Development of Magnetic Fast Steering Mirror Prototype for Optical Pointing Applications

G. Aigouy, K. Benoit, E. Betsch, T. Maillard, M. Fournier, F. Claeyssen
CEDRAT TECHNOLOGIES S.A., Meylan, France

Abstract:
Fast Steering Mirrors are core products continuously developed by Cedrat Technologies (CTEC) for optical pointing applications, for Space, and Optronic domains. During the last decade, main development efforts where focused on piezoelectric mechanisms technology, in order to achieve ultra-high frequency bandwidth control performance over small angle strokes. New applications under maturation in Europe, such as laser optical communication, require much higher angle strokes compared to the existing state of the art, which cannot be easily achieved by piezoelectric technology. Therefore CTEC is focusing on the development of a new Fast Steering Mirror family based on high angle stroke magnetic actuators. This paper presents this new steering mechanism concept, and the prototype performance results expected.

Keywords: Fast Steering Mirror, Optical Pointing, Magnetic Steering Mechanism, Laser Beam Steering, Laser Optical Communication

Introduction

Fast **S**teering **M**irrors (FSM) are required for embedded applications demanding high level of control performance, with high frequency bandwidth, as well as mechanical robustness w.r.t. environmental mechanical conditions such as vibrations and shocks. Typically, Free Space Optic (FSO) communication have driven the development of FSM based on Voice Coil Motors [1,2].
During the last decade, CEDRAT TECHNOLOGIES (CTEC) main development efforts where focused on piezoelectric mechanisms, in order to achieve high precision and/or high frequency bandwidth control performance over small angle strokes, for space & optronic needs [3,4].

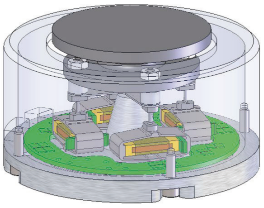

Fig.1: *CTEC Piezoelectric FSM DTT35XS*

Developing a magnetic actuator based FSM technology, requires encompassing the magnetic force limitation, compared to piezoelectric one, which allows high stiffness and quasi-static operation up to high frequencies about 1kHz, but with lower angular stroke. In order to achieve this target, and to provide a magnetic FSM based technology having comparable frequency bandwidth performance, as piezoelectric one, but with high angle stroke, CTEC has achieved a magnetic trade off among existing magnetic topologies, to defined best appropriate one. As a result, CTEC has selected a magnetic design, based upon a polarized variable reluctance principle, deriving from its proprietary MICA^{TM} (**M**oving **I**ron **C**ontrollable **A**ctuator). MICA^{TM} linear actuators are already being brought to high maturity for industrial markets while still being improved for space applications needing high efficiency and ultra-long lifetime [5]. Fig.2 reminds the principle of MICA linear actuator. The stator is a magnetic circuit integrating the coil and polarizing permanent magnets. The driven part is only a 'Moving Iron'. This leads to low inertia and robustness, as well as low power consumption and optimal thermal draining.

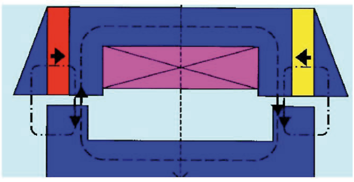

Fig.2: *MICA^{TM} variable reluctance principle*

Magnetic Fast Steering Mirror Concept

To start the works, various magnetic FSM concepts based on magnetic actuators have been investigated: Moving Coil, Moving magnets and Moving Iron. **The former state of the art has been kept in terms of mass and size, in order to fit with current existing integration requirements.** A typical investigated magnetic FSM topology is shown on fig 3. As in piezo FSM, two pairs of opposite actuators are driven in push-pull to move the mirror with a tip tilt Tx Ty motion (z being the optic axis).

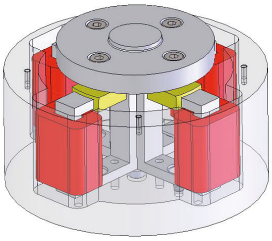

Fig.3: *Typical magnetic FSM configuration*

Early activities on magnetic FSM where focussed upon the selection of the magnetic design. A trade-off was performed, targeting same operational constraints, i.e. resonance frequency at 150Hz, stroke angle of +/- 3° and a bandwidth of 1 kHz with manageable power and heating.

