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Miniature Fast Steering Mirrors for Space Optical Communication on NanoSats and CubeSats

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***Abstract*—**With the increasing digitalization of society, access to data has become vital and strategic for individuals and nations. In this context, the number of satellite constellation projects is growing drastically worldwide and is a next-generation challenge of the New Space industry. So far, existing satellite constellations have been using radio frequencies (RF) for satellite-to-ground communications, inter-satellite communications, and feeder link communication. However, RF has several limitations, such as limited bandwidth and low protection level. To address these limitations, space optical communication will be the new trend, addressing both very high-speed and secured encrypted communication. Fast Steering Mirrors (FSM) are key components used in optical communication as well as space imagery and for a large field of functions such as Point Ahead Mechanisms (PAM), Raster Scanning, Beam Steering Mirrors (BSM), Fine Pointing Mechanisms (FPM) and Line of Sight stabilization (LOS). The main challenges of space FSM development for optical communication are to propose both a technology and a supply chain relevant for high quantities New Space approach, which requires secured connectivity for high-speed internet, Earth planet observation and monitoring, and mobility applications. CTEC proposes a mini-FSM technology offering a stroke of +/-6 mrad and a resonant frequency of 1700 Hz, with a mass of 50 g. 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.

***Keywords*—**Fast steering mirror, feeder link, line of sight stabilization, optical communication, pointing ahead mechanism, raster scan.

I. 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 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.

II. MINIATURE FSM DESIGN

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

The Miniature FSM is a tip tilt platform based on four CEDRAT TECHNOLOGIES APA35XS® [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).
- Four 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 flexure bearing welded onto the central cylinder that allows pure tilt motion without lateral parasitic translation.
- A mirror holder in aluminum.
- Four arms (in stainless) welded onto the guiding blade.
- The mirror.

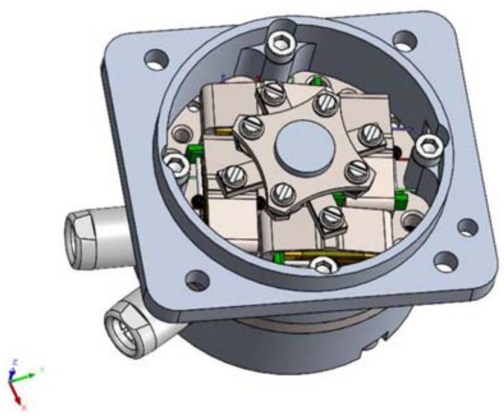

Fig. 1 Miniature FSM overview

The APA® are patented compact space-qualified Amplified

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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 2 x 5 x 10 mm^3 piezo MLA. Their stroke is about 40 µm, while the MLA stroke is 10 µm. 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 sensors will be used with the controller to control the real position of the FSM and reach the desired accuracy. Nevertheless, such 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. Two printed circuit boards are proposed to connect the two separate sensors and piezo output pigtails.

III. STATIC ANALYSIS

A. 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 Fig. 2.

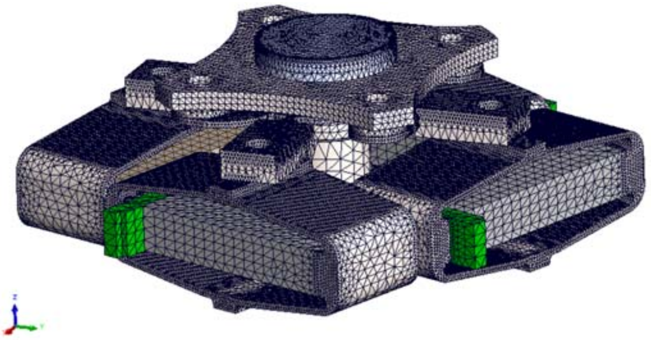

Fig. 2 Mesh model

B. Analysis Results

The maximum stress on the guiding blade is 162 MPa and 84 MPa on the APA shell as shown by Fig. 3. The displacement is illustrated by Fig. 4.

