THE DEVELOPMENT OF A MULTI-PURPOSE THRUSTER ORIENTATION MECHANISM

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ABSTRACT

One of the issues with the use of Electric Propulsion (EP) for satellites is that the satellite manufacturer has to integrate the EP Propulsion system and the Pointing Mechanism from different suppliers so the resulting Thruster Unit is not optimised for performance. RUAG Space has recognised this situation and has been working with EDB FAKEL, one of the leading suppliers of EP Propulsion systems, to develop an Integrated Thruster Module (ITM) that can utilise a range of EP Thruster combinations using a basic structure that provides the thrust vector pointing, shock isolation and the thermal control of the EP subassembly assembly on one integrated unit which can be easily built into a satellite.

RUAG Space has developed a Thruster Pointing Assembly (TPA) that can currently support one SPT140 Thruster or two SPT100 Thruster modules. The TPA is based on a common lower structure with a tailored upper thruster support structure.

During the development, breadboard tests were undertaken to mitigate many of the risks that were identified.

Following the breadboard testing, the design of the TPA was updated and a QM model built for two versions of the mechanism to support two SPT100 and one SPT140 Thrusters from EDB FAKEL.

The two QM models were based on a common lower structure but differed at the level of the Thruster mounting, and with the support of the EP subsystem. To achieve this, it was necessary to make compromises during the design process which also had a significant impact on the final design of both mechanisms.

The QM TPA models have both been subjected to a classical qualification campaign which will include a life test on the complete system.

This paper will describe the impact that testing two mechanisms using a common basic structure has on the design and the compromises that have to be made. In addition, an overview of the breadboard testing undertaken to mitigate the risks will be described and the results briefly discussed.

Finally, it will be shown in this paper how it is possible to qualify different versions of a mechanism using a common structure with add-on equipment to complete each of the mechanism versions. The impact that this approach has on the test programme will also be presented.

1. INTRODUCTION

In 2002, the SMART-1 spacecraft flew with a PPS 1359 Plasma Thruster developed by Snecma Moteurs in France [1]. The Thruster was successfully steered by a mechanism developed by RUAG Space [2].
Following this development, RUAG realised that the technology could be used on applications with other single and multiple Thruster applications and could utilise the flexibility of the design to provide larger thrust pointing angles.

One of the main issues with the use of Electric Propulsion (EP) for satellites is that the design of the EP system is not optimised with the Pointing Mechanism and the EP System being developed independently by different suppliers.
Both RUAG Space as a supplier of Thruster Orientation Mechanisms (TOM) and EDB FAKEL from Russia recognised this deficiency during a collaboration on a future space platform. One of the outcomes from this collaboration was to jointly develop an Integrated Thruster Module (ITM) which provides an optimised EP and Pointing Mechanism solution to customers.

EDB FAKEL is one of the leading suppliers of EP Subsystems worldwide and have various EP Thrusters available for satellite propulsion. To meet market needs, it was decided to develop an Integrated Thruster Module (ITM) that could utilise a range of EP Thruster combinations using a basic structure to provide the thrust vector pointing, shock isolation and the thermal control of the EP subassembly on one integrated unit which can be easily built into a satellite.

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The current development for the Thruster Pointing Assembly (TPA) can support either one SPT140 Thruster or two SPT100 Thruster modules. The TPA is based on a common lower structure with a tailored upper thruster support structure.

In order to qualify the ITM with both sets of thruster types, a Qualification Model (QM) mechanism was built for both mechanisms utilizing the same lower structure. This required careful consideration during the design process and compromises had to be made that impacted the final design of both mechanisms. These compromises are discussed further within this paper.

As the TPA unit has to support significant environmental loads as well as function over a large pointing range, extensive breadboard testing was undertaken to mitigate many of the risks that were identified. These Breadboards which are discussed within this paper, were established; for the Shock Damper where the design was optimised using several iteration loops; for the Harness, where the temperature effects and angular deflection were characterised against torque; and for the Xenon Tubing where a full scale angular deflection life test was carried out to characterise the effects of temperature and angular deflection on torque on both titanium and steel tubes.

2. CRITICAL FUNCTIONS FOR THE POINTING MECHANISM

The purpose of the TPA is to support the EP Subsystem consisting of the Thruster and Xenon Flow Controller (XFC) and to be able to rotate the Thrust Vector about the S/C Z axis by -35°/+15° in elevation and ±15° in Azimuth.
This is achieved by rotating the upper structure with respect to the lower structure using two CSA10 actuators produced by RUAG Space.
The TPA mechanism has to allow for the transition of the Xenon Tubes and EP Electrical Harness from the moving part to the stationary structure.
As both the SPT100 and SPT140 Thrusters contain critical parts that are susceptible to both Shock and Vibration loads, a further function of the TPA is to limit the exposure of the Thrusters to these loads.
The performance of the EP System is compromised when the temperature of the XFC exceeds 40°C so unlike the SMART-1 EPMEC which was enclosed within the cone of the spacecraft, the ITM will be fully exposed to the extremes of the space environment and therefore has to be protected.

