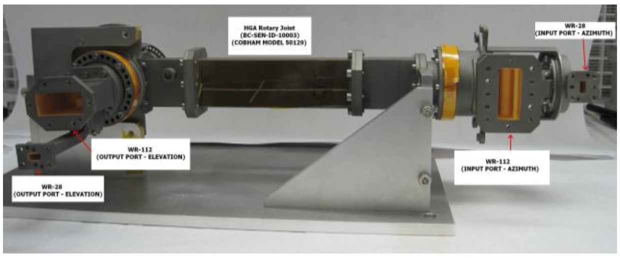

Figure 9 Rotary Joint

The rotary joint achieved the following performances:
- Insertion loss: 0.22 for X band, 0.77 for Ka band
- Return loss: 20.8 dB for X band and 28.85 for Ka band
- WoW: less than 5º (TX & RX) for X band and less than 15º for Ka band

Titanium was selected for thermal compatibility with the mechanism and rest of the radio frequency chain. The poor electrical conduction of titanium requires a plating over this substrate which proved rather difficult to achieve for several companies. A gold plating solution was finally qualified by Epner in collaboration with Cobham for the high temperatures required.

The external parts of the rotary joint are sandblasted in order to improve the emissivity of the titanium. In this way gradients with the mechanism are lower and RF power dissipation of the rotary joint is radiated limiting its internal temperature. It has been tested that emissivity up to 0.45 may be achieved for sandblasted titanium and improving for higher temperatures.

Rotary joint internal motions are ensured as for the mechanism with MoS_2 bearings with PGM cages.

Rotary joints were tested at high temperature (290ºC) for RF parameters stability test and successfully subjected to high temperature multipaction and corona in ESA VSC facilities in Valencia.

2.7. Medium gain antenna and waveguides

The medium gain antenna and waveguides are designed and manufactured by Rymsa. The solution is a Titanium horn antenna with septum polarizer with externally sandblasted and internally silver plated titanium waveguides along the boom qualified up to 350ºC. The configuration ensures that radiation pattern pointing and performances are not affected by temperature. Radiation pattern was tested in temperature by means of a dedicated furnace enclosure with radiation transparent windows and inert gas overpressure developed by SENER.

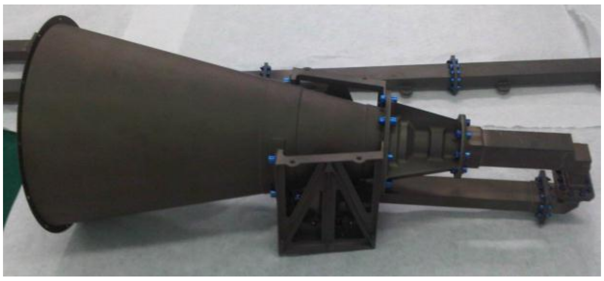

Figure 10 MGA Horn Antenna and waveguides

The medium gain antenna system (rotary joint, boom and external waveguides, septum and horn) the total gain in downlink frequency is 22.26dB as mean of the different RJ positions. Return losses better than 19dB:

2.8. Medium gain antenna structure and release

The boom for the medium gain antenna is composed of thin titanium plates creating a square beam with internal support for waveguides. The boom is covered with high temperature MLI in order to avoid thermal bending of the boom when illuminated in one side.

The boom is retained with two holddown areas with preloaded three sphere contacts. The holddown uses a NEA non explosive device to release the system which guarantees low shock emission. Once released a spring catcher retracts the titanium preloaded rod against damping belleville washers, to avoid entrapments and to close the aperture of the preload area.

Structural behaviour and release shock were measured in the structural model of the MGA main assembly.

Figure 11 MGAMA STM Model in vibration test

2.9. Thermal insulation

The thermal insulation of the APM is a high temperature MLI developed by RUAG Space Austria, based on a thermal shield of Nextel® fabric with titanium and aluminium internal layers, in some cases or areas with VDA Polyimide internal layers. The thermal insulation is attached to the mechanism with titanium stand offs or with Inconel wires at dedicated MLI fixation labyrinths.

The MGA APM and short boom were tested in solar simulation with the rest of MPO. As an outcome of the test, excess of heat flux to the spacecraft was detected. Measures were taken to reduce MLI efficiency, but the most important outcome was the need to reduce the heat leak through gaps and attachment labyrinth retainers.

