Magnetically actuated Fast Steering Mirrors

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Abstract

Free-Space Optics (FSO) for optical communication request new compact low-power high-stroke high-bandwidth Fast Steering Mirrors (FSM). To address this need, CEDRAT TECHNOLOGIES has developed a Magnetically-actuated Fast Steering Mirror called M-FSM, taking heritage of its MICA™ actuators. This FSM offers Rx Ry strokes larger than +/-2° with a 250Hz bandwidth when tilting a ∅31mm mirror. Requested power is minimized leading to low heating. Vibration tests have been performed to define first limits and conditions for the M-FSM to bear external vibrations. Large bandwidth closed loop control is achieved using integrated eddy current sensor and a state feedback-based controller.

1 Introduction

Low-power high-stroke high-bandwidth Fast Steering Mirrors (FSM) are demanded for Free-Space Optical communication (FSO) in future LEO constellations inter-satellite links as well as in Deep Space Optical Communications (DSOC).
For 20 years, CTEC has provided piezoelectrically-actuated Fast or Fine Steering Mirrors (FSM) for space missions and optronics [1,2]. In 2020, CTEC has delivered the Flight Models of the FSM required for PSYCHE DSOC mission of NASA JPL [3]. These FSM named PAM30 are Tip-tilt mechanisms based on 4 APA®. They offer a large bandwidth (> 2kHz) and fine resolution but angular strokes are limited to +/-2.8mrad (**Figure1**).

Figure 1 PAM30 for NASA JPL PSYCHE Mission

As such small strokes are constraining for optical and control design for FSO optical terminals, CTEC has developed a new FSM based on magnetic actuation called M-FSM62 (**Figure 2**). This targets larger tilt stroke, larger than +/-2 mechanical degrees (+/-35mrad), low power, low heating and high bandwidth: 200Hz full stroke and 1kHz at low level. At first a Breadboard Model (BBM) was realised using a ∅10mm glass mirror. Then an Engineering Model (EM) has been developed [4]. It steers a SiC mirror with a ∅31 mm diameter using a better mirror support, keeping the same magnetic actuation design.
The paper will review the technology of the M-FSM62 as well as its performances.

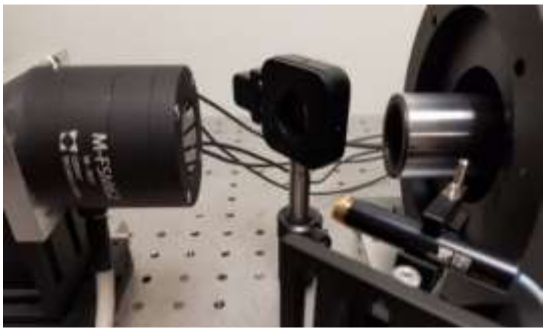

Figure 2 M-FSM62 EM on optical test bench

2 M-FSM Technology

The most conventional magnetically-actuated FSMs for space rely on Voice Coil Motors using Lorentz forces [5]. Although CTEC manufactures also Voice Coil actuators for space applications, another type of magnetic actuators is selected for the M-FSM: The M-FSM exploits a derivation and an integration of the CTEC MICA™ based on variable reluctance forces [6] to drive a mobile part in Rx and Ry motions in an efficient way.
Some FSM have already been designed using variable reluctance forces [7,8] to provide improvements above Voice Coil but they exploit attraction forces by reducing the air gap thickness leading to some drawbacks: Contact with attracting poles is responsible for strokes limitations and may generate damages, especially under launching vibrations and shocks. Torques that are not constant versus position are complexifying the drive of such devices.
CTEC patent-pending M-FSM removes these limitations thanks to a derived MICA concept. MICAs are biased variable reluctance tangential forces actuators. They are interesting in embedded application, such as new space compressors [9]. This space application provides heritage on magnetic components as well as on ultra-long lifetime flexure bearing, useful for space-grade M-FSM.

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The M-FSM are based on 4 MICA-like magnetic actuators. As for MICA™ [6], the stator contains the coils and the magnetic poles. These poles are located in front of the moving part. The moving part of the M-FSM exhibits a 32mm diameter 17gr cylindrical magnetic plate. It can be actuated in Rx and Ry rotations when the air gaps between the stator poles and the moving part are energised by feeding the coils of currents. This moving part can tilt inside the stator without air gap thickness reduction but with air gap surface modification.

