Low order high accuracy deformable mirror based on electromagnetic actuators

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ABSTRACT

Building on the technology developed to build deformable secondary mirrors for large telescopes, we show that a new breed of tip-tilt and low order deformable mirrors can be designed to satisfy the need of a large number of traditional astronomical AO systems that rely on a high order piezo deformable mirror compounded with a tip-tilt mirror to compensate for the large image motion present in the atmosphere. Using a new paradigm, we are developing a compact 50mm deformable mirror which benefits from a large computer power used to implement powerful control algorithms that allow speeding up the mirror response. Freed from the space and geometrical constraints that deformable secondary mirrors must respect, our mirror also displays elegant simplicity and compactness.

Keywords: Adaptive Optics, Tip-tilt tracker, wavefront correction

1. INTRODUCTION

For over a decade now, there has been a significant interest and much work done toward developing deformable secondary mirrors (DSM) for use on astronomical adaptive optics (AO) system. This effort has already produced a 336 actuator mirror working on the 6.5m MMT adaptive optics system[1,2,4]. This mirror is actually a full size prototype used to gather experience on all aspect of the complex technology involved, but it is producing science-grade results. See for instance references 5 and 6. Today this technology is being pushed towards higher order deformable mirrors (DM) for use on the LBT (672 actuators) [9,10] and the VLT (1170 actuators) [7]. However, a niche for the use of these mirrors has been neglected so far: the possibility to use the same mechatronic configuration as the DSM to produce simple and compact tip-tilt mirrors of high speed and high stroke for various applications. Having identified this niche, the Applied Optics lab of the West Switzerland University of Applied Science has started the development of a small (50mm) low order (5 actuators) deformable mirror, to explore the design parameters offered by the more relaxed environment of an optical bench.

2. SYSTEM CONSIDERATION

Commercial off-the-shelf solutions exist in the field of tip-tilt mirrors (also called “trackers” or steering mirrors); some with remarkable throw and/or speed[11]. These devices are not offered with position controlled systems and the system integration is left to the customer, with the advantage that it can be optimized for each application. However, when targeting AO systems with tight wavefront error (WFE) budgets, one sees that the high speed of the mirror is not sufficient to allow high speed closed loop operation with sub millisecond settling time. This is why a cottage industry has developed in academia, offering custom solution to the astronomical AO user. To our knowledge, these solutions are all based on rather traditional piezo actuated gimbals or flex structures, which guarantee stable operation under all but the most aggressive conditions. They use various types of high-end position sensors[12].

On the other hand, the DSM’s make use a voice-coil actuator (i.e. a force actuator unlike the piezo which is a position actuator) where a magnet is attached to a glass meniscus floating over a mechanical reference. Sophisticated multi-variable control methods using a blend of feedback and feedforward have been developed to control several hundreds of actuators in parallel. In this case, the complexity of the control architecture is both a drawback and a blessing: It is a drawback because it forces the designer to provision a significant amount of processing power just to hold the mirror in

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place. But it is also an advantage because this processing power can be used to program powerful control algorithms that are out of reach of regular analog controllers like the ones customarily used on tip tilt mirrors.

Another consideration makes the use of voice-coil activated mirrors attractive: The closed loop bandwidth of the traditional flexure or gimbals design is intrinsically limited by the resonant frequency of the oscillator made of the flexure's inertia (with the mounted mirror) and the piezo springiness. Even with FEA optimized designs this frequency can hardly reach 1kHz. Systems complete with controller and voltage amplifier will have closed-loop bandwidth significantly lower than this. On voice–coil activated DM's the inertia is dramatically reduced because the meniscus mirror is essentially free floating, with only the actuators' magnet adding to its inertia. The "spring" of the potential oscillator is now made of the controller which parameters are largely in the hand of the designer.

ASM's must satisfy a large set of constraints due to their location: Variable gravity, wind, temperature variation, form factor. The DM we are building will not work in such a difficult environment and this frees several design parameters:

- The mirror is not meant to be installed in a centerered telescope system: It is possible to have the mechanical diameter of the mirror larger than the optical diameter without vignetting the beam. This allows holding the meniscus by the external edge, simplifying the build.
- The mirror is designed to work on a bench and the electronic control can be dissociated from the optomechanical part. This makes the electronics design and the packaging much simpler.
- The mirror is designed to work in vertical position. Therefore, the gravity quilting is not a dimensioning factor for the meniscus thickness. Its is dimensioned by manufacturing considerations and the gravity induced bending caused by the weight of the magnets (see figure xxx)
- Another factor that we can take advantage of is the limited diameters of our DM. This imposes a much thinner reference body and allows shorter actuator length. This in turns decreases the thermal resistance.

