TOWARDS THE USE OF COMMERCIAL OFF-THE-SHELF MOTORS IN SPACE

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ABSTRACT

There is growing interest in use of Commercial-Off-The-Shelf (COTS) motors (and other components) in space. These offer low-cost and occasionally unique performance benefits compared to bespoke space motors. Recent examples of their use include Beagle II, Rosetta and numerous micro-satellite applications. However, application engineers who propose the use of COTS devices face a challenging series of materials and tribology-related issues, together with performance uncertainties. The way these challenges are met will ultimately determine whether a COTS approach to space motors and other devices will be deemed acceptable.

This paper takes examples of recent programmes in which ESTL has played a role, either supporting manufacturers or space-equipment developers, in the adaptation of COTS technologies, primarily motors, to space use. The range of devices used, the scope of modifications and lubricant evaluation programmes carried out and the approach to performance evaluation are discussed.

1. INTRODUCTION

Three types of motor were upgraded for use in space. These motor types comprised two DC wire-brushed models and one piezomotor.

Specifically the following upgrades were made:

- modification of Faulhaber DC-brushed micro-motors to allow operation in vacuum at cryogenic temperatures (for Rosetta anchoring device). The modifications included the application of novel, ultra-thin solid lubricant coatings to the commutator. Functional testing of modified micro-motors under thermal-vacuum were undertaken to assess performance.

- fluid re-lubrication of Maxon motor bearings to make them space-compatible for use on Beagle 2 solar array and lid hinges. Results of the thermal-vacuum, life-testing of modified Maxon motors are presented.

- modification and performance evaluation of adapted Shinsei piezomotors for use on the MIDAS instrument on Rosetta.

2. FAULHABER MICROMOTOR

The Faulhaber 1016M003G micromotor was chosen by the Max-Planck Institute for Extraterrestrial Physics (MPE) for use on the ROSETTA Lander Anchoring System {Ref.1}. The motor is of the DC brushed type, fitted with precious metal wire brushes running against a gold –plated commutator (Fig.1). The housing has a diameter of 10mm and length 15.7mm.

Fig.1: Faulhaber 1016M003G Micro-motor

The ROSETTA application requires the motor to function under vacuum and at cryogenic temperature (-190 deg.C). The as-supplied, off-the-shelf motors are oil-lubricated, the lubrication being applied to the commutator and the bronze bushes supporting the drive shaft. Since this lubrication is incompatible with both vacuum and cryogenic temperatures it was decided to upgrade the motors to make them function in cryo-vacuum. This upgrading involved disassembly of the motors, removal of existing oil lubrication by solvent cleaning and the application of dry lubrication to the commutators and bushes.

The work was carried out at ESTL in two phases. In Phase 1, a number of different lubricants were tested to determine which lubricant provided the most effective lubrication solution. A second phase was then undertaken in which the most effective lubricant (as identified in Phase 1) was applied to 20 off-the-shelf motors and these were then functionally tested under cryogenic-vacuum. These units were then delivered to the Max-Planck Institute for further testing.

Disassembly, cleaning, lubrication and re-assembly

The motors were dismantled and re-assembled using a procedure and tooling supplied by MPE. This procedure included modification of the end cap/brush holder to allow insertion of a tool, which held the brushes away from the commutator during re-assembly, and also the provision of a vent hole to aid evacuation of the motor body during vacuum testing. A disassembled motor is shown in Fig.2.

Fig.2: Disassembled micro-motor showing housing, rotor/commutator, pinion & shaft, bushes, washers and end-cap.

All the components, which had been handled and which had been lubricated with oil by the manufacturer for terrestrial use, were cleaned after dismantling. The main bearings (sintered bronze bushes) and thrust washers were ultrasonically cleaned in isopropyl alcohol (IPA) and Freon 113 solvent. The motor bodies and end cap/brush holders were rinsed in the same solvents after the identity labels had been removed. Traces of adhesive from the labels were removed with clean wipes moistened with IPA. The armature/commutator assemblies were rinsed in Freon 113 (no IPA as this dissolved the insulating lacquer on the armature).

The main bearing bushes from all the motors were sputter coated in the bores and part of the adjacent end faces with approximately 1µm of MoS_2. The thrust washers were similarly coated on their faces. For Phase 1, the commutators of five motors were lubricated with a variety of materials as detailed in Table 1.