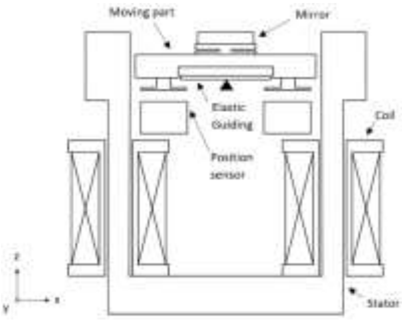

Figure 3 M-FSM structure (ZX cross section)

As a consequence, angular stroke is not limited by poles contact. Thus, there is no risk to damage the poles or the moving part when launching vibrations and shocks. In addition, torque is rather proportional to applied current and torque versus position is relatively uniform (**Figure 4**), providing good controllability. Torque constant is 10mN.m/A. The coils are designed to support 10Apk current. A small reluctance torque at rest if tilted ensures an alignment of the moving part with the poles.

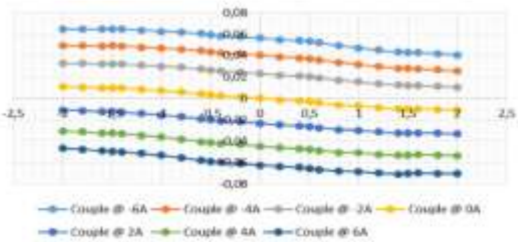

Figure 4 Torque vs angle at different currents

A frictionless flexure bearing guides along Rx and Ry the moving plate on which is fixed a mirror oriented along z. This flexure bearing ensures both high resolution and infinite lifetime. The guiding stiffness is chosen to get the first resonance frequency at 100Hz. The mirror's diameter can vary from 10mm as in the BBM to 31mm as in the EM. To sense the mirror position, the M-FSM contains 4 probes called ECP500 located below the mirror. These ECP500 are small proximity Eddy Current Sensors based on PCB coils, developed by CTEC, spatialised with CNES support and available as standard products. ECP500 can measure up to 1mm range with a 3nm resolution at 1kHz. Today this 1mm range provides the stroke limits of the moving part. Using 4 ECP500 allows to measure Rx and Ry tilts in a differential mode to avoid temperature dependency and integration bias by offset compensations.

These sensors allow a good observability of the mirror position and improve the controllability of the mechanism when working in closed loop.

Associated electronics for sensing, driving and controlling are the ECS45 conditioner and the MCSA480 driver (**Figure 5**). The ECS45 is a two channels conditioner reading the 4 ECP500, offering a bandwidth of 20kHz.

The MCSA480 is a new two channels current switching amplifier from CTEC for inducting loads. It is able to provide both 10 A AC current and 48 V AC voltage per channel. It drives the M-FSM in push-pull mode. Its 10kHz@-3dB bandwidth is compatible with required large bandwidth in closed loop. Today the closed loop control is a PID, offering overall performances after a trade-off of control/drives study. But the implemented controller with very high sampling rate (> 50ksamples/s) could support advanced control laws for better performances.

These electronics offer both open & closed loop control modes with high dynamic performances thanks to high power limits and a fast controller.

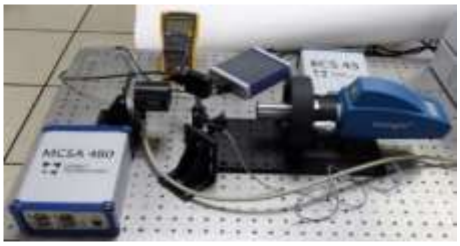

Figure 5 Optical test bench with ECS45 and MCSA480

3 M-FSM Open Loop Performance

The electromechanical strokes have been measured with a dedicated optical test bench **(Figure 5)**, because there was no standard equipment measuring accurately the +/-2° mechanical stroke on a bandwidth up to 1kHz. This combines a TRIOPTICS TriAngle autocollimator and a SITEK PSD. The PSD calibration has been performed using the autocollimator. Then the M-FSM ECP500 sensors have been calibrated using the PSD.

Low level angular strokes vs frequency (**Figure 6**) shows a constant gain up to the first resonance frequency (100Hz). Comparison of gain and phase of 2 different M-FSM62 for both channels shows a satisfying reproducibility.

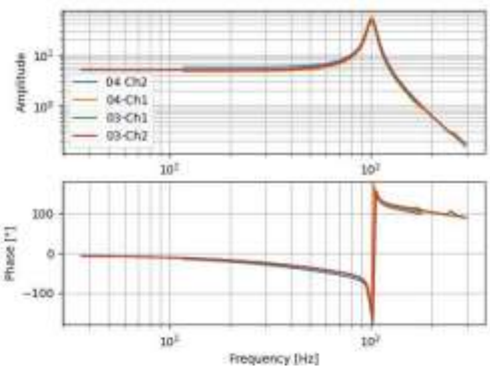

Figure 6 Low level of 2 M-FSM62 bandwidth.

