A SPACE QUALIFIED MECHANICAL SPEED REGULATOR FOR DEPLOYABLE DEVICES THAT PROVIDES SPEED CONTROL WITHOUT ELECTRICAL POWERING OR COMMANDING

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ABSTRACT

Based on the EADS CASA Espacio experience on flight deployment mechanisms, conventional spring motor appears like the most light and reliable method to perform one-way deployments, but this kind of deployment requires a controlled final speed to avoid the use of dampers and/or similar devices to minimize end-of-travel shocks. In order to avoid sophisticated mechanisms based in centrifugal or electromagnetic principles to get a fully controlled deployment speed EADS CASA Espacio has qualified a simple and reliable mechanical speed regulator without thermal and/or electrical powering or commanding.

This Mechanical speed regulator (Patent N^{er}: P9600684 – 27/03/00) has been developed and qualified in the frame of several space programmes: MINISAT Satellite (May 1997), DESAT project for HISPASAT C Satellite (1998), and ASAS and MIRAS deployable antennas (1999 – 2000) with a regulation capability up to 10 Nm. An extended qualification test campaign was performed to increase the functional environmental range.

1. INTRODUCTION

The main design concept of this mechanical speed regulator arrives from the main requirement : to control the speed during the deployment travel. That is, to control the movement along the time. This problem has been solved with traditional devices centuries ago. Mechanical devices that control the time step and used to measure the time works continuously everywhere, all the day, during years in several environments and in a reliable way. These mechanical devices are the clocks, and this is the basic principle of this mechanism.

The opening speed control is made by an escape mechanism, just the same one used by a clock to control the time. It consists of a double pawl and a gearwheel that are synchronized in such a way that the gearwheel is freed or retained alternatively by the pawl allowing a speed control of the main shaft, but without hindering the transmission of the torque from the motor spring to the main shaft allowing a smooth, safe and continuos structure deployment.

This device can be used either directly as a motor element (with the spring motor integrated; it was flown as an experiment on board of MINISAT Satellite) or simply as a speed regulator.

What has been qualified is not only a mechanism but also a mechanical concept (the escapement mechanism) able to work successfully in a space environment after undergoing the dynamic loads from the rocket launching. The design can be tailored to hold higher applied torque with the same deployment velocity.

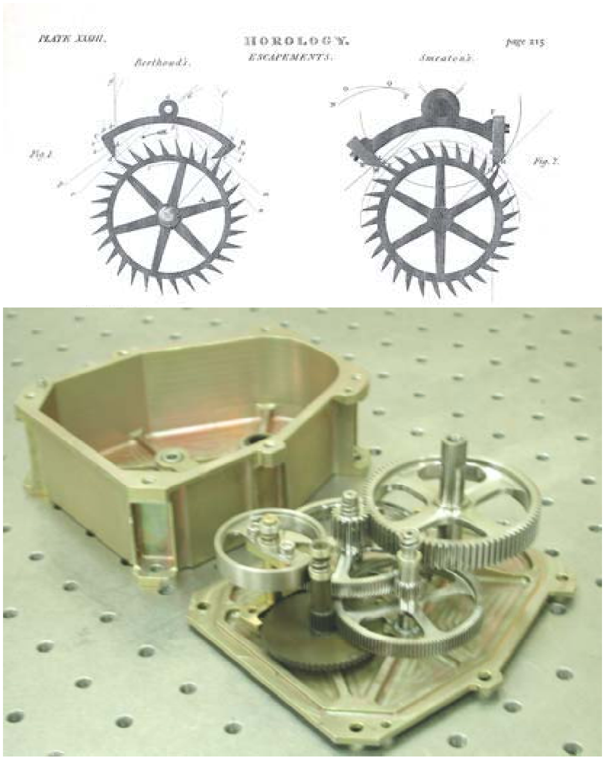


Figure 1 : Speed regulator and heritage

2. REQUIREMENTS

The design requirements for the speed regulator were built using data extracted from a variety of flight mechanism specifications in order to envelope most of the possible missions.

