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Miniature Piezo Fast Steering Mirrors (FSM) for Space Optical Communication in NanoSats and CubeSats

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Abstract

CTEC proposes a mini-FSM technology offering a stroke of +/-6 mrad and a resonant frequency of 1700 Hz, with a mass of 50 gr. This FSM mechanism is a good candidate for giant constellations and all applications on board NanoSats and CubeSats, featuring a very high level of miniaturization and optimized for New Space high quantities cost efficiency. The use of piezo actuators offers a high resonance frequency for optimal control, with almost zero power consumption in step and stay pointing, and with very high-reliability figures > 0,995 demonstrated over years of recurrent manufacturing for Optronics applications at CTEC.

1. Introduction

This paper presents the design of a mini-FSM and associated CCBµ20 drive electronics, as well as test results including pointing performances, closed loop position control, long duration vibrations test over hours and other environmental tests performed on the system.

Starting from former space heritage CEDRAT TECHNOLOGIES (CTEC) has achieved the design and qualification of a piezo mini-FSM for 3U CubeSats, targeting an undisclosed constellation composed of several hundreds of satellites, with cost and reliability being the main drivers [1], [2]. The highest reliability and small size APA® piezo actuator reference from CTEC optronics heritage was selected, having demonstrated zero failure over more than 3000 XY piezo-stage mechanisms produced in the last 10 years. The FSM mechanical parts number was reduced as far as possible, choosing an all-in-one concept-based flexure bearing, mirror flexible interface mounting, and flexural pivots, machined within one single piece. By this innovation and former test approach from optronics recurrent manufacturing, the total MAIT time for this device has been reduced to less than 2 days, while providing 100% testing to insure zero defect at customer level.

3. Miniature FSM Design

The main specifications for this product are to ensure a ±6 mrad angular stroke (@25°C) in a miniature volume (30mm diameter / 20 mm height). The mechanism must move a 6mm diameter mirror with a 500 Hz control bandwidth.

The Miniature FSM is a tip tilt platform based on four CEDRAT TECHNOLOGIES APA35XS®. This patented platform is a miniaturization of the P-FSM150S [3]).It is composed of the following parts:

- A frame baseplate (in stainless steel) on which each APA® is fixed. The central cylinder is fastened on this baseplate.
- Two housing parts (in aluminum)
- 4 APA35XS-SG® (with stainless steel shell): They provide the required displacement and are fixed to the frame and to the guiding blade. The APAs are equipped with SG sensors.
- A guiding blade (stainless) welded onto the central cylinder that stiffens radially the assembly and prevents parasitic motions during actuation.
- A mirror holder in aluminum.

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- 4 arms (in stainless) are welded onto the guiding blade.
- The mirror

