DEVELOPMENT OF AN ACTUATOR FOR SOLAR-ARRAY DEPLOYMENT

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ABSTRACT

The aim of the project is to develop an engineering model of an actuator foreseen for the deployment of high power solar arrays.
The requirement of not using ITAR parts is essential for the commercialization of the product as the number of potential customers increases significantly. Although similar products exist, most of them underlie export restrictions and no sound tribological evaluation or other data is available.
The finished product consists of a redundant sealed brushed DC motor with a four-stage planetary gear head attached. The subassemblies and the whole unit were tested to show the compliance with the requirements.
Based on the outcome of the tests it was decided to go on with the project and to build, based on the EM, further models intended for flight on telecommunication satellites.
This paper reports the development process and the design of the actuator, and will focus on the different lubrication methods and test data obtained.

1. DESIGN

The actuator consists of a sealed electric motor with a planetary gear head attached. The gear motor is used to regulate the deployment speed, hence it must be designed for actuating and breaking. The load transmission from motor to gear head and vice versa is achieved with a magnetic coupler.

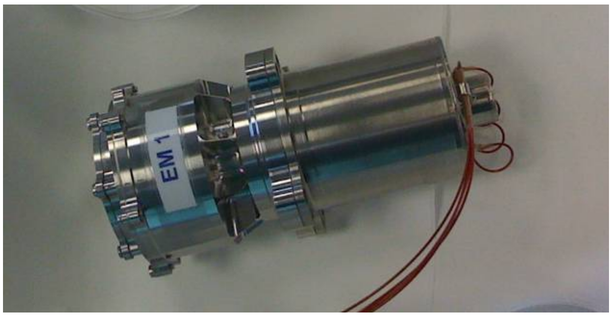

Figure 1. Gear motor

1.1 Motor

The advantage of a Sealed Brush DC Motor for space applications is:

- Direct power supply with simplified controller
- Motor sealed in a tight, air filled housing to solve the problem of reliability of the brushes behaviour under space vacuum (dust, arcing, high rate brush attrition)

The motor is derived from a previous development for a sealed motor. Its main features are:

- Redundant induced coils
- Designed torque constant : 0.151 Nm/A
- Housing leak rate < 10^{-7} mbar*l/s

Its characteristic curves are given here below.

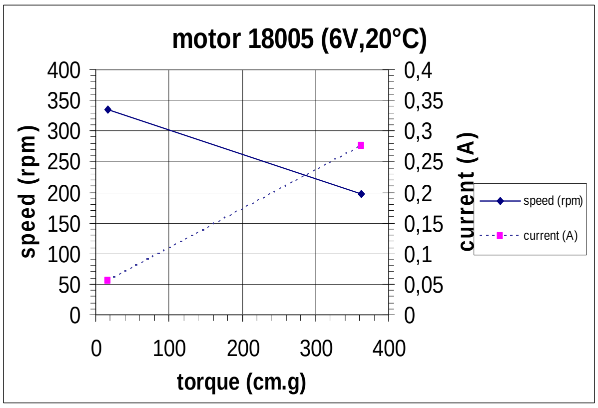

Figure 2. Motor characteristic

The torque transmission is performed by a magnetic coupler consisting of an inner rotor with magnets on the motor axis and an external hysteresis iron stack on gear axis. The torque is transmitted without slippage up to the coupler torque limit. Above the coupler limit value slippage occurs and the transmitted torque is constant.

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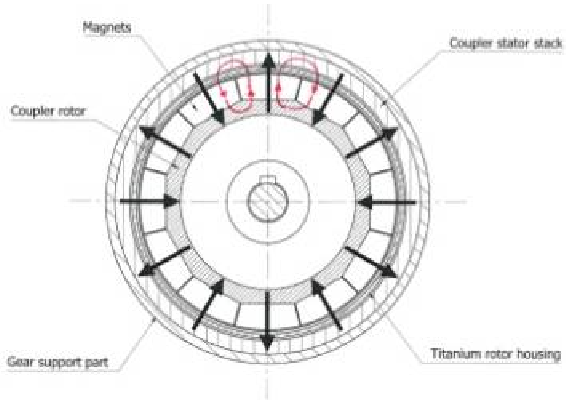

