ELECTRIC PROPULSION POINTING MECHANISM FOR BEPI COLOMBO

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ABSTRACT

Since 17 years the development of Electric Propulsion Pointing Mechanisms for commercial and scientific satellite applications is a key-product activity for RUAG Space in Vienna.

As one of the most innovative EP mechanisms presently under development in Vienna this paper presents the Electric Propulsion Mechanism for the ESA Bepi Colombo Mission.

RUAG Space delivers the mechanism assembly, consisting of the mechanisms and the control electronics.

The design-driving requirements are:

- the pointing capability around the stowed configuration under resitive torque coming from the thruster supply harness, the thruster supply piping, and the mechanism harness. The pointing capability around the stowed configuration is realized via a central release nut together with a spring loaded knuckle-lever system which in essence forms a “frangible pipe” that is stiff during launch and collapses upon release. The resistive torques are minimized by a helical arrangement of the supply pipes and of the mechanism harness, and a guided low stiffness routing of the thruster supply harness. A high detent torque actuator is used to maintain pointing direction in un-powered condition. Also the direct measurement of the torque on the actuator shaft during random vibration is presented in the paper.

- the specified maximum input loads to the thruster. The mechanism has not only to point the thruster, but also to protect it against high launch loads. A very low Eigen-frequency of the mechanism/thruster sub-assembly of around 65 Hz was selected to minimize coupling with the thruster’s modes and so to minimize load input to the thruster. An elastomer damping system is implemented which minimizes amplification in this frequency area so that the sine input can be sustained by the mechanism and the thruster. The measured amplification of 3.1 turned out to successfully protect the thruster from the launch vibrations.

- the thermal load on the mechanism from the dissipation of the thruster and from the solar radiation.

A staged temperature zone concept was selected, separating different temperature zones, and keeping the thermally sensitive elements in their operating temperature ranges.

This paper outlines the design solution for these design driving requirements, presents the test results, and compares the results of the predictions with the tested values of the qualification tests. It also points out the lessons learnt during this development process.

1. GENERAL SPECIFICATIONS

The BepiColombo Mercury Transfer Module will be equipped with four Electric Propulsion Thrusters. For each of these thrusters one Thruster Pointing Mechanism (TPM) is foreseen.

The following figure presents 4 TPMs still mounted on their integration adapters arranged in a flight like configuration:

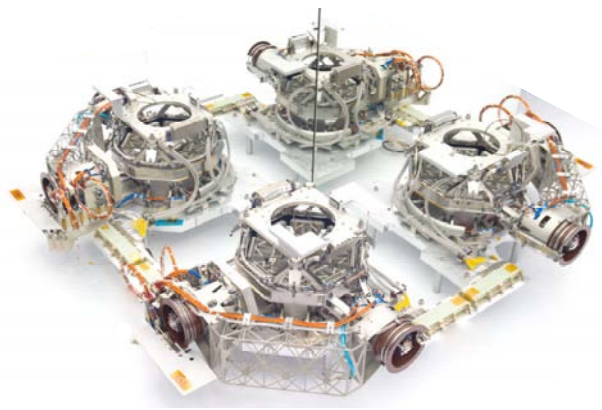

Figure 1. 4 TPMs in flight like configuration.

Each mechanism shall support one QinetiQ T6 thruster during launch and protect it against launch and separation loads via a load attenuation system. Once released it shall point the thruster accurately and provide support for the high voltage power supply and the Xenon gas supply of the thruster.

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Main parameters of the mechanism:

Pointing Range - Axis 1	-16.5° / +8°
Pointing Range - Axis 2	+16.5° / -8°
Pointing accuracy	better than 0.2°
Resistive torque	5.6 Nm (thruster harness and piping)
Supported Mass	10 kg (Thruster, Harness, Sun-shield)
Thruster CoG Height	130 mm
Mechanism Mass	11.0 kg (w/o Sun-shield)
Main Dimensions (LxWxH):	660 x 660 x 223 mm
Stiffness	65 Hz (stowed configuration, lateral) 7 Hz (deployed configuration)
Temperature	-40°C to +100°C for TPM components
Drive Unit	2 Stepper motors Power supply 26V
Release of HDRM	Non-explosive resetable device (1x, central)
Mechanical I/F to S/C	8+1 bolts M5
Life time	7 years storage, 6.6 years in orbit

The configuration of the mechanism is a cross cardan type, with its rotation axes intersecting in the thruster center line.