3. OPTOMECHANICAL DESIGN

3.1 General concept

The general concept of our DM is the same as the one presented in [3], but we repeat it here for completeness:

- A deformable glass meniscus (1.5mm thick) with magnets glued to its back surface. A stop located at the outer edge of the mirror hold the mirror when unpowered.
- A copper plate (*cold plate*) that provides support and cooling for the actuators. This plate forms the external mechanical interface to the DM.
- A thick (10 mm) glass plate (*reference plate*) fixed to the cold plate. It is held in position by three ball bearings and an O-ring. This plate is considered a solid body to which the thin deformable meniscus can be referenced. The coil cold-fingers, pass through holes bored in the reference plate to reach the meniscus.
- The electromagnetic actuators. For each actuator, a coil is placed atop a copper cold finger faced to the corresponding magnets bonded on the back of the thin mirror.
- The meniscus position sensors. For each actuator, the position is sensed using the capacitive sensors using the variable capacitance between a electrode deposited on the back the meniscus and an annular electrode deposited around the actuator hole in the reference plate. Each signal is conditioned and amplified by an analog circuit placed in the immediate vicinity of the actuator.
- A control electronics unit with the necessary computing power, electronic conditioning for the distance sensors and power circuitry for the actuators.

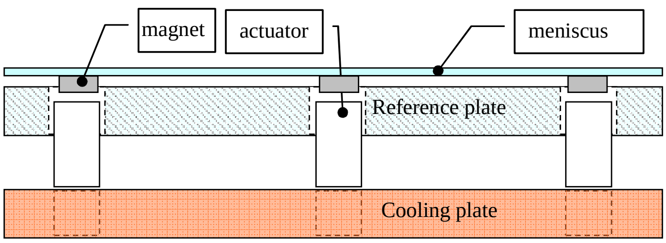


Figure 1: functional break-down of a voice-coil activated deformable mirror

3.2 Reference plate

Sine our target position resolution is a few the nanometers, the reference plate must have a stability of about this order. Other drivers are manufacturability, ease of mount, and reliability.

Mechanical stability is reached by avoiding making hyperstatic system. The reference plate is held on three ball bearings that define the plane of reference f the whole system. Rotation and translation are constrained by applying a light load with an O-ring. This will of course cause a localized stress and this is why having a reference plate thick enough is necessary.

Reference plate temperature expansion must be as small as possible. The material of choice for ASM's is Zerodur® with a coefficient of thermal expansion (CTE) of $0.1*10^{-6}\,K^{-1}$ for the lower grade. It is however rather difficult to machine and to figure optically so the reference plate must be as simple as possible. At the scale of our DM however, fused silica is quite satisfactory, because the larger CTE can be traded for better thermal conductivity

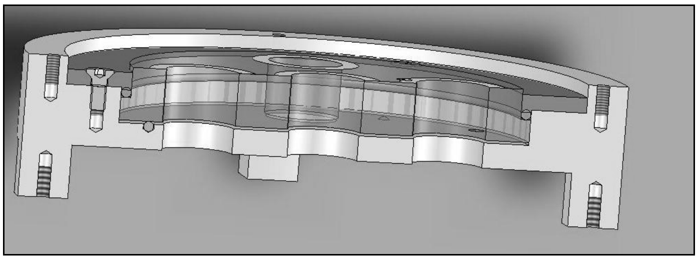


Figure 2: Cut through the reference body: An O-ring presses the reference body on the ball bearings which form the reference plane. The large piece is the chassis of the system

One important aspect of the design is that the position sensors, in the form of annular capacitors, are deposited directly at the surface of the reference body. They can be seen in Figure 2. Thanks to the reduced number of actuators/capacitors pairs, we were able to route the connection lines to the electrodes to the edges of the mirrors where they can be connected easily to the preamps. This elegantly solves one of the severe problems that has hampered the MMT336 DM since its early days, but unfortunately it is not scalable to high order DM's.

3.3 Deformable meniscus (Mirror)

For thermal expansion reasons, the deformable mirror is made of Zerodur®. Its mechanical constants were implemented in an FEA study for evaluating the required thickness of the mirror. We must add here that we intend to use the mirror to correct more than just the image wander but to correct also the lower atmospheric modes, in particular the focus and astigmatism. Therefore, due to the meniscus rigidity, a compromise must be found between defocus stroke and thickness.

