DESIGN, DEVELOPMENT AND TESTING OF THE MOTORISED UMBILICAL SEPARATION DEVICE

O Poyntz-Wright [(1)], W Holmes [(1)], Peter Doyle[(1)], Grant Munro[(1)]

[(1)] ESR Technology Limited, 202 Cavendish Place, Birchwood Park, Warrington, WA3 6WU, UK.
Email: oliver.poyntz-wright@esrtechnology.com

ABSTRACT

This paper describes the design, analysis and test campaign of the Motorised Umbilical Separation Device (MUSD). This mechanism is an Engineering Model development programme performed by ESR Space and funded by ESA. The design of the mechanism is based around a rotating cam driven by a brushed DC motor that captures and ejects the connector, it is also resettable. The paper presents the design of the mechanism, results of the test campaign and discuss any lessons learnt. Suggestions for future development are also discussed.

1. INTRODUCTION

The Motorised Umbilical Separation Device (MUSD) (see Fig. 1) is a programme to develop an Engineering Model (EM) mechanism capable of disconnecting a spacecraft umbilical connector. Currently, the demating of electrical umbilicals is usually performed simultaneously with the mechanical separation operation or by a pyro-actuator. One drawback with these methods is that the de-mating forces can significantly increase if the connector alignment is not maintained and connector binding can occur, as seen in the development of the Orion Crew-Service Module Umbilical Retention and Release Mechanism. [1].

To solve this problem ESA has been looking at miniaturised separation devices for spacecraft umbilicals at individual connector level. Furthermore, this project has the additional requirement of being able to reconnect the connector once it has been separated. This key requirement fundamentally defines the architecture of the device.

The device is targeted at missions involving planetary landers, re-entry vehicles and the separation of scientific payloads on a planetary surface or sample return canisters. Additional terrestrial applications may also exist in extreme environments.

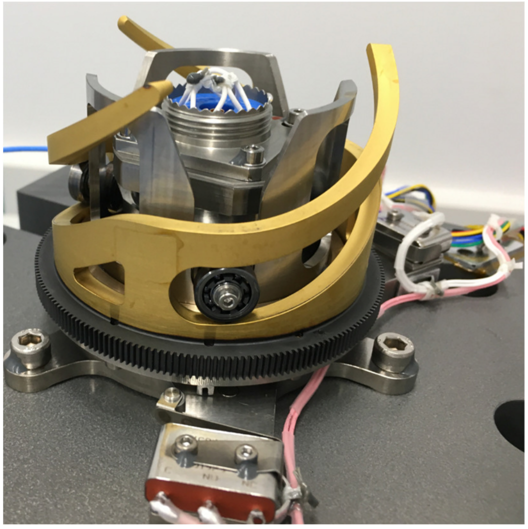

Figure 1 Motorised Umbilical Separation Device

2. MECHANISM DESIGN

2.1 Main Requirements

The key requirements in the development of the device were the ability to disconnect and recapture the connector. Aside from the functional benefits, an additional advantage of this would be borne out in testing as the device would not need to be manually reset, as would be the case for any single shot mechanism.

Miniaturisation is a key theme for this mechanism and the initial mass budget was set at 260 g. From the outset this was known to be a highly challenging requirement. Albeit on a vastly different scale, the only similar device that could perform the same functions as MUSD is in use on the International Space Station and has a mass of 32 kg.[2]. This device mates and demates multiple connectors with actuation forces in excess of 1 kN.

With no specific mission opportunities for the device, the environmental testing requirements needed to umbrella a wide range of scenarios in order to ensure the developed device is compatible with as many future missions as possible. This resulted in an extreme vibration envelope and a wide operating and non-operating temperature range.

As part of the reconnection function, it is assumed the Upper Connecting Part (UCP) will be manipulated into position by a robot arm or actuator. There will inevitably be a tolerance on the accuracy of this positioning capability so the MUSD needs to be able to deal with misalignments and offsets in this positioning. Through initial work on likely capabilities of robotic arms, the tolerances were defined as +/- 2 mm translation in any direction and +/- 3 ° rotation in any axis. An additional goal requirement of +/- 5 ° rotation in any axis was also added.