Environmental requirements :	
Stiffness (Hard-mounted)	> 100 Hz
Vacuum	< 10^{-6} Torr
Operating Temperature range	-60ºC to +80ºC
Non Operating Temperature range	-80ºC to +100ºC

Random Vibration :			
⊥ to Mounting Plane		// to Mounting Plane	
Range [Hz]	**Level**	**Range [Hz]**	**Level**
20 - 100	+6dB/oct	20 - 100	+6dB/oct
100 - 400	0.75 g^2/Hz	100 - 400	0.75 g^2/Hz
400 - 2000	-6 dB/oct	400 - 2000	-6 dB/oct
Global: 22.16g RMS		Global: 22.16g RMS	

Functional Requirements :	
Total Mass	< 0.5 Kg
Max. Radial Loads at input shaft	150 N at 15 mm from mounting plane
Max. Axial Loads at input shaft	150 N
Max. Constant Input Torque	10 N·m
Lifetime under 10 N·m torque	>100 turns* at 20 ºC and vacuum
Speed	< 2.5 deg/sec at 10 N·m
Electrical Power Supply	none
Active Thermal Control Necessity	none**
Stored Life	10 years

* 1 cycle = 2 complete turns of input shaft
** considering the wide range of functional temperatures, passive thermal control will be sufficient in most of the cases.

Shock Spectrum : the following profile is applied to the worst direction (qualification level).

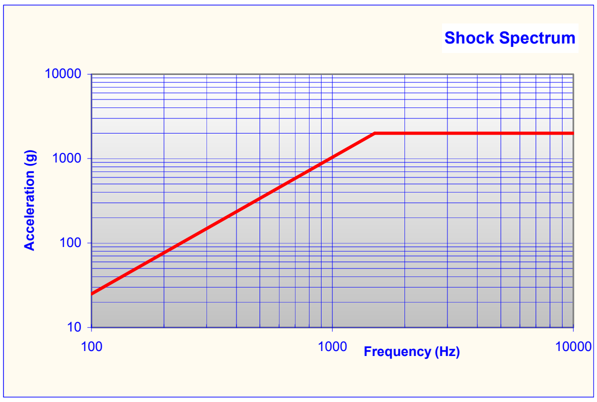


Figure 2 : Shock requirement

3. DESIGN

The mechanical speed regulator is designed to limit the angular speed of the output shaft as a function of the motor torque. This speed is in the range of 0.9 deg/s to 1.5 deg/s depending on the input torque.
The main parts of the mechanical speed regulator are:

- Gearbox
- Escapement Mechanism
- Housing

Gearbox : It is composed of four gear stages. It has been selected straight tooth gears and a gearbox ratio of about 200:1. Dissimilar and self-lubricant materials have been used to avoid cold welding. Shafts of 2^{nd}, 3^{rd} and 4^{th} stages of gearbox and the escapement mechanism, subjected to high speed with moderate loads, are mounted on micro-ball bearings. Shafts of the 1^{st} gearbox stage, subjected to low speed with bigger loads, are mounted on Vespel® bushings.

Escapement : Performs the angular speed control of the last gear. The escapement wheel rotation is controlled through the flywheel, designed with a specific pawl teeth profile. The flywheel alternatively holds and releases the escapement wheel with a designed time period. Two parameters drive the angular speed with respect to a reference input torque:

- Mass and inertia of the flywheel
- Pawl – Escapement Wheel teeth profiles

Housing : This is an aluminium alloy box, made in two pieces, where the different parts are accommodated. Supports all the mechanical loads and has a stiffness higher than 250 Hz.

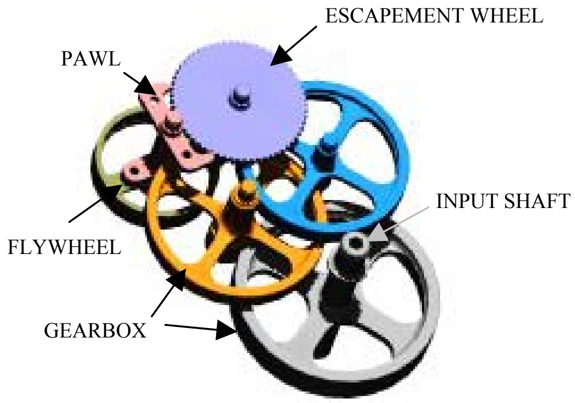


Figure 3 : Main parts

<u>Mechanical interfaces</u>:

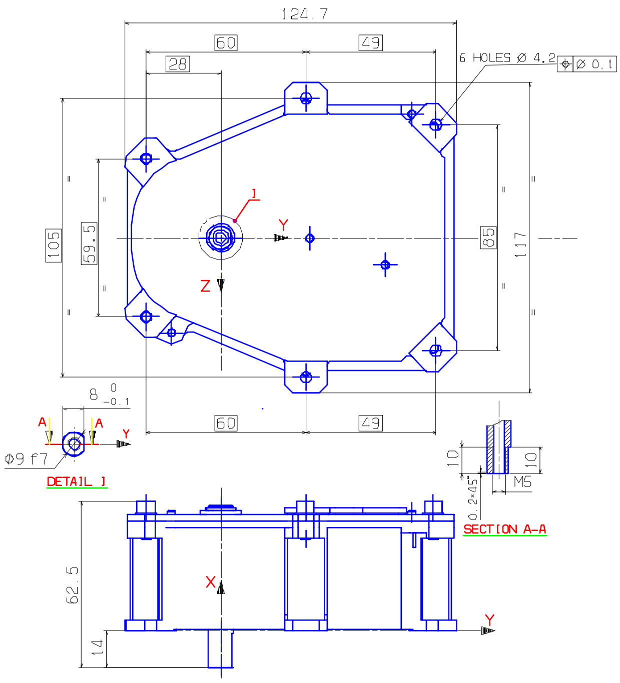


Figure 4 : Main dimensions

Box Envelope	125 x 117 x 50 mm
Mounting Bolts	6 x M4 bolts
Input Shaft	Ø 9 x 14 mm

The speed regulator is able to control the angular speed of a torque-powered shaft. The speed is a quasi-linear function of the input torque. The main functional characteristics are:

Directions of rotation
Two directions Clockwise & Counterclockwise
Max. measured friction (peak)
0.7 N·m (corresponds to static friction)
Min. measured friction (valley)
0.219 N·m (corresponds to dynamic friction)
Speed variation along lifetime
from 0 to 50 % of the initial speed (progressive increase from the beginning to the end of lifetime.)
Peak Input Torque
12 N·m (In both directions of rotation)
Input shaft Torsional Stiffness
980 N·m/rad (In both directions of rotation)
Max. Backlash
± 0.152 deg (After lifetime).

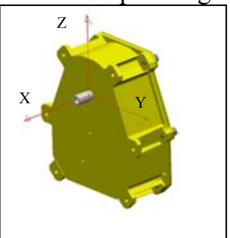
4. QUALIFICATION TESTS

Qualification tests has been made according to the following sequence:

- ☑ Gearbox running-in
- ☑ Mass properties measurement
- ☑ Electrical bonding measurement
- ☑ Functional Test I
- ☑ Quasistatic Test
- ☑ Functional Test II
- ☑ Random Vibration Tests
- ☑ Functional Test III
- ☑ Thermal Vacuum Tests
- ☑ Lifetime Test in Vacuum
- ☑ Functional Test IV
- ☑ Shock Test
- ☑ Functional Test V

Gearbox running-in : To check the gearbox state of health. Running during 60 minutes in each direction.
Mass properties measurement : To determine the mass and the center of mass of the speed regulator.

Datum	Value
Mass	410 grs
X_{CoM}	-23 mm
Y_{CoM}	4 mm
Z_{CoM}	-31 mm



Electrical bonding : < 5 mΩ It is not recommended to use the Mechanical Speed Regulator as bonding path for a mechanism. This feature is usually performed by a metallic spring motor, which connects the deployable items with fixed items.

Quasistatic Test : It was checked the positive margins of safety after maximum torque (12.5 N·m) applied.
Random Vibration Tests : Performances were not degraded after applying the specified random vibration levels. The specimen was tested with the input shaft unsupported (free). Maximum measured acceleration was 33.0 g RMS in X direction.
Functional Tests Envelope : Carried out to measure Speed-Torque values and internal friction. <u>Static Friction</u>: the required torque to start the motion. <u>Dynamic Friction</u>: once in motion, the torque at the point when rotation is stopped. Speed-Torque variation along temperature excursion in vacuum :