Table 1 Trial commutator lubricants

Motor I/D	Trial lubricant	Rationale for choice of lubricant
SN11	Sputter coated lead	Established space lubricant which remains effective at cryo-temperature in vacuum
SN12	Sputter coated MoS2	Low friction and long life under pure sliding motion in vacuum. Also effective at cryo-temperatures. Modest electrical conductivity, therefore ultra-thin films only.
SN13	Sputter coated MoS2/Au	As above, but presence but the MoS2 is co-sputtered with gold; gold inclusion expected to improve electrical conductivity.
SN15	Burnished MoS2/Ag	Ag/MoS_2 brushes have extensive space heritage on motors and slip-rings; impracticable to fit Ag/MoS_2 hence the concept of burnishing a layer of Ag/MoS_2 onto the commutator
SN16	Fomblin Z25	To check whether a space-compatible fluid was at all feasible

The sputter coating was done using a mask to prevent material bridging the commutator segments. In the case of the MoS_2 and Au/MoS_2, the sputter-coated films were kept extremely thin (~500A) in order to minimise the additional contact resistance generated by the presence of the film. The burnished MoS_2/Ag layer was accomplished using a piece of Ag/MoS_2 brush material (ref. PRS OTS 42015 - IMI, Kynock Ltd) held against the commutator whilst it was rotated. The Z25 oil was applied using a 0.2mm diameter wire. Two drops of oil were applied and spread as evenly as possible over the commutator surface.

Testing (Phase 1)

The five motors were accommodated between two heat exchangers having machined semi-cylindrical recesses of the same radii as the motor housings. A silver filled gasket material was used in order to ensure good thermal contact between the motors and the heat exchangers. The compliance of this material also spread the clamping forces evenly between the motors. Two PT100 temperature sensors were attached to the heat exchangers and the assembly wired up and then installed in a vacuum system. The electrical connections were made to allow measurement of the motor resistances and to drive them via circuitry supplied by MPE. A recording oscilloscope was used to record the current when driving the motors at 5 volts. The current was derived from the voltage across a 2 ohm resistor on the MPE drive electronics.

After evacuation of the vacuum chamber each motor was shown to be operational. They were then run-in for ~50 secs. The heat exchanger was then cooled with liquid nitrogen and the resistance across each motor was monitored (without operating the motors).

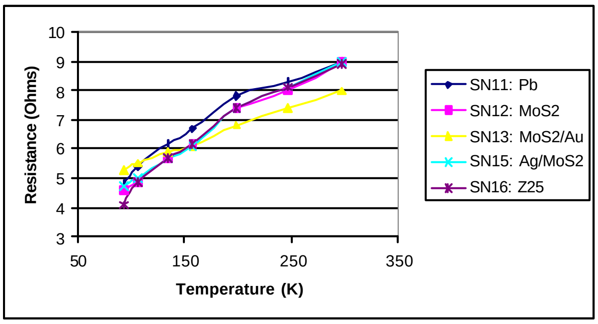

Fig. 3: Measured electrical resistance across motors as function of temperature (in vacuum)

The changes in resistance with temperature are shown in Fig.3. The temperature was then raised to 173K (-100 deg.C) and each motor run for 5 secs. At this point motors SN11 (lead) and SN16 (Z25) failed to rotate. The temperature was then increased to 293K (room temperature) at which point all motors were operational (including SN11 and 16). The motors were again cooled to 84K at which point all motors, with the exception of SN16 (Z25) which failed to rotate, operated. The rig was then left to return to room temperature and the system vented with dry nitrogen.

Conclusions (Phase 1)

All the motors bar the one lubricated with oil (SN16) operated at –189°C. The motor with the lead-lubricated commutator (SN11) failed to run at –100°C but operated subsequently at –189°C albeit in a noisy manner. All three motors having an MoS_2-based lubricant operated under all test conditions with the commutators having the burnished film (SN15) drawing the least current. The motor thrust washers (lubricated with sputtered MoS_2) behaved in a satisfactory manner. When operating, the noise generated by the motors was audible - and particularly so when the current drawn was noisy or intermittent. It was observed that the clearances in the bronze bearings, which had been designed to operate with oil lubrication, where quite large compared to the shaft diameter and might be allowing excessive shaft vibration and its attendant noise. At this point a decision was taken by MPE to make new bushes with smaller bore size. These were manufactured from self-lubricating Vespel SP3 by MPE. On the basis of the ESTL tests and further tests done at MPE on the Phase 1 development units, ultra-thin sputtered MoS_2 was chosen as the commutator lubricant for the flight model units.