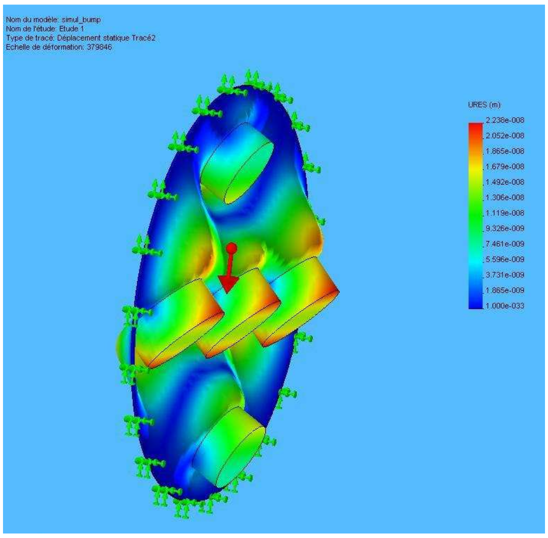


Figure 3 Effect of magnet torque due to gravity (arrow) with a mirror of 0.5 mm of thickness. 45 nm peak to valley (90 ptv WFE). This value is 6nm ptv WFE with a thickness of 1.5mm

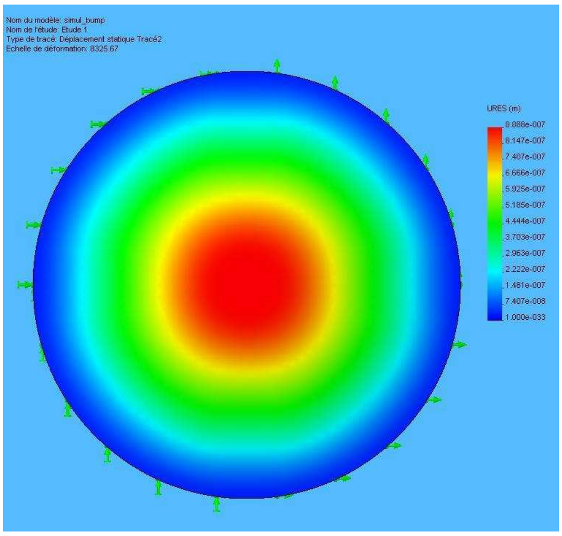


Figure 4 Deformation induced by pushing with 1 N on center and -0.25 N on the other actuators. Peak to valley deformation is 1.2µm peak to valley

We can see that the stroke of defocus is modest. But it is absolutely necessary to make that sacrifice otherwise the bumps due to magnets weight would be optically significant.

3.4 Flex structure

To hold the meniscus mirror we are using a flex structure. The flex structure must hold the meniscus laterally without impeding the tip-tilt motion. The thermal expansion of the flex structure is not the same as the one of the mirror and therefore, care must be taken that this difference does not translate into mirror deformations.

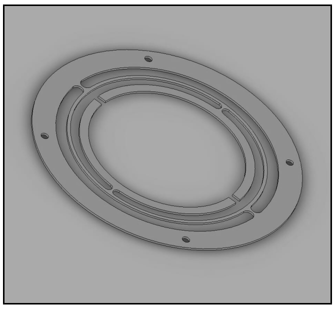


Figure 5 Flex structure design. It provides lateral support but only minimally constrains tip, tilt and piston. This design is manufacturable on a conventional machine tool (no laser or water dicing).

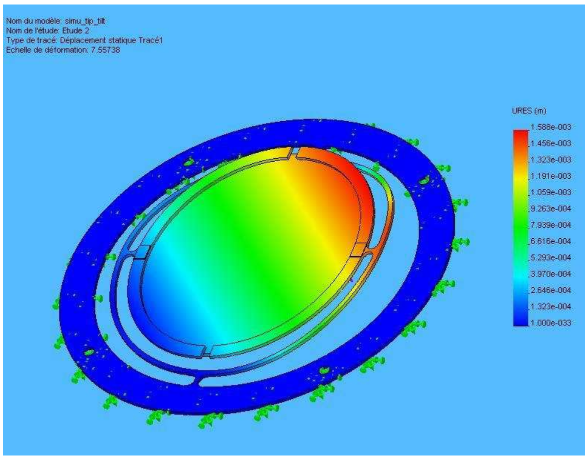
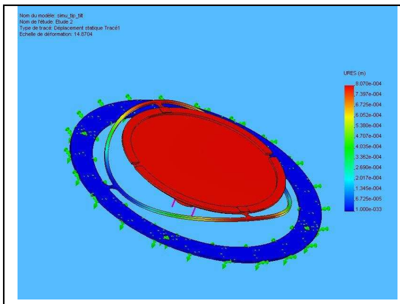
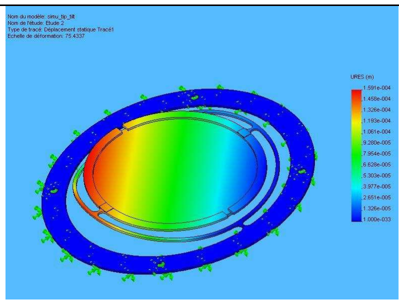
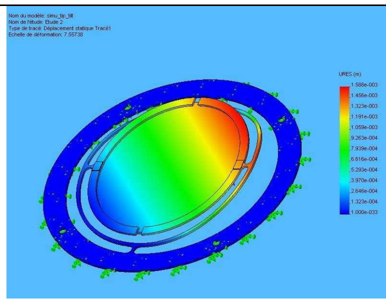