3. COMPARISON BETWEEN THE TWO THRUSTER TYPES

3.1. Overview of two subsystems

Depending on the mission to be flown, the ITM will utilise either two SPT100 or one SPT140 Thrusters.

An overview of the differences between the Thrusters is provided on *Table 1*.

Parameter	SPT100	SPT140
Thrust (mN)	< 90	< 300
Consumed Power (W)	1350	4500
Total Power Dissipation (W)	320	930
Power Dissipation to Space (W)	285	905
Power Dissipation to S/C (W)	45	25
Temperature at Thruster I/F (°C)	200	340
Mass (kg)	3.5	7.5
No. of Xenon Tubes transferred	3	3
No. of Wires transferred (per EP Thruster)	<u>2 Harnesses</u> 2 x 9 wires (Cathode) 1 x 7 wires (Anode)	<u>2 Harnesses</u> 2 x 5 wires (Cathode) 1 x 4 wires (Anode)
No.of Wires transferred (1 x internal harness)	<u>1 Harness</u> 30 wires (Heater & PT100) 18 wires (motor, pot, PT100)	<u>1 Harness</u> 22 wires (Heater & PT100) 18 wires (motor, pot, PT100)
No. of XFC's per thruster	1	1

Table 1: Comparison between the SPT100 and SPT140 Thrusters (per Thruster)

The main differences between the two thruster configurations that influence the design are:

- The number of XFCs that are needed
- The no. of Xenon Tubes transferred across the mechanism
- The no. of wires from the EPS transferred across the mechanism
- The temperature at the Thruster I/F with the mechanism

The thruster mass for the two configurations is similar.

3.2. EP Subsystem for SPT100

An overview of the SPT100 EP subsystem that has to be supported by the TPA is shown on *Figure 1*. The subsystem utilised for the Qualification Model consists of several dummies.

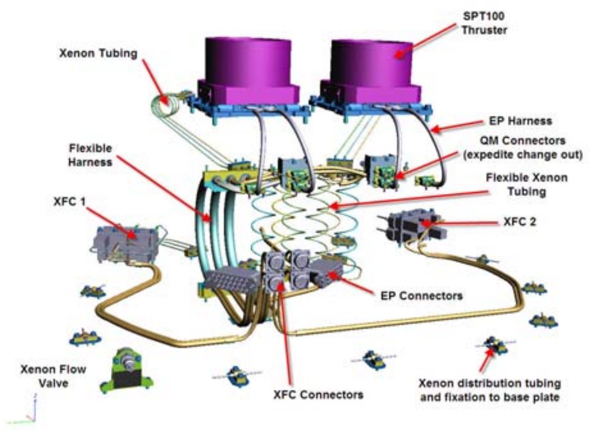

Figure 1: EP Subsystem for SPT100

3.3. EP Subsystem for SPT140

An overview of the SPT140 EP subsystem that has to be supported by the TPA is shown on *Figure 2*. As with the SPT100 subsystem, the SPT140 utilised for the Qualification Model also consists of several dummies.

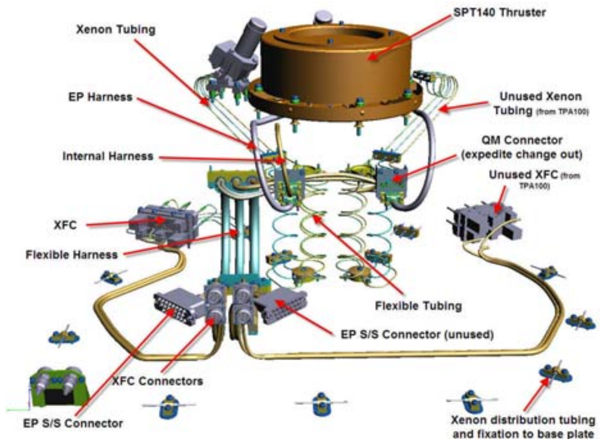

Figure 2: EP Subsystem for SPT140

4. BRIEF DESCRIPTION OF THE TWO DESIGNS

4.1. General Introduction to the design philosophy

The development of the Multipurpose TOM was undertaken to provide support and steering possibilities for the two thruster configurations.

Clearly, two separate mechanisms could be produced which are optimised to the requirements of both thruster configurations but this makes the development process both lengthy and costly.

Since many of the requirements for the two thruster configurations are similar and the differences do not have a major impact on the design it has been possible to produce common lower structure that can be used to qualify both mechanisms, and to have an exchangeable upper structure which supports the two thruster configurations.

4.2. Design considerations for the Common Structure

Since the SPT100 and SPT140 subsystems use common interfaces with the exception of the thrusters, it has been possible to utilise a common lower structure with an exchangeable upper structure in the design of the TPA.

The main difference in the two TPA designs is that the TPA100 accommodates two SPT100 Thrusters and the TPA140 accommodates only one SPT140 Thruster.

To ensure that the change out between the two mechanisms can be undertaken quickly, several elements of the SPT100 subsystem are retained even though they are not used in the SPT140 subsystem.

The final EP subsystem configuration that was implemented on the QM is shown on *Table 2*.