Figure 3. Cross-section of gear motor at coupler

1.2 Gear Head

The gear head is a four stage planetary gearbox with two small and two larger stages. The cogging was designed to meet the requirements (e.g. torque, high efficiency). For maximum efficiency deep groove ball bearings are used for the mounting of the planetary wheels. The gear head has a gear ration of around 1 to 2500. To limit shock and vibration loads on the bearings an axial preload system was implemented.

For a later comparison two models were built, one grease lubricated (Braycote 601EF) the other dry lubricated (sputtered MoS_2). Considering the requirements, the dry lubricated gear head was expected to have a more constant behaviour over the complete temperature range whereas the grease-lubricated should have a higher efficiency at higher temperatures.

2. REQUIREMENTS

Key requirements for the actuator are:

- Low mass, smaller than 1.4 kg
- Compact design, maximum overall envelope is a cylinder of 90mm diameter and 160mm length
- High efficiency compliant to ECSS rules permitting a sufficient motorization margin
- Operational temperature range: -65°C to +85°C
- Torque on output-axis up to 100 Nm, input and output
- No use of ITAR parts

The requirement of not using ITAR parts is essential for the commercialization of the product as the number of potential customers increases significantly.

3. TESTING

3.1 Gear Head Testing

Test Setup

The gear head has been tested using a dedicated test-rig in a vacuum chamber. A modified commercial of the shelf brushless-DC motor was used to drive the gear input. The only modification to the motor was the replacement of the bearings to allow operation in vacuum. The input motor was coupled to the gear using a torque-gauge for direct measurement of the input torque.

The load torque on the gear head output was generated by another gear-motor on the outside of the vacuum chamber. As the output torque can reach values up to 100 Nm a large rotary vacuum feed-through was necessary. The gear output torque was measured using a torque gauge and a closed loop regulation to control the output torque. Using this system, it is possible to vary the output load over the full operation range of the gear without manual intervention. Thanks to the closed loop regulation the load torque is independent of speed, rotation direction or load inertia.

Figure 4. Gear head test setup

Test Programme

The tests on gear head level were aimed at characterising the gear head performance over the full operational range. The following parameters have been varied from min to max values:

- Temperature
- Load torque
- Rotation speed
- Operation mode

Depending on the direction of the load torque and the rotation two operation modes are possible. In motor mode the gear rotates against the external load torque. In generator mode the gear rotates in the same direction as the load torque is acting. In the first case the input motor has to drive the load torque plus the gear friction torque. In generator mode the motor torque is equal to the load torque minus the friction torque.

A test sequence with different combinations of the above parameters has been applied on gear head level. After an initial characterisation a partial life tests was performed.

<u>Grease Lubricated</u>

The initial characterisation of the gear showed no significant difference at cold, ambient and hot temperatures for high load torques. For lower load torques the friction torque influence is higher and the efficiency is strongly affected by the temperature. The test runs at –65 °C revealed much higher friction torque levels and the efficiency was significant lower.

Temperature	**Efficiency**		
	14.1 Nm (motor mode)	45 Nm (motor mode)	100 Nm (generator mode)
–65 °C	0.41	0.57	0.81
Ambient	0.66	0.76	0.82
+85 °C	0.76	0.82	0.81

Table 1. Gear head efficiency

The gear head running behaviour was very smooth. The torque values were almost constant. Figure 5 shows the input torque during a test sequence with zero-running torque, and load torques of 14.1 Nm, 45 Nm and -100 Nm.