The design-driving requirements are:

- Minimized dynamic load and shock load introduction into the thruster, induced by launch loads, separation loads, and thruster release,
- Pointing capability in both directions around the stowed configuration. The stowed configuration is required to be between the two extremes of the pointing range, and
- Very high reliability,
- Minimized mechanism mass,
- Low micro-vibration load input into the thruster during pointing.

2. POINTING DRIVE

High resitive torque is coming from the thruster supply harness, the thruster supply piping, and the mechanism harness. The actuator must provide a motorisation of these resistive torques respecting ECSS torque margin requirements for pointing. The thrusters supply harness, the thrusters supply piping, and the mechanism harness also cause a spring torque on the pointing drive. This spring torque must be sustained by the actuator in its un-powered condition to maintain the pointing direction.

The assembly of the 4 pointing mechanisms consists of eight pointing drives, so a mass efficient solution is requested there. To attain such a mass efficient solution a high detent torque actuator having low mass was developed in the frame of this project. Also a routing design with minimum resistive torque was developed for the thruster supply harness and for the thruster supply piping.

2.1. High Detent Torque Actuator (GA15)

The actuator is based on a high detent torque permanent stepper motor, supplied by CDA, Intercorp. (US). This motor was selected for the excellent torque/mass ratio, and for the “clean detent torque” feature, meaning that the motor has high detent torque positions on any full step position and on any half step position. So the motor drive electronic can command the motor to any half step or full step angle, and the actuator maintains its pointing direction once un-powered. When the actuator is powered again for the next pointing operation, it is still on the same step position as the last commanded position of the previous pointing command. This allows a reliable open loop control of the actuator despite un-powering the actuator in steady-state phases of the actuator.

The high detent torque motor drives a harmonic drive as output stage by means of an intermediate gear. This intermediate gear allows the selection of a lower torque stepper motor because the harmonic drive is not driven directly but the intermediate gear acts as a torque multiplier, which in turn allows the selection of a very low mass stepper motor. Even taking into account the additional mass of the intermediate gear, this concept saves considerable mass. The selection of the gear ratio of this intermediate gear also allows the adjustment of the stepping angle of the actuator to the mechanism’s needs and allows a high resolution of 0.001°.

The housing and the shaft of the actuator are made of Titanium Alloy for mass saving reasons.

The customer required that the thrusters’ pointing electronics can deliver an absolute angular position information for each actuator. The selected design concept consists of a high precision reference switch with sign indicator in coarse/fine arrangement on the actuator and a step indicator on the motor shaft. After powering the electronics, the actuator is commanded to its reference position. The drive direction to the reference position is determined from the sign output of the reference switches. Once the reference position is reached, the electronics continuously counts the steps that are indicated by the step indicator on the motor shaft. So the electronics can deliver an absolute angular position information for each actuator at any time after referencing.

The reference switches and the step indicators are an arrangement of identical hall sensors stimulated by a shaped permanent magnetic field on the rotating parts of the actuator. Each sensor has a nominal and a redundant electrical sensor element. The sensor elements are adjustable to allow fine tuning of the switch points after integration. This hall sensor arrangement is free of friction and magnetic hysteresis torque, and it has unlimited life as is not prone to wear. Compared to standard solutions, it is also more mass efficient.

The described mass saving concepts allowed an actuator mass as low as 1.2 kg for an actuator with more than 15 Nm factored output torque fully respecting the ECSS motorisation rules and applying the worst case temperature environment. The actuator's maximum output torque, which is sizing the end-stops amounts to 88 Nm.