The additional Xenon tubes and EP Harness have an influence on the stiffness and resistance torque of the mechanism and covers a worse case solution in terms of mechanical and electrical performance. During testing, this configuration will be life tested which represents the worst case situation.

Since the EP sub system, with the exception of the thruster itself, use common interfaces, the impact on the design of the TPA100 and TPA140 is minimal.

Parameter	2xSPT100	SPT140	Final QM Design
Xenon Tubing	2 x 3	1 x 3	2 x 3
No. of XFC	2	1	2
Flexible Harness 1	2 x 9 Wires	2 x 5 Wires	2 x 9 Wires
Flexible Harness 2	1 x 7 Wires	1 x 4 Wires	1 x 7 Wires
Flexible Harness 3	48 wires	40 wires	48 wires

Table 2: EP Subsystem- Final QM Implementation

The additional XFC contributes to the loads on the base plate but does not have a significant influence on the main Eigen-frequencies of the mechanism.

Since a quick change between the two mechanisms is demanded, it has been necessary to implement an additional set of connectors on the thruster plate to allow for the quick decoupling of the EP harness at the thruster levels and for the heaters attached to the upper structure. This interface adds additional mass to the Thruster Plate and will have a slight effect on the Eigen-frequencies. The connectors, shown on *Figure 1* and *Figure 2*, are only included on the QM model and will be replaced with a continuous harness on the Flight Models.

4.3. Common Lower Structure

Although the two thruster systems are different, it is possible to build the separate TPA mechanisms using the same common lower structure which includes the actuation system, hold-down and release mechanisms and shock damper. The principles of operation are the same as those used on the SMART-1 EPMEC [2].
The Common Lower Structure is shown on *Figure 3*

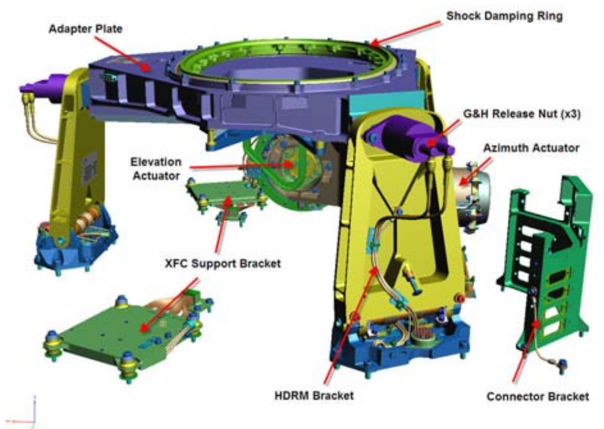

Figure 3: Common Lower Structure

By using a common lower structure for the TPA mechanism, the design has to accommodate the environmental loads induced during launch and spacecraft separation from the launch vehicle and additionally has to protect the EPS from the extreme temperatures during exposure to the space environment. In addition, the structure will be subjected to two qualification test cycles so it has to be robust.
The two thrusters have differing requirements for the Xenon tubes and EPS Harness both of which have to be accommodated within the lower structure. This means that interfaces with both EPS subsystems have to be available. Fortunately, both EP subsystems have common interfaces and use the same components. In reality the ITM140 has a slightly different XFC, has fewer Xenon tubes and wires in the EP harness but as discussed in chapter 4.2, components from the SPT100 will be retained to expedite the change over.
The internal harness for the TPA100 will also be retained on the common lower structure and terminate at the QM connectors to the upper structure and at the Connector bracket on the base plate.

A staged thermal isolation consisting of titanium standoffs and vetronite washers is common to both designs. The differences between the two designs are found in the thruster support plate, the radiator and the MLI used protect the structure.

4.4. Upper Structure for SPT100

Although the SPT100 thrusters can be used together, this is not often the case. Generally one thruster is utilised as a backup. This means that although the TPA has to support two SPT100 Thrusters, and it only has to allow for the conduction of the heat dissipated from one thruster into the mechanism (45W) and provide a radiator that can reject 285W to space.

This has two consequences for the design of the Upper Structure. Firstly, the radiator has to be designed to radiate the heat to space and the second is that the thruster support plate must allow the dissipation of the heat through the mechanism. This ensures that the temperature of the thruster is maintained within its allowable range.
The TPA for the SPT100 is shown on *Figure 4*.

4.5. Upper Structure for SPT140

The TPA has to support one SPT140 Thruster, and allow for the conduction of 25W into the TPA mechanism and provide a radiator that can reject 905W to space.

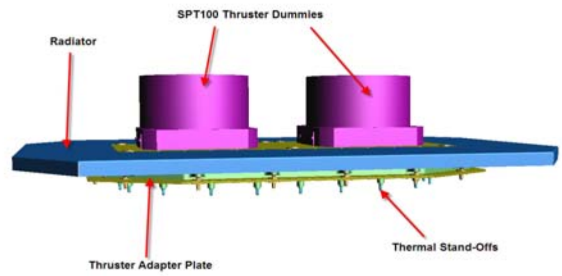

Figure 4: TPA for SPT100

The Radiator required for the SPT 140 has to reject three times more heat to space than the one for the SPT100 and therefore requires a much larger radiative area. The size of this radiator is critical because of it can have an impact on the deployment angle that can be achieved.

