DEVELOPMENT OF A MECHANISM FOR SPACE FROM A NEWCOMER'S PERSPECTIVE

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ABSTRACT

Whilst the process of mechanism development and mechanism features are similar between the aerospace, nuclear, scientific instrumentation and space industries, there are also fundamental differences in the development approach to the design of a mechanism for space.

The recent "European Stepper Motor Gearbox" (EuroSMG) programme, undertaken by Reliance and part-funded by ESA, has not only been about the development of a mechanism for space, but importantly has also given an established terrestrial supplier a fuller understanding of the rigorous nature of the space industry in terms of design and quality/product assurance requirements. This paper presents some of the lessons learnt and pitfalls experienced by a newcomer and the challenges of this development.

INTRODUCTION

Reliance Precision Limited have a strong heritage in terrestrial sectors but no prior experience of developing a mechanism for use in space.

Following a business review of an opportunity with an acceptable level of risk, making use of existing in-house competencies, Reliance embarked upon the EuroSMG development.

While the EuroSMG product is approaching the end of its Qualification campaign, there is a chance to reflect on the experiences had by Reliance throughout the process of space mechanism development.

It is intended that the feedback here may be useful to other Small to Medium Enterprises (SMEs) in terms of planning, as well as potential customers and ESA in terms of ideas for future optimised workflow.

RELIANCE BRIEF HISTORY & HERITAGE

Reliance has a long-standing history in the supply of intricate mechanical products and specialist design and manufacturing services.

Reliance was incorporated in 1920 as "Reliance Gear Company Limited" and remains known to many for its expertise in gears and geared assemblies (example shown in Fig. 1 is the Rosetta Solar Array Drive Mechanism (SADM) ring gear manufactured in 1999).

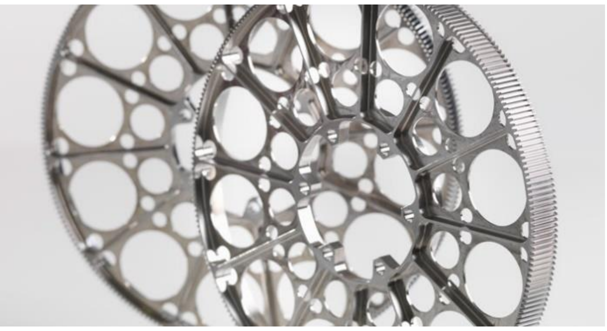

Figure 1. Rosetta Ring Gear supplied to Kongsberg

In 1955, the company was purchased by the Selka family, who still own Reliance today.

In the 1980s the company expanded into scientific instrument manufacture and assembly work, investing in cleanroom capabilities together with engineering skills in research, development and test. This became a further core focus for the business. The main cleanroom product is the Quadrupole Mass Filter (see Fig. 2), which requires manufacturing and assembly accuracies to micron tolerances.

Figure 2. Mass Spectrometry Quadrupole Filter

After further investment and expansion, in 2005 the company was renamed Reliance Precision to reflect its wider scope of business and expertise.

Today, the 230 employees enjoy working on new diverse products and subsystems that are key building blocks within bionic prosthetics, life-science automation, DNA analysis, optical control mechanisms (see Fig. 3), and precision products within terrestrial aerospace and space.

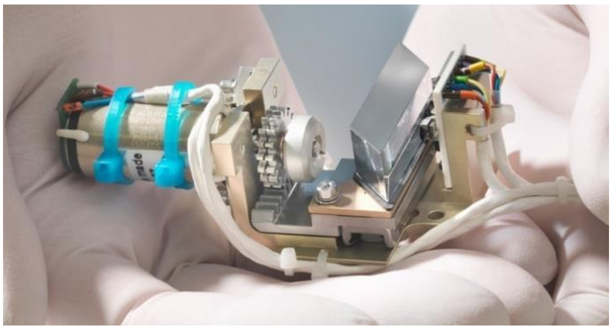

Figure 3. Example of an Opto-Mechanical Build

Throughout its history, Reliance has been driven by a culture of innovation and entrepreneurship, which has maintained the group at the forefront of changing technologies.