High level angular stroke has been measured at different frequencies. For example, a measured +/-35mrad sine stroke at 20Hz is produced with 1.56Vrms and 2.64Arms meaning a power of only 3.75W. The full stroke open-loop is larger than 200Hz. Experimental functional performances are sump up in table 1.

Parameter	Unit	Value
Angular stroke max	Mrad	+/- 34
Full Stoke Open Loop Bandwidth	Hz	250
Mirror stroke @200Hz	Mrad	+/- 34
1st resonance frequency (31mm mirror)	Hz	100
Resolution	µrad	2-5
Resistance @ 20°C (incl. cables)	Ohm	0.5
Inductance @20°C	mH	0.64
Max drive voltage	V	24
Max drive current	A	10
Dimensions	mm	Ø62 x H56
Total weight	gr	400

Table 1 M-FSM Performances

A thermal analysis has been performed in air for different driving conditions.

At nominal conditions, for full stroke and low AC frequency (typically below 50Hz), because of the low electric power, the steady state of the mechanism is possible without overheating and damages.

Another driving conditions, representing severe conditions at 200Hz with 10Apk to get the max stroke is analysed. The frequency is twice above the resonance frequency explaining the required current. Heating measurement versus time (**Figure 7**) show that this severe drive condition can be maintained for 10 minutes. In correlation with low power requirement and the coils location in the stator, the thermal heating of the mechanism appears quite limited (lower than 100°C at the heat source) and concentrated in the stator. This reduces the heating of the mobile part supporting the mirror. This limits mirror thermal deformation and so keeps the flatness of the mirror.

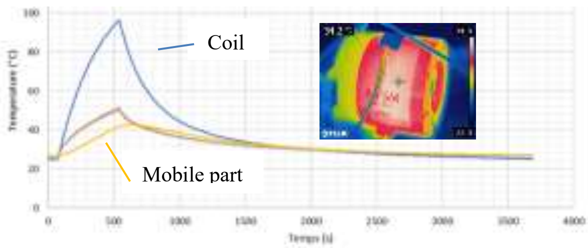

Figure 7 Heating at 10Apk 200Hz drive

Some vibration analysis have been performed both theoretically and experimentally. In the [0-2kHz] bandwidth, only 4 modes have been found and identified by FEM. The vibration tests have been realized with B&K LDS electrodynamic shaker at CTEC. In these tests, the mirror has been replaced by a lightweight tri-axis accelerometer (0.8g). The MFSM Z-axis excitation shows mainly the pumping mode around 150Hz (**Figure 8**).

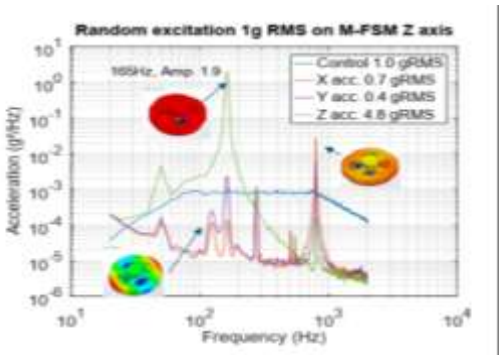

Figure 8 M-FSM Test in random vibration (Z axis)

4 M-FSM Closed loop control

For using the M-FSM in FSO, a closed loop control is required for different functions such as step & stay positioning, scanning and stabilisation.

The selected control strategy is at first meant to compensate some eddy current effects. These introduce some phase shifts between the motion and the order when going up in frequency.

Thus, the approach is based on a state feedback controller as [5] but explicitly integrating the eddy current effect. The observer rebuilds the states that cannot be sensed, and the state feedback controller provides damping to the system.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -k_t/J_t & -c_t/J_t & k_m/J_t & 0 \\ 0 & -k_m/L_H & -R_f/L_H & R_f/L_H \\ 0 & 0 & R_f/L & -(R+R_f)/L \end{bmatrix} \qquad B = \begin{bmatrix} 0 & 0 \\ 1/J_t & 0 \\ 0 & 0 \\ 0 & 1/L \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Figure 9 State space representation of the mechanism

This strategy allows to reject the eddy current effect and then achieve efficient damping on the system.

The tuning of a state feedback-based controller is based on the identification of the model of the system, including the eddy current effect. This first step is essential in case of developing model based advanced control (**Figure 10**).