The TPA for the SPT140 is shown on *Figure 5*.

5. CRITICAL COMPONENTS

5.1. Overview

As has already been stated, the concept for the Multi-Purpose Thruster Orientation Mechanism (TOM) was derived from SMART-1 EPMEC [2]. This mechanism was developed for one PPS1350 Thruster which has slightly different performance characteristics. The Multipurpose TOM has to support either two SPT100 thrusters which are similar to the PPS13 50 or one SPT140 which is significantly different in performance and mechanical properties

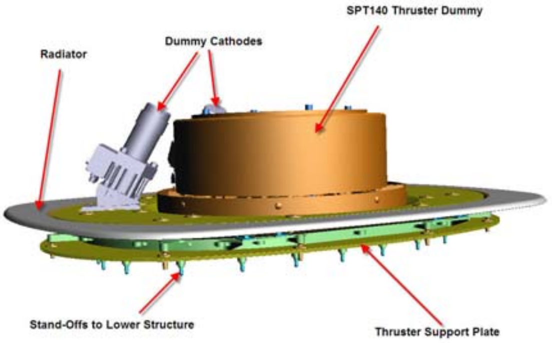

Figure 5: TPA for SPT140

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In addition, the pointing range for the SMART-1 EPMEC was only a half-cone of 9°. The pointing range for the TOM is significantly larger with a pointing range of -35°/+15° and ±15°.

Breadboard testing of components is expensive especially in the current climate when many customers are looking to make products cheaper and quicker, however development can benefit from breadboard test activities as this helps to mitigate many of the risks associated with complex developments. There are many cases where complex developments have gone directly to qualification only to have unanticipated failures during testing which lead to increased development costs and extended development times whilst problems are resolved.

The actuators used to drive the mechanism are based on components that have already been qualified on other development programmes and are therefore not considered critical to the development of the mechanism. However, due to the extended pointing range and the different environmental conditions acting on the mechanism, three of the elements in the design are considered critical and have therefore been tested at breadboard level before the design was finalised to mitigate risks during the development.
These breadboards are described in the following chapters.

5.2. Shock Damper

The purpose of the shock damper is to minimise the transmitted shock and vibration from the spacecraft to the thruster(s) during the launch phase of the mission. The secondary function is to reduce the heat flux transmitted from the thruster to the Spacecraft during operation.
Whilst the Shock Damper employed for SMART-1 EPMEC consisted of a simple ring structure, one of the compromises of accommodating two different thruster configurations is that the worst case solution taken for the two thruster option has to be considered for both designs.
The one for the SPT140 option is slightly heavier than the two SPT100 thruster option and has a different Mass Moment of Inertia. The design of the Shock Damper then has to satisfy the requirements for both thrusters.
The design of the damper has to maximise the damping characteristics and at the same time ensure that the Eigen-frequency of the complete assembly is as high as possible, preferably above the High Sine Test level of up to 100Hz.

During the preliminary development, various damper configurations were investigated, but finally, an oval design enveloping both thruster configurations was selected.

As the shock damper is produced from a two component elastomer, the mix was optimised through sample testing. The Shear Modulus G, which is used to determine the stiffness in the analysis, is derived from the Secant Modulus and the Hardness of the material. Tests showed that although the mix only slightly influences the stiffness of the material, the damping properties are significantly affected by the mix ratio.

Since the Thrusters are supported only by the shock damper alone, if this was to degrade over the 15 years mission life, ITM performance could be compromised. The test samples were therefore subjected to a Radiation Exposure equivalent to 15 years on orbit. SMART-1 had a life of only 2.5 years so the effects of radiation exposure to the elastomer were not significant.
The sample tests showed no significant effects on the Hardness and Tensile Strength characteristics of the material.

Having selected the design and formulation for the shock damper, a breadboard was built and tested under vibration and shock conditions.
During the first breadboard test, significant frequency shifts were observed which were attributed to material failures. The short investigation led to a redesign of the damper. During the SMART-1 EPMEC testing, small shifts in the frequencies were observed at the start of each day of testing which were attributed to a warming up of the material. To confirm this, during the second test, temperature sensors were embedded within the elastomer to investigate this effect.
These sensors recorded some interesting effects especially at the Eigen-modes under high sine vibration. An example of this effect is shown on *Figure 6*. What is interesting is that as the energy builds up at the Eigen-mode, the temperature within the elastomer also rises rapidly. This heat dissipates however very quickly into the surrounding structure.
The typical effect of the damping with frequency can be seen from Figure 7. This shows that at frequencies above ca 200 Hz, the damping effect is significant.
The mechanical energy produced during vibration is dissipated as heat in the elastomer, the higher this is, the higher the temperature in the elastomer.

The problem with the heat generation is that the elastomer becomes “softer” and hence the Eigenfrequencies shift downwards.