Phase 2: Upgrading of flight model motors

As a result of the findings of Phase 1, 20 micro-motors were upgraded to achieve space-compatibility as follows:

- the original bronze main bearings were replaced with bushes supplied by MPE made from Vespel SP3
- the thrust washers were sputter-coated with (nominally) 1µm of MoS_2 on both faces
- the commutators were sputter-coated with an extremely thin layer (nominally 500 Angstroms) of MoS_2.

Following assembly, the motors were assembled in a thermal-vacuum test rig and first run for 5 seconds in air to check operation. After evacuation of the vacuum chamber, the motors were run-in and then subjected to thermal-vacuum testing. It was found that eleven of the twenty motors performed satisfactorily in the first cold test at nominally –190°C. The remaining nine motors, which had given un-satisfactory results (either stalling, going open circuit or showing erratic current traces) were run-in further at room temperature in vacuum to give a maximum in all tests of 120 secs. All the motors were then cooled again to nominally –190°C and the nine tested for a final 5 seconds. Of these nine motors, three performed satisfactorily at this temperature. Thus a total of fourteen motors gave an acceptable performance in cryo-vacuum. Four of these units have now been selected by MPE for flight application after further tests by them.

3. MAXON MOTORS

Commercially available Maxon RE13 motors (approx 13 mm diameter) were selected for use by Astrium on the Beagle 2 Robotic Arm actuators, the Main Lid Hinge Mechanism and the Solar Array Hinge Mechanisms. In the commercial design, the rotor shafts are supported by bushes lubricated with an oil which is not space-compatible. For the upgrade, the bushes were replaced with ball bearings and these in turn were lubricated with a space-compatible grease. Commutation was achieved using unlubricated silver-palladium brushes.

The motors were required to operate at temperatures as low as –40 deg C and survive exposure to –90 deg C. The Martian environment is one of low pressure (8 mbar) of carbon dioxide.

Initially, a review of candidate lubricants was carried out to identify those most suited to the Beagle hinge and robotic arm actuator applications, with particular emphasis on ball bearing test data.

Figure 4: Motor support bearings (mm scale shown)

A fluid lubricant was selected on the basis of performance, ease of application and comparatively low cost. The grease selected, Maplub PF101a, is based upon Fomblin Z25 oil and contains PTFE filler and MoS_2. Following cleaning, the motor bearings were lubricated with the grease and the bearing shields and circlips were then installed. The lubricant quantity applied was based upon analysis using a method developed by Palmgren {Ref. 2}. The bearings were then despatched to Maxon in Switzerland for installation in the motors.

Motor Testing

All the modified motors were tested with gearboxes attached (these were also adapted for use in space by lubricating with PF100a a space-compatible grease - applied at ESTL). Testing was carried out in carbon dioxide (at 8mbar) in the temperature range 20 deg.C to –40 deg C and comprised motor current measurements. Testing showed that all of the motor-gearboxes performed satisfactorily with currents less than the upper limit of 100 mA at the lowest test temperatures..

The Main Hinge Mechanism (FM) and the Solar Array Hinge Mechanisms (FM's), both types being fitted with the modified Maxon motors, were acceptance-tested at ESTL . Testing was carried out in 8mbar of CO_2 and at temperatures in the range -25 to +25 deg C. The motor currents were monitored during testing and all of the mechanisms deployed successfully with the motor current remaining below the upper allowable limit of 100 mA. This testing demonstrated that there was adequate torque available to deploy the hinges under the worst-case load conditions.

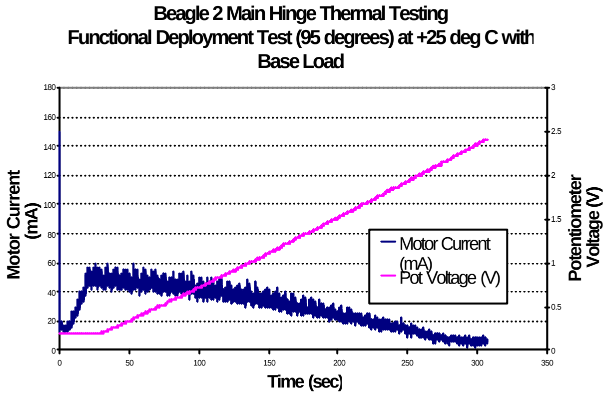

Figure 5: Example of Main Hinge deployment motor current as it lifts simulated base load from horizontal to 95 deg

A life test of one motor was also carried out under conditions (Table 2) and loads representative of the Robotic Arm actuators.

