FPSA & BSMA: Nanometric positioning actuators for ground and space applications

F. Barillot, J. Rebufa, J. Stentz, A. Guignabert, F. Claeyssen,
CEDRAT TECHNOLOGIES, 38240 Meylan, FRANCE, francois.barillot@cedrat-tec.com

Abstract

Many applications and more specifically space projects show need for a stable sub-micrometre positioning actuator. In order to meet this need, Cedrat Technologies has designed the new FSPA brand. This linear stepping actuator offers sub-micrometric positioning resolution along 5mm stroke combined with high actuation force (>100N) and the ability to hold its position without power.

The IASI-NG instrument is one of the key payload on-board METOP-SG which is a new meteorological satellite for Europe. The instrument is based on a Mertz interferometer and requires a very precise positioning of an optical blade used to separate the interferometer's branches. A dedicated version of the FSPA, the Beam Splitter Mechanisms Actuator (BSMA) is then developed to achieve this nanometric positioning which is a key parameter for the overall instrument performance.

This paper firsts present the internals of both FSPA and BSMA actuators. Major design differences and their respective impact on the resulting performances are detailed. Results from the acceptance and qualification test campaigns are also presented.

1 Standard fine stepping piezoelectric actuator (FSPA)

1.1 Introduction

The FSPA is a new brand of patented motors of Cedrat Technologies. This motor is mainly proposed for industrial and laboratory applications [1].

However, the compact design (**Figure 1**) and vacuum compatibility is an opportunity for low cost space applications such as microsatellites. Its main advantages are:

- typical stepping size adjustable from 50nm to 250nm,
- fine mode with resolution better than 10nm
- 5 mm displacement range with up to 120 N driving force (**Figure 2**),
- compact casing (Ø50mm x 45mm) and low mass (150g),
- hold position while unpowered against forces that can exceed 1kN,
- end-stops that passively prevent the motor from exceeding its operational stroke even in case of a faulty command from the user.

Figure 1. FSPA35XS & Driving electronic

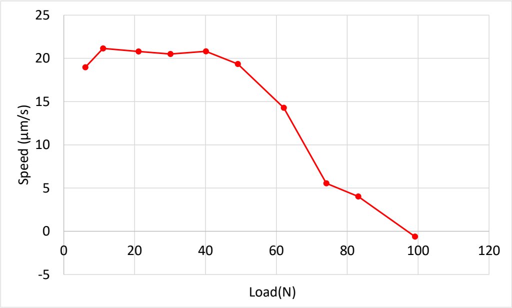

Figure 2. Speed vs load curve for FSPA35XS

1.2 FSPA architecture and design

The FSPA motor is a combination of a Rotating Stepping Piezoelectric Actuator (RSPA) with a differential screw.

The RSPA is stick-slip rotating piezoelectric motor [2]. Figure 3 shows the two phases needed to produce one step. First, a slow contraction of the actuator generates a rotation of the output shaft. Then, a fast actuator expansion generates dynamic forces due to the output shaft inertia. These forces overcome the friction forces that connect the actuator to the output shaft. The shaft then mostly stays in place while the actuator returns to its initial position. By repeating this operation, rotation of the output shaft is achieved.

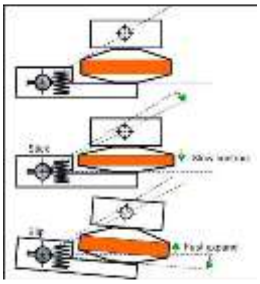

Figure 3. RSPA principle

In order to make a FSPA, the RSPA module is connected to a differential screw as shown in Figure 4. The differential screw converts the rotation movement of the RSPA's rotor into a translation movement of the output shaft.
The specificity of the differential screw is that, for each turn of the rotor, the output shaft will move by only the stepping difference of the screws. Large threads can still be used while preserving a high resolution. However, it has to be noted that the rotor translation may be much larger than the output shaft's one.

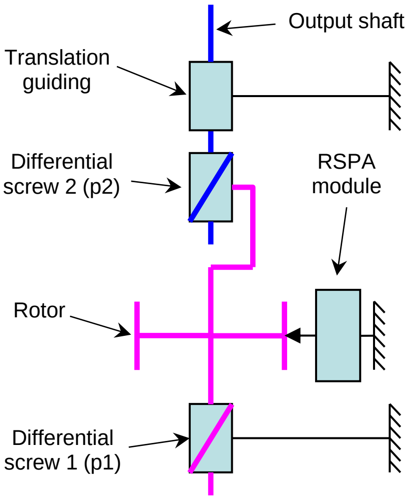

Figure 4. Cinematic chain of FSPA

2 IASI-NG Instrument

Figure 5. IASI NG Interferometer Mechanism (Courtesy of Airbus DS)

The Interferometer embeds a beam splitter blade. The blade tip-tilt positioning is critical with respect to IASI NG performances. Two BSMAs are then implemented to readjust in orbit the Beam Splitter Tip/Tilt alignment. They provide a linear motion to lever arms acting either in push-push or push-pull to provide both axis tilt.
An additional "vibration mode" (small oscillations at high frequency) is needed to assess the dynamic sensitivity.