Figure 6. A tip-tilt induces with 0.1 N pushing and 0.1 N pulling. At the limit of entrance pupil (D = 50mm) we have a 200 µm peak to valley tip-tilt. Stiffness of flex structure is very low and will not make actuators heat too much

Flex structure is made of aluminum alloy 1060. Its CTE is quite different from CTE of Zerodur®. The differential expansion between mirror and flex structure must be entirely taken over by the flex structure. It’s why the first ring is cut at middle part. The mirror is glued on two points diametrically opposites and near from the gaps on the first ring.

3.5 Modal behavior

Thorough analysis of modes is necessary for prevent damages on the mirror when he is used in resonant frequencies. With five actuators, five mechanical modes are present.

			
piston	tip	Tilt	
Fres = 28.4 Hz	Fres = 46.9 Hz	Fres = 49 Hz	

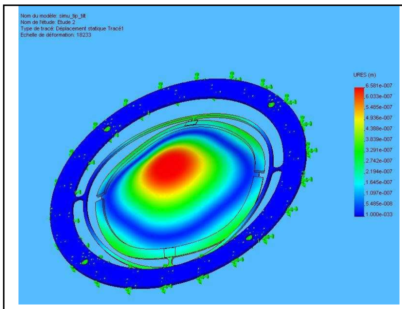
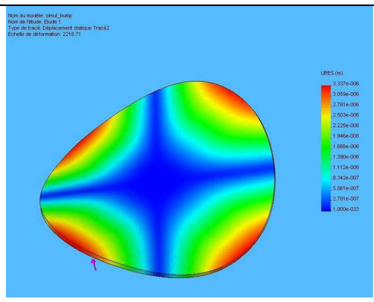
	
defocus	astigmatism
Fres = 2219 Hz	Fres = 2028 Hz

Figure 7: There are modes that are in useful bandwidth. But the analysis didn't includes squeeze-film air damping due to the proximity of mirror too reference body. Squeeze film air damping is really useful to avoid damaging mirror at Fres.

4. CONTROL SYSTEM AND DYNAMIC SIMULATIONS

4.1 Context

Because time has elapsed since the present day ASM where designed and the simplified system we are considering , we have revisited the architectural trade studies that led to the MMT and LBT designs. Originally, one of the goals of our study was the design an actuator with a better efficiency in terms of $N/W^{0.5}$. In particular, we considered addin a magnetic circuit to better guide the field. However, it became quickly clear that the radially magnetized magnet over a axial coil was a best choice for our application. Therefore, the study has focused on the control architecture and the choice of processor.

4.2 Models

We have used the following mirror configuration

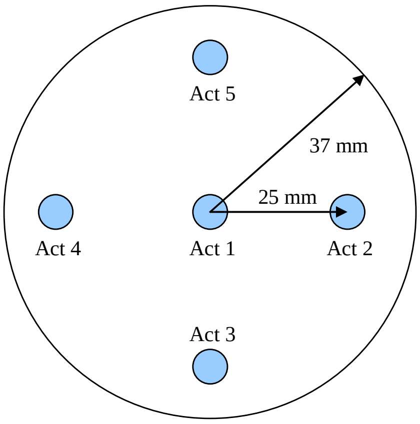


Figure 8: The following mirror parameters have been assumed: Initial gap: 50 micron; meniscus thickness: 1mm, Material: Zerodur (2530 Kg/m^3, 91 GPa Young modulus, 0.24 Poisson modulus.) The actuators have 8.5Ω and 244 µH

The complete control architecture is represented in the figure below. Let us review the building blocks:

- Target: This is a multi-dimensional vector with the target position of each actuator.
- Controller: Implements the position control of each actuator
- Actuators: This block holds the current loops, the model of the E-M circuit. The input is the current target and the output is the actual current.
- Meniscus: Model of the mirror. The input is the actuators currents vector. Output is the actuators position vector.Gap sensors
- Feedforward : Generation of the feedforward command. See below.