Table 2: Summary of life-test conditions and test environment

Test ID	Environment	Cycle definition	Number of cycles	Max No. of motor revs at 8,300 rpm
1	Air, 20 deg C	1 minute CW, 1 minute ACW	200	3.3 million
2	Air, 20 deg C	9 minutes CW, 9 minutes ACW	20	3 million
3	CO_2, -20 deg C	1 minute CW, 1 minute ACW	120	2 million
4	CO_2, -20 deg C	9 minutes CW, 9 minutes ACW	24	3.6 million
5	Air, 20 deg C	1 minute CW, 1 minute ACW and 9 minutes CW, 9 minutes ACW	3 cycles 1min CW/1min ACW and 1 cycle 9 min CW/9 min ACW	0.2 million
Total Motor Revs				**12.1 million**

Following 12 million revs of operation, no detrimental changes were measured in the motor current performance, thus it successfully completed the life test.

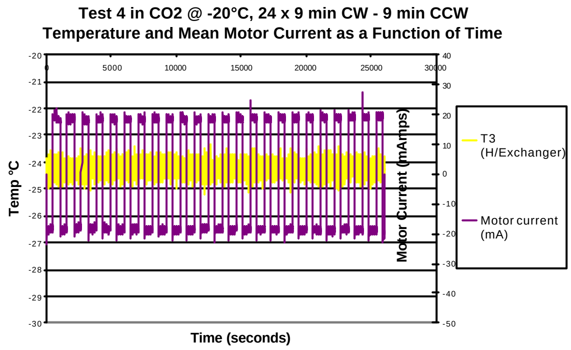

Figure 6: Example of motor current for life test

The motor was not stripped after test as it was required for further work at Astrium, but Figure 7 shows that the grease applied to the motor pinion was still in good condition following testing and excess had been pushed to one side.

Figure 7: Maxon motor pinion following life-test

Conclusions

Based upon the test undertaken, it is concluded that the expected lifetime of the space-upgraded Maxon motor (and gearbox) is more than adequate for the Beagle 2 Robotic Arm joint actuator and Hinge (Main and Solar Array) applications. The upgraded motors have also displayed an adequate torque margin.

4. SHINSEI PIEZOMOTOR

Commercially available rotary piezomotors type Shinsei USR30-B3 were selected by ESTEC for use in the MIDAS instrument, an Atomic Force Microscope to fly on Rosetta. The motors were proposed to power the translation stage, wheel and shutter mechanisms of the MIDAS unit because of their high un-powered holding torque (approximately 100gcm) - a feature which was used to provide un-powered locking and in-operation position holding. Taking into account qualification testing, EQM, flight and flight-spare units, probably less than 20 such motors were procured by ESTEC for the programme.

In the commercial design the rotor is located by means of a single shielded radial bearing which is preloaded using a circlip and the elasticity of the rotor disc itself. The unit is shown in Figure 8 below.

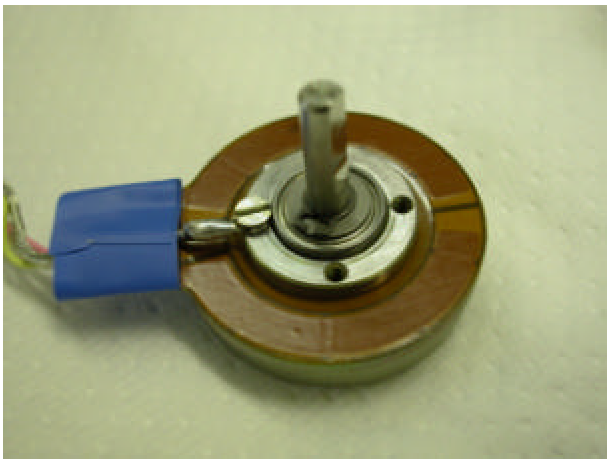

Figure 8: Shinsei Rotary Piezomotor

The preferred approach in the MIDAS programme was for the selection of a common lubricant throughout all bearing applications. Therefore the refurbishment carried out at ESTL for flight use was relatively straightforward and consisting of two principal tasks:

1) Replacement of the radial bearing by an equivalent bearing lubricated by a combination of ion-plated lead and Braycote 601EF micronic grease applied to the raceways and steel cage.