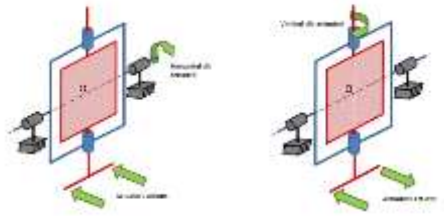

Figure 3. BSMA actuators "push-pull" configuration inside ISASI-NG instrument (Courtesy of Airbus DS)

Major BSMA requirements are

- Cold redundancy for every functions
- Stroke: +/- 40µm
- Stepping resolution: 30nm
- Non powered stability:
    - 0.15 µm over 24h/1K
    - 0.30 µm over 6 months
    - 1,4 µm long term
- Position sensor to validate step achievement
- Vibration mode: 0.8 µm, 10-70Hz

3 BSMA design

3.1 General architecture

Figure 6. BSMA EM with connector saver

The core BSMA is based on the combination of the following elements:

- Fine Stepping Piezoelectric Actuator (FSPA): these piezoelectric motors provide a 320µm displacement range and a smaller than 50nm resolution,
- Parallel Pre-stressed Actuators (PPA): these actuators are used to generate the sine oscillations for the vibration mode.
- Eddy Current Sensor (ECS): these sensors are used to monitor the effective position of the BSMA output shaft.

In order to achieve cold redundancy, each of these elements have to be doubled inside the BSMA.

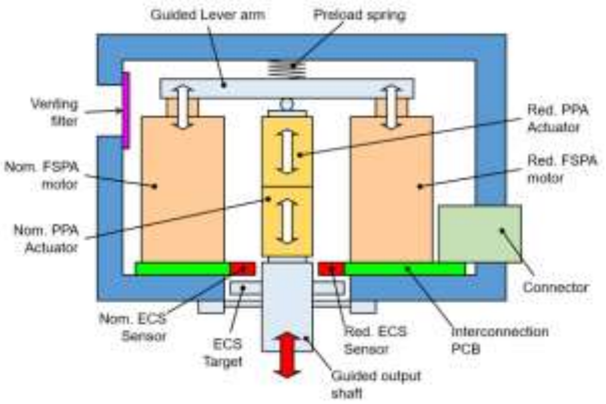

Figure 7. BSMA internal architecture

Electrical interconnection of the components is achieved through a multilayer PCB that also includes the ECS sensors. A single SUB-D connector is then attached on the side of the BSMA to connect the harness.

3.2 Eddy Current Sensor (ECS)

An eddy current sensor [3] is used to monitor short term position of the BSMA. Each sensor is composed of a coil included in the interconnection PCB and of an aluminium target. When the coil is powered by a 0.5 MHz current, the target position can then be recovered through the measurement of the coil's impedance variation.

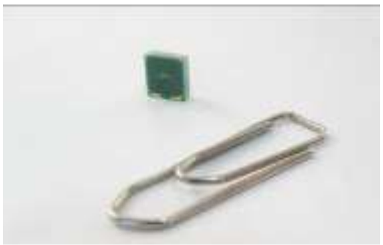

Figure 8. Standard 500µm ECS probe

3.3 Magnetic clutch

A magnetic clutch was then added to disconnect the rotor from the RSPA module. This active clutch offers several advantages:

- RSPA driving current is significantly reduced,
- Larger torque can be transmitted to the rotor,
- Compliance with margins required by space standards is much easier to demonstrate.

However, several constraints had to be considered during the design of the clutch:

- Passive (i.e. unpowered) locking during launch,
- High reliability to achieve more than a million steps,
- Generated heat during operation needs to be minimised to preserve position stability.

The clutch is basically based on 6 pallets driven by a single central coil (**Figure 9**). Each pallet can rotate around a flexible blade when the magnetic coil is powered. At the pallet extremity is a friction tooth that will interface with the rotor and transmit torque from the RSPA module.

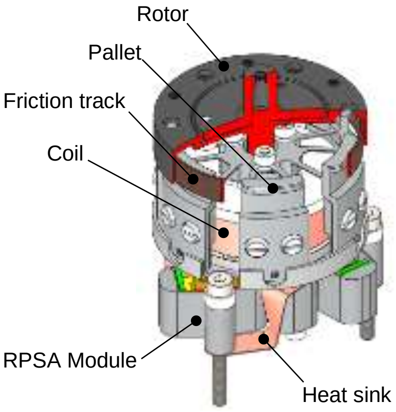

Figure 9. Clutch & cut view of Rotor over RSPA module

A permanent magnet ensures a magnetic flux remains present even while the coil is unpowered, thus ensuring the clamp closure during launch.