THE EUROSMG OPPORTUNITY & APPROACH

The Opportunity

In 2011 Reliance decided to target increased growth in new business areas. Space was identified due to the potential of combining the 50+ years of gears and gearbox heritage with 30+ years of ISO 7 cleanliness.

A feasibility study "European Gearbox for Space Applications" Ref [1] was conducted by Reliance to map the market to gain an understanding of key players, prospective customer base, support organisations and availability of funding. In parallel, a gearbox specification was developed in conjunction with industrial sponsor Airbus Defence and Space (Stevenage), which allowed Reliance to evaluate the technical hurdles and risks, Reliance's technical readiness, and ESA harmonisation strategy.

As a result of this Reliance identified target customers and funding support from national agencies as well as gaining a deeper understanding of new product development requirements for space.

The conclusion from Ref [1] was that "the space community, whilst small in terms of the number of participants, is not as coherent in its approach to product development compared to the more longstanding aerospace industry we are familiar with. The involvement of the space agencies, the relative youth of the industry and the demands of the different market segments (commercial, institutional and government) make it a more complex development environment."

Based on the particular identified opportunity being a known system requirement with a known future demand, this was seen as the lowest risk path to secure space flight heritage. The Reliance board of directors then approved the start of the inaugural space mechanism development.

Development Phasing

The entire development programme was initially split into typical stages of design, development breadboard testing, design refinement then qualification testing.

Splitting the development into a three-phased approach using different funding mechanisms required ESA coaching due to unfamiliarity with funding rules. With each phase, a letter of support was required from the UK Space Agency (represented by Innovate UK).

The first phase was funded under "ARTES 3-4 Telecoms Newcomers". The "newcomers" purpose is to be a stripped-down and flexible ARTES contract to ease new parties into the ESA traditional development approach. The activities included trading off gearbox and motor design architecture/concepts and then development of three advanced breadboards to enable validation of critical parameters at gearbox, motor and actuator level. The activities took place between Q3 2012 and Q4 2013.

The second phase was originally proposed to be the means of getting from a validated concept through to manufacturing drawing/data pack for the Qualification Model (QM) build. During the proposal review, ESA recommended that due to the immaturity of Reliance's space heritage that an Engineering Model (EM) phase was introduced into the programme, specifically to prove that the bearings and tribology met life requirements. The idea outlined by ESA was that the EM iteration would greatly de-risk the QM qualification campaign.

The development philosophy was re-planned and the second phase of EM development and test was awarded to Reliance. Phase 2 ran between Q2 2013 and Q4 2016 with ARTES 5.2 funding. Design and analysis activities were conducted in parallel to Materials & Process development. Originally, three EMs were manufactured; EM1 was the QM pathfinder and went through an entire test campaign to qualification levels (including functional, vibration, shock, thermal vacuum, life and strip down); EM2 was the second in the dataset and was used as test rig setter and tested for magnetic moment; EM3 was the third data point and was subsequently used for development of a different motor.

During testing, EM1 showed some shortfalls in performance so the design was evolved slightly in order to meet performance requirements. Under a CCN, ESA then agreed the manufacture of a further EM to prove the changes were positive for the QM. EM4 and EM5 were assembled and used as the final QM pathfinder.

In parallel to QM pathfinder activities, the proposal was made for the third phase. This was awarded in Q4 2016 with ARTES 3-4 funding and is expected to conclude with Qualification Review in January 2018. This focuses on build of QM1 and QM2 (second data point) and the Qualification Campaign. At this time of writing, the Critical Design Review and Manufacturing Readiness Review have both been completed.