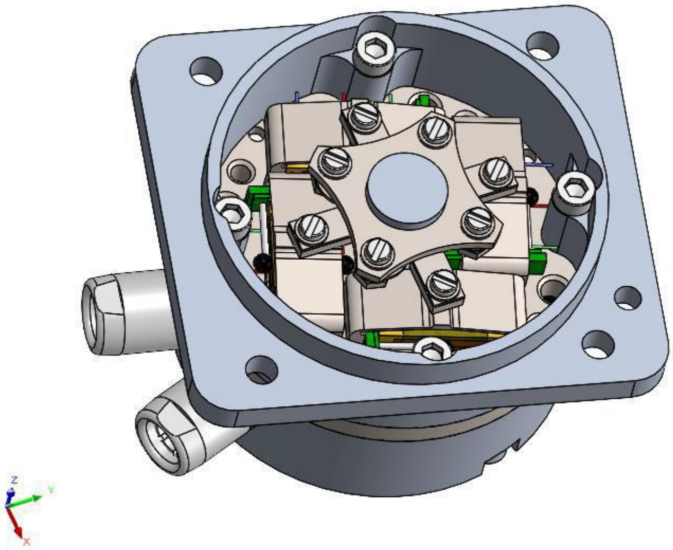

Figure 1: Miniature FSM overview

The APA® are patented compact space-qualified Amplified Piezo Actuators from CTEC based on a low voltage multilayer piezo ceramic (MLA) and a shell ensuing both MLA pre-stressed and amplification of the MLA displacement. They include strain gages (SG) for sensing the stroke. The APA® offers a stroke proportional to the voltage, in closed loop control with SG. The APA35XS are based on 2x5x10mm3 piezo MLA. Their stroke is about 40µm, while the MLA stroke is 10µm. Driving the APA® in push pull by opposite pairs, this Tip-tilt allows deflections of the mirror around X and Y axis.
The observability of the mirror position is assured by embedded strain gages onto MLA ceramics. Theses compact sensors will be used with the controller to control the real position of the FSM and reach the desired accuracy. Nevertheless, such a solution is not optimal because the angular position of the mirror is not accurately observed impacting the controllability of the FSM.
To embed such technology in the mechanism, a particular attention is given to the internal electrical connection with multiples signals, high amplitude voltage or ultra-low amplitude signals. 2 Printed Circuit Boards are proposed to connect the two separate sensors and piezo output pigtails.

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3. Static Analysis

1.1 Finite Element Modeling

For the static simulation only the active parts of the mechanism are considered. Moreover, the impact of the fasteners is neglected for those simulations.
The mesh model is presented in the Figure 2:

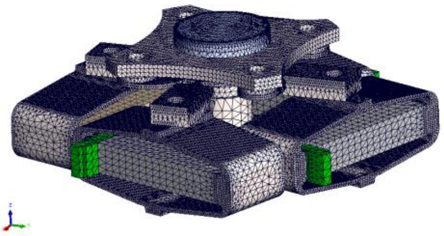

Figure 2: Mesh model

1.2 Analysis Results

The maximum stress on the guiding blade is 162MPa and 84MPa on the APA shell as shown by the Figure 3

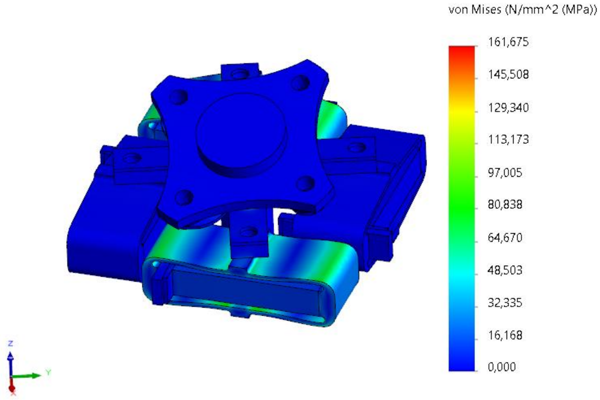

Figure 3: Stress at half stroke

The displacement is illustrated by Figure 4:

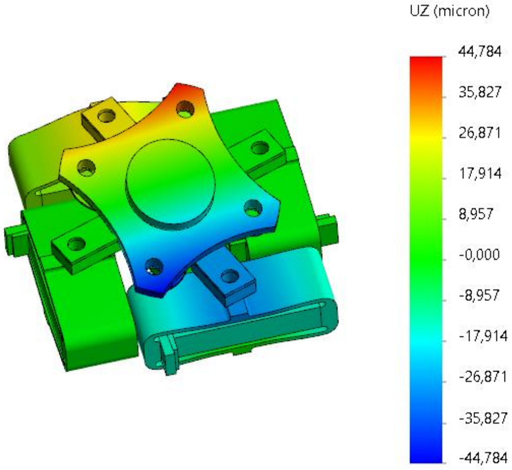

Figure 4: Displacement at half stroke

The rotation of the can be calculated using trigonometric formula. The mirror stroke is +/-6.5mrad @25°C.