Figure 12 MGAMA Thermal model with short boom

In the labyrinths between degrees of freedom external retainers are now hidden and gaps reduced. Analytical temperatures and flux figures of the detailed gaps models will be evaluated with the solar simulation test to be done at high gain antenna assembly level and with MPO flight model.

3. DEVELOPMENT OF THE GEARHEAD MOTOR FOR LIFE REQUIREMENTS

The gearhead motor continued the developments done in the TDA conducted by Kongsberg, ESTL and CDA. The gearhead motor is a compact permanent magnet stepper coupled to a planetary reducer. Planetary stage carriers are supported bearings and planets through sliding pins.

The current life requirements to be achieved with factors applied are

	ENVELOPE NUMBER OF CYCLES		
'	Cycles	APM Deg	Motor Mill rev
Ambient+Cold	8021	2887488	9.625
Hot	13705	2741040	9.137
	21726	**5628528**	**18.762**

It was a difficult path to achieve a gearhead motor as the problematic areas found during inspection of the failed unit generally masked other incipient problems or didn't allow their appearance at all. Therefore the problematic areas showed one after the other during sequential tests in subsequent or refurbished units. Finally all the problems were solved as the solutions agreed showed correct. Some of the issues found and solved during the technology development phase were the following:

- The use of glue to bond the external sleeve covering the magnets to the magnets was unstable in high temperatures, even if the bonding properties were correct. That instability resulted in bumps and bubbles that distorted the external surface and closed the air gap to the stator and blocked one of the life units. Gluing of the sleeve of the rotor magnets was substituted by a hot mounting sleeve for shrink fit into the magnets. Post curing inspection of the rotors showed a good run out.

- Curing of the high temperature glue in oven resulted on contamination of the MoS2 which oxidized with the presence of oxygen and depleted early in the life of a gearhead motor. The problem was solved by creating the curing of the MoS2 in moderate vacuum. Further investigation [4] on the sensitivity of MoS2 on temperature in air, showed that for temperatures under 200ºC there was no major problem, but those were exceeded. To obtain the maximum end of life value of MoS2 coating it is decided to cure adhesive in high vacuum.

- The cantilever configuration of the gearhead output pinion transforms torsional load in the meshing teeth in bending torque to the gearhead output bearings. For the dry lubrication and the small clearance in the output stage gears the value of output torque has to remain relatively low. An overload during functional test resulted in early failure during life testing. As a result it was decided to reinforce and separate the bearing and reduce the allowable torque.

During the phase C/D the first life test unit was tested at APM actuator level at CSL (Centre Spatial de Liege), it increased its friction after 7 million motor revolutions in ambient and 2.8 million in cold. While the factored mission scope back at that time required 29 million motor revolutions. The unit was subjected to several inspections: Direct friction measurement at motor shaft and threshold current testing in order to find friction patterns. It was inspected by tomography to find mechanical problems that could be masked during disassembly. Then the unit was disassembled stage by stage at CDA and parts coatings inspected at ESTL.

Friction patterns measurement, stages check and microscope/ spectrography (SEM/EDAX) pointed out that the most severe wear occurred in the pin sliding contact to planet and carrier area. There was general dry lubrication depletion of gear teeth in some areas with substrate reduction, but this did not cause a lack of functionality or general raise of the friction apart from friction pattern areas. Status of bearings of both motor and planetary stages was satisfactory. Ambient testing was not able to screen some small clearance closure caused by differential CTE in cold cases. Cold basic functional testing of qualification unit at CDA showed correct performance. Even if tolerances allowed that cooling thermal excursion, contact stress may raise and/or wear rate of MoS2 may become accelerated as clearance is reduced in cold conditions. Along with other measures it was decided to avoid cold temperatures by using heating during cold situations.

In order to confirm the susceptibility to cold temperatures one of the gearhead motor units intended for the qualification model of the APM was subjected to ambient life testing. It resulted in 17 million motor revolutions before general friction raise. Inspection showed general increase of wear without a single cause or without the possibility of differencing initial cause and resulting damages. The figures of life were assessed valid for the mission upon certain cruise link guidelines changes. But it was required assessment that the obtained results were stable. Moreover still high temperature performance was not demonstrated.

