Limited angel torque actuator for fine angular positioning

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Abstract:
A Limited Angle Torque (LAT) actuator has been designed by Cedrat upon request of the European Space Agency (ESA) for fine pointing applications based on gimbals assembly. The required angular stroke for this application is 13°. Other required features are controllability, high resolution, no micro vibration. Therefore the selected concept is a coil-redounded electromagnetic actuator using Lorentz force. The functional test shows that the generated torque is linear until 200mN.m, but torques up to 300mN.m are achievable. The torque constant of the designed LAT is about 0.167 N.m/A and the motor constant is about 0.048 N.m/√W all along the 13° angular stroke. Performed environmental tests include thermal vacuum cycling tests as well as 50 thermal shocks to evaluate the over-moulding robustness. The objective of the paper is to describe the space application requirements, the actuator design, the performed tests, the test results and the lessons learned.

Keywords: Fine angular positioning, Lorentz actuation.

Introduction

A Limited Angle Torque (LAT) actuator has been designed by Cedrat upon request of the European Space Agency (ESA) for fine pointing applications based on gimbals assembly. The required angular stroke for this application is 13°. Other required features are controllability, high resolution, no micro vibration. Therefore electromagnetic actuators have been preferred to piezoelectric actuators or piezoelectric motors. Although those technologies have already been used in space mechanisms [1-4], there are very few European companies which produce those actuators for the space market.

For a new accurate pointing application based on a gimbal assembly, a new Limited angle Torque (LAT) actuator has been designed and tested [5]. Moreover, the Limited Angle Torque actuator was submitted to thermal shocks and a thermal vacuum burn-in test. This paper introduces the design and test activities around this actuator.

Technology solution

Several configurations of electromagnetic motors are dedicated to rotary motion. In the case of pointing applications, the selection between them is made according to the following requirements:

- creation of a pure torque,
- coils at the stator side to evacuate the Joule's losses,
- redounded actuations strategy,
- constant torque over the limited angle,
- low electrical time constant,
- linear torque versus the driving current.

To comply with these requirements, the use of Lorentz force is mandatory, since in alternative designs (variable reluctant actuator [6], moving magnet actuator [7]) the reluctant force would create some cogging forces. The last alternative consists in Conventional design, which is based on a regular Permanent Magnet Brushless (BLDC) motor, in which a laminated stack of the Armature Assembly consists of the slots, teeth and the back iron. Those solutions have their pros and cons. The most important drawbacks of the BLDC motors are the high electrical time constant and cogging torque. The voice coil motors (VCM) are well adapted to avoid the limitations of the BLDC motor. Nevertheless, the angular VCM has a low torque. The critical point of the VCM is the heat elevation, especially in the radiation case (space). The LAT, as well as the VCM, is the Lorentz force motor which implies a non cogging torque. The comparison between these solutions is given hereafter (Tab. 1)

BLDC motor	LAT	VCM
High torque	Lower torque	Lowest torque
High motor constant	Lower motor constant	Lowest motor constant
High hysteresis and eddy current losses	Low hysteresis and eddy current losses	No hysteresis and eddy current losses
High cogging torque	No cogging torque	No cogging torque
High electrical constant time	Lower electrical constant time	Lowest electrical constant time
Best heat dissipation	Good heat dissipation	Heat dissipation may problematic
Large sensitivity to rotor out-centring	Medium sensitivity to rotor out-centring	No sensitivity to rotor out-centring

Tab. 1 : Electromagnetic motors comparison

It was concluded that the LAT represents the best trade-off for the given requirements. A deeper study of this solution is done here after.

Design

The LAT is composed of a conducting rotor supporting the permanent magnets. The stator is based on a conducting torus, supporting a toroidal wounded coil. The change of dynamic behaviour of the LAT is dependent on its shape.

The geometry

Various shapes of LAT (Fig. 1) could be designed. The FLUX® [9] software has been used to estimate the actuator's behaviour and for the sensitivity study. The sensitivity of the properties and performances to dimensional changes (gap diameter, the depth and coil thickness) were analysed. The optimal solution corresponds to the highest motor constant and mass ratio (K_{MW}) :

$$K_{MW} = \frac{N.m}{Kg.\sqrt{W}},$$

Where :

- N.m is the produced torque,
- W is the dissipated power,
- Kg is the mass.

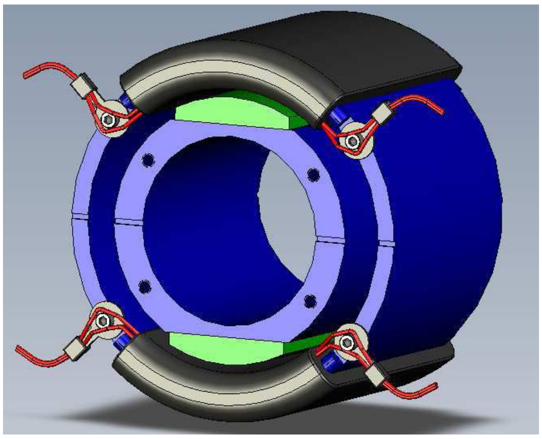

Fig. 1 : CAD view of the LAT

Because one part of the coils is located on the outer diameter, it was preferred to over mould the coils with a dedicated potting. Samarium-Cobalt (SmCo) magnets have been selected for their very stable behaviour over a large temperature range, despite their lower intrinsic energy. Finally, two redundant coils were wound up. Space qualified materials have been used for the prototype.