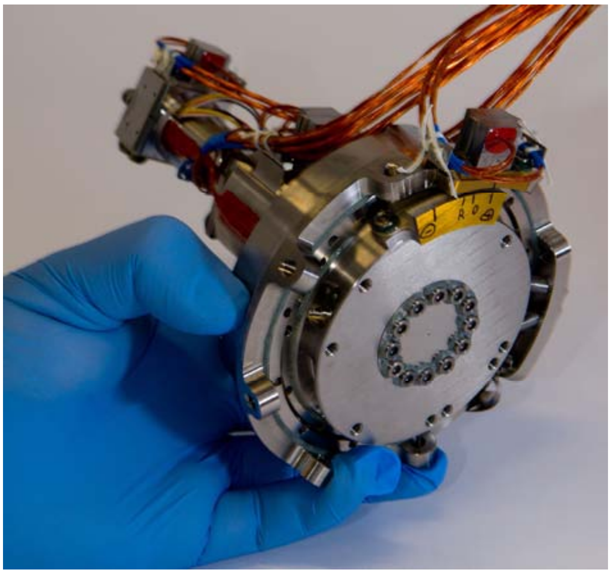

Figure 2. Geared Actuator.

All elements of the actuator, which contribute to the resistive torques, were characterised to determine their friction torque at the lower and the upper qualification temperatures, and to determine the end-of-life friction of the harmonic drive at temperature extremes a life test with continuous efficiency measurement was performed on gear level.

The high step resolution of the actuator allows operation of the pointing drive with a high step frequency of 200 Hz. Together with the low stiffness in deployed configuration this results in a micro-vibration level induced into the thrusters below the specified value for the thrusters.

2.2. Harness and Piping

The thruster supply harness, the thruster supply piping, and the mechanism harness are the contributors to the resistive torque for the pointing drive.

The thrusters supply harness consists of cables, that are needed for the operation of the Qinetiq T6 ion thruster. As the center point for pointing of the mechanism is in the central axis of the mechanism, it is possible to route the cable bundle on the lateral side of the mechanism directly from the spacecraft floor up to the thruster. It is guided in place on one side by the mechanism's elements, and on the other side by the elements of the sun-shield. This concept allows a large bending radius of the cable bundle, which leads to a low resistive torque for the thrusters supply harness.

The thruster supply piping coming from the spacecraft floor, is routed across the first actuator, then along the pointing arm, and then across the second actuator to the thruster. The routing across the actuators is done in a helical manner, whereas the helix is concentrically to the actuator axis. Elements of Vespel SP-3 provide guidance of the pipes during vibration and shock loads. During pointing operation of the mechanism the pipes do not touch these snubber elements and therefore do not create friction. This routing also allows a launch configuration in an intermediate position of the travelling range of the actuator. Analysis of the resistive torque of the pipe can be done by simple hand-calculation. The concept is scalable to larger pointing angles by increasing the number of turns of the helix. A patent is filed for this pipe routing.

The mechanism harness is also routed across the first actuator, the pointing arm and then the second actuator. To minimize the resistive torque, a free harness loop was added to surpass the first actuator with low resistive torque. As most of these cables terminate before passing the second actuator the few remaining cables were routed directly across the second actuator to the mobile plate.

The resistive torques of all these contributors were measured at the lower and the upper qualification temperatures to verify the motorisation margin of the actuator. A dedicated breadboard model was designed for these measurements. The geometry, the pipe and cable material, and the interfacing materials of the routing were representative of the final mechanism design. The pointing axes were equipped with torque transducers to allow direct measurement of the contributors. After a vibration test this breadboard model was exposed to a TV life test to measure the temperature dependability of the resistive torque as well as its evolution over the life of the mechanism.

The following figure shows 2 example results of the hysteresis curves of the resistive torques:

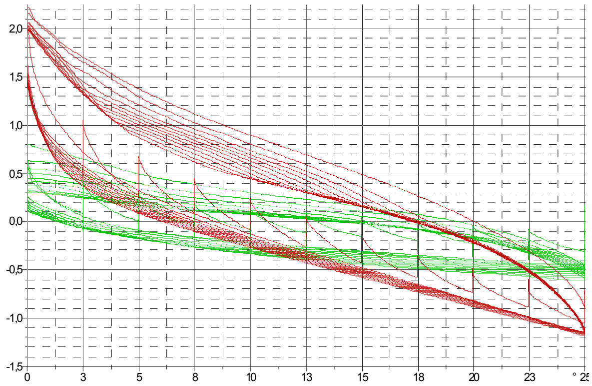

Figure 4. Measured Resistive Torque Examples.