The controller implemented is a simple multiple SISO with PID's for each actuator. The actuators are linear L-R circuits with current loop and voltage saturation. The closed loop bandwidth with the analogue controller computed is about 90 kHz. The gap sensors are modeled with a gain of 1, no noise. The feed forward command is generated statically: It produces a command equal to the final values expected after the transient. It is derived from the stiffness matrix K, giving the forces required to hold the deformable meniscus in any position.

$$\vec{f}_{ff} = K \times \vec{u}_{final}$$

The only sophistication in our model is the squeezed air damping force: The coefficient of damping force for an annular plate is obtained from [14]:

$$C_{ann} = \frac{3\mu a^2 A}{2h^3} \cdot g(\eta)$$

Where A = πa^2, η = b/a (outer and inner radius) and $g(\eta)$ is:

$$g(\eta) = 1 - \eta^4 + \frac{(1-\eta^2)^2}{\ln(\eta)}$$

For tip and tilt modes, an area is defined around the actuator who pulls the mirror. Others areas are neglected because of the h^3 at denominator. The mirror is supposed to be at 50 µm from reference plate. Resonant frequencies for tip tilt modes are about 50 Hz. $g(\eta)$ is fixed by devices geometry. Finally we find C_{ann} = 4.3. Stiffness of flex structure found by simulation is K = 800 N/m. The system transfer function model:

$$H(s) = \frac{A}{1 + \frac{2\zeta}{\omega_n} s + \frac{1}{\omega_n^2} s^2}$$

ζ is proportional to C_{ann}, ω_n = 2.π.Fres

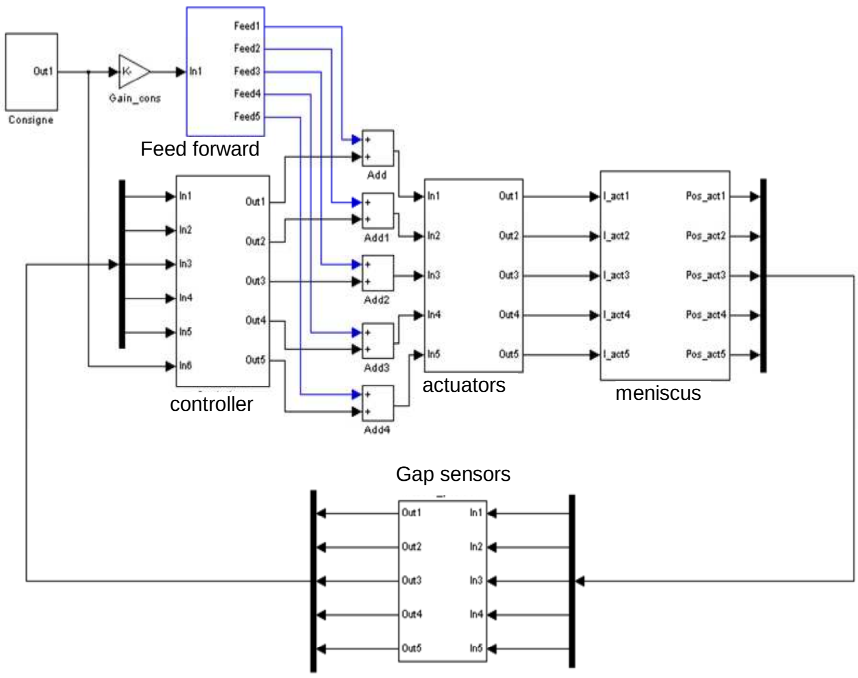


Figure 9: Global control architecture. The command of the 5 actuators is the sum of the feed forward component and the feedback through the controller. Our intent is to explore the possibilities offer by a fully multivariable control but the simulations so far have assumed a localized control with a vectorized feed forwards.

4.3 Performace

After turning of the controllers to optimize the responses (in the frame of the PID controllers) we end up with two different controllers: one for the central actuator and one for the ones on the mirror edge. The Figure 10 shows the step responses obtained using a static feed forward command.