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

IV. VIBRATIONS AND SHOCKS ANALYSIS

A. 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.

1) Vibrations

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

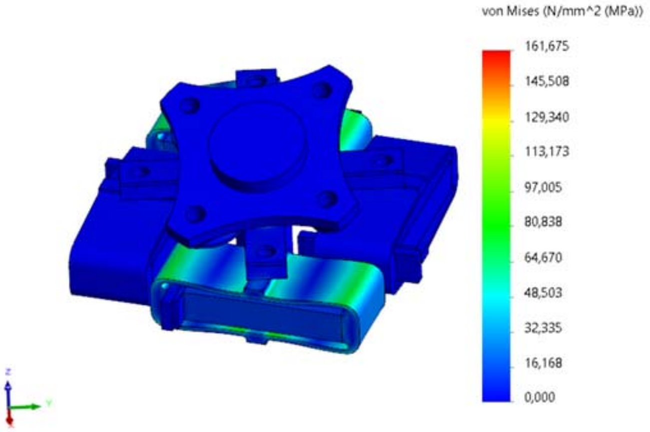

Fig. 3 Stress at half stroke

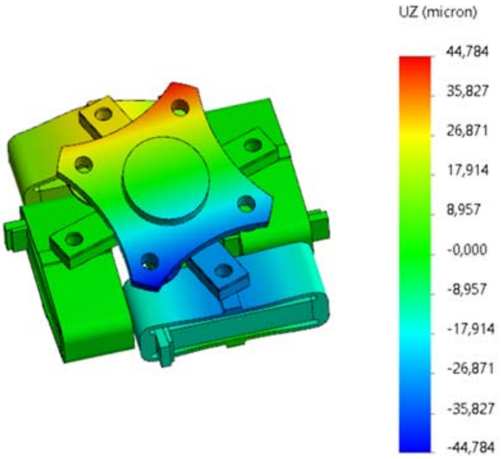

Fig. 4 Displacement at half stroke

TABLE I
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

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 Table II.

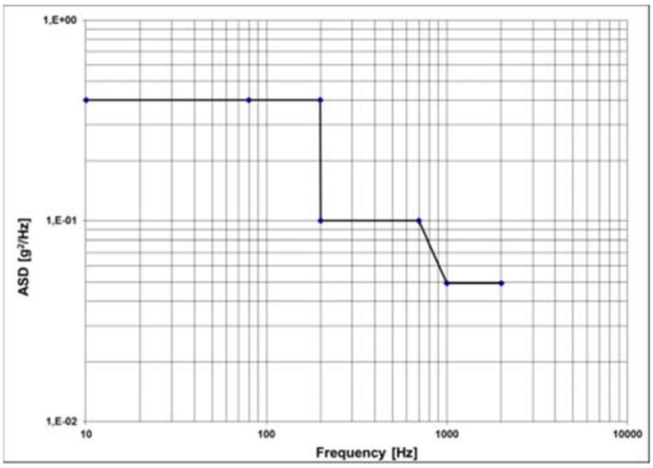

Fig. 5 PSD type 2 profile

TABLE II
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

B. Analysis Results

1) Vibrations

The maximal stress on the mechanism components have been multiplied by 5 to represent the value at 5 σ.

For X axis random vibration, the maximum stress is 60 MPa for the guiding blade, 25 MPA for the APA and 5 MPa 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 35 MPa, 10 MPa for the APA and 5 MPa for the MLA.