The lifetime requirements were calculated as 148 actuations (including ECSS factors). This was based on 2 full mate-demate operations in flight and a generous allocation of actuations for ground testing.

A detailed Requirements Review was conducted early in the programme and this involved discussion with potential end users of the device. These highlighted additional considerations such as minimising the complexity of the drive electronics.

In order to allow the MUSD to be compatible with a range of connectors, the target peak actuation force was selected at 250 N - this was considered a conservative worst case based on experience. Most spacecraft connectors are rated much lower than this, even in vacuum. The selected connector measured actuation forces were approximately half this value and so testing to this level would require additional resistance loading.

2.2 Concept Evaluation and Trade Off

A key priority for ESA was for the device to be modular and scalable. This would provide the greatest flexibility and applicability to future mission requirements. In evaluating concepts the different elements of the mechanism were broken down and options reviewed. This included an analysis of what type of motion was required from the mechanism, what actuators could be employed and an assessment of the forces involved.

A matrix was developed that aligned the various actuator options against the different types of motion needed. This was then subject to a detailed trade-off analysis where candidate options were scored against the following criteria:

- Compliance to the specification
- Modularity
- Testability
- Potential Failure Modes
- Qualification and Recurrent Costs
- Miniaturisation

A range of options were looked at including various linkages, scotch yoke and a rotating cam concept. Throughout the trade off analysis the cam concept yielded a number of key advantages over the other candidates. These included the ability to tailor the cam geometry to different force profiles and the ability to recapture the connector requiring little modification. Concepts involving mechanical levers and links tended to be higher mass. They weren't able to generate a mechanical advantage where the connector forces were at their highest; this resulted in large structures and bigger actuators being required.

2.3 Selected Design Concept

The trade-off analysis identified the cam and gear concept as the most promising and this design was taken forward for detailing.

The initial sizing of the device was reviewed and detailed calculations performed to size the bearings, motor and cam.

An overview of the mechanism is shown in Fig. 2 with a cross section in Fig. 3.

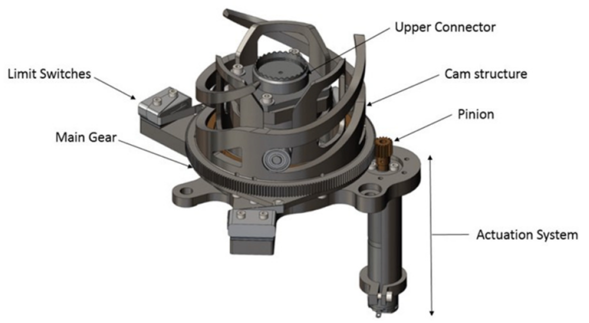

Figure 2 Mechanism Overview

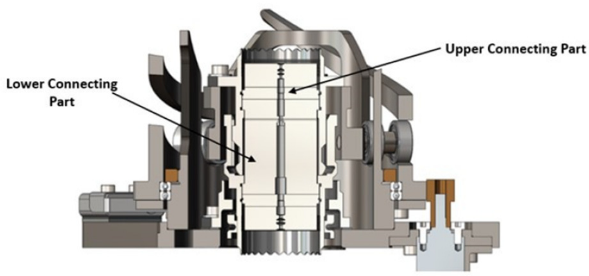

Figure 3 Mechanism Cross Section

In operation, the cam structure is driven round by the motor and gearbox. As the cam rotates, the Upper Connecting Part (UCP) Assembly (Fig. 4) is moved axially by the cam with rotation being constrained by vertical guides.

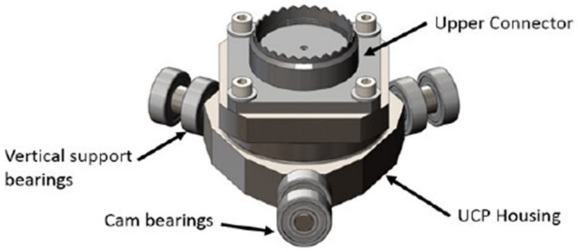

Figure 4 Upper Connecting Part (UCP) Assembly

Two Honeywell limit switches are fixed onto the baseplate. Positioned just outside the cam diameter these switches are triggered by a ramp on the cam clamp ring. One limit switch is positioned to be triggered at the fully connected location and the other at the fully demated position. The mechanism control software drives the mechanism in the desired direction until the limit switch is activated.