With the favorable hypothesis that the meniscus is 1.0mm thick, the expected 10%-90% rise time is around 100 µs and the 10% stabilization is about 500 µs. One also sees that the feed forward is pivotal is obtaining a fast response. To take full advantage of the embedded computer power, we have also simulated the systems response when using a dynamic feed forward command: i.e. the force command vector computed from the actual meniscus positions at each sampling period.

$$\vec{f}_{ff}(k) = K \times \vec{u}(k)$$

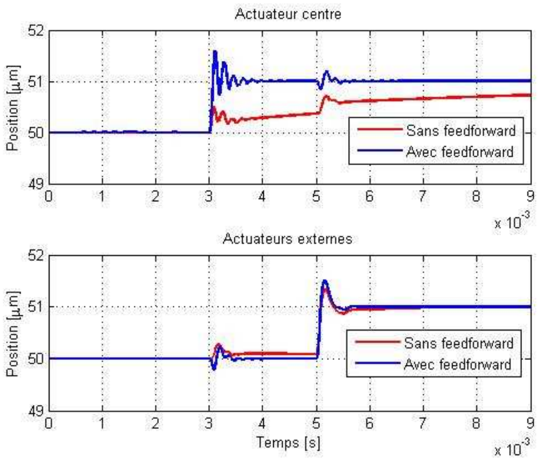


Figure 10: Step response of the central (top) and an external actuator (bottom) at T0+3ms repectively T0+5ms. The blue and red curves are without and with feed forward repectively. The actuators are coupled and each actuator's response will disturb the other's. The static downward feed forward force is applied before the upward force induced by neighbor actuator is felt. Hence the down-and-up motion on the bottom graph. Note also the tremendous improvement in rise time brought by the feedforward command

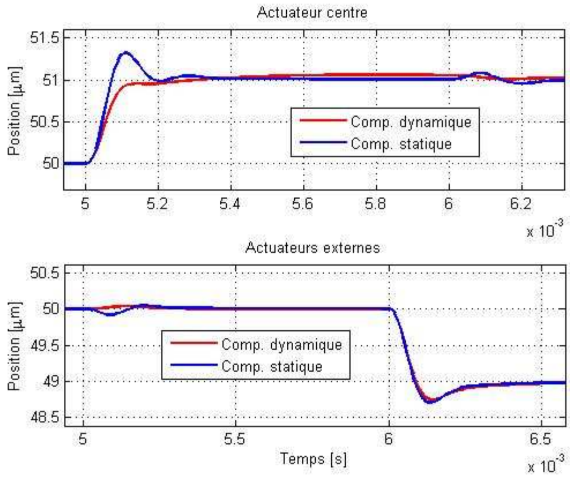


Figure 11: Step response of the central (top) and an external actuator (bottom) at T0+5ms repectively T0+6ms. The blue curve is with static feed forward and the red curve is with dynamic feed forward. The coupling between actuators is significantly reduced and the transient behavior is improved. Note that on both figures the horizontal scale is given in milliseconds.

5. TESTS AND MEASUREMENTS

5.1 Project status

Different organizational and procurement problems have delayed the implementation phase of this project and the present status is that

- The opto-mechanics has been designed and built
- The glass is being manufactured. For procurement reasons, both reference plate and deformable meniscus is be in fused silica in a 1st phase.
- The electronic circuits have been prototyped and the final design is being routed

- The control software implementation is nearing the end at the time publication. The DSP chosen is a TMS320C6727. The sampling frequency of the position control, as measured using the final circuits, will be around 80kHz or somewhat below the targeted 100kHz. It is essentially limited by peripheral and memory access. Therefore, we expect that the test of more sophisticated algorithms than the localized feed back we have baselines will be possible without major impact on the sampling frequency.

5.2 Capacitive sensor

The capacitive sensors circuit has been prototyped using a servoed x-y piezo stage from Physik Instrumente, the dedicated pre-amp and conditioning circuits foreseen for the final design and an off-the-shelf acquisition board. The capacitor electrodes were made off two circular aluminized mirrors. Because the resolution of the x-y- stage control is only 100nm, we used a setup were the plates displacement was lateral rather than axial and this allowed replicating the effect of nanometer scale gap variations.

By comparing Figure 12 and Figure 13, one can see that the voltage measured at the arbitrary zero position during the lateral displacement measurements corresponds to a gap of 31nm.