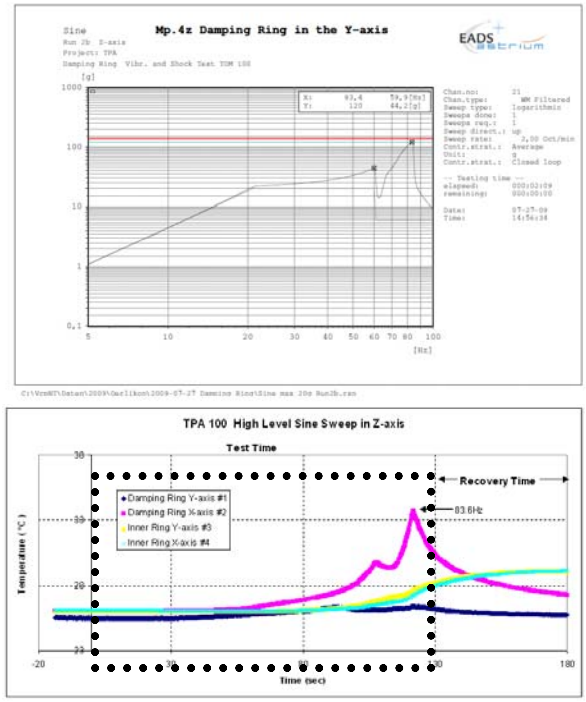

Figure 6: Typical reaction between temperature and Eigenfrequency

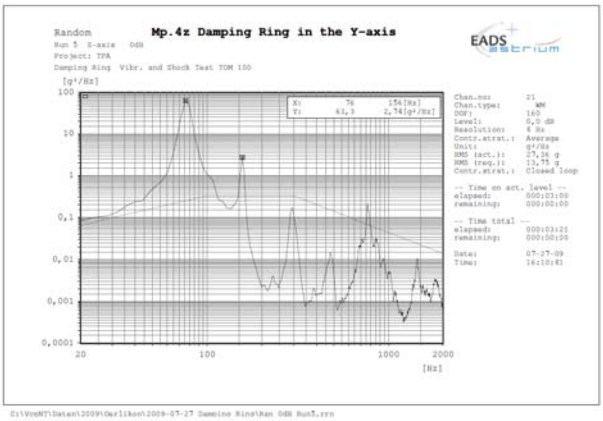

Figure 7: Typical Damping against Frequency

5.3. Xenon Tubing

The Xenon tubing transfers the Xenon gas from the XFC to the thruster. The tubes bridge the stationary and moving part of the mechanism and the moving part undergoes significant movement, rotating about the azimuth axis by -35°/+15° and in elevation of ±15°. This can lead to material fatigue in the tubing especially as the mechanism will be subjected to 115’000 cycles including 7’500 full range cycles and the rest, small angular movements of ±5° and ±1° movement cycles at different starting positions inducing high oscillating stresses in the tubing.

The design of the tubing has to mitigate the risk of tube failure. The concept for the tubing from SMART-1 EPMEC was used in the new design but several design and iteration loops were needed to finally define the design based on a trade off of mass, stiffness and stress for the tubes.

The design iteration was undertaken for both titanium tubes and at the request of EBD FAKEL for stainless steel tubing as this is easier to produce and weld to the thruster.

Whilst the margins obtained for titanium tubes were all positive, the margins obtained for stainless steel tubes were less promising and failure before the end of life was predicted. It should be noted however, that the assumptions that were made for material properties and tubing fixation led to the more pessimistic results.

Although predictions were not optimistic for the steel tube, it was decided anyway to perform a bending life test on both the titanium and steel tubes.

During the life test, with the set up shown on *Figure 8*, the Xenon Tubes were evacuated and the pressure constantly monitored to identify if and when a rupture occurred in the tubing.

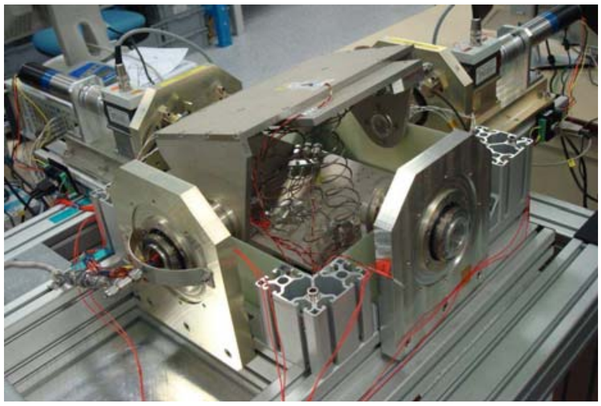

Figure 8: Test Set Up for Xenon Tubing Life Test

Both the S/S and the titanium tubes survived the life test so in view of the better weldability of the S/S tubes these were selected for the final design.

As well as demonstrating that the tubes can survive the specified operational life time, it was important to measure the resistive torque for inputs into the torque margin analysis. During the movement, the Xenon tubing acts as a spring and exerts a variable resistive force which acts as a torque on the actuators and affects the motor margin. This variable force is shown on *Figure 9*. The “calculated” alpha and beta forces have been derived to remove the residual effects of the test rig without the tubes.