2.3.1 Cam and Gear

To provide precision alignment of the rotating elements, the cam and gear were machined from Grade 5 titanium as a single component. Whilst this creates a technically demanding part to machine, it reduces the tolerance build up on aligning the bearings and also is more mass efficient.

Titanium was selected as the cam material for its high strength to mass properties. Tribologically though, titanium is soft, and prone to galling. Therefore, hardening measures were explored. Typically, plasma nitriding can be used to harden titanium; with a depth of only a few microns and a predicted peak stress in the titanium at a few tens of microns this was quickly identified as unsuitable.

A novel heat treatment and hardening process specifically aimed at titanium alloys was found from Wallwork Heat Treatment Ltd. This Nitron-O treatment promised a hardness in excess of our minimum requirement of 500 Hv, combined with a case depth of greater than 20 microns. The cam and gear was treated using this duplex process in which a nitride diffusion zone is produced beneath a hard, thin film PVD coating. This process was a key enabling technology that allowed the use of titanium alloy for the cam and gear. The alternative would have been to use stainless steel, but that would have come with a large mass penalty. Whilst this process is not believed to have any direct space heritage, this EM programme was considered an ideal opportunity to try something new and promising. Success in this programme could lead to the wider use of this treatment in future programmes.

The treated cam and gear is shown in Fig. 5, note that the gold appearance is a result of Nitron-O heat treatment.

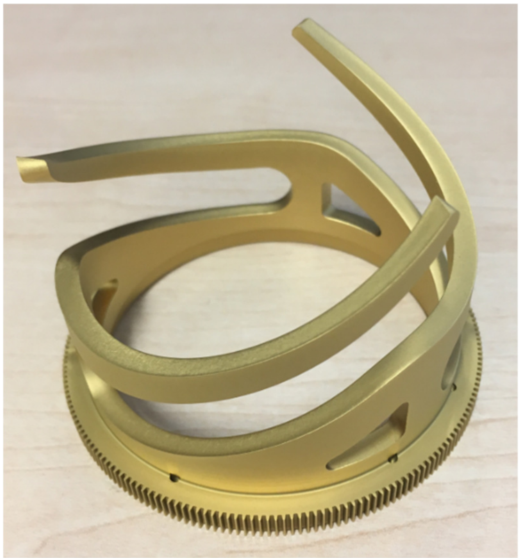

Figure 5 Cam and gear after heat treatment

2.3.2 Cam Profile Optimisation

One of the principal benefits of the cam concept is the ability to select the cam pitch to suit the connector mating force profile.

The calculated cam torque as a function of cam rotation is shown in Fig. 6. The cam profile selected was based on a simple harmonic motion curve which was tuned to limit the peak torque and also minimise it as far as possible in the 0 – 15 degree region, where the connector forces are highest and the largest uncertainty is. A further aim was to minimise the cam rotation needed to achieve the required axial travel as this impacts de-mate time and the number of motor revolutions required.

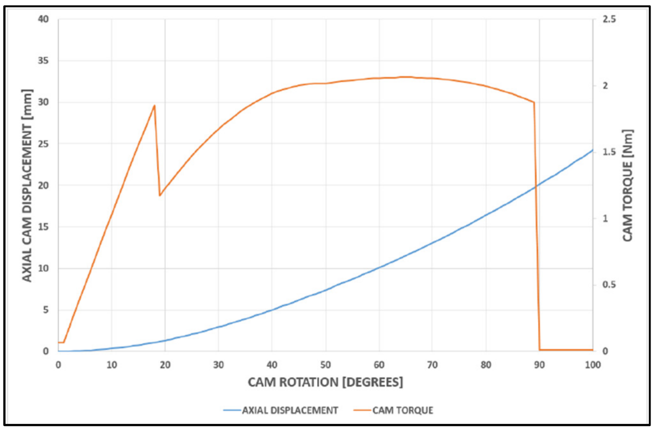

Figure 6 Cam torque as a function of rotation

2.3.3 Motor and Gearbox

The selected motor was a Maxon RE13 brushed DC motor. A brushed motor was selected to minimise the complexity of the control electronics – this was highlighted as a key requirement from discussion with end users. The motor was paired with a 5 stage 3373:1 reduction ratio planetary gearbox.