The redundancy scheme

For the redundancy, two coils must be wound upon the magnetic torus. The redundancy strategy should satisfy the failure propagation aspects and the dynamical behaviour.

On the fist solution, both coils are placed on different position on the torus (Fig. 2). The horizontal configuration is better from a failure propagation point of view. Nevertheless, the magnetic field generated from the nominal coil (the redounded coil is not excited) flows over the whole torus thus increasing the induction and the electrical time constant in the same way. The second solution consists in the vertical symmetry. Each coil is divided on two parts (Fig. 3). In this case, the magnetic flux of the nominal coil flows in opposite directions through the torus. This implies a low electrical time constant. The half coils are separated by a polyester segregation before the overmoulding.

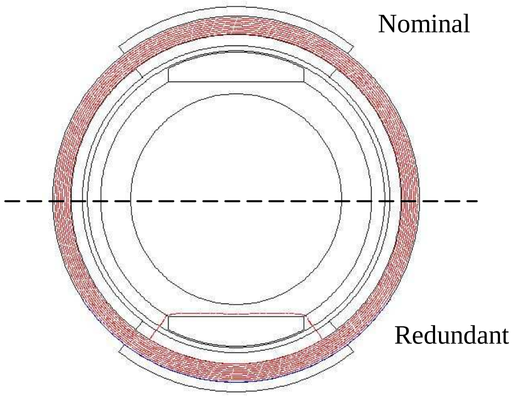

Fig. 2 : Redundancy on the horizontal configuration

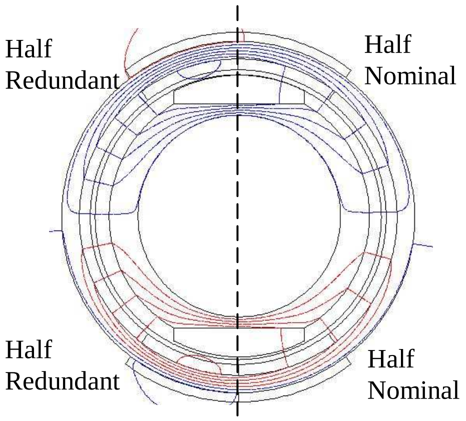

Fig. 3 : Redundancy on the vertical configuration

Thermal consideration

The FLUX® software was also used to evaluate the thermal worst case assuming radiative and conductive thermal paths (Fig. 4). The self heating of the coil is around 30 °C, assuming one third of the thermal dissipation is evacuated by conduction through the torus. Thus, the heat elevation is computed for the nominal torque applied (100 mN.m).

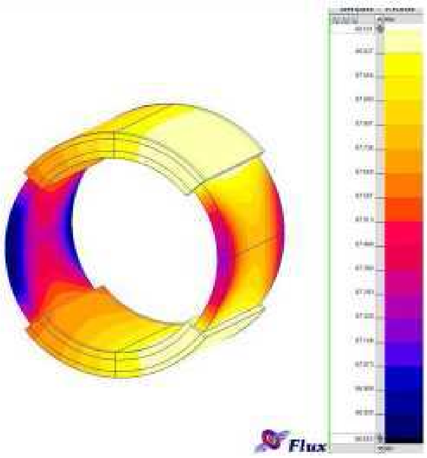

Fig. 4 : Heat elevation on the LAT

The design of the LAT has been optimized for a better motor constant/weight ratio. The redundancy of the coil has been chosen based on the lowest electrical time constant motor. And the heat elevation has been evaluated for a continuous applied torque.

Test campaign

The Limited Angle Torque actuator (LAT100) has been integrated (Fig. 5). The LAT has been tested on a dedicated test bench. This test bench included (Fig. 6):

- two flexible pivots,
- a differential eddy current sensor to read the angular position,
- a force sensor able to read the torque.

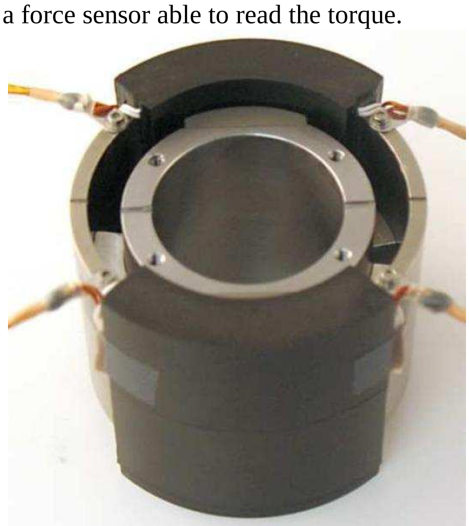

Fig. 5 : The first LAT prototype

The acceptance functional cycles shows that the behaviour of the LAT is linear until 200 mN.m. The measurement on both the nominal and redundant coils, of the produced torque versus the angular position requires some particular care. The actuator was then subjected to an evaluation campaign including:

- functional tests,
- 50 thermal shocks to evaluate the robustness of the over-moulding,
- a thermal-vacuum test including 2 storage cycles and 6 functional cycles.