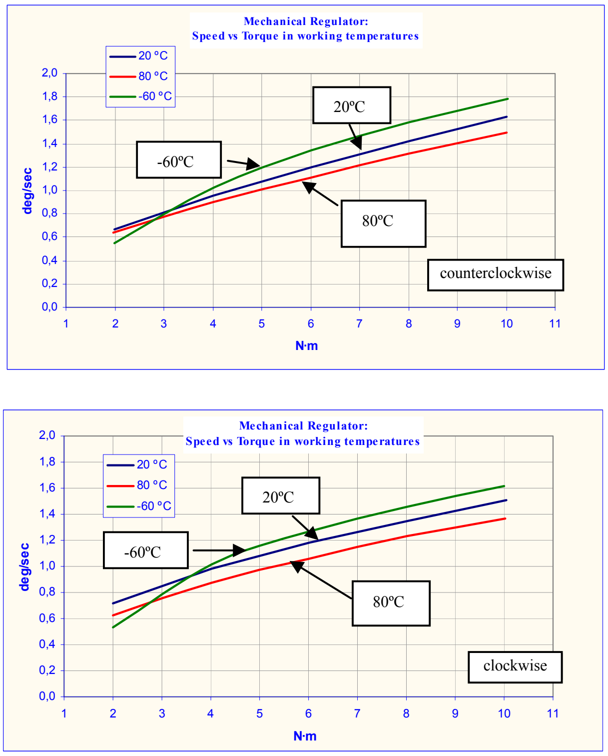


Figure 5 : Speed - Torque variations

Envelope of all the measured speeds (clockwise and counter-clockwise) along the qualification test champaign.

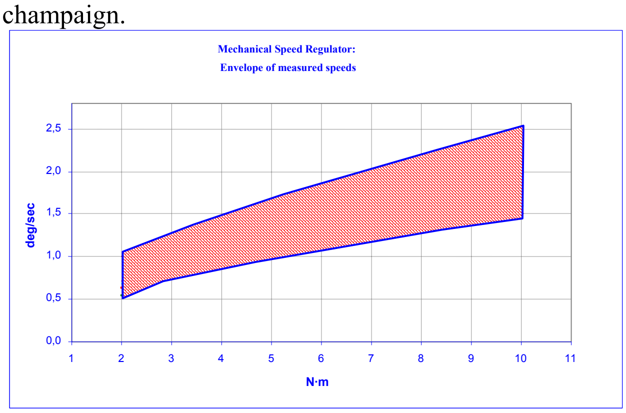


Figure 6 : Speed - Torque envelope

Friction values at maximum hot and cold operational temperatures are shown in the next graphs.

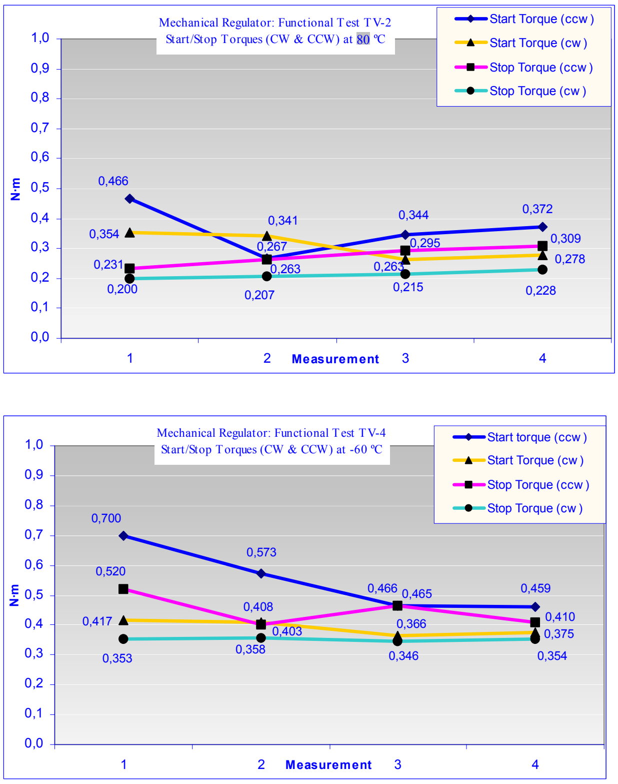


Figure 7 : Friction values

Lifetime Test in Vacuum : The specimen meets the lifetime requirements at maximum continuous input torque (10 N·m).

