LARGE-STROKE FAST STEERING MIRROR
FOR SPACE FREE-SPACE OPTICAL COMMUNICATION

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ABSTRACT:

Free-Space Optics and Deep Space Optical Communication request new compact low-power high-stroke high-bandwidth Fast Steering Mirrors. To address this need, CEDRAT TECHNOLOGIES has developed a Magnetically-actuated Fast Steering Mirror called M-FSM, taking heritage of its MICA™ technology. This mechanism offers Rx Ry strokes larger than +/−2° with a 250Hz bandwidth when tilting a 10mm-diameter mirror. Closed loop control is achieved using integrated eddy current sensors. 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 bear external vibrations.

1. INTRODUCTION

Low-power high-stroke high-bandwidth Fast Steering Mirrors (FSM) are demanded for Free-space optical communication (FSO) in future 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 (PHARAO, ATLID) and optronics [1,3]. Currently, CTEC is in charge of delivering the piezo FSM required for PSYCHE DSOC of NASA JPL [4]. These piezo FSM offer a large bandwidth (up to 2kHz) and very fine resolution but strokes below 1° (Fig.1).

As such small strokes are constraining for optical and control design according to customers, CTEC has developed a new FSM based on magnetic actuation called M-FSM (Fig.2), targeting larger tilt stroke, typically more than +/-2 mechanical degrees (+/-35mrad), low power, low heating and high bandwidth: 200Hz full stroke and 1kHz at low level.

The paper will review the technology of the M-FSM as well as its electromechanical and environmental performances via a Breadboard Model (BBM) and an Engineering Model (EM) accounting for perspectives in space applications.

Figure 1. Comparison of high-level Bandwidth between the M-FSM and CTEC piezo FSMs

Figure 2. M-FSM BBM with Ø10 mm glass mirror (left) or Ø25.4mm glass mirror (right)

2. M-FSM TECHNOLOGY

The most conventional magnetically-actuated FSMs for space rely on Voice Coil Motors generating Lorentz / Laplace forces [5,6].

Although CTEC manufactures also Voice Coil actuators for space applications [7], 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 [8] to drive a mobile part in Rx and Ry motions in an efficient way.
Some FSM have already been designed using variable reluctance forces [9,10] 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 complicifying the drive of such devices. 

CTEC patent-pending M-FSM removes these limitations thanks to a derived MICA concept.

2.1. MICA™ actuators

The patented MICA stands for Moving Iron Controllable Actuator. MICA™ linear actuators are based on reluctant forces, as per electromagnets, but with a magnetic topology polarised with permanent magnets, in order to achieve a variable reluctance according to the current direction (Fig. 3). The stator contains the coil in a magnetic circuit. The moving part can translate inside the stator without air gap thickness reduction but with air gap surface modification. This topology allows a force and motion direction change, according to the current direction, as per Laplace force actuators, given by following formula:

\[ F_s = \frac{B_d B_s S}{\mu_0} \]

where \( B_d \) is the dynamic magnetic field in the air gap due to the coil current, \( B_s \) is the static magnetic field due to the permanent magnets, \( S \) is the pole surface and \( \mu_0 \) is the vacuum permeability. This formula (strictly valid when the actuator is centred) shows that the force is proportional to the coil current. As detailed in [8], good force uniformity and force-versus-current proportionality are even achieved in large ranges of positions and currents around the centre and the zero current.

![Figure 3. MICA principle (half cross section)](image)

The MICA™ achieves a performance breakthrough, compared to the weaknesses of the former state of the art on moving coil’s one, especially in terms of efficiency, compactness, and long life nonstop continuous operations over years without maintenance.

This enhanced feature is achieved by the use of a magnetic principle having both coils and magnets fixed, allowing an efficient heat dissipation by conduction. Moving parts need no electrical connection nor heat dissipation. This is optimal for draining heat sources as the Joule Losses of the coils. Its moving part is made of only one ferromagnetic part, driven by biased magnetic reluctance, offering high efficiency.

Compared to former voice coil technology, this actuator topology offers a twice higher force per mass and per input power [8]. This allows a long term operation at stabilised low coil temperature, as well as optimum electrical input power with reduced coil’s Joule effects.