For each design, moving masses and flexure bearing stiffness resulted different, according to the force to compactness ratios of each. Analysis shown that variable reluctance design, based on moving magnet or moving iron magnetic principles, where achieving the best force to compactness ratio, and as a consequence lowest moving masses, lowest flexure bearing stiffness, lowest inductance (i.e. higher frequency bandwidth), and lower force requirements. As a most important criteria, which allowed to select the preferred configuration, the Joule heat power was calculated, which is a key design feature w.r.t. transient temperature effects upon stability. The proposed MICA^{TM} concept, resulted as the best one for the FSM requirements.

	Inductance	Heat Loss
Moving Coil	101 mH	22,5 W
Moving magnet - Axial	2,52 mH	1,28 W
Moving magnet - radial	1,52 mH	4,5W
Moving iron - Axial	0,22 mH	1,5W
Moving iron - MICA^{TM}	0,7mH	0,8W

Fig.4: *Preliminary magnetic FSM Trade Off*

Long Lifetime flexural bearing design

In order to achieve perfect two axis tilt design, with linear mechanical motion, enhance performance long stroke flexure bearing had to be developed. The proposed bearing design was sized to achieve ultra-long lifetime, as well as mechanical strength w.r.t environmental requirements such as vibrations, shocks, and temperature.

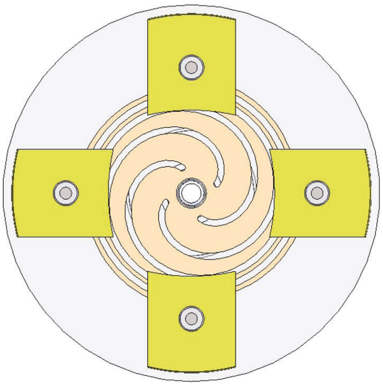

Fig.4: *Long angular stroke flexure bearing*

The actuation resonance frequency being the key of control performance, the flexure stiffness was tuned to achieve a first resonance mode above 150Hz, as mandatory requirement to survive launch loads for space application.

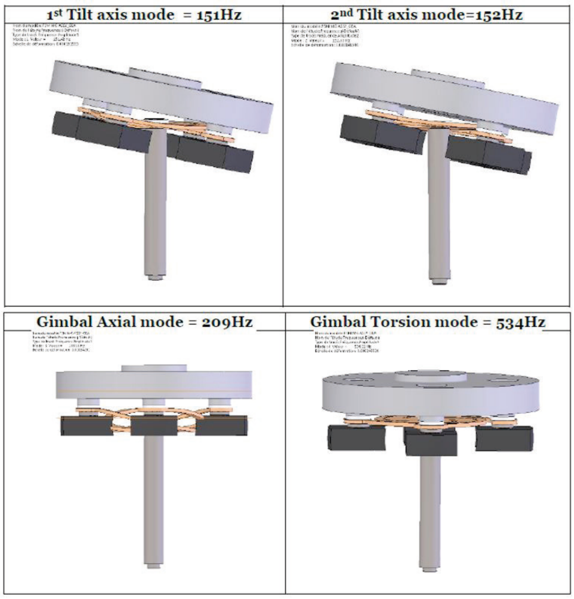

Fig.5: *1st Flexure bearing resonance modes*

The lifetime sizing achieved is shown here under, which correspond to an 11 years nonstop operation at 50Hz full stroke, or 70% of full stroke at 1000Hz.

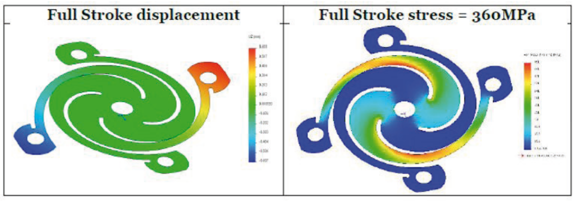

Fig.6: *Flexural bearing stress analysis*

ISBN 978-3-933339-30-0

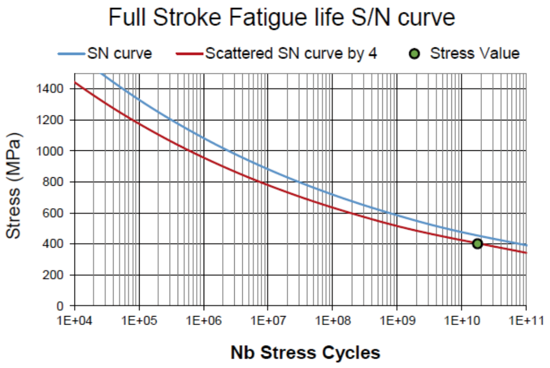

Fig.7: *Flexure bearing fatigue analysis*

Linearity analysis

Linearity performance upon long stroke, of torque versus angular position, achieved with variable reluctance magnetic designs, is not as good as could be expected compared to a moving coil one, as can be seen in fig.8 here under. Nevertheless, such a performance, achieving a 7% maximum variation at maximum current (compared to full scale), is considered as acceptable considering the other performances which have been supposed non achievable (or achievable with very high design effort) with moving coils designs. Such torque variations can be manage with close loop to get the required precision.

