Nanometric positioning with IASI-NG ‘s Beam Splitter Mechanism Actuator

Francois Barillot*, Jocelyn Rebufa*, Gladys Jaussaud* and Adrien Guignabert *

Abstract

This paper presents a piezoelectric motor which provides linear motion and very high resolution (40 nm steps). First, the space application (IASI-NG instrument onboard METOP-SG satellite) and associated performance requirements are presented. The internal architecture of the motor and its main components are then explained. A first focus is done on the experimental verification of the threaded interface lifetime which is a key element of the mechanism. A second focus is on the nanometric position test bench. Achieved results are provided for resolution, motion quality and position stability. Finally, results from the vibration test campaign are presented.

Introduction

Many space projects have shown need for stable sub-micrometer positioning linear actuators. They are typically needed to adjust the mirror position of sensitive optical instruments after launch during initialization or throughout flight life to accommodate aging and other long-term variations. In addition, as long periods can be expected between position changes, it is mandatory that the actuator remains passive (i.e., not powered) once the adequate position is achieved. This need is met in the IASI-NG space instrument, where a linear actuator offering a 30-nm step resolution and an unpowered position stability of 0.30 µm over 6 months was requested. Combined with the requirement of surviving launch, these specifications are beyond the capacity of existing linear piezo motors. For example, in [1] the piezomotor survival against vibration loads was not proven. Such external forces will apply directly on both the motor friction surface and the piezo ceramic and may damage the motor. This can be circumvented using a launch lock mechanism at a price of added mass and complexity.

In order to meet such a need, Cedrat Technologies (CTEC) has built a hybrid actuator, starting from its patented Fine Stepping Piezoelectric Actuator (FSPA) [2], but using a combination of its magnetic and piezoelectric technologies to reduce electrical requirements. This new linear stepping actuator first generates a rotating movement and then turns it into a translation movement. It offers nanometric positioning resolution combined with the ability to hold its position without power and during launch without the need for any launch lock mechanism.

IASI-NG & Beam Splitter Mechanism

The Infrared Atmospheric Sounding Interferometer New Generation (IASI-NG) is a key payload element of the second generation of European meteorological polar-orbit satellites (METOP-SG) dedicated to operational meteorology, oceanography, atmospheric chemistry, and climate monitoring. It will provide operational meteorology data such as temperature and humidity atmospheric profiles and also monitor other gases like ozone, methane or carbon monoxide on a global scale.

The instrument is developed under the lead of CNES, who is responsible for the development and procurement of the IASI-NG System (Instrument, Ground Processing software, Technical Expertise Center). Airbus Defence and Space was selected for development of the “Space Segment” mainly consisting of the Instrument itself.

* CEDRAT Technologies, Meylan, France ; francois.barillot@cedrat-tec.com

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The heart of the instrument is a modified Michelson type interferometer based on the Mertz concept. This interferometer embeds a beam splitter blade. The blade tip-tilt positioning is critical with respect to IASI NG performance. Therefore, specific actuators are implemented to readjust in orbit the Beam Splitter Tip/Tilt alignment: the two BSMA. They provide a linear motion to lever arms acting either in push-pull or push-pull to provide both axis tilt. Actuation forces shall be sufficient to counteract the stiffness of the mechanism and to maintain its position after setting; it means a sufficient passive unpowered holding force (actuator non-powered). Moreover, an additional “vibration mode” (small oscillations at high frequency) is needed to assess the dynamic sensitivity.

**Figure 1. BSMA Actuators “Push-Pull” Configuration**

The major requirements for the BSMA are the following:
- Movement: 45-nm resolution step motion over a ±40-µm range with up to 20N force
- Launch: withstand launch including up to 50N force on output shaft
- Unpowered position stability:
  - 0.15 µm over 24h/1K stability
  - 0.30 µm over 6 months
  - 1.4 µm long term
- Vibration mode: 0.2 to 0.8 µm oscillations with 10 Hz to 70 Hz frequency
- Driver capability:
  - Piezo: Max voltage 120V, Max current 0.1 A
  - Mag: Max voltage 50V, Max current 0.3 A
- Cold redundancy

**BSMA Architecture**

**Figure 2. BSMA EM With Connector Saver**
Overall architecture
The core BSMA is based on the combination of the following elements:

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

In order to achieve cold redundancy, each of these elements has to be doubled inside the BSMA. The two FSPAs motors are connected by a lever arm which sums the position of the two motors. This architecture divides by a factor of two the displacement generated by the FSPA. This improves motor resolution by a factor of two but at the cost of a doubled stroke for the motor.