The motor and gearbox pairing were COTS parts with Braycote 601 EF lubrication added by Maxon. The RE13 was chosen due to having some heritage in the form of being the base for motors used for ExoMars [3].

2.3.4 Bearing Selection

In a mass critical application, the choice of bearings was of huge importance. The bearings sit at the heart of the mechanism and need to provide the load capacity to withstand the connector mating and demating forces and the mechanical vibration loads. The bearing torque was not a critical parameter as this value only makes up a small part of the motorisation chain. The lifetime, at only 148 actuations, was deemed to be easily achievable. The bearing selection was driven by the requirement for low mass/size. The diameter of the bearings needed to be at least 60 mm to allow for the connector to be mounted inside the bore.

The lowest mass bearings that could be found were from the Kaydon Ultra-Slim range. These full complement bearings have a 2.5 mm cross section and 126 ceramic load balls separated by stainless steel spacer balls. The bearings are shown in Fig. 7. The mass of each bearing is 9 g.

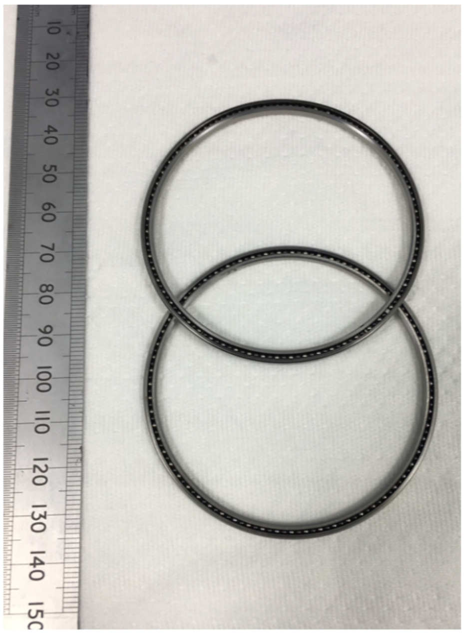

Figure 7 Kaydon Ultra Slim Bearings

The bearings are hard preloaded by a locking nut. The preload is achieved by clamping the bearing races together. Excessive force is avoided by applying a controlled rotation to the lock nut. With such thin section bearings (that can flex with normal handling) care was taken so that the bearings were not deformed. The nearest alternative bearings of an appropriate geometry would result in an increased mass of at least 100 g.

An aluminium bronze pinion is mounted to the gearbox output shaft to drive the main gear. Aluminium bronze was the selected material for the pinion because it would be the weakest point of the motorisation chain. This would mean in the event of jamming or excessive loads, the pinion would be sacrificial and the more expensive cam and gear should not be damaged.

2.3.5 Lubricant Selection

For the bearings, ESTL MoS_2 lubrication was selected. For cleanliness reasons, wet lubrication was not considered for any exposed parts of the mechanism (this would give greatest flexibility for potential planetary missions). The low number of actuations also meant that the limitations of using MoS_2 in air would be less severe.

The gear teeth (on both the cam and pinion) were coated with ESTL MoS_2; as were the six bearings that guide the UCP into position. In addition, the external diameters of the UCP bearings were also coated – these are the surfaces that roll along the cam and vertical guides.

Wet lubrication of the motor and gearbox (with Braycote 601EF) was considered acceptable from a cleanliness perspective as it is contained. The low temperature performance on the motor and the associated viscous losses at -40 °C were considered in the motorisation margin calculations. Future applications could implement a creep barrier if specific concerns on contamination exist. The application of the Braycote was performed by the manufacturer.

2.3.6 Connector

As part of the requirements review it was necessary to select an appropriate connector for the mechanism. A key requirement from ESA was that MUSD should not be tailored to work with only a specific type of connector. Therefore a number of candidate connectors were reviewed from a range of suppliers that would meet the project criteria of 25 signal lines, 12 power lines and a single RF coaxial line.

To simplify the motion required on the connector, it was desirable that the connector should be a simple push-pull rather than a bayonet type.