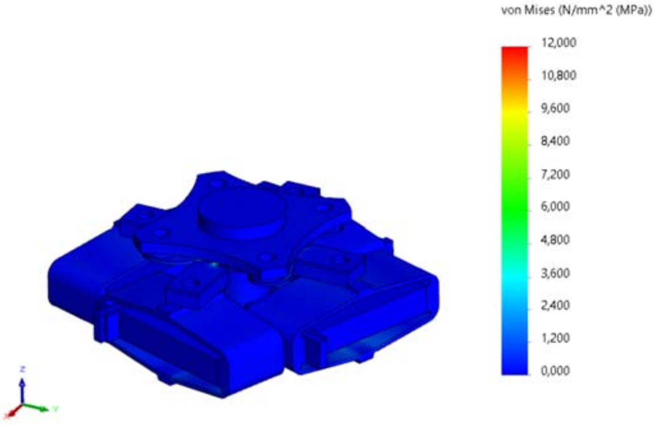

Fig. 6 Result for PSD on X axis

2) Shocks

The maximum stresses for the X and Y axis during shock simulation are 19 MPa for the guiding blade, 4 MPa for the APA and 1 MPa for the MLA. For the Z axis, the maximum stresses are 29 MPa for the guiding blade, 7 MPa for the APA and 1 MPa for the MLA.

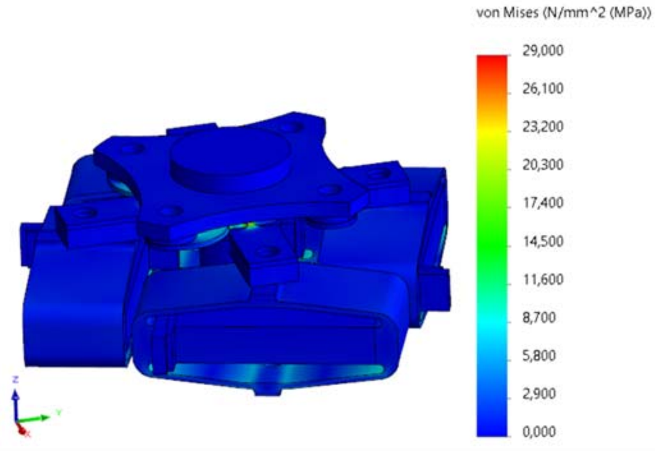

Fig. 7 Shock result on Z axis

C. 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 hereafter were achieved successfully.

V. MINIATURE FSM TESTS RESULTS

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

A. 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 (± 6 mrad) with a significant margin.

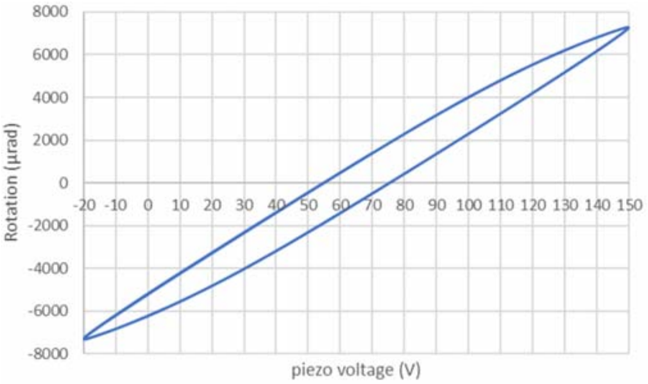

Fig. 8 Mirror stoke vs. piezo voltage

The stroke value is higher than expected by the predicted results due to our 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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B. 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.