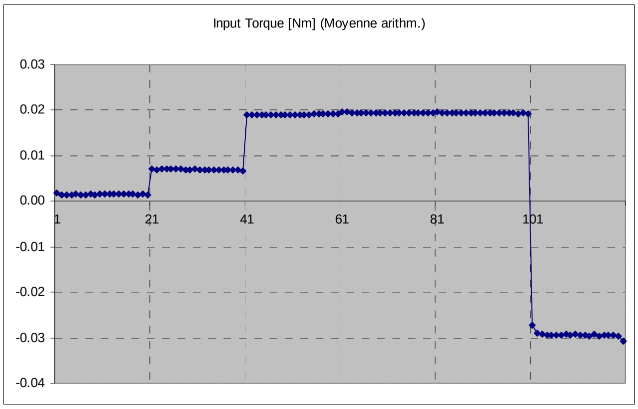

Figure 5. Input torque at varied load torques

Following the initial characterisation life cycling has been performed at cold, ambient and hot. No change of performance was observed over 75 revolutions at the gear output.

<u>Dry Lubricated</u>

For comparison, the same test sequence as for the wet lubricated gear was applied to the dry lubricated gear-head. The initial characterisation showed significant higher efficiency values especially at cold temperature and low load torques.

During life cycling the gear performance was very unsteady. The friction torque heavily increased over time. Figure 6 shows the friction torque during life testing at ambient, cold and hot.

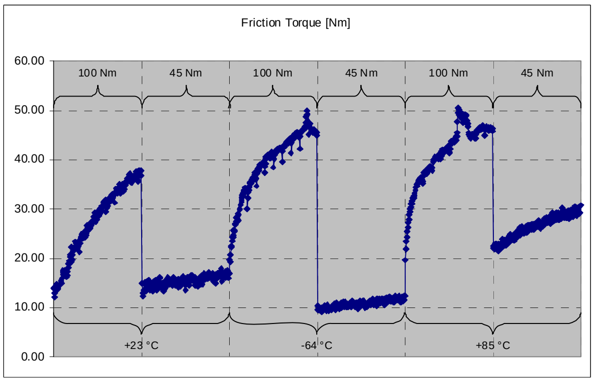

Figure 6. Dry gear friction torque during life testing

Following the performance test, the gear head has been disassembled and inspected. A pin of the axial preload system was worn down and a considerable amount of debris has been spread into the gears and the bearings.

Detailed analysis revealed an incident after the first 5 gear revolutions, which is equivalent to ~1200 cycles at the failed pin. Additional tests with this pin at ESTL confirmed that this pin design fails after the same count of revolutions.

3.2 Motor Testing

The measured EM motor characteristics are shown in the Figure below:

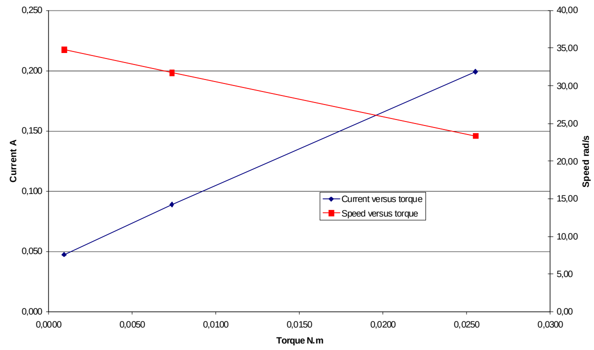

Figure 7. Measured motor characteristic

The measured torque constant is nine percent above the estimation. Additionally, following values where measured for the motor:

- Mass: 0.710 kg
- Coil resistance: 10 Ω
- Motor dry losses: 6 to $7*10^{-3}$ Nm
- Limit coupler torque: 0.035 Nm

3.3 Gear Motor Testing

The actuator has been submitted to the following test sequence:

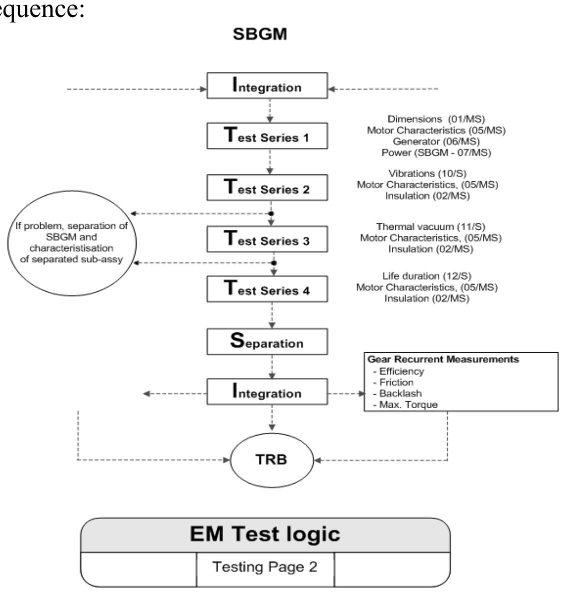

Figure 8. Gear motor test sequence

The main results of the gear motor tests are:

- In Motor mode, 14.1 Nm output torque and a voltage of 5.5 V, the SBGM generates:
  - Motor dry friction: 0.0060 Nm
  - Visquous friction: $0.12.10^{-4}$ Nm/rad/s
  - Gear efficiency: 0.58
  - Current: 0.097 A
  - Gear speed: 0.094 rpm
- ECSS motorisation margin at 0.22 A = 2.03, where:
  - T_{motor} = 95 Nm at gear output
  - T_{load} = 14.1 Nm
  - Sum of frictions: 26.5 Nm
- A gear input torque of 100 Nm in generator mode produces:
  - Voltage = 9.98 V
  - Current = 0.145 A
  - Rotational speed = 0.262 rpm

Friction torques measured at -65°C, +20°C and +85°C (in a no-load configuration) are given in the following figure:

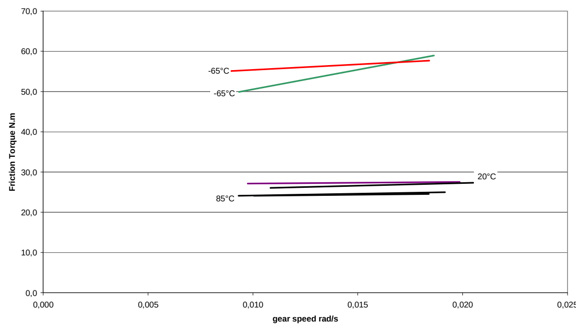

Figure 9. SBGM friction torques

In the worst case, at -65°C, the SBGM is able to produce the nominal torque of 14.1 Nm with a margin of 0.9 thus remains non compliant with ECSS rules.

Actuator friction values derived from no load measurements between 0.01 and 0.02 rad/s, at gear output are summarised in the following table:

	Actuator dry friction torque [Nm]	Actuator visquous frictions (at gear output) [Nm*s/rad]
-65°C	40 – 50	300 – 700
+20°C	25 – 30	50 – 130
+85°C	23 – 25	40 – 90

Table 2. No-load friction values

4. SUMMARY

The aim of the project was to develop an engineering model of an actuator designed for mechanism deployment, mainly high power solar arrays.
Key requirements for the actuator were: low mass, compact design, high efficiency, operational temperature between -65°C and +85°C, maximum torque on output-axis up to 100 Nm (input and output).
The finished product consists of a redundant sealed brushed DC motor with a four-stage planetary gear head attached. The subassemblies and the whole unit were tested on an engineering model submitted to a complete qualification test sequence.

5. LESSONS LEARNED

This project has led to a successful development of a sealed motor and of the associated planetary gear.

The comparison of the grease with the dry lubricated revealed that the dry lubricated is much more prone to failure. The failure wasn't caused at the bearings or the cogging but at the preload system of the gear stages. Therefore, the design concept will be reassessed and further tests are foreseen with dry lubrication.
The coupler performance has been successfully tested and it has been demonstrated that its limit torque value can be precisely adjusted.
The motor post test expertise shows a very good behaviour of the brushes and brings useful informations for upgrading some manufacturing processes (e.g. magnets redundant encapsulation).
The actuator tests confirm the non compliance in the worst cold case with respect to the ECSS motorization margin requirements. This non compliance will be solved after adaptations of the specifications. A Qualification Phase is starting; flight models are foreseen for early next year.