The selected connector was a Glenair Series 253 with a 17-02L layout. The Lower Connecting Part (LCP) is shown in Fig. 8. The LCP features a small clearance that allows the connector barrel to float in translation by approximately 0.5 mm with respect to the interface flange. For MUSD, ESR installed a Viton sleeve to provide an elastic support that allows compliance but also locates the connector position.

Figure 8 Selected Glenair Connector

3. TESTING

3.1 Test Facility

A bespoke test facility was designed and developed to allow verification of the requirements. The facility CAD model is shown in Fig. 9.

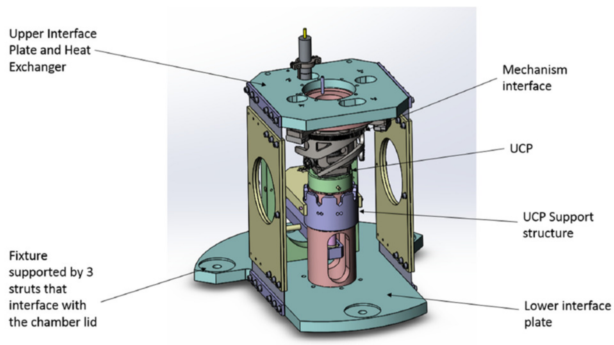

Figure 9 Test Facility Overview

The test facility was developed to measure and track key mechanism performance parameters. Key considerations in this regard were to monitor the connector health both electrically and mechanically and the performance of the mechanism.

Connector health was monitored by taking measurements of the mating and demating force. This was achieved by integrating 3 small load cells into a modified upper connector housing. The load cells could be read out as a single summed signal or individually. The individual measurement would allow for the force distribution around the 3 UCP support arms to be assessed. The load cell configuration is shown in Fig. 10.

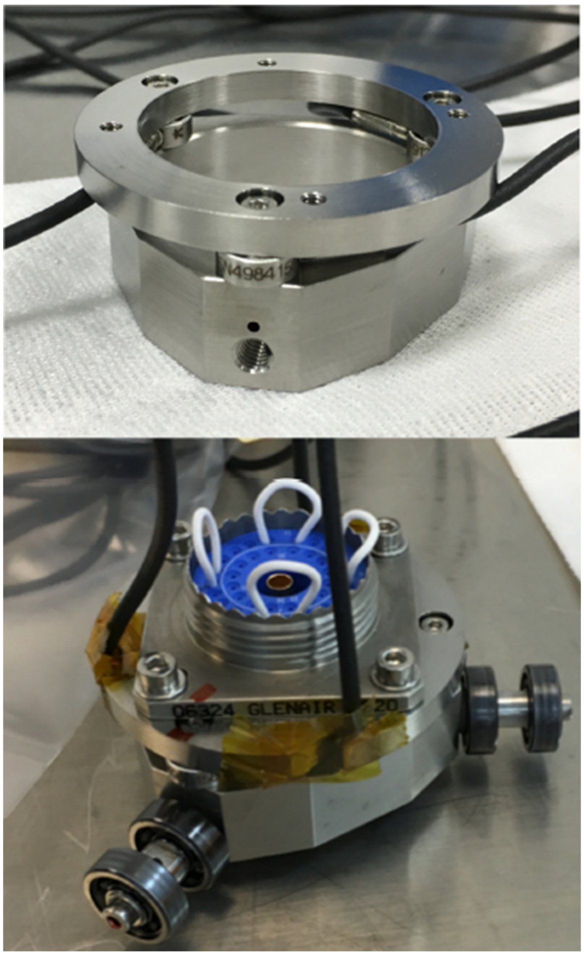

Figure 10 Load cells mounted with UCP

The axial position of the connector is measured by a Linear Variable Displacement Transducer (LVDT). This allows for the connector force to be plotted against displacement which will be the key metric against which changes to the connector health can be identified.

A dedicated data acquisition programme was created in LabVIEW which monitored the following parameters:

- Temperature
- Motor voltage
- Motor current
- Limit switch status
- LVDT position
- Load cell forces
- Continuity through the mated connector

3.2 Test Results

The developed Engineering Model is subject to a full range of qualification tests including – life-testing, misalignment testing, vibration, shock and thermal cycling. Fig. 11 shows the force-displacement curve from an early functional test. The negative forces are the mating loads and positive forces are demating loads. The X axis of the graph represents the connector axial position, with zero being the fully mated position.