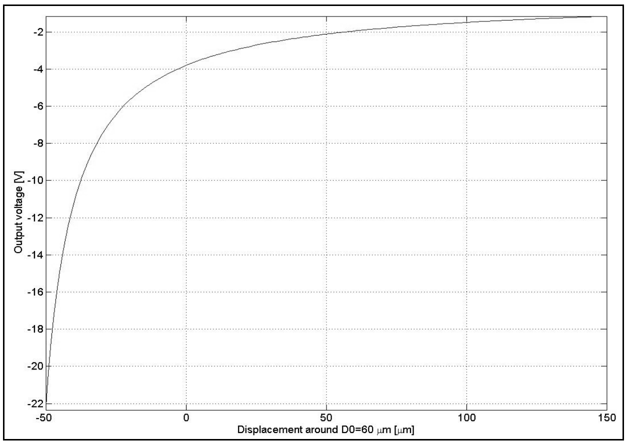


Figure 12: Calculated Output voltage versus gap curve.

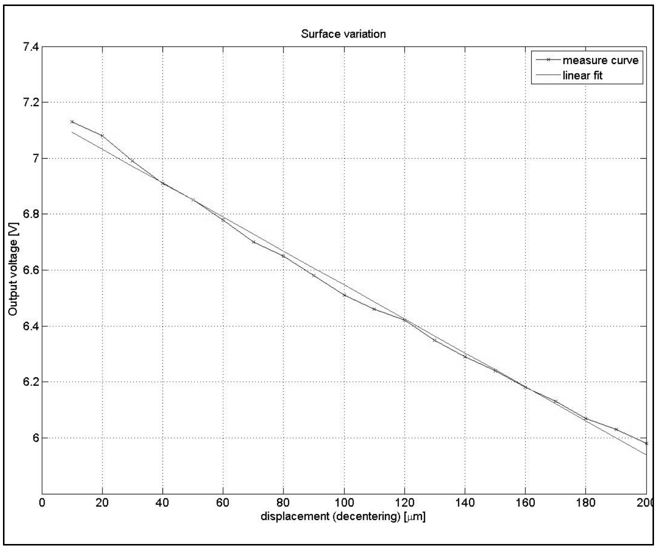


Figure 13. Measured output voltage versus lateral displacement.

Given the non-linearity of the capacitance response, one can compute that a sensitivity of S=189 nF/m at a gap of 100µm is required to be able to discriminate 10nm with a 16 bit transducer. The gain of the circuit measured on Figure 13 is 1.37 V/pF, and the noise is 900µV or σ_c = 0.66e-3 pF. Therefore the resolution possible is σ_c /S< 4nm

5.3 Thermal dissipation

A mock-up the opto-mechanical structure has been built to test the thermal behavior of the design chosen. The major lesson is that the thermal conductivity between the coil and the base plate is <2ºK/W, a fourfold improvement over the results reported in [15].

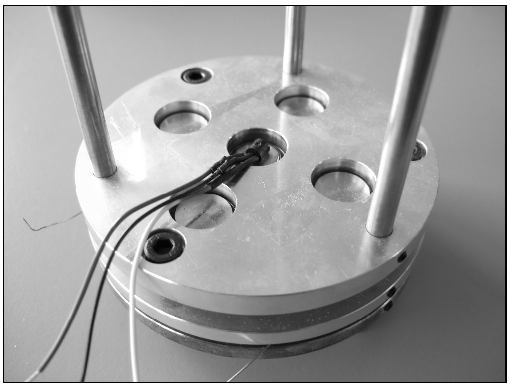


Figure 14. Thermal mock-up of the DM

6. CONCLUSION

We are developing a tip-tilt and low order correction 5-actuator deformable mirror to explore the possibilities offered by the voice-coil actuators co-localized control technology pioneered at Osservatorio di Arcetri. Taking advantage of the lesser constraints of a bench mirror, we were able of design a much simplified opto-mechanical mount with shorter actuators and separate electronics. It has the advantage of having a full aperture which can make it attractive for applications outside the astronomical community. Simulations show that sufficient computing power is implemented to run the DM at 80kHz using a single DSP and high stoke (200nm ptv WF) high speed response is guaranteed by the use of high voltage current loop. We are impatiently awaiting the delivery of the glass and the final electronics to start imtegration and characterization of our DM.