EUROSMG DEVELOPMENT OVERVIEW

Design Elements

Figure 4. EuroSMG Engineering Model 1

The EuroSMG (see Fig. 4) is an ITAR-free rotary actuator that was designed primarily in accordance with an Airbus DS procurement specification to suit a Solar Array Drive Mechanism (SADM), whilst also addressing ECSS requirements and Airbus DS Product Assurance Requirements.

As a single point failure mechanism which needs to operate throughout life, this led to the most conservative factors being applied to the mechanical design.

The motor design saw a number of iterations of a permanent magnet stepper motor at the early stages of the EuroSMG development using SPEED and FEA. The finalised design is eight full steps per revolution, with a laminated electrical steel stack and Samarium Cobalt “parallel” magnets. There is an entire redundant motor.

The 201:1 gearbox was assessed initially and orbiting and epicyclic arrangements were traded off against part count, spatial envelope (length), ease of manufacture, tribology and cost. The trade-off showed that the orbiting gearbox was best suited to the slow speed application.

The motorisation margin requirement within ECSS-E-ST-33-01 was applied in order to determine the minimum requirements at the motor. The motor stall torque was then used to size the remaining components with the required Margin of Safety.

All materials and processes have been declared and approved for use. Stressed materials were predominantly selected from the Table 5-1s within ECSS-Q-ST-70-36. Organic materials have been assessed for outgassing properties. Leadwire conforms with ESCC requirements.

System-level analyses include FMECA, PFMEA, modal, micro-vibration, stress/thermal (using FEMAP with NX NASTRAN), reliability, venting, tolerance, backlash, mass, thread strain, bi-metallic compatibility, radiation assessment, double insulation and leadwire de-rating.

Bearing analyses conducted include pre-loading, sizing (for loads, vibration and shock), gapping, and tribology.

Specific gear analyses consisted of tooth curvature, trochoidal, crowning, sliding, sizing, and tribology.

Summary of Qualification Testing

Throughout the process of the EuroSMG development, three breadboards, five EMs and two QMs have been subjected to a variety of sequential test steps which can be split into three types of test.

All functional tests were conducted at Reliance. This included checking physical properties/ interfaces, motor electrical characteristics, performance (including start-up torque, detent and maximum torque), transmission error, backlash, output stiffness, hysteresis and efficiency. The majority of these tests were carried out on a bespoke test rig in a vertical orientation to negate the eccentric mass imbalance within the gearbox configuration.

Reliance also commissioned a portable test rig in order to travel with the test unit and provide a standardised way of measuring minimum running current in-between tests to assess degradation or issues.

BBM1, a gearbox only breadboard, was subjected to some early tests in an air environment. This included low and high temperature start up torque in Reliance’s environmental chamber as well as the gears being subjected to a life test.

BBM2 and EM2 have been subjected to a sequence of confidence tests at parent assembly (SADM) level to assess suitability (see Fig. 5).

EM1 has been subjected to a full test campaign as per the specified requirements up to qualification levels. Vibration (sine, random and constant acceleration) and shock were conducted with Low Level Resonance Search between each test per axis. This was followed by TVAC characterisation, TVAC cycling and then Life Test achieving 36 years. Following Life Test, a final functional test was conducted at Reliance and then EM1 was stripped to piece parts to assess changes. QM1 will follow the same process and is expected to complete by the end of 2017.

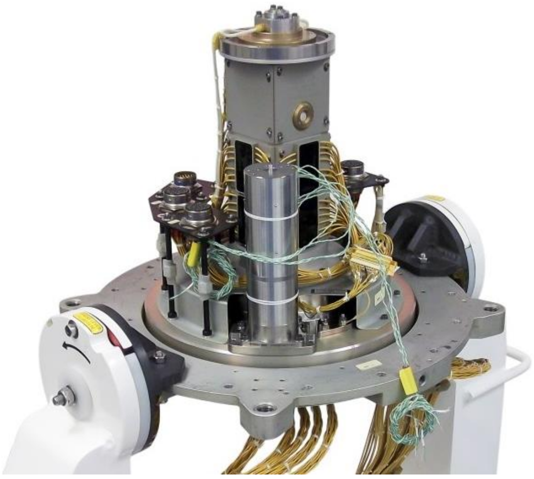

Figure 5. EuroSMG Breadboard on SADM

Product Data

Table 1 outlines the primary/critical parameters of the EuroSMG product and Fig. 6 shows the spatial envelope.