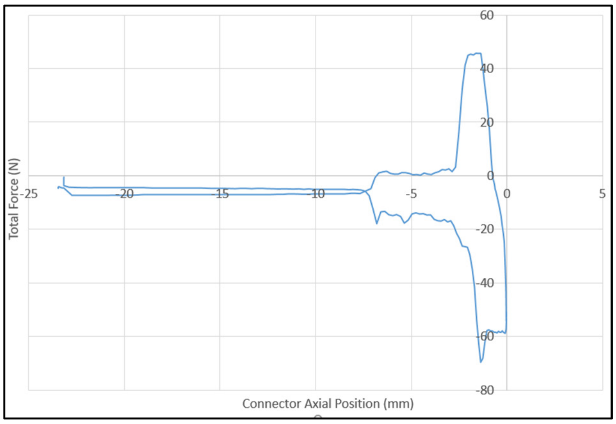

Figure 11 Functional Test Results

The peak loads of 70 N (in N2) are consistent with the expected loads from this type of connector. The results show that the connector mating forces remain low until the final ~ 7 mm of travel with a rapid increase in the final few millimetres. In the fully mated position, the cam exerts a force of around 60 N on to the connector. This was done deliberately to prevent movement under vibration. The demating forces approximately mirror the mating forces, although are slightly lower.

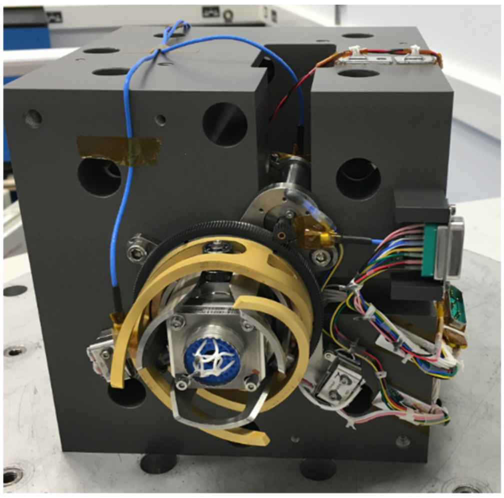

Figure 12 Mechanism on Mechanical Test Fixture

Vibration testing was completed at the RALSpace facility in Oxfordshire, UK. The mechanism on the mechanical test fixture is shown in Fig. 12. The loads were modified slightly from the original specification as there was a limitation on what could be achieved by the shaker and also to provide notching against a known frequency of the motor windings. The as run levels are given in Tab. 1Table 1 and Fig. 13.

Table 1 As Run High Sine Loads

	Frequency band (Hz)	Level	Sweep rate (Oct/min)
All directions	5 - 30.8	6.54 mm (0 - peak)	2
	30.8 - 52	25g	
	52 - 100	60g	

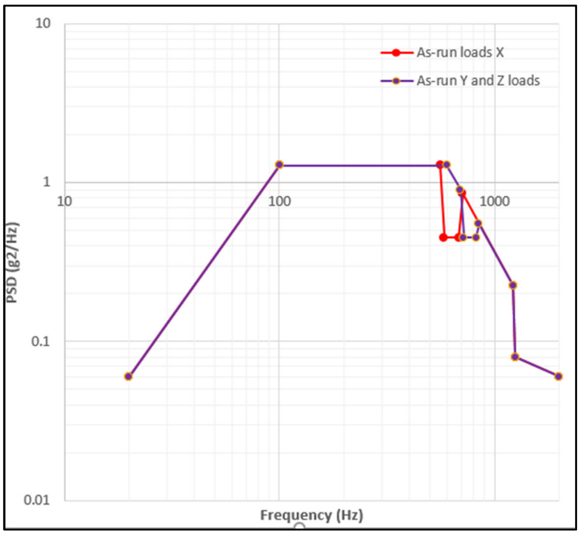

Figure 13 As Run Random Levels

Accelerometers were mounted on the mechanism interface, the cam and the bottom tip of the motor.