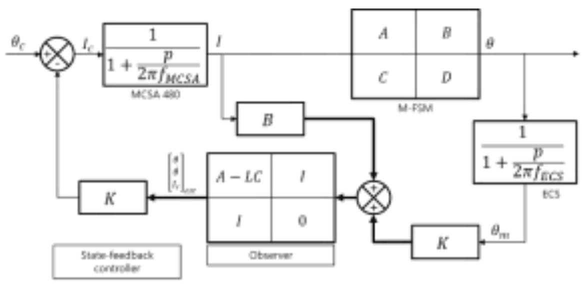

Figure 10 Controller architecture

The **Figure 11** compares the measured low level open loop response with the model. The good corelation of amplitudes and phases shows that the methodology is consistent and thus the model is reliable for control.

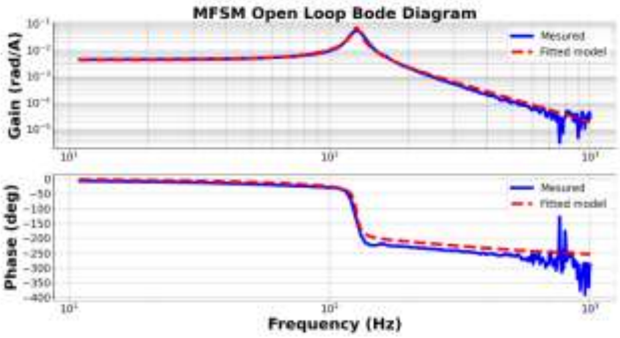

Figure 11 Comparison between model and measurement

The first milestone of the workplan is to control the system slightly above the first resonance frequency (~150Hz).
The results presented in **Figure 12** show the experimental results with first various controller implementations. These are encouraging.
The next step is to achieve ~1kHz reference tracking bandwidth. Modelling shows a feasibility as in **Figure 13**.

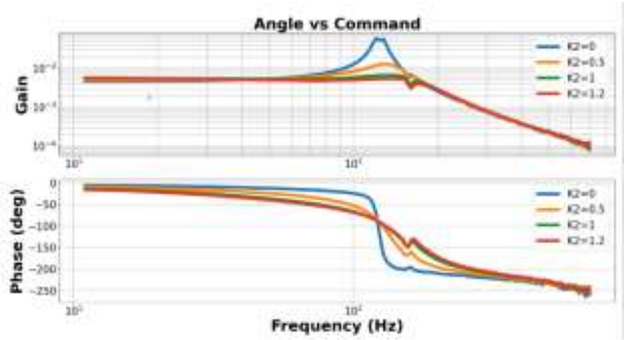

Figure 12 Experimental results of the controller (achieved damping)

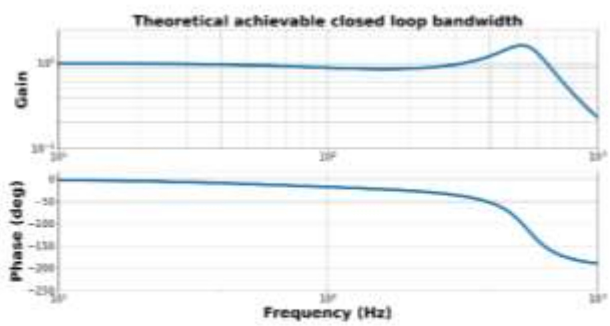

Figure 13 Theoretical achievable closed loop bandwidth

It is assumed that the final performance will be close to the theory because the previous steps have shown good agreement between the theory and the tests. In addition, very early tests of this control parameters provide good agreement with the figure 13 bandwidth.

5 Conclusion

New requirements from Space FSO and DSOC have driven CEDRAT TECHNOLOGIES (CTEC) to develop a new type of Fast Steering Mirror mechanism, the M-FSM62, based on magnetic actuation. It targets larger strokes than piezoelectric Tip tilt mechanisms developed by CTEC.
The M-FSM62 takes heritage of CTEC patented MICA™ technology. When tilting a 31mm-diameter mirror, this mechanism offers reproducible Rx Ry strokes > +/-2° with a 200Hz Full Stroke bandwidth. Requested power is reduced leading to low heating and allowing high duty cycle. Vibration tests allow to define first limits and conditions for the M-FSM to manage external vibrations.
Advanced control is achieved using integrated eddy current sensors and a closed loop control based on a state feedback-based controller. Experimental results show the closed loop control is achieved above the resonance frequency. Modelling and early tests show the feasibility to achieve a bandwidth of some hundred Hertz.

6 Acknowledgement

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