It shows that there is not only a spring type resistive torque but also a significant hysteresis contributor. It showed that the hysteresis is mainly coming from the harness, confirming the pipe routing concept.

For the thermal insulation a contact-less concept was selected, so there is no source of resistive torque from the thermal hardware.

2.3. Dynamic Loads on the Actuator

The hold down and release mechanism of the mechanism connects the mobile plate with the spacecraft floor during launch. The utilized "frangible pipe" design is described in [5]. The pointing arm which is placed between the actuators is not equipped with a dedicated hold-down. So this pointing arm introduces torques into the actuators when exposed to launch vibrations. To verify these torques not only an analysis was performed, but a direct measurement was performed. A dummy actuator with representative stiffness and envelope was designed. Instead of a harmonic drive gear, this dummy actuator comprises a shear plate which is equipped with strain gauges so that this dummy actuator can act as a torque transducer during the vibration tests.

The following figure shows the main parts of this dummy actuator, including the shear disc used for stiffness representation as well as for torque measurement.

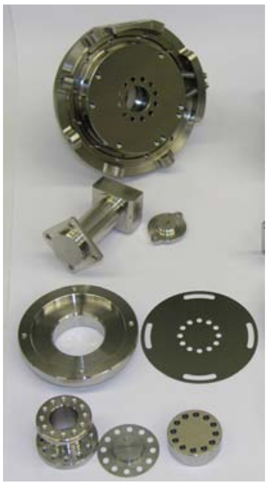

Figure 5. Torque Transducing Dummy Actuator Parts.

The dummy actuator was mounted in the thrusters pointing mechanism STM during vibration and shock testing. The predicted loads on the actuators were confirmed by this test.

3. VIBRATION AND SHOCK

It is specified that the thruster shall not be exposed to considerable lateral random loads in frequency regions above 100 Hz. To de-couple the dynamic mechanical environment of the thruster from the dynamic load input coming from the spacecraft, the mechanism is designed to a first fundamental Eigenfrequency of 65 Hz in lateral direction. The spacecraft panel itself is quite stiff in lateral direction, so the dynamic load from the spacecraft is directly transmitted into the mechanism. Then within the mechanism there occurs the desired load attenuation in the thruster's critical frequency range. By "tuning" the mechanism to this low Eigenfrequency, the thruster is protected from the dynamic lateral load environment coming from the spacecraft in the higher frequency range.

However there is also an unwanted amplification in the lower frequency band. The selected low first fundamental frequency would lead to an unacceptable high amplification during sine load application and lead to unacceptable high thruster loads at these frequencies, even if the thruster is more robust in this frequency band. So a damping system is needed. The damping system is made of elastomer dampers which are placed in the load-path of the mechanism in its stowed configuration. The attenuation system is described in more detail in [5].

3.1. Attenuation System Test Results

Following a risk reduction approach, and allowing early design iterations, the attenuation system was tested in a stepped approach. At begin of the project a breadboard model of the HDRM was produced to allow early testing.

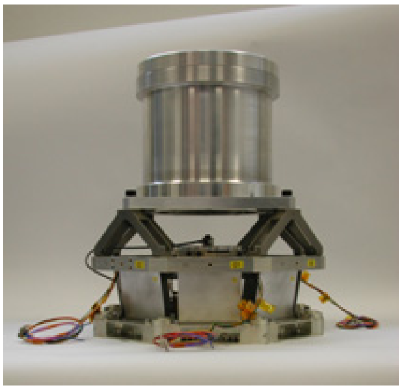

Figure 5. HDRM breadboard for early testing.

Based on the results the STM model was designed. This STM already fully reflects the QM in terms of the HDRM design, and the pointing arm design. The STM model was also equipped with the torque transducing actuator dummy, as described above to allow measurement of the dynamic loading of the actuator during vibration and shock testing. The pre-loading elements of the STM were equipped with strain gauges. Before, during and after shock and vibration testing the actual pre-load of the pre-loading elements was recorded. Also the accelerations on the thruster interface were recorded. The loads were in the predicted ranges and no setting effects could be detected.

