Demonstration prototype and breadboards of the piezo stack M4 adaptive unit of the E-ELT

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ABSTRACT

In order to mitigate the risks of development of the M4 adaptive mirror for the E-ELT, CILAS has proposed to build a demonstration prototype and breadboards dedicated to this project. The objectives of the demonstration prototype concern the manufacturing issues such as mass assembly, integration, control and polishing but also the check the global dynamical and thermal behaviour of the mirror. The local behaviour of the mirror (polishing quality, influence function, print through…) is studied through a breadboard that can be considered as a piece of the final mirror. We propose in this paper to present our breadboard strategy, to define and present our mock-up and to comment the main results and lessons learned.

Keywords: Adaptive optic, Adaptive unit, Demonstration prototype, E-ELT, hexapod, mirror, PZT actuator

1. INTRODUCTION

ESO has initiated in October 2007 a preliminary study [1] (part of phase B) to demonstrate the feasibility of the M4AU, adaptive unit with an adaptive mirror ϕ2,7 m, for the European extremely large telescope (E-ELT). This telescope has a novel 5 mirror design [2] [3] including the adaptive mirror in the telescope, explaining its exceptional size.

CILAS has proposed, in partnership with AMOS, BOOSTEC, ONERA, Observatoire de Paris Meudon a concept based on piezostack technology [4] that fulfills all the requirements (no show stopper identified). Breadboards and demonstration prototype are manufactured and tested to validate our present assumptions and to mitigate the risks. The demonstration prototype is dedicated to the global behaviour of the mirror while the breadboards are focus on the local behaviour.

2. RISKS ASSESSMENT STRATEGY

Adaptive optical mirror with diameter of more than 500 mm are unusual for CILAS even we are confident our technology is scalable. In order to address the specific issues relative to large adaptive mirrors, CILAS has proposed to design, manufacture and test a demonstration prototype and dedicated breadboards. We proposed here to summarize the critical issue we planned to check during this contract. The list presented in this paper is not exhaustive of the work done by our team in the framework of this study but intend to give a synthetic and short overview.

The free stroke: CILAS uses specific hard PZT avoiding large hysteresis effect but this type of material limits the stroke capability to small value. In order to obtain a stroke capability of 80 µm we need to stack lots of piezo layers leading to unusual geometrical ratio of the piezo stack parts (thin and long). Manufacturing feasibility shall be checked as well as capacitance and stroke.

- Stroke capability and mechanical coupling: The impact of the thickness of the optical plate, the size of the actuators and the inter actuator spacing have an impact on the mechanical coupling and the stroke capability.
- The global thermal behaviour: Zerodur®, SiC and invar are not used in our classical design. Tri-metallic effect between those materials shall be checked in order to evaluate the curvature induced in the operational thermal range.
- The local thermal behaviour: By introducing the capability to dismount actuators, the whole design of our PZT actuators was modified such as the interface between the actuators and the optical plate. Print through effect shall be checked.
- The global and local dynamical behaviour: For most of the DM in operation, the eigen modes are out the rejection band. Regarding the mass of the M4AM (nearly 3 tons), lots of them are bellow 1kz and may have an impact on the close loop. The dynamical behaviour of the mirror shall be studied to evaluate the impact on the close loop.
- The hysteresis and creep effect: The mirror is not only working in close loop operation but also in open loop. In such mode, the mirror shall keep the same shape whatever the orientation of the unit, the external temperature, the history of the command sent to the mirror and the duration of this mode. In order to reach this objective, we shall define a strategy to compensate the hysteresis effect and the creep effect that are commonly observed with PZT materials.
- Exchange of the PZT actuators: Dismounting procedure was checked as well as the impact of the remounting of novel actuators on the local optical quality
- Reliability of the actuators: We plan to perform environmental accelerated aging test as well as mechanical stress aging to check the source of failure of the actuators and estimate their lifetime and reliability.
- Manufacturing credibility: The high number of actuators leads to define a novel approach to assemble the final mirror. The demonstration prototype opto-mechanical design principles are the same as the final one and allow trying and testing the manufacturing and assembling issues. The base plate manufactured by BOOSTEC is made of a piece of SiC drilled of 852 holes to allow the integration of the actuators. ASTRIUM has qualified a process for the assembly of the SiC and the invar and assists CILAS during this critical step. Finally, the demonstration prototype was polished by AMOS. We resume this roadmap on the table below :

Risks	Demonstration prototype	Breadboard 1	Breadboard 2
Free stroke		x	
Stroke capability and mechanical coupling			x
Thermal behaviour	x (global)		x (local