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

FSPA Actuator
The FSPA is a new brand of patented piezoelectric motors from Cedrat Technologies. It is a combination of a Rotating Stepping Piezoelectric Actuator (RSPA) and a differential screw.

This FSPA piezomotor is mainly proposed as a product for industrial and laboratory applications, among CTEC range of SPA piezo motors [3].

However, its compact design and vacuum compatibility is an opportunity for cost-effective space applications such as micro satellites or constellations nano satellites.

FSPA piezo motors main advantages are:

- 5-mm displacement range with up to 120N driving force,
- compact casing (Ø50 mm x 45 mm) and low mass (150 g),
- typical stepping size adjustable from 50 nm to 250 nm,
- holding force while unpowered, against external forces, that can exceed 1 kN,
- end-stops that passively prevent the motor from exceeding its operational stroke including in case of a faulty command from the user.

The high holding force at rest allows to avoid the use of an additional launch-lock mechanism.

This FSPA motor can be used for nano positioning of an optical payload. It could even be used as an HDRM (Hold Down and Release Mechanism) for another mechanism.
The FSPA stick/slip operating principle is based on inertial forces as other SPA [4]. The consequence is that some short current spikes are needed to generate the pulses. For IASI-NG a requirement is to minimize the need for current spikes in order to facilitate electronic design.

A magnetic clutch is then added to the original RSPA motor. This clutch allows to open the contact between the RSPA module and the rotor when it reverts to its original position. The maximum current for piezoelectric components can then be reduced below 100 mA (even using larger ceramics than usual).

Figure 5 shows the kinematic chain for the FSPA inside the BSMA. The step sequence is the following:

1. Start powering the magnetic clutch to reinforce the torque transmission between the RSPA module and the rotor
2. Power the RSPA module to generate a small rotation. Rotation is transmitted to the rotor through the clutch.
3. Reverse power in the magnetic clutch to cut the contact with the rotor
4. Cut power of the RSPA to have it return to its initial position. The rotor stays in place.
5. Cut power of the magnetic clutch. Rotor is then locked in place.

Each step results with a fraction of a turn rotation (\(\alpha\)) for the rotor. As the rotor is connected to the structure through screw 1, the rotation causes a small translation (\(\alpha \cdot p_1\)) of the rotor relative to the structure. Further, the output shaft (which cannot rotate) moves relative to the rotor in the opposite direction (\(-\alpha \cdot p_2\)) because of screw 2.
The resulting displacement of the rotor versus the structure is then \( \alpha(p_1-p_2) \). This configuration allows the use of larger threads, which are needed to withstand the loads, while allowing very small steps per turn otherwise not possible.

**Magnetic clutch**

A key aspect of the BSMA is then its electromagnetic clutch. This clutch was designed based on the following constraints:

- transmit torque during stepping sequence,
- complete loss of contact during release,
- closed when unpowered,
- perform more than 1 million operation cycles without detrimental wear
- coil temperature within acceptable range,
- mass allowing RSPA module to support clutch without assistance of any launch-lock mechanism.

The clutch design is based on an electromagnet principle. Magnetic technology was selected as it allows larger displacement compared to piezoelectric ceramics. This is needed to generate a gap which is large enough to accommodate for manufacturing and assembly tolerances.

In practice, the clutch consists of 6 pallets driven by the central coil and magnet. Each pallet can rotate around a flexible blade when the magnetic coil is powered. At the end of the pallet is a friction tooth that will interface with the rotor and transmit torque from the RSPA module. A permanent magnet generates some flux which closes the pallets (and therefore the clutch) when the electromagnet is not powered.

Performance of the clutch was optimized using magnetic simulation (Figure 7) in order to minimize its size and heating while providing enough force to ensure torque transmission.

As the rotor turns, the distance between the tooth and rotor contact surface can vary significantly depending on the rotor runout and other manufacturing tolerances. A major point of concern during the design was to ensure that magnetic forces would not vary excessively, remaining high enough to ensure proper torque transmission.
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 including the fatigue effect over lifetime.

Prestressed Piezoelectric Actuator (PPA)
A double PPA is placed between the lever arm and the output shaft. This PPA is composed of 2 stacked piezoelectric components to provide redundancy. The supplied piezo components have been validated for space application with a LAT (Lot Acceptance Test). This LAT sequence, composed of several test group samples, was established thanks to previous work with agencies (ESA and CNES).