Following the conclusion of the test, the FEM model used for the analysis of the tubes was correlated with the available results. The updated analysis showed positive margins for all load cases.

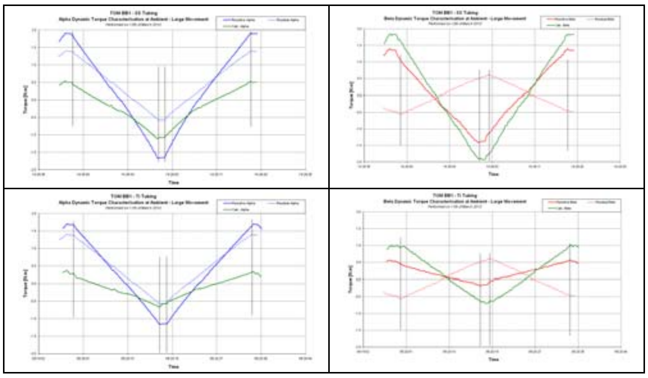

Figure 9: Resistive Torque exerted by S/S and Titanium Tubes

5.4. EP Harness

Similar to the Xenon tubing, the EP Harness also has to bridge the transition between the stationary and moving part of the mechanism and is subjected to the same movement cycle as the Xenon Tubing and is therefore also susceptible to Fatigue.
Depending on the thruster configuration, the harnesses have slightly different configurations but each harness has a significant stiffness which provides a resistive force that the mechanism has to overcome.

An outcome from the SMART-1 EPMEC testing was that the cable that bridged the transition was too stiff and although providing significant additional damping to the structure also contributed considerably to the resistive torque on the actuators.

A new design was selected using a "C" form and splitting the cables into three separate bundles.

As shown on *Figure 10*, each group of cables is shielded with a mesh tube which has been surface treated with Dicronite to minimise the possibility of cold welding of the mesh. In order to demonstrate the resistance of the Dicronite coating as well as determining the resistance torque at the temperature extremes for the full angular travel and also to demonstrate the life of the cable itself, a breadboard was established. The test rig was the same as that used for the Xenon Tubing life test, but contained an additional cooling and heating plate and a recirculating system to maintain the temperatures at the extremes.
The test set up is shown on *Figure 11*.

Before the life test began, the torque from the harness bundles was characterised for ambient and cold temperatures (warm temperatures were not characterised because the cable sheath is made from "plastic" and this gets softer with temperature).

Since the harness torque can be dependent on the starting position, the dynamic torque characterization was made at discrete positions of the mechanism. The results from the test are shown on *Figure 12* for the two temperatures considered during the breadboard testing. The results that were obtained were fed back into the performance analysis to revise the motor margin analysis for the TPA mechanism.
The characterization was repeated at the end of the test and showed no significant differences.

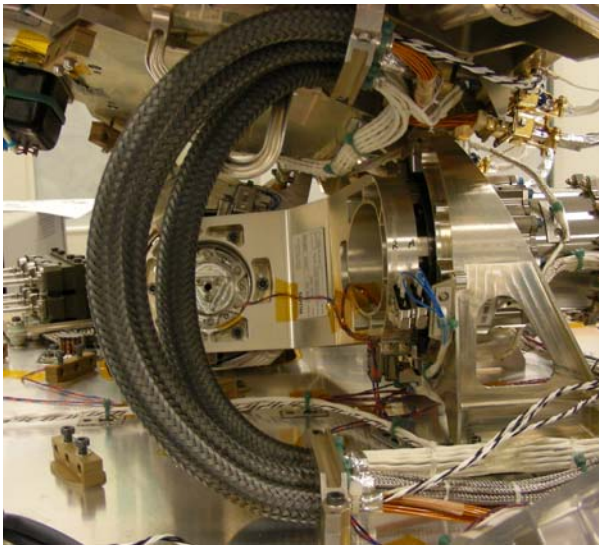

Figure 10: EP Harness Bundles

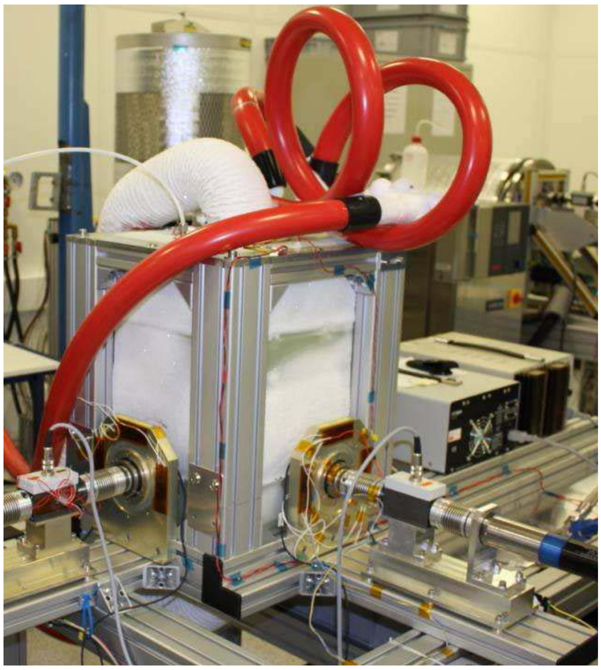

Figure 11: EP Harness Breadboard Test Setup

To demonstrate that the cable survived the life test, the electrical continuity of the cables was measured continuously. After the test, the cable was inspected for damage.