Performances of the clutch were optimised using magnetic simulation (**Figure 10**) in order to minimize its dimensions and heating while providing sufficient forces to ensure torque transmission.

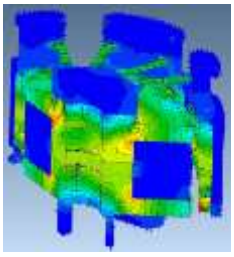

Figure 10. Clutch magnetic simulation

Figure 11. Flexible pivot stress simulation

Specific attention was also needed for the design of the flexible blades in order to ensure a high transmission stiffness while preserving a low flexure stress and flexure stiffness.

High strength steel was used to ensure a >99% reliability of the clamp regarding the fatigue effect over lifetime.

4 Step size and repeatability

A major characteristic of the BMSA is its ability to generate very small steps.

Step sizes are then measured when cycling over the complete operational range (**Figure 12**). Note that average displacements (black curves) for 5 consecutive steps show, over the complete range, a very stable behaviour for both motors.

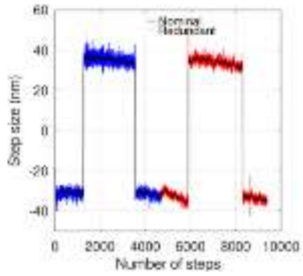

Figure 12. EM3 Measured step size for nominal & redundant, black is sliding average of 5 points

Another very interesting feature of BSMA is its capability to reverse direction without any significant backlash (**Figure 13**) nor step size variation.

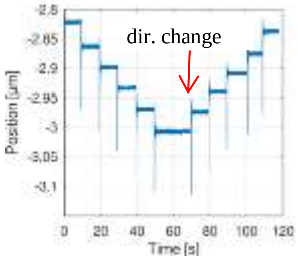

Figure 13. Position using laser interferometer during direction change (EM3)

5 Stability tests

One crucial requirement is to verify the stability of the BSMA position over time. A dedicated test bench (**Figure 14**) is designed and built to verify this performance. It is based on a 3 channels fibered infrared laser interferometer, operated in vacuum, and includes a closed loop thermal control that allows a 0.2K peak-peak stability.

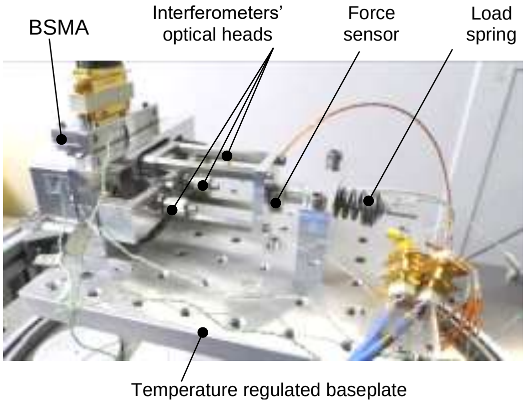

Figure 14. BSMA stability test bench

Using the test bench, the required +/-150nm stability over 24h is then demonstrated (**Figure 15**).

It has to be noted that the test bench temperature variations are deemed responsible for a significant (if not most) of the position variations.

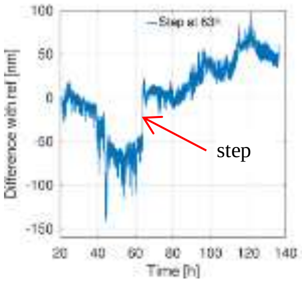

Figure 15. EM3 Post-processed position during 140h stability test

6 EM3 vibration test & lifetime

A first lifetime test is performed. The nominal motor performed about 1 000 000 steps, covering about 200 operational ranges (50% of qualification lifetime).

Following this test and in order to simulate launch conditions, 26g sine and 6g to 11g RMS random vibrations spectrums were applied to EM3 on all 3 axes.

It has to be noted that the motor moved during this test, which was not expected. However, no damage occurred during the test and that the BSMA was still fully functional after vibration tests.

7 Conclusion

The FSPA and its BSMA derived space variant are presented in this paper. These new mechanisms demonstrate extremely fine positioning capability (~40 nm steps) while being robust to space environments.

This paper also presents test results showing the stepping resolution, and stability performances.

As of November 2020, already 3 prototypes and 3 flight models (FM) have been manufactured, tested, and delivered to Airbus DS. Another 5 additional FM are in production or under testing. Part of the FSPA works has been funded by EU GA 831795 AUDACITY

Literature

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