Differential Screw Wear Test Bench

Guided lever arm
A lever arm connects the two FSPAs and the output shaft. The resulting position of the shaft is the mean position of the two FSPAs. Redundancy is then achieved as each FSPA can move the output shaft independently from the other one.

However, a major consequence of this architecture is that the lever arm tip displacements are not straight. The rotation of the arm induces a side displacement which must be supported by the threaded interfaces.

This design was selected due to its compactness and considering that:
- Static load is rather small (<100N) compared to allowable screw tension in static conditions,
- Speed is very low (allowing contact heat to dissipate),
- Limited lifetime requirement (100 operations).
Screws excessive wear
As expected, the alignment of the clutch with the rotor was a major difficulty during assembly. Several assembly methods had to be tested on the first engineering models to identify the best options. During one of the tests and due to a mishandling, one of the screws was damaged and had to be replaced. After disassembly, it was found that the other screws showed excessive deformation and wear (even considering the specific history of the model).

![Figure 10. EM1 Screws, Left Screw Shows Excessive Wear, Right Screw Was Damaged Due to Mishandling](image)

Following this result, it was decided to upgrade the design of the BSMA. The major design improvements were to:
- replace initial soft screw material with a high strength stainless steel with space heritage,
- use both liquid and solid space qualified lubricants to minimize the risk of dry contact.

Test bench verification
In order to validate the updated design, it was decided to build a dedicated test bench. Two major elements were to be considered for the test bench design:
- Kinematic Accuracy: movement shall be as close as possible to the effective movement in the BSMA,
- Load Accuracy: preload shall be the same as in the BSMA,
- Accelerated Test: rotation speed must be accelerated to get an acceptable test duration.

A geared electric motor was used to drive the differential screw rotor. Transmission to the rotor was done using gear wheels. Gears would not be acceptable for normal use as their resolution is much too large for the application, but this was acceptable for the accelerated test, where each cycle was a complete turn of the rotor.

![Figure 11. Differential Screw Test Bench](image)
The results using the test bench validate the applied changes: Although acquisition noise reduced measurement quality, no significant torque trend was observed during the test (see Figure 12). Comparison of initial and final friction coefficient showed no significant trend either. Finally, an inspection of the tested parts was performed by CNES which concluded that thread wear was acceptable.

**Nanometric Step Size and Stability Test Bench**

**Test Bench Architecture**

A test bench was designed to analyze the output position of the motor over its full stroke, in vacuum conditions and under static load. A second key feature of the test bench is the ability to measure the position stability against time of the motor at the nanometric scale over a period of more than 100 hours. This test bench exploits previous successful experience on long-term nanometric stability measured on PPA piezoelectric actuators [5].

For this purpose, a 3-channel interferometric displacement sensor (Figure 13a & b) was used in vacuum to achieve a sub-nanometer precision with high repeatability. Each channel measures the length of the laser beam between a fiber-based sensor head (or optical collimators) and a mirror. The position target mirrors shown in Figure 13b made identically and bonded at the same time with the same cure process.

A load spring was included as well as a force sensor to verify BSMA’s behavior while loaded with a constant axial force. The test bench was built on a baseplate with closed loop thermal control. The goal was to stabilize the test bench temperature within a 0.2K peak-peak range.

**Stroke Verification**

The first test aims to verify the extreme stroke of the 2 FSPA motors. Extreme stroke means reaching the mechanical end-stops of each motor while the other motor is at maximum operational position. This test allows to validate that, in case of a motor failure, the other motor will be able to compensate and preserve BSMA capability to reach any position inside the operational range.

Figure 14 shows the output shaft position. Positions for the nominal and redundant motors are estimated from the commands sent to the BSMA.
Figure 13 - BSMA Stability Test Bench

(a) Overview of the loading assembly
(b) The 3-channel interferometric displacement sensor without loading assembly
(c) Inside overview of the test bench
(d) Outside overview of the test bench in ISO7 clean room

Figure 14 - Extreme Position Verification Test in Air

(a) Full stroke
(b) Direction change
Step Sizes
A major characteristic of the BMSA is its ability to generate very small steps. Figure 15 shows analyses of step size for nominal and redundant motor when cycling over the operational range and against its lifetime. Performing a direction change does not impact step size nor shows any sign of backlash (Figure 15b). Average displacements (red points) for 3 consecutive steps are very stable for both motors and over the complete range (Figure 15a). Step size appears noisier for forward steps compared to backward. This result remains to be investigated to separate effective step variations from acquisition and post-processing noise.