Upon these test results, some improvements for following units were decided with CDA to help ensure the flight and new qualification unit maintain the achieved values: Inter-layer coatings used between gears and MoS2 such as Balinit® were removed as dedicated pin on disk tests showed no improvement by these in vacuum and spectrograph of units inspected by ESTL did not show these area was in contact in the gears, being either covered or deleted, and thus not functional.

Smoothing of the carrier to pin surfaces to allow secondary/redundant sliding for failure cases was also applied to the baseline design of the gearheads.

The other qualification gearhead motor of the APM was then tested to life focusing first in high temperatures and with subsequent ambient lifetest. The APM stage was tested in CSL were a special chamber may rise to high temperature in the items with capacity of quick shroud cooling down. The unit achieved all the required lifetest cycles in hot temperature. It had a blockage problem of the twist capsule at the beginning of the test that was quickly solved latter forwarded to redesign. The ambient temperature part of the test was interrupted by the failure of the twist capsule that led to a redesign of it. After reprise of the test it completed all the required ambient cycles, thus providing viability of the gearhead baseline design for the mission scope.

Thus ambient and hot/ambient achieved the required endurance. Life will be further proof in the qualification unit of MGA EQM with the back fed design.

4. MICROVIBRATION, STABILITY AND CONTROL

Other key aspect of the APM is that it requires high stability and pointing accuracy. The exported vibration to the spacecraft should be limited as well as the pointing error variation.

The mechanical system has several elements with nonlinear behaviour such as hysteretical-spring behaviour of the twist capsule, backlash, and variable inertia in azimuth stage depending on elevation position.

All these elements along with controller, driver, current control microstepping, motor, planetary gearhead, were modelled in a Simulink with good correlation with the behaviour observed. The model is used for the optimization of the control and the derivation of phase and gain margins for stability.

The APME electronics and control developed by SENER tries to minimize those by closed loop control, a control architecture was developed in collaboration with Astrium Friedrichafen.

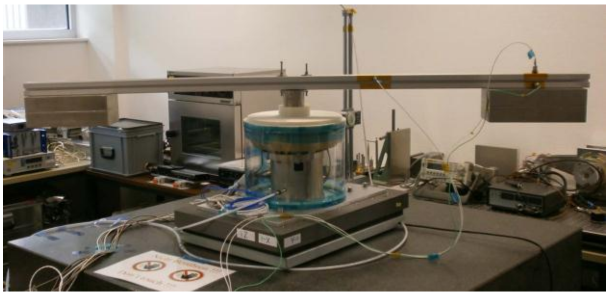

Figure 13 Microvibration test on kistler table at Astrium

Three different microvibration test have been performed for design improvement of the controller and feedback.
The first without control looped provided information about the dynamic of the system for design decision. The other two were performed with different set-ups at SENER and Astrium Friedrichafen with the proposed control loop and different parameters. Due to the MoS2 dry lubrication they were performed in controlled environment purge boxes.

Through closed control loop is stable and corrects the error, the outcome was that due to the flexibility of the movable inertia the position sensor does not follow correctly the reflector load and thus some perturbation sources cannot be controlled and error variation cannot be reduced to the scope values.

The accuracy of the system is validated in two degree of freedom to detect cross coupling between stages, that is achieved by laser tracker set-up over a instrumented lever arm steered in two degrees of freedom. This set-up will be used also in thermal test at high temperatures with several modifications and limitations.

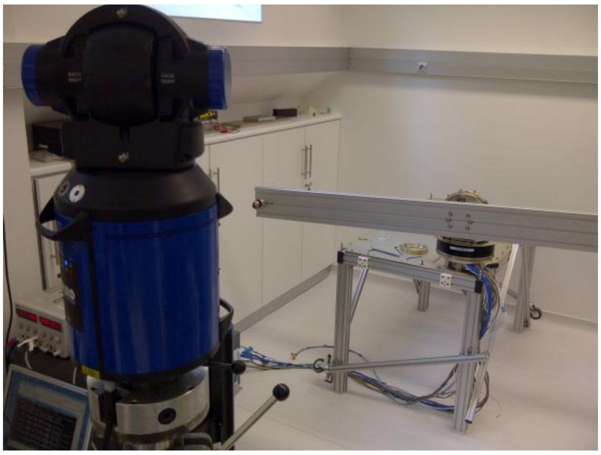

Figure 14 Laser tracker APM accuracy measurement

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