Table 1. EuroSMG Parameters

Parameter	Detail/ Comments
Mass	1.85 kg including leadwires
SMG Output Torque	2.94 Nm min Peak 9 Nm measured at 20 °C
SMG Holding Torque	2.15 Nm min at output shaft while unpowered
SMG Backlash	0.3 ° max
SMG Stiffness	42 Nm/° min
Gearbox Ratio	201:1
Motor Output Torque	57.9 mNm min
Motor Detent	8.75 mNm min
Motor Control	Current-driven 2-Phase Mini-Stepping 1608 full steps around an output revolution
Motor Current	0.63 A peak
Motor Resistance	10 Ohms nominal/ phase
Motor Inductance	20 mH nominal/ phase
Redundancy	Full motor (SMG has two stators and two rotors)
Damping Windings	Included as standard but may be removed (cost/mass reduction benefit)
ECSS	ECSS motorisation margin addressed
ITAR restrictions	None

The pinion may be changed or removed to suit the specific application requirement without necessarily affecting qualification status of the gearbox/motor elements.

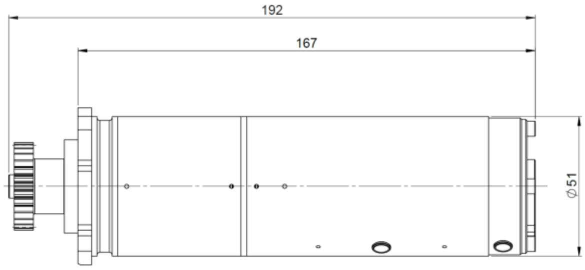

Figure 6. EuroSMG Spatial Envelope

OUTCOMES AND CONCLUSIONS

General Feedback

The development, following detailed requirements review, included several iterations, each aiming to de-risk the Qualification Model campaign. The risk-reduction strategy, considered essential for a newcomer, was successful but extended the development from three years to five years. This included a number of breadboards and engineering models, each targeted at specific technical parameters and which now formed the basis of our lessons learnt for future developments. Most importantly, the development is not just about qualifying a single product, as this is the initial means for Reliance to consolidate what has been learnt and carry across qualified materials, processes and design principles to new developments without needing the same levels of risk reduction.

The “ARTES 3-4 Newcomers” in place is really suited to those that require a “taster” to space development principles. Due to the entire three phase programme being set, from the outset it made sense to cover substantiation/ material/ process requirements as early as possible in order to reduce iterations later in the development. With this in mind, the “Newcomers” was sometimes more confusing to ESA and Airbus DS due to their unfamiliarity, which had the reverse effect of enabling an easy introduction.

It was noted throughout that ESA do have onerous formal requirements, but the core requirements are not too dissimilar to some aerospace customers and ESA match the requirements with excellent technical support and guidance.

Although the EM phase was more thorough than anticipated, by undertaking the EM test campaign, the QM qualification campaign is expected to be clean. At the outset, the importance of a “clean qualification” was not known or understood.

Certainly, the entire development process has been enjoyable for all at Reliance, albeit slower than originally anticipated. The technical requirements within both the product specification and general prime documents and ECSS requirements have been understood and met. Reliance are on course to qualify the EuroSMG product for space use, which is exciting for all involved.

General Benefits of the Development

Starting with the Reliance Space Mechanism Team, the EuroSMG project has led to the development of a niche competence in a complex, conservative sector. The lessons learnt include design, build and validation and can be applied to all future developments (space or otherwise).