The step size distribution appears to follow a normal law with a standard deviation of 4.3 nm for the nominal motor and 4.9 nm for the redundant motor (Figure 15b). In other words, the variation for more than 99% of steps is lower than ±10 nm. Averaging on 3 steps decreases significantly the step size scattering (less than 12% variation for 3 steps averaging).

Lifetime Test
The lifetime qualification was still underway at the time of this document. Air lifetime is complete and shows a slow decrease of the average step size. Less than 4 nm of step size decrease has been verified after 1 million steps (320 times the cycle life). The step size distribution shows a comparable standard deviation before and after the lifetime test in air.
Test Bench Verification for Nanoscale Stability

A major difficulty with the stability test is that a temperature variation of 0.1K is sufficient to create a position deviation higher than 70 nm on the test bench references.

First, the test bench intrinsic stability, without BSMA, was verified. For this purpose, an aluminum board was used instead of the BSMA to measure the drift (Figure 17).

![Figure 17 - Test Bench Stability Verification without BSMA](image)

The center position shows a very stable behavior while the side references were equally drifting (Fig. 18a). The conditions of the test show a stability of around ±100 mK over more than 200 hours (Figure 18b). The phenomena explaining this drift is still under investigation. The difference between the central mirror and the reference significantly reduce short term thermal noise.

A second verification was to ensure that thermal stability was below 100 mK in short-term (30 min) and 300 mK in long-term (60h). The Figure 19 shows the temperature profile during the stability test presented on Figure 20 (FM1).

Reference measurements are then used to compensate test bench thermal expansion. This method was found necessary to verify stability requirements. However, it remains difficult to compensate very fast or very slow variations due to complex heat propagation in the test bench. For this reason, it remains key to reduce temperature variations to a minimum.
Stability Test
One crucial objective of this test bench is to verify the stability of the BSMA position over time. The first step of the test is to place the BSMA in stable environmental conditions (vacuum, regulated temperature) and then wait more than 60 hours for test bench and BSMA internal components to stabilize. A single step is then performed, and position is monitored for another 30 hours. The stability test shows that the ±150-nm stability requirement over 24 hours is achieved.

Figure 20 shows the results of the stability test for the flight model FM1. A difference between the output shaft position and references is performed in order to remove the main effects from temperature variation. Moreover, a correction slope is removed from the test bench verification test without BSMA described in the previous paragraph.

The post-processed stability curved shows an exponential decrease, then the step and a rather stable behavior. A possible explanation for the exponential effect at the beginning would be the PPA ceramics stabilization following air-vacuum transition. It is interesting to note that the step is not followed by a loss of stability.

Mechanical Environment Testing

Random vibration testing was performed on the qualification model and flight models. Three axes were tested. Flight models were protected against contamination during the test by a plastic film.
The power spectral densities presented on the Figure 22 were applied on all 3 axes. The RMS levels were gradually scaled to different amplitudes up to the maximum RMS values shown in the Table 1.

The eddy current sensors embedded in the BSMA were monitored during the tests to detect any change in position of the rotor. Above a given vibration level the BSMA rotor moved slightly during the Y and Z axis vibration tests (Table 1). It is interesting to note that no damaged occurred during the tests and neither the step size or stroke were influenced when comparing the functional tests before and after vibration. Investigations are still ongoing for a better understanding of the rotor movement.

**Table 1 – BSMA reliability against vibration levels**

<table>
<thead>
<tr>
<th>BSMA Excited axis</th>
<th>Random level (g RMS)</th>
<th>Actuator damaged</th>
<th>Step size or performance change</th>
<th>Position shift during test</th>
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<td></td>
<td>11</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Conclusion

A new patented piezoelectric motor is presented with associated experimental results achieved on the qualification and flight models. This motor is undergoing qualification to be used inside IASI-NG Instrument onboard METOP-SG satellite.

The major requirements for the BSMA were fulfilled:
- Movement: 40-nm resolution step motion over a ±40-µm range with up to 20-N force
- Position stability experimentally verified: less than 100nm variation over 48h,
- Launch capability without launch-locking mechanism: No damage at all tested levels, some movements occurred for highest levels.

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References

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