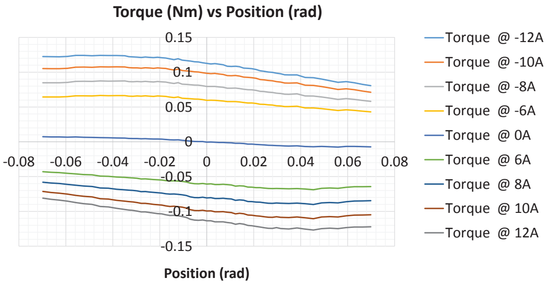

Fig.8: *Torque versus angle position analysis*

Limit analysis with COMMACT software

The existing COMMACT™ in-house software has allowed to optimize the frequency bandwidth of this new FSM in regards to both the actuators and drive electronics electrical limitations, i.e. w.r.t. stroke, force, current and voltage. The limits analysis allows to know the mechanical and electrical bandwidth, without control device, which are plotted in the figures here after.

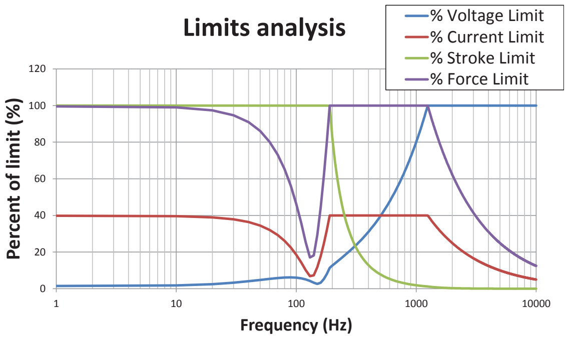

Fig.9: *Limits analysis with COMMACT™ software*

The results obtained with a 50V/10A drive electronic, shown a full stroke bandwidth about 6° pk-pk (i.e. +/-3°) up to 200Hz, resulting to about 0.1° pk-pk at 1000Hz.

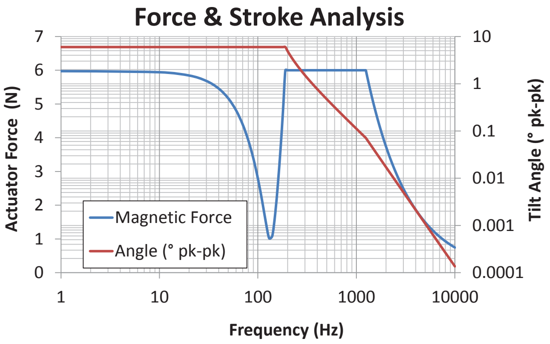

Fig.10: *Frequency bandwidth analysis with COMMACT™ software*

Electrical Analysis results

Fast steering mirrors are compact systems of very small dimensions, which have to fit as well with miniature size drive electronics. Therefore careful optimization has been achieved to reach low voltage and current electrical requirements, in regards to the targeted frequency bandwidth.

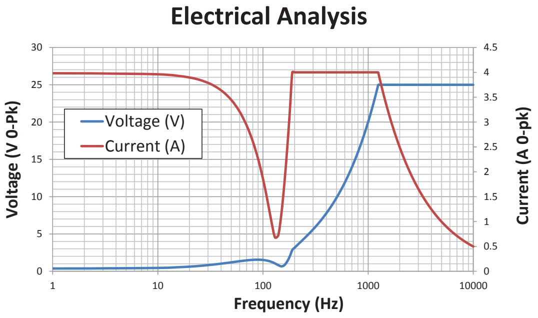

Fig.11: *Electrical analysis with COMMACT™ software*

As can be seen, electrical power analysis shows a power absorbed lower than one watt. This power results in a maximum one watt joules effect heat dissipation, which is optimised.