ACKNOWLEDGMENTS

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REFERENCES

1. F. Wildi, G. Brusa, A. Riccardi, M.. Lloyd-Hart, L. Close. "1st ***light of the Adaptive optics system at the 6.5m MMT***", *Astronomical Adaptive Optics Systems and Applications*., vol. 5169 of *Proc. SPIE*, pp. 17-25 (2003)
2. G. Brusa, A. Riccardi, P. Salinari, F.P. Wildi, M. Lloyd-Hart, H.M. Martin, R. Allen, D. Fisher, D.L. Miller, R. Biasi, D. Gallieni, F. Zocchi, "MMT ***adaptive secondary: performance evaluation and field testing***", *Adaptive Optical System Technologies II*. Vol. 4839 of *Proc. SPIE*, pp. 691-702 (2003)
3. Riccardi, G. Brusa, C. Del Vecchio, R. Biasi, M. Andrighettoni, D. Gallieni, F. Zocchi, M. Lloyd-Hart, H. M. Martin, F. Wildi "***The adaptive secondary mirror for the 6.5 conversion of the Multiple Mirror Telescope***" *Beyond conventional adaptive optics*. European Southern Observatory, 2002 ESO Conference and Workshop Proceedings, Vol. 58, ISBN 3923524617, p. 55
4. M. Lloyd-Hart , F. Wildi, G. Brusa, "Lessons learned from the first adaptive secondary mirror", SPIE international symposium on Optical Science and technology, 4-5 August 2003, San Diego CA, USA (5169-10)
5. L. Close, B. Biller, W. Hoffmann, P. Hinz, J. Bieging, F. Wildi, M. Lloyd-Hart, G. Brusa, D. Fisher, D. Miller, R. Angel, "***Mid-infrared images of post AGB star AC Herculis with the MMT Adaptive optics system***", *ApJ letters*, Nov. 20, 2003 issue.
6. L. Close, F. Wildi, M Lloyd-Hart, G. Brusa, D. Fisher, D. Miller A. Riccardi, P. Salinari, D. McCarthy, R. Angel, R. Allen, H. Martin, R. Sosa, M. Montoya, M. Rademacher, M. Rascon, D. Curley, N. Siegler, W. Duschl, "***High resolution images of orbital motion the trapezium cluster: first scientific results from the MMT deformable secondary mirror adaptive optics system***", *Astrophysical Journal*, 599, 2003
7. R. Arsenault, R. Biasi, D. Gallieni, A. Riccardi, P. Lazzarini, N. Hubin, E. Fedrigo, R. Donaldson, S. Oberti, S. Stroebele, R. Conzelmann, and M. Duchateau, "***A deformable secondary mirror for the VLT***," in *Advances in Adaptive Optics II*, vol. 6272 of *Proc. SPIE*, p. 0V, July 2006

8. A. Riccardi, R. Biasi, G. Brusa, C. Del Vecchio, S. Esposito, D. Gallieni, and P. Salinari, "***Giant segmented adaptive mirrors: progress report***," in *Future Giant Telescopes.* vol. 4840 of *Proc. SPIE*, pp. 246-257, Jan. 2003
9. A. Riccardi, G. Brusa, M. Xompero, D. Zanotti, C. Del Vecchio, P. Salinari, P. Ranfagni, D. Gallieni, R. Biasi, M. Andrighettoni, S. Miller, and P. Mantegazza, "***The adaptive secondary mirrors for the Large Binocular Telescope: a progress report***," in *Advancements in Adaptive Optics*, vol. 5490 of *Proc. SPIE*, pp. 1564-1571, 2004.
10. R. Biasi, M. Andrighettoni, A. Riccardi, V. Biliotti, L. Fini, P. Mantegazza, and D. Gallieni, "***Dedicated flexible electronics for adaptive secondary control***," in *Advancements in Adaptive Optics*, vol. 5490 of *Proc. SPIE*, pp. 1502-1513, 2004
11. See for instance Physik Instrumente S334 tip tilt mirror.
12. P. Gigan, communication internal to the SPHERE consortium, 2007
13. G. Brusa, A. Riccardi, S. Ragland, S. Esposito, C. Del Vecchio, L. Fini, P. Stefanini, V. Biliotti, P. Ranfagni, P. Salinari, D. Gallieni, R. Biasi, P. Mantegazza, G. Sciocco, G. Noviello, and S. Invernizzi, "***Adaptive secondary P30 prototype: laboratory results,***" *Proc. SPIE*, 3353, pp. 764-775, 1998.
14. Minhang Bao, Heng Yang "***Squeeze film air damping in MEMS***". www.sciencedirect.com
15. Riccardi A., Brusa G., Biliotti V., Del Vecchio C., Salinari P., Stefanini P., Mantegazza P., Biasi R., Andrighettoni M., Franchini C., Gallieni D., Lloyd-Hart M., McGuire P. C., Miller S. M., and Martin H., "***The adaptive secondary mirror for the 6.5m conversion of the multiple mirror telescope: latest laboratory test results of the P36 prototype***" *SPIE Proc* 4007, p.524, 2000
16. J.-M. Conan, G. Rousset, P.-Y. Madec "Wave-front temporal spectra in high-resolution imaging through turbulence", JOSA A, Vol 12, No7, 07.95.