After the life test the only failure that was o bserved was on the cable sheath which was due to the radius of curvature of the bundle which led to high stresses in the braid.
It had also been assumed that there was sufficient Dicronite coverage on the braid to minimise the chance of cold welding at untreate d areas, however, it was discovered that only the e xternal and internal surfaces of the braid had been coated. Where the braids crossed there was very little Dicronite which although no such effect was found, inc reased the risk of co ld welding of the mesh.

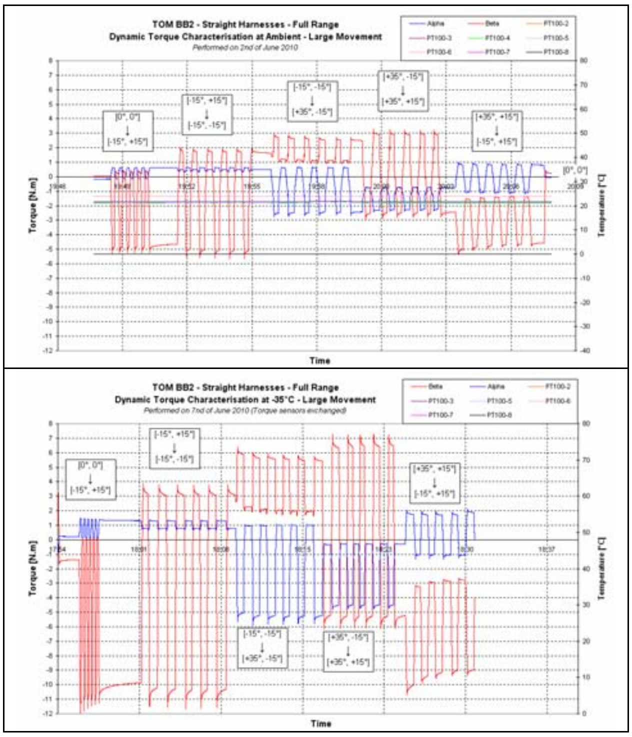

Figure 12: Results from EP Harness Characterisation

To resolve this issue, the length of the Harness Bundle was increased to enlarge the radi us of curvat ure and hence reduce the stresses in the mesh. The Dicronite coating process for the m esh was also improved to achieve a better coverage and provide better protection against cold welding.
The cables that were co ntained within the cable tube exhibited no issues after the life test.

6. TEST ISSUES WITH COMMON DESIGN

As already discussed, both the TPA100 and TPA140 will be subjected to a co mplete qualification programme. Since both mechanisms are similar, it was decided to utilise the common lower stru cture and to exchange the upper structure for the two mechanisms.
With the m ass and size of both mechanisms, external facilities for the qualification testing have to be used as suitable facilities were not available at RUAG Space.

Since it will be requ ired to test both the TPA100 and TPA140 at th e same facilities, this will h ave considerable cost and resource issues.
It is th erefore essential to optimise the test flow to reduce the logistics necessary during testing.
To minimise the cost, resource and logistic issues, it was decided to change the configuration of the test item at various stages through out the test programme.
Normally this would not be allowed for a m echanism qualification, however, the changes occur at one structural interface (t he damping ring) shown on *Figure 4* and *Figure 5*, and electrically at the additional connectors shown on *Figure 1* and *Figure 2*. As the lower common lower structure contains the mechanism part of the TPA, the performance of the m echanism is not affected, whic h means that the configuration change during testing can be tolerated.

During the d esign of both mechanisms, considerations were made to allow for an easy ch ange out of th e two configurations. The MLI around the interface has to be released but this is attach ed using Velcro to allow for quick release. The additional connectors, mentioned above, were added to the design to allow for the EP thruster exchange.
In the flight model of the TPA, the cables will pass directly from the Thruster to the connector bracket and these connectors will not be necessary.

To ensure that the design could accommodate the simple change out, it was important to define the MAIT activities at th e very start o f the development programme. By doing this it was possible to incorporate the changeover process into the design from the start. It would be difficult to include these features later du ring the development without significant consequences on the design.

The impact on the lower structure and the performance of the mechanism is minimal. Although the EP subsystem for the TPA140 contains one less XFC and the associated Xenon tube s and Harness, the QM mechanism will be tested in the configuration to suit the TPA100. As all the additional parts are mounted to the base plate, there is no direct influe nce on the mechanism performance. The only effect of any significance is th e additional resistance torque due to the redundant tubing and harness, which as t his represents a worse case for the mechanism, will b e used for the life test and is therefore acc eptable to qualify both mechanisms.