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4. Vibrations and shocks analysis

4.1 Finite Element Analysis Approach

The screws are removed from the model and the virtual mass is added to replace their mass. A qualify factor of 100 is used to define the modal damping which is conservative.

4.1.1 Vibrations

The PSD type 2 with 13.1g-rms is used to processed simulation (conservative). Thus, the PSD is defined as illustrated by the Table 1 and the Figure 5. The simulation is run on the three axes.

Table 1: PSD type 2

Frequency (Hz)	PSD (g^2/Hz)
10	0.4
80	0.4
200	0.4
200	0.1
700	0.1
1000	0.049
2000	0.012

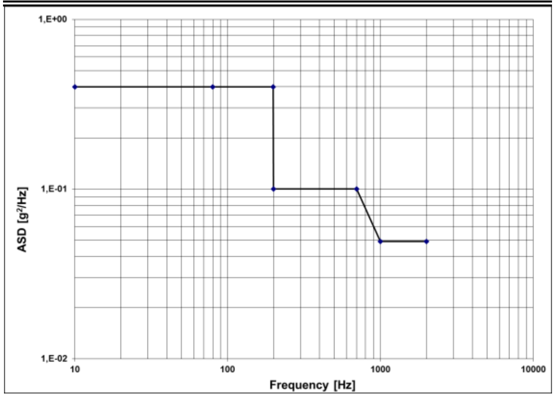

Figure 5: PSD type 2 profile

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4.1.2 Shocks

The shocks are simulated by quasi static acceleration with a coefficient of 1.8 (to be conservative). As the simulation is linear only one direction is computed. For the axis X and Y the acceleration is set to 20g*1.8 and 55g*1.8 for the Z direction.
The shocks specifications are summarized in the Table 2.

Table 2: Shock specification

Shock Type	Type 1	Type 2	Type 3	Shock Type
Acceleration (g)	20	55	-15	20
Duration (ms)	20~30	11	20~40	11
Shock number of times	1	2	2	3 times per direction
Waveform	Half sinusoid	Half sinusoid	Half sinusoid	Final peak saw-tooth

4.2 Analysis Results

4.2.1 Vibrations

The maximal stress on the mechanism components have been multiplied by 5 to represent the value at 5σ.
For X axis random vibration, the maximum stress is 60MPa for the guiding blade, 25MPA for the APA and 5MPa for the MLA. These values are the same for Y axis due to the design symmetric. For Z axis the maximum stress in the guiding blade is 35Mpa, 10 MPa for the APA and 5MPa for the MLA. Stress in the mirror is totally negligible thanks to the guiding blade.

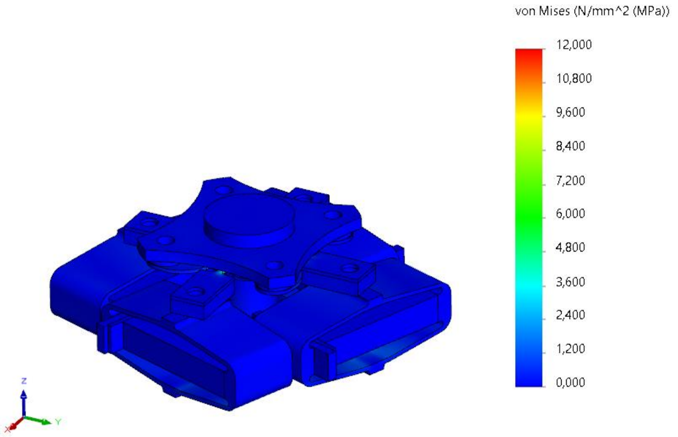

Figure 6: Result for PSD on X axis

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4.2.2 Shocks

The maximum stresses for X and Y axis during shock simulation are 19MPa for the guiding blade, 4MPA for the APA and 1MPa for the MLA. For Z axis the maximum stresses are 29MPa for the guiding blade, 7MPA for the APA and 1MPa for the MLA. Stress in the mirror is totally negligible thanks to the guiding blade.