Having the opportunity to generate family data and correlate the data with motor/gearbox design system models has already allowed the team to demonstrate similar actuator designs to customers with confidence.

Reliance is benefitting from the EuroSMG development with an increased growth in a new and exciting business area. Having a first product qualified for space use will open the door to other opportunities.

Reliance is an ISO 9001 and AS9100 accredited company with an established high level of quality control to suit the requirements of terrestrial aerospace and defence. However, the exposure to ESA processes has been beneficial in terms of Reliance seeing opportunities to enhance or adopt differences. One such example is the Review Item Discrepancy system which has been found to streamline the Design Review processes in place.

The final benefit is more generally a step further towards the ESA target of an independent European supply chain.

Space vs Terrestrial Research & Development

In summary, there are an increased number of steps included within a development for space, which are in place to de-risk the product failing during storage/launch/life. These broadly fall into two categories – formal and subjective.

Formal risk reduction steps are specified in ECSS or within a customer's Product Assurance requirements. These often mean the production of a suite of formally declared substantiation documents accompanied by an increased number of additional formal reviews to establish the status of risks at each stage.

In the example of mechanical calculations, these are very much the same that would be expected within terrestrial developments, but formalising and disseminating the calculations (rather than merely retaining auditable records) means additional submission/acceptance loops between parties. An increased level of scrutiny leads to an increase in ESA/customer satisfaction but not necessarily a transfer of risk responsibility. It is understood that the level of scrutiny during development is the same level of scrutiny applied by satellite operators to space primes, hence this is unavoidable.

Subjective risk reduction steps tend to be raised during design reviews. In each case the reason for the additional requirement is predominantly due to either a failure or non-conformance discovered during historic mechanism development or in-service issues. These risk reduction steps can often be spotted with wording such as "demonstrate that the [mechanism] will not cause [issue] under [condition]". These often cannot be added to a specification at the outset mainly due to the very specific and complex nature of each risk, but are identified upon gaining the higher level of scrutiny throughout the development. This has led to unplanned work and delays to programme, albeit necessary in order to satisfy the customer or satellite operator.

The operational environment tends to be more aggressive due to launch vibrations then being in vacuum while seeing temperature extremes. This does lead to specific material selection but the supporting analyses remain the same method as per terrestrial applications, albeit with more conservative Margins of Safety on top of factored stresses. This approach favours risk reduction over design optimisation.

Finally, a "clean" qualification requirement is unique to space development, being a qualification campaign totally devoid of any issues. Although the intent with any development (space or otherwise) is to have a successful qualification first time, the difference with space development is that the qualification requirements often demand lengthy/expensive validation and any partial deviation needs to be substantiated at every FM batch thereafter.

Consider that the lower the TRL of the mechanism, the more iterations are required to achieve a clean qualification, thus placing a strain on newcomers that cannot show traceability through to products with space heritage.

Commercial Picture

The commercial breakdown of the EuroSMG product has been compiled for the purpose of presenting what is considered to be typical for a space mechanism, showing the challenge to the competitiveness that Europe seeks.

The key point from Fig. 7 is that manufacturing of parts, build and test amounts to less than 50% of the cost build up. This is unusual to see in similar terrestrial systems where it may be more towards 75% as a minimum. The reason for this is due to specific space-driven requirements in terms of bought out (e.g. bearing traceability, titanium fasteners, creep barrier), subcontract operations (e.g. dry lubrication coating, painting) or FM product assurance support (e.g. additional preparation for reviews).