The mechanism successfully passed the test, with functional testing performed before and after vibration showing no evidence of a performance degradation. One of the main findings however was that the acceleration levels recorded at the end of the motor were particularly high. Due to the cantilevered motor mounting arrangement, high levels were expected and an additional support structure was put in place to limit the loads. The acceleration experienced however was greater than predicted with values in excess of 140grms being recorded. The main factor for this was that the observed motor mode frequency was lower than predicted. A correlation of the FEA model was performed post-test which demonstrated that the initial modelling assumptions overestimated the stiffness at the motor interface. One area for future work will be to fully characterise and better control this interface.

The responses at the other two locations (baseplate and the cam) were much more closely matched to the input and resonant peaks were much lower. The random response for the Y axis is shown in Fig. 14.

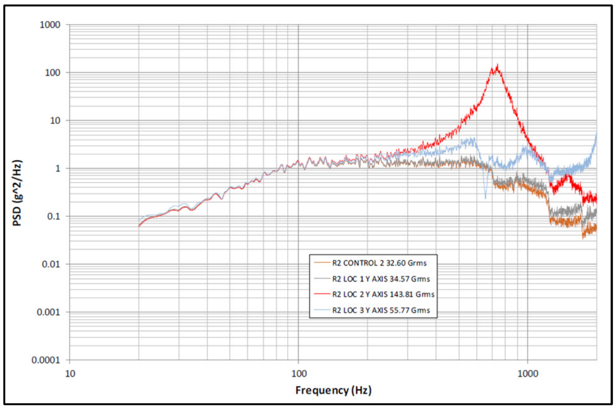

Figure 14 MUSD Random Response (Y axis)

Shock testing was performed at the Airbus Defence and Space facility in Portsmouth, UK. The test was conducted successfully with the full specified loads being achieved. Functional testing back at ESR indicated consistent mechanism performance pre and post test. The shock test levels are shown in Tab. 2.

Table 2 MUSD Shock Test Levels

Frequency (Hz)	Levels (g)
100	50
1000	1000
10000	1000
3 shock pulses per axis	

4. LESSONS LEARNT AND FUTURE DEVELOPMENT

Areas for improvement have been identified if this were to be taken forward for a flight opportunity. Whilst the mechanism survived the vibration loads, the loads measured at the tip of the motor were extremely high (140 g rms). Any future development should look at reducing these loads as a precaution. A customised interface with larger fasteners and a mating flange would be a desirable change to increase the stiffness and moment carrying capability. This could be justified in the context of a larger programme, particularly if multiple units were being produced.

The profile of the cam in the fully mated position could be improved to provide a retaining feature for the mated connector. In the current design, the connector is held in place only by the high torque needed to back-drive the motor and gearbox. If a different actuator and gearbox were used then this approach may not be suitable.

The cam and gear component could be manufactured in a variety of ways and any future application may wish to review the options in more detail. Additive manufacturing could be an option although the surface finish of the cam surfaces and the bearing seats would likely need precision post machining.

5. CONCLUSIONS

The test programme to date has been successful; the mechanism performs well and has demonstrated consistent functionality. It has demonstrated compliance with the misalignment tests (including the goal requirements) – a key performance parameter that will affect any potential flight opportunities.

The demanding mechanical testing including very high structural loads has been completed without any degradation in performance of the mechanism.

At the time of writing, the mechanism has completed over half of its life-test actuations (148 cycles required in total). No significant signs of wear exist and there are no specific concerns about meeting the liftetime requirement.

Of the remaining tests, the cold motorisation test is considered to be the most challenging. This is partly due to uncertainties with the low temperature performance of the wet lubricant inside the motor and gearbox but also due to the minimum start-up current of the motor which is not considered in the calculation of the motorisation current limit.

Overall, the MUSD Engineering Model that has been developed has successfully completed all tests so far. The goal of the programme was to develop a design where formal qualification would be achievable. At this stage of testing, all indications are that there are no specific barriers to achieving formal qualification on this design.

Once the EM programme is completed further development of the device will likely depend on finding a specific flight opportunity. The work performed in this programme has given a solid base for any future development to proceed at much lower risk. The developed design is both scalable and adaptable to meet a variety of potential future mission needs.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

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