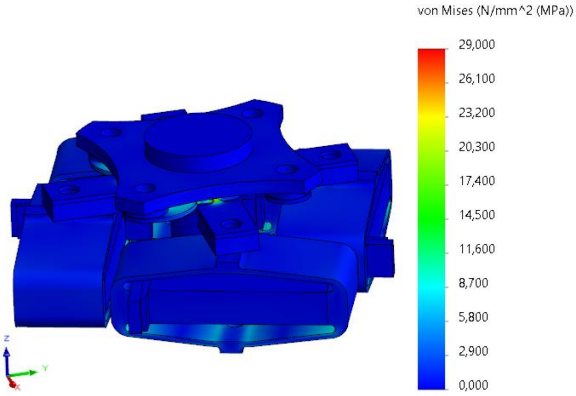

Figure 7: Result for PSD on X axis

4.3 Conclusion

The analysis shows very low stress values and significant margins w.r.t. vibrations and shocks levels specified, which is an important feature targeted on such small size FSM. The test results presented here after were achieved successfully.

5. Miniature FSM tests results

Two prototypes were manufactured and tested in 2022. Several tests were performed to establish the main performances of the system.

5.1 Angular stroke

The minimal stroke measured on the two prototypes is 14.55 mrad on Y axis of prototype 2 (@25°C). This performance is compliant with the specified target (±6mrad) with a significant margin.

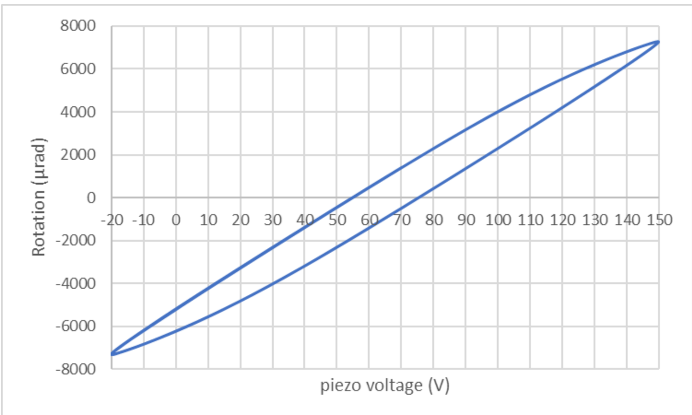

Figure 8: Mirror stroke vs piezo voltage

This value is higher than expected by the predicted results due to the range of tolerance on the flexible part to ensure the mechanism stroke. This higher stroke will induce a lower frequency value of the admittance but is still compatible with the expected dynamic performance by re-tuning the control in accordance with these results.

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5.2 Modal frequencies measurements

The mechanism stiffness and associated modal landscape is evaluated with an admittance sweep. With that method, only the piezo coupled modes are visible, hence the vertical pumping mode (cancelled from piezo point of view) is not visible.

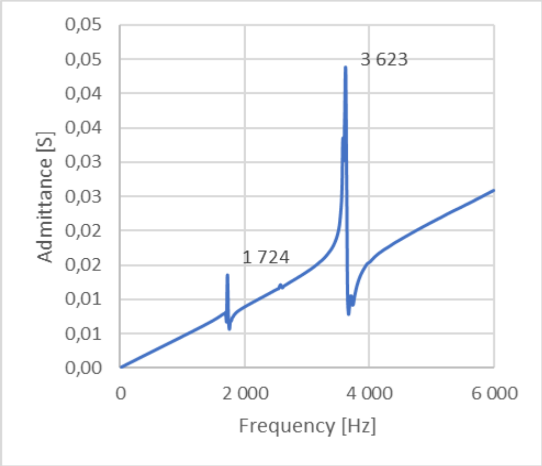

Figure 9: Typical axis admittance

The first mode is measured around 1700Hz which gives enough margin to ensure a 500Hz bandwidth. This mode is followed with a second mode located to 3700Hz which needs to be filter by the controller to reach the desired accuracy performances.