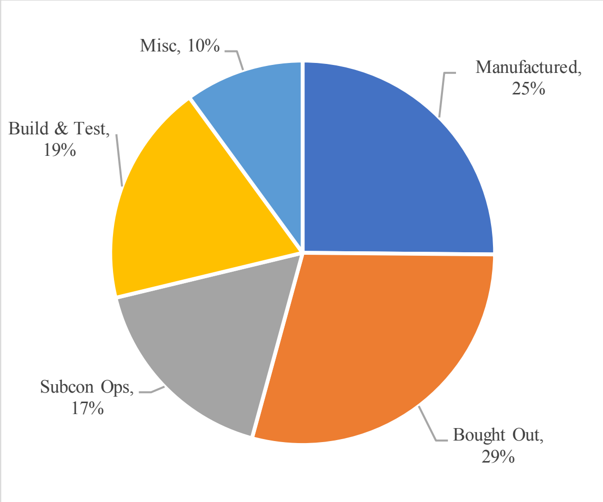

Figure 7. EuroSMG Cost Breakdown by Type

Taking fasteners as an example, there is a requirement for some space customers to specify TiAlV fasteners which must be manufactured and then validated to explicit standards. For a mechanism of this size, the low quantity of fasteners required typically leads to the majority of fastener suppliers either no-quoting or quoting a fiscally challenging minimum order quantity.

Another example is creep barrier, which is something specific to space mechanisms. This is a substance typically with short shelf life, high minimum order quantity and high cost. Unless there is a continuous flow of mechanisms being built, the chances are that very little is being used and thus much of the substance is wasted and the price is increased accordingly.

The above examples demonstrate where space-specific requirements and a small demand increases unit cost. It is suggested that European space agencies could combine requirements in order to increase order quantity and thus provide value across the European SME supply chain.

Similarly, the batch-based process requirements could be combined to increase batch sizes where possible. For example, painting often requires specific space compatible primer and paint and will be completed at many facilities around Europe on behalf of SMEs. If paint or the painting could be centrally coordinated this would also increase European competitiveness.

Through the process of establishing a cost breakdown, it has also been possible to show how the cost is spread by location (see Fig. 8) for the EuroSMG product. Besides the 7% spend on bearings from Germany, the remainder of the cost is predominantly UK based.

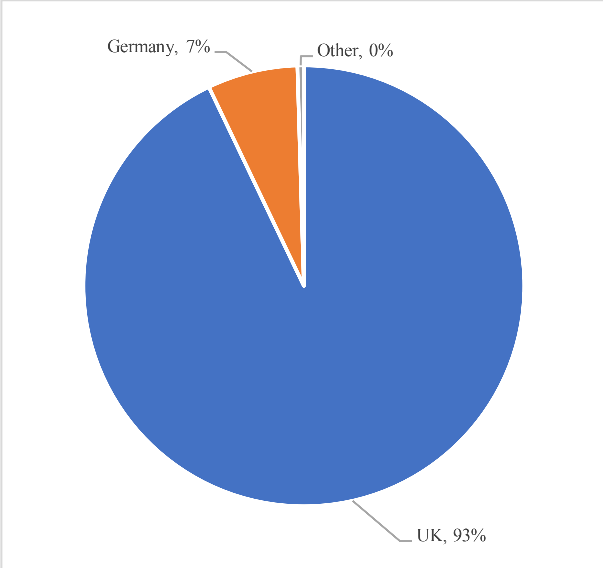

Figure 8. EuroSMG Cost Breakdown by Location

Specific to this inaugural development, the strategy was to retain a local supply chain in order to ease management/ communication through the development process, with the belief that this also optimises costs going forward.

Future Planning

Reliance are engaged in two further SMG projects which have applied material/process knowledge and system design experience gained through the successful ESA-funded EuroSMG development.

The first is a variation of the EuroSMG which uses a completely different and challenging type of permanent magnet stepper motor. This is expected to be qualified for space use in 2018.

The other is a 25mm OD SMG which uses a two-stage epicyclic 16:1 gearbox and a hybrid stepper motor. It is expected that this product will be qualified for space use in 2017.

In parallel to the above, Reliance is seeking to spin into space mechanisms its developed competence in Brushless DC motors while looking to add further smaller-scale ITAR-free actuators to the product range.

SPECIAL THANKS

A very special thank you to all who have helped Reliance during the course of the development.

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