The QM testing finally confirmed the design of the attenution system resulting in a measured amplification of 3.1 of the mechanism assembly and thus successfully protecting the thruster from the launch vibrations.

4. THERMAL DESIGN

The dissipated heat of the thrusters that is transferred into the spacecraft shall be minimized. This is realized by a concept of separated temperature zones of the mechanism, as shown in the following figure:

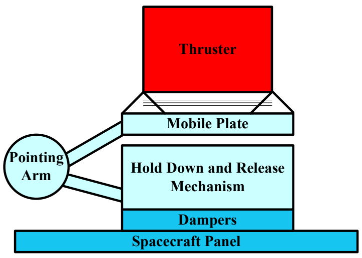

Figure 6. Temperature zone concept.

To minimize the conducted heat from the thrusters into the mechanism, the thruster is placed on kinematic mounts of Titanium Alloy, having a high ratio of length to cross section area. These kinematic mounts also allow for thermal expansion of the different elements. To minimize the radiated heat, multilayer insulation is placed in a gap between the thrusters and the mobile plate.

To allow radiation of the heat to deep space a radiator is attached to the thrusters, which also acts a sun-shield in case of sun illumination during the transfer to Mercury. This sun-shield also comprises a stationary part which is mounted on the base structure of the mechanism, only leaving a small gap between the two parts. Both have spherical geometry, and the over-lapping length is sufficient to prevent direct sun illumination into the engine bay. As there is no mechanical contact between the movable and the stationary sun-shield elements, no resistive torque is introduced to the pointing drive. On the ring shaped part of the stationary sun-shield element the multilayer-insulation of the spacecraft is attached.

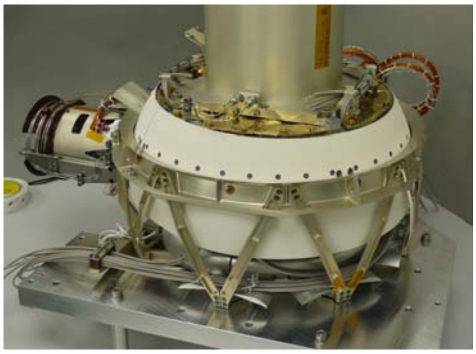

Figure 7. Sun-shield and top MLI.

The conducted heat of the pointing arm is very limited due to it length and cross section. To reduce the temperature of the mobile plate it is black coated on the bottom side to control its temperature. This coating provides good heat radiation to the engine bay.

Dissipated heat of the motors is transferred to the engine bay by radiation. The motor temperature is kept in a temperature range that allows grease lubrication of the motor with a PFPE grease. It was confirmed by the component level and the assembly level tests that the motorisation is fully compliant to the ECSS motorisation requirements over the full temperature range despite the increase of the friction torque of the actuator bearings and gears caused by the stiffness increase of the grease at low temperature, and the stiffness increase of the harness.

During the thermal test of the QM, different temperature gradient load cases were applied, confirming the thermal design of the mechanism.

5. SUMMARY AND CONCLUSION

The BepiColombo Electric Propulsion Thruster Pointing Assembly consists of 4 identical thruster pointing mechanisms and the drive electronics. Each mechanism supports an Electric Propulsion Thruster (QinetiQ T6) in stowed configuration during launch, by means of a dedicated Hold-Down and Release Mechanism (HDRM). Upon its release, the Pointing Mechanism Platform can be tilted around two perpendicular axes. This motion is facilitated by two geared rotary actuators.

Figure 8. Thruster Pointing Mechanism (TPM) with Thruster Mass Dummy and Sun-Shield attached.

A low mass, high detent torque actuator was developed for the pointing drives, and a low resistive torque routing of the hruster supply harness, the thruster supply piping, and the mechanism harness was designed.

An attenutation system was developed to protect the thrusters from the launch loads. The qualification tests confirmed the proper function of the mechanisms.

6. REFERENCES

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7. REMARK & ACKNOWLEDGEMENT

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