5.3 Vibrations tests

The Miniature FSM was tested in random vibrations along the 3 axes in non-operational mode.

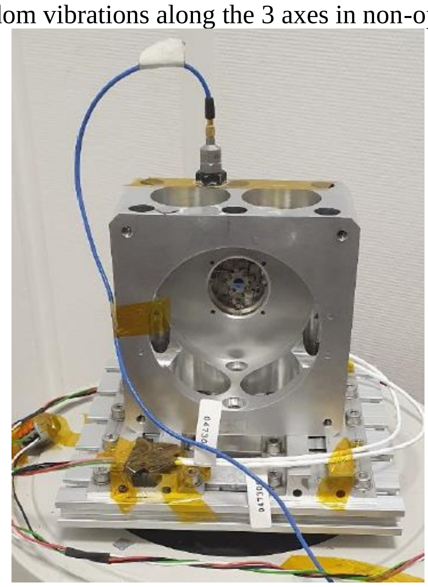

Figure 10: Vibration and shock test bench

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A first test was performed during a lapse of 1 hour under 4.5gRMS acceleration and a second was performed during 3 minutes under 13gRMS acceleration.

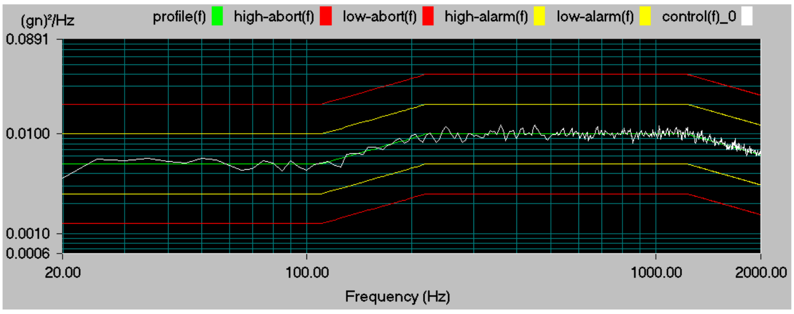

Figure 11: 1h test profile and result

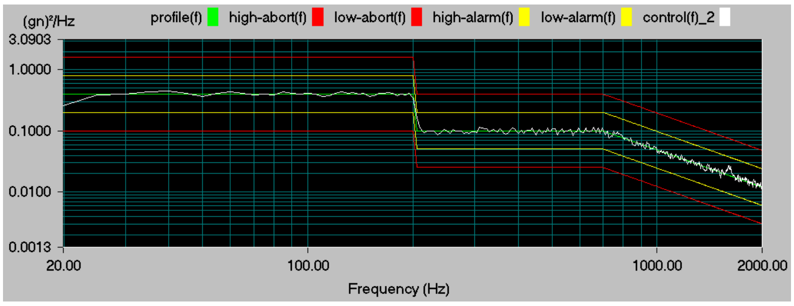

Figure 12: 3min test profile and result

All performances were measured after tests and the miniature FSM behavior did not change.

5.4 Closed loop position control performance

The miniature FSM was tested with a standard CCBu20 controller, rugged for NewSpace applications, using the embedded strain gauges position sensors (SG). This controller has a peak output current limitation of 0.2A and an RMS maximum output current of 35mA per axis, which reduces the frequency bandwidth on larger sizes FSM, but not on the miniature ones.

Figure 13: Rugged NewSpace version of the CCBu20 Drive Electronics

With a very basic Proportional Integral controller associated with notch filters, a bandwidth greater than 550 Hz was measured.