No particular change in the actuator's behaviour was noticed. As expected, the electrical impedance depends on the temperature.

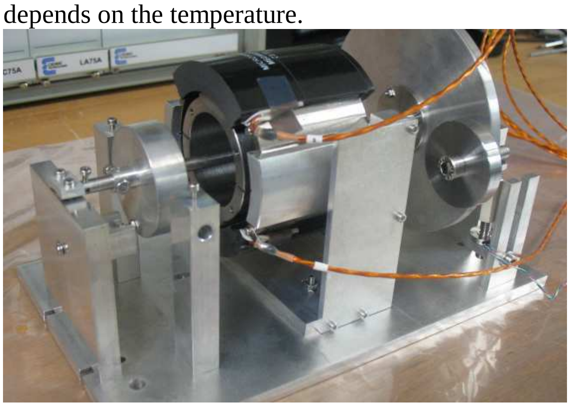

Fig. 6 : The LAT installed on its test bench

Results

The obtained functional performances are compared in the table below (Tab. 2). Some functional tests were performed both on the nominal and redundant coils. Some comparisons with the magnetic modelling have been used to explain the difference on the motor constant between the nominal and the redundant coils (Fig. 7 and Fig. 8). For instance, the magnets (if none are centred) can lead to a local magnetic saturation of the torus, which further causes a change of the motor constant (K_M).

	Units	Design		Measured
		2D	3D	
Kt	N.m/A	0.207	0.157	0.167
Km	N.m/√W	0.059	0.045	0.048
L	mH	12	15	15.2
R	Ohm	12.07	12.07	12.25

Tab. 2 : Performances from the functional test

The torque sensitivity (K_T) of the LAT is measured during the functional cycling at the high and low temperature plateau [70, -30] °C. The variation in torque sensitivity is less than 2 % at the high plateau and rises to 8 % for the low plateau.

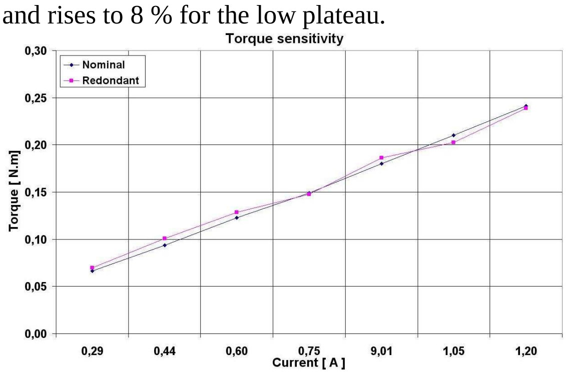

Fig. 7 : The torque vs. Current curve

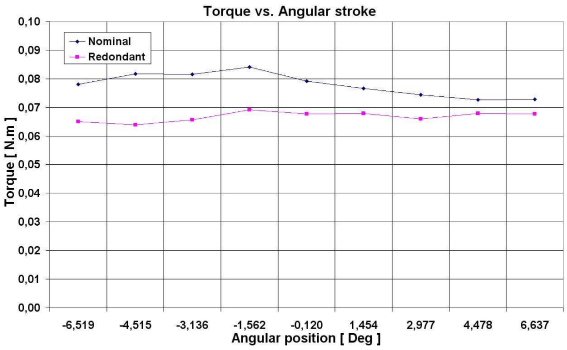

Fig. 8 : Torque variation over the angular stroke

Discuss

Several lessons have been learned from this test campaign:

- to design an adequate tool to ensure a good centring of the rotor versus the stator and a good angular indexing,
- to include some metrology check of this centring,
- to follow the coil's temperature in thermal vacuum conditions though the resistance changes.

The LAT was driven by a linear amplifier LA24 from CEDRAT TECHNOLOGIES SA. The high signal to noise ratio of the amplifier (90 dB) allows us reaching a torque resolution of 25 µN.m, limited by the angular position sensor resolution.

This technological development is available for linear Voice Coil Motors [10] that find typical applications in Fourier Transform spectrometers, or for two DOF pointing mechanisms.

Outlooks

Several solutions (including the number of poles) can be compared, as it was done in [1]. This approach shows the interest to reduce the air gap. Thus, the design could be adapted to the applied duty cycle between the cylindrical and disc shape LAT.

The actual design of the LAT, the internal part of the toroidal winding (the internal diameter of the torus) is subjected to the magnetic field. Unlike the external diameter of the torus, the winding does not contribute to the generated torque. Then, an important part of the consumed power is not exploited. A folded rotor configuration increases the torque sensitivity (K_T) and the motor constant (K_M). Nevertheless, an additional mass is to be expected due to the shape changes of the rotor. This implies a decrease of the motor constant and the mass ratio (K_{MW}).

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