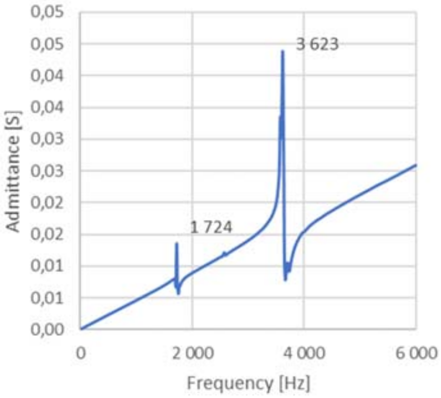

Fig. 9 Typical axis admittance

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

C. Vibrations Tests

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

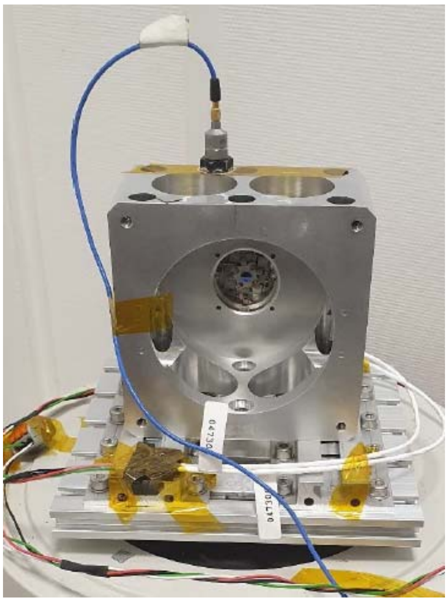

Fig. 10 Vibration and shock test bench

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

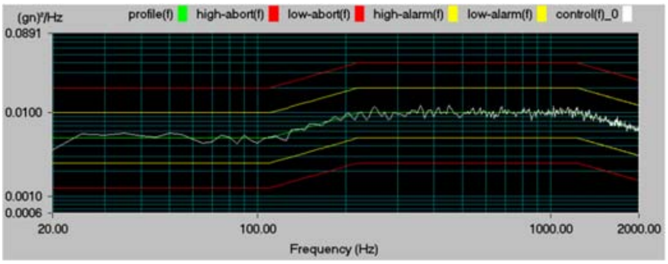

Fig. 11 The 1 h test profile and result

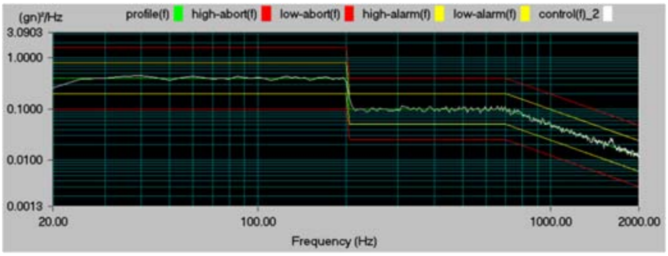

Fig. 12 The 3 min test profile and result

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

D. 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 0.2 A and an RMS maximum output current of 35 mA per axis, which reduces the frequency bandwidth on larger sizes FSM, but not on the miniature ones.

Fig. 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. This performance allows a rise time about 0.4 ms and a settling time about 1.1 ms. These measures have been done with a 3 mrad (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%).

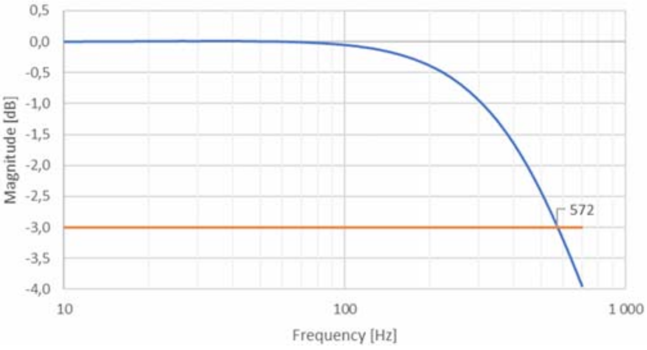

Fig. 14 Typical closed loop bandwidth

Fig. 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.

VI. PERFORMANCES SUMMARY TABLE

Table III summarizes the miniature FSM performances verified by tests.

TABLE III
MINIATURE FSM PERFORMANCES

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

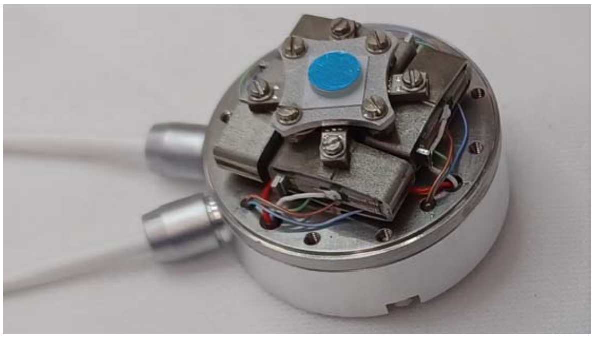

Fig. 16 Miniature FSM picture

VII. 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.

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