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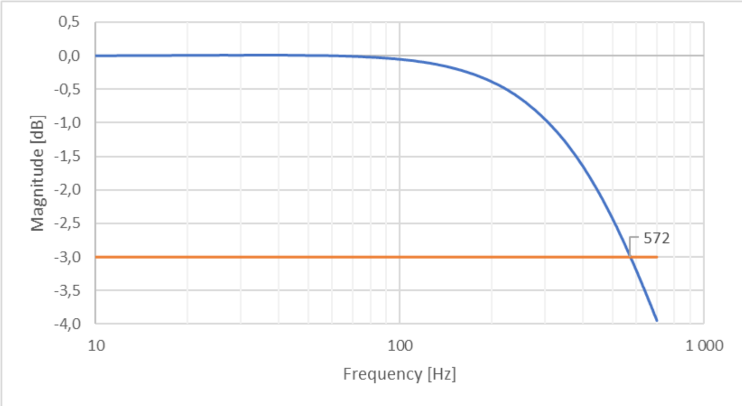

Figure 14: Typical closed loop bandwidth

This performance allows a rise time about 0.4ms and a settling time about 1.1ms. these measures have been done with a 3mrad (50% of full stroke) step. The settling time is the time elapsed from the application of an ideal instantaneous step displacement order to the time at which the mechanism reach the new position set point (at ±5%).

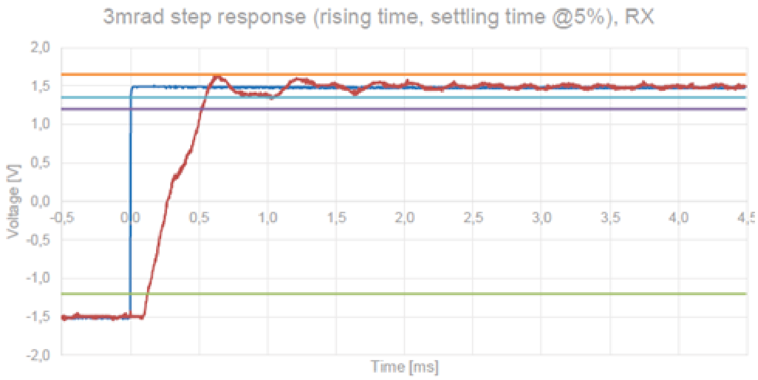

Figure 15: Step and stay rise time test

The rise time definition is the time required by the response to increase from 10% to 90% of the order.

6. Performances summary table

Table 3 summarizes the miniature FSM performances verified by tests.

Table 3: Miniature FSM performances

Mechanism's diameter	30mm
Mechanism's thickness	20mm
Mirror's mass	Up to 0.1g
Angular stroke	±6.5mrad
Control bandwidth	>550 Hz
First resonance frequency	1700Hz
Rise time	0.4ms
Settling time	1.1ms

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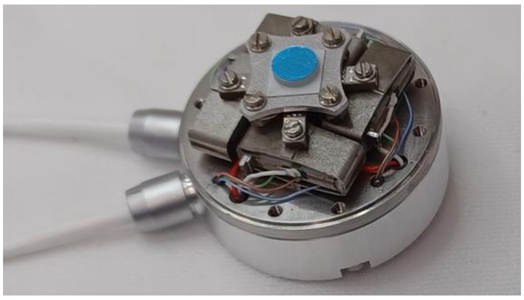

Figure 16: Miniature FSM (with a protection layer on mirror)

7. Conclusion

The Mini-FSM development has allowed to achieve a very high level of compacity, together with very high stiffness and high resonance frequency. This advantage within a such small size FSM gives the capacity to withstand very high vibration and shock loads while keeping high angular stroke capacity, and resolution, relevant for Space Optical Communication on board NanoSats and CubeSats [4]-[5]. The very low moving mass of the optical assembly implemented allows as well to achieve position closed loop control with high frequency bandwidth with the constrain of using a very low power CCBu20 NewSpace drive electronics, featuring low current value limitation, but which is perfectly appropriated for NanoSats' sizes.

References

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