For this reason, these MICA advantages are particularly interesting in embedded applications, such as new space compressors [11] for ZBO liquefaction and cryocoolers. Their development benefit of CNES and ESA support. This space application provides heritage on magnetic components as well as on ultra-long lifetime flexure bearing, useful for space-grade M-FSM.

2.2. M-FSM structure & components

The Breadboard Model (BBM) of M-FSM shown in Fig 2 containing the mirror is based on 4 MICA-like magnetic actuators. As for MICA™ of Fig.3, 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 4. M-FSM structure (ZX cross section)](image)
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 (Fig 5), 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.

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 108Hz corresponding to one tilt. The mirror's diameter can vary from 10mm to 25.4mm (1") (Fig.2), but the presented experimental results relate to the BBM with the 10mm diameter glass mirror.

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 [10], spatialised with CNES support and available as standard products [11]. 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 bias of integration by offset compensations.

Associated electronics for sensing, driving and controlling are the ECS45 conditioner and the MCSA480 driver (Fig 6).

The ECS45 is a two channel conditioner [11] 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. Today the closed loop control is a PiD, offering overall performances after a trade-off of control/drives study.

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

3. M-FSM PERFORMANCE

3.1. Optical test bench

The electromechanical performances have been measured with a dedicated optical test bench (Fig.4), because there was no standard equipment measuring accurately the +/-2° mechanical stroke on a bandwidth up to 1kHz. This bench combines a TriAngle autocollimator from TRIOPTICS and a PSD from SITEK to measure strokes. The autocollimator is an instrument performing precise optical angle measurement offering a 3.6µrad accuracy, and a 0.1µrad resolution but with a reduced angular range and a bandwidth of only 50Hz. The PSD (Position Sensing Detector) is an opto-electronic device which converts an incident light spot into continuous position data on a XY quadcell. It offers a 1MHz bandwidth and an angle range larger than +/-2° but it is not calibrated, depending on geometrical relative positions between the laser's source, the mechanism and the PSD. So, to provide precise full stroke measurements up to 1kHz, a calibration of the PSD has been performed using the autocollimator (Fig.5). Then the M-FSM ECP500 sensors and electronics have been calibrated using the PSD.
3.2. Functional performance

The M-FSM angular strokes have been measured using the calibrated PSD.

Low level angular strokes versus frequency (fig 6) shows a constant gain up to the first coupled resonance frequency at 116Hz (higher than 108Hz due to the lower weight of the mobile part).

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 an electric power of only 3.75W revealing the low required power.

Experimental functional performances are given in table 1. At the time of the paper writing, the full stroke is achieved up to 200Hz.

![Figure 6. Low level M-FSM bandwith.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular stroke max</td>
<td>Mrad</td>
<td>+/- 34</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Hz</td>
<td>250</td>
</tr>
<tr>
<td>Mirror stroke @200Hz</td>
<td>Mrad</td>
<td>+/- 34</td>
</tr>
<tr>
<td>1st resonance frequency</td>
<td>Hz</td>
<td>116</td>
</tr>
<tr>
<td>Resolution</td>
<td>µrad</td>
<td>2-5</td>
</tr>
<tr>
<td>Resistance @ 20°C (incl. cables)</td>
<td>Ohm</td>
<td>0.5</td>
</tr>
<tr>
<td>Inductance @20°C</td>
<td>mH</td>
<td>0.64</td>
</tr>
<tr>
<td>Max drive voltage</td>
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<td>24</td>
</tr>
<tr>
<td>Max drive current</td>
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<td>10</td>
</tr>
<tr>
<td>Dimensions</td>
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<td>Ø62 x H56</td>
</tr>
<tr>
<td>Total weight</td>
<td>gr</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 1. M-FSM Performances

3.3. Thermal performance

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 (Fig.8) show that this severe drive condition can be maintained for 10 minutes.

In correlation with low power requirement and the coils located at the stator, the thermal heating of the mechanism appears quite limited (lower than 100°C at the heat source) and concentrated in the stator (Fig.9). This reduces the mirror heating and limits mirror thermal deformation and so keeps the flatness of the mirror.