2) Application of creep barriers to rotor shaft and disc. This was necessary in order to prevent oil contamination of the piezomotor which relies on friction for the transmission of drive.

Motors modified in this way were then subjected to a programme of Qualification testing. At ESTL, this consisted of operation of the motors in-vacuo at –20°C, 22°C and 70°C in a set-up capable of measuring the maximum delivered torque and motor current drawn.

It was rapidly discovered that the motor performance degraded markedly after a period of continuous operation in-vacuum. This degradation is shown in Figure 9 below.

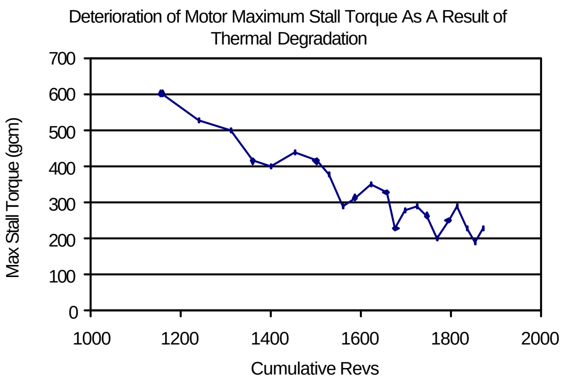

Figure 9: Deterioration of piezomotor maximum stall torque as a result of thermal degradation

The performance changes were attributed to thermal changes in piezo-polymer material when operated under elevated thermal conditions. After this discovery the flight operational regime for the piezomotors was reviewed and it was established that the 70°C qualification temperature requirement was too high. For subsequent operations the maximum motor body temperature was constrained to 55°C. Furthermore, the MIDAS operational regime allows motor active periods to be interspersed with inactivity. Taking into account the new operational regime, typical output torques remained within the range 1000-1200gcm at all test temperatures: a performance which was very similar to that obtained in-air.

With this thermal constraint the piezomotors successfully completed a lifetest carried out at ESTEC for approximately 40,000 revs without significant degradation of torque performance and with only minor changes observed in the piezo-material as shown in Figure 10 below.

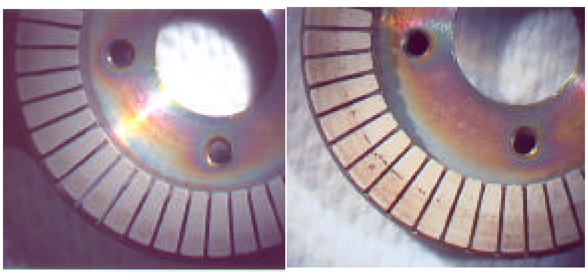

Figure 10: Piezomotor segment condition before (left) and after (right) the successful lifetest

The Flight and Flight-spare units were also refurbished in the manner described above, but each was subjected to a reduced number of thermal cycles (with limits –20°C and +55°C). Performance of the flight units was found to be very repeatable, and maximum output torques of order >1250gcm providing large torque margins and typical drive currents around 225-275mA.

5. CONCLUDING REMARKS & LESSONS LEARNED

The three examples presented in this paper illustrate the measures required to modify (tribologically) a range of COTS motors for space usage. It is concluded that the replacement and re-lubrication of bearings can be undertaken in a relatively straightforward, effective and cost-effective manner. Brush/commutator modification (in the example given) did require some development activity prior to motor upgrading and, in consequence, the associated non-recurring costs were not insignificant.

The lessons which emerge are:

- When tribology and materials issues are tackled, the performance of the COTS devices are adequate for space applications.
- Whilst the cost of replacing/upgrading bearings is relatively modest, the development costs, albeit non-recurring, needed to upgrade brushes and commutators may be significant. Also, the costs of qualification should be taken into account and are likely to be similar to those for a bespoke space motor.
- The COTS approach will prove most cost-effective when a single generic device is used in several locations within a device/mechanism or series of mechanisms. In this situation one qualification exercise should suffice provided this is based on the most demanding of the given applications. The use of a single COTS motor in one location is unlikely to be economic.
- The COTS approach is only possible with a co-operative supplier. This was the case for the three manufacturers who supplied the motors discussed here. However, in general, the degree of co-operation tends to relate to the size of order and this could prove problematic since, for space projects, the order size is usually small.

6. REFERENCES

1. M Thiel et al 'The Rossetta Lander Anchoring System" published elsewhere in these proceedings.

2. T A Harris, Rolling Bearing Analysis, 3rd Edition, John Wiley and Sons, 1991

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