7. IMPACT OF COMMON DESIGN ON THE TEST PROGRAMME

As certain of the qualification tests are more critical for particular mechanism configurations, the test programme has to be planned such that the mechanism changeovers are coordinated to e nsure that the mechanism is in the corre ct configuration for the

specific test to save time and unnecessary change over costs.
The tests that are critical for each configuration are shown on *Table 3*.

In the end due to scheduling issues during parts manufacture, the testing of the TPA100 and TPA140 will be carried out sequentially which requires just one change over instead of the 3 to 4 changeovers that were initially planned.
As the features were included to support changeover process during the design phase, the changeover can be carried out quickly which means delays at external facilities and unnecessary waiting time is reduced.

Test	TPA 100	TPA 140
Functional Performance	X	X$^{(1)}$
Vibration	X	X$^{(2)}$
Shock	X$^{(3)}$	X$^{(3)}$
Thermal Balance	X	X$^{(4)}$
Thermal Vacuum	X$^{(5)}$	$^{(5)}$
Life Test	X$^{(6)}$	

Notes:

(1) Radiator area is larger and could reduce scope of movement. This is therefore more critical.

(2) TPA140 is heavier and effects mode shapes, but vibration levels are the same.

(3) Shock levels are the same for both mechanisms.

(4) The SPT140 dissipation to space is high. Thermal Control Subsystem (TCS) needs to be demonstrated. This case is more critical.

(5) Thermal Environment for both mechanisms is the same.

(6) The Life Test has to be performed on the worst case configuration which is the TPA100. This represents the worst case for the TPA

Table 3: Test Configuration criticality

The final test programme showing the sequential testing of the TPA100 and TPA140 with the single changeover is shown on *Figure 13*.

8. SUMMARY AND CONCLUSION

There are two aspects that have been discussed in this paper.

Firstly, breadboard testing provides excellent support during the design process and helps to mitigate issues that could occur downstream in a development and introduce unnecessary delays and extra costs.
Breadboard testing of critical components although contributes significantly to the development schedule and project development costs, enables the mitigation of many of the risks and problems that may not have been anticipated. Although analysis is a useful tool that is used in development, sometimes in complex situations, assumptions are too conservative due to a lack of information and may lead to decisions being made that increase costs rather than reducing costs by taking simpler options.. The case in point here is the final selection of the Stainless Steel Xenon tubing which is far easier to weld (steel to steel) to the EP subsystem than would have been the case if titanium tubes had been selected.
In addition, the breadboard tests on the shock damper allowed the know how with respect to how the damper worked to be expanded.

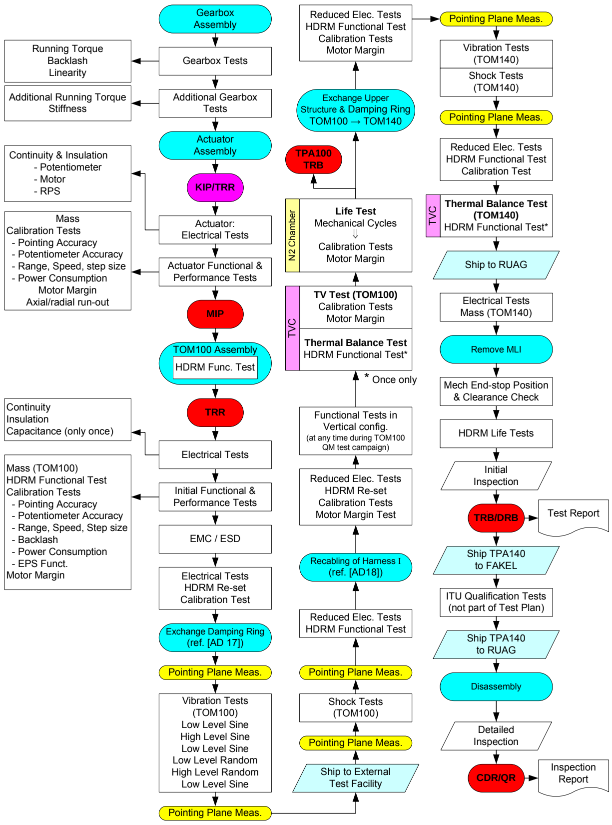

Figure 13: Test Programme for TPA100 and TPA140

Secondly, thinking about the development and qualification process at an early stage and incorporating features within the design at the very beginning that support the qualification testing lead to more flexibility in the development process. Incorporating late changes in design to support changes to the qualification test programme can also lead to delays and additional costs in the development.

Using a robust common lower structure reduced both the development time and costs, but it has to be considered that the common lower structure will be over tested, being subjected to two times the qualification programme, when the qualification of the TPA100 and TPA140 has been completed. The risks of failure at any time can be mitigated by analysis and appropriate breadboard testing.

Although the QM configuration is not 100% representative of the Flight Models for the TPA100 and TPA140, the differences are negligible and can be covered by delta testing the first flight model in the correct configuration as a Proto Flight Model (PFM).

In the end the critical issues with the mechanism such as susceptibility to the environmental mechanical and thermal loads, and the demonstration of the mechanism lifetime will have been achieved for two mechanisms in the most cost effective and quickest way.

9. REFERENCES

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