![Figure 7. M-FSM angular displacement at 20Hz measured by PSD-01 in XY graph](image)

![Figure 8. Heating at 10Apk 200Hz drive](image)
3.4. Vibration performance

Some vibration analysis have been performed both theoretically and experimentally. In the [0-2kHz] bandwidth, only 4 modes have been found and identified with an electrodynamic shaker (Fig.10).

- **Mode 1** - Tilt 110Hz (double)
- **Mode 2** - Pump 160Hz
- **Mode 3** - Torsion 600Hz
- **Mode 4** - Shear 860Hz (double)

The vibration tests have been realized with a B&K LDS electrodynamic shaker (Fig.11 in Z excitation). In the experiments the mirror has been replaced by a lightweight tri-axis accelerometer (0.8g). The three different axis have been monitored to estimate the guiding solicitation (Fig.12 and Fig.13).

The MFSM Z-axis excitation shows mainly the pumping mode around 150Hz (random excitation on Fig.12). The MFSM Y-axis excitation shows only one main mode around 800 Hz (sine excitation on Fig.13). This relatively high frequency of this mode guarantees a low displacement amplitude for this mode. Additional damping for reducing the mode Q factors will be tested in further investigations. These tests will also allow to define the limits and conditions for the mechanism to bear external vibrations.
3.5. Future works

The first electromechanical, thermal and vibration results on the M-FSM BBM are compliant with specification. However, the expectation of various space applications and other embedded applications includes other requirements than those addressed:

The electromechanical performances should be measured in the specified temperature range and not only at ambient, by considering environmental conditions, in both ambient and vacuum conditions. The Thermal behaviour in vacuum condition is more severe than in air, considering only heat conductivity and no more natural convection, and should checked with the specified thermal interface (typically 20°C at the mechanical interface or base plate of the M-FSM).

A mirror with high surface flatness and possibly larger diameter is generally required. This implies further works about stress and deformation induced by thermal variations, actuations, vibrations and shocks. A dedicated mirror holder is required. As the mirror mass and shape impact vibration modes, the ability to withstand vibrations and shocks needs also to be revisited by design with the selected mirror and further experimented.

At last as some constellations request hundreds units there is a need to address industrialization’s issues and to reduce series costs.

In this context, the development of a second version of the M-FSM is in progress, leading to the M-FSM62 definition. As the stator and the moving part are nearly the same as the BBM, the angular stroke and actuation torque of the M-FSM62 are the same. To improve thermal behaviour, it features a higher thermal conductivity by potting the coils. 2 Pt1000 (redundancy’s goal) per axis of rotation are included to monitor the temperature inside the stator.

But as key new features, it includes a SiC mirror with a 31 mm diameter and a dedicated mirror’s support minimizing induced stress. An Engineering Model (EM) being tested is shown in Fig 14.

The performances and especially strokes have been checked by using the same dedicated optical test bench and results are compliant to specifications (+/- 2 mechanical degrees for 4 A peak). The monitoring of both position in Rx and Ry, thanks to the ECP sensors and the ECS45 provides good results, highlighting low cross-coupling between the axis (lower than 5%) of the M-FSM62. (Figure 15 and 16).

Some environmental condition tests are under progress (vibration, thermal analysis), to check compliance of the mechanism to space application’s specification.

4. CONCLUSION

New requirements from Space FSO and DSOC have driven CEDRAT TECHNOLOGIES (CTEC) to develop a new type of Fast Steering Mirror mechanism, based on magnetic actuation, called M-FSM. This type of FSM targets larger strokes than piezoelectric Tip tilt mechanisms developed by CTEC.

The M-FSM derives and takes heritage of CTEC patented MICA™ technology. A first Breadboard Model (BBM) of the M-FSM has been designed, realised and tested.
When tilting a 10mm-diameter mirror, this mechanism offers \( Rx \) \( Ry \) strokes larger than \(+/-2^\circ\) with a 250Hz bandwidth and reduced heating. Closed loop control is achieved using integrated eddy current sensors. 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 bear external vibrations.

A second generation of M-FSM, named the M-FSM62 has been realised to deeper address space requirements.

5. ACKNOWLEDGEMENT

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6. REFERENCES