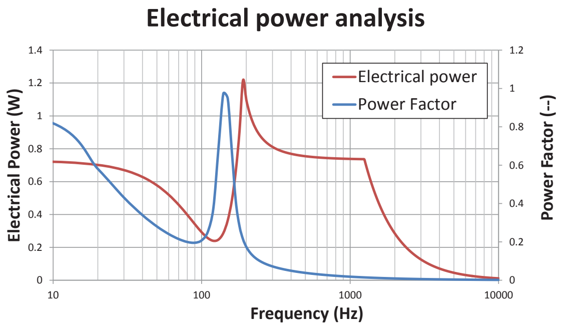

Fig.12: *Electrical power analysis with COMMACT™*

Compared to moving coil designs, the MICA^{TM} concept is built upon fixed coil, and fixed magnet principle, which gives the opportunity to achieve an efficient heat sinking by conduction of the Joules effects, in order to achieve temperature stability versus time, even during transient operation. This feature is especially relevant for use under vacuum condition, or for space applications.

Piezoelectric and Magnetic FSM technologies performance comparison & conclusion

As the result of this new technological development target, one can compare at first the targeted magnetic FSM stroke mechanical bandwidth, with the existing piezoelectric FSM state of the art at CTEC. One can see in fig.11 that both technologies differ in stroke capability at low frequency, and that highest stroke capability at high frequency remains achievable by piezoelectric technology.

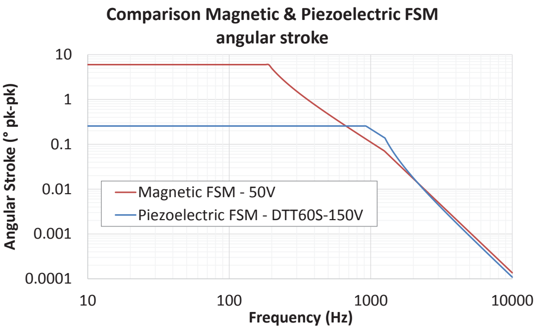

Fig.13: *Magnetic & Piezoelectric bandwidth comparison*

In a second time, one can compare the controlled bandwidth achievable with position feedback.

In order to assess the controllability over frequency of a FSM, one has to consider the first resonance. Indeed the phase lag which appears after resonance frequency, makes the rejection of parasitic vibrations not possible. This means that only asymptotical position (step and stay) control without perturbation rejection should be considered starting from first resonance frequency and above. One can see in fig.13 here after that a FSM would behave in quasi-static mode with zero phase lag in position feedback closed control loop, only up to about 1/3 of the resonance. The resonance frequency being increased by the closed loop controller, as seen in fig.14, compared to a 150Hz magnetic FSM design, and a 1200Hz piezoelectric one, the controllable bandwidth with vibrations' rejection result up to about 200Hz for magnetic FSM, and up to about 1000Hz for a piezoelectric one.

Best appropriate technology with classical position feedback control methods at high frequencies up to 1000Hz, and with perturbations' rejection, is considered as the piezoelectric one. Considering open loop control instead, or other feed forward control methods better appropriate for vibrations' rejection, both technologies could be considered as comparable.

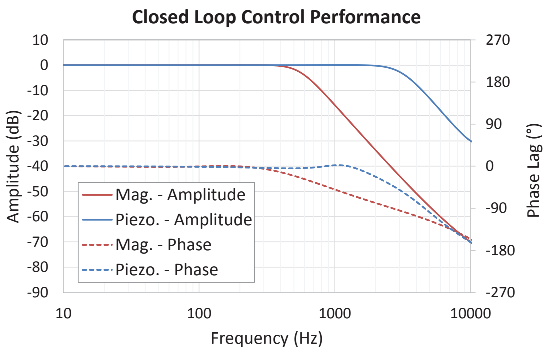

Fig.14: *Phase lag due to resonance*

Acknowledgements:

This work benefited from financial support from BPI.

References:

[1] F. Di Gesu, Silex Mechanisms : which lessons after qualification ?, Proc ESMATS conf, 1995
[2] W. Coppoolse, Dual-axis single-mirror mechanism for beam steering and stabilisation in opticalinter satellite links, Proc ESMATS conf, 2003
[3] E. Prevost, and all, Beam Steering Mechanism For Earthcare Atmospheric Lidar Instrument Atlid – An Ultra-Stable Piezoelectric Tip Tilt Mechanism, Proc. ICSO 2016, Biarritz, Fr., 18 - 21 Oct. 2016
[4] F.Claeyssen, and al, Beam Steering Mirrors from space applications to optronic solutions, Proc. OPTRO Conf, Paris Fr., 6-8 Feb.2018
[5] G. Aigouy, Development of the Plain bearing & Flexure Bearing MICA300CM Actuator, Proc ACTUATOR Conf, Bremen, 2018

ISBN 978-3-933339-30-0