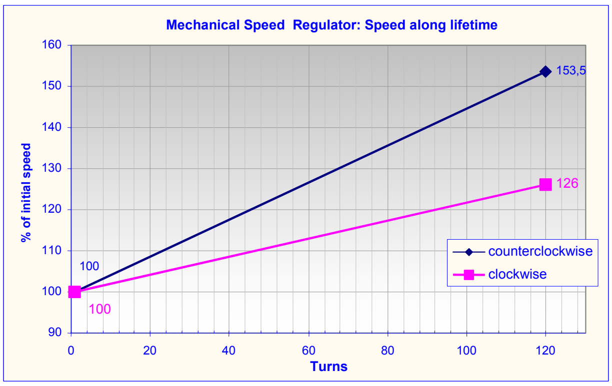


Figure 8 : Speed variation along lifetime

Initial Speeds (100 %): 1.6 deg/sec (counterclockwise) and 1.51 deg/sec (clockwise). With this plot, it is possible to determine the effective lifetime versus speed variations. For example, speed values within 150 % of the initial value are achieved with a lifetime of 110 complete turns (more than 2 turns per cycle).

The regulated speed shows values within the 126 % of the reference value for clockwise run and 154% for counterclockwise run at virtually any input torque. This change is justified by the extreme lifetime test (120 turns per sense), where wearing becomes relevant. For reference purposes, the escapement mechanism (in particular the Pawl) worked more than 3.8 million times. This produces a wear which can modify the teeth geometry , and the subsequent regulation performances.

It is also noted that velocity increases more rapidly in the counterclockwise rotation. It is explained by the non-symmetric geometry of the escapement mechanism.

Shock Test : The following plot shows the accelerometer measurement in the X-direction of the Mechanical Speed Regulator, being the maximum shock test:

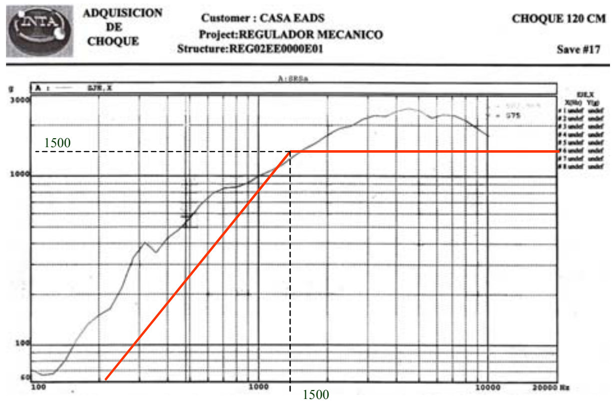


Figure 9 : Shock response

5. PERFORMANCES

A summary of the performances is present below :

Stiffness:> 250 Hz (hardmounted)
Vacuum:<10-6 Torr
Operating Temperature Range:+80 ºC ÷ -60 ºC
Non Operating Temperature Range:+100 ºC ÷ -80 ºC
VCM content (calculated):0.0015 mg (max.) (test method SP-R-0022A)
Total Mass:< 500 g
CoG offset from I/F plane:23 mm
Max. Radial Loads at input shaft:150 N at 15 mm from mounting plane
Max. Axial Loads at input shaft:150 N
Max. Constant Input Torque:10 N·m
Max. Peak Input Torque:12 N·m
Lifetime under 10 N·m torque:> 100 turns per sense of rotation at 20 ºC and vacuum
Speed:< 2.5 deg/sec at 10 N·m (After Lifetime)
Max. rotation degrees:Up to 2.0 revolutions per cycle
Senses of rotation:2 senses
Max. measured friction:0.7 N·m (peak of static friction)
Min. measured friction:0.219 N·m (valley of dynamic friction)
Speed variation along lifetime:from 0 to 50 % of the initial speed (progressive increase from the beginning to the end of lifetime).
Input Shaft Torsional Stiffness:> 980 N·m/rad
Max. Backlash: ± 0.152 deg (after lifetime)
Electrical Power Supply: none
Active Thermal Control Necessity: none
Stored Life: 10 years
Input Shaft Material: Titanium Alloy.
Reliability = 0.9999984. Include structural reliability (0.9999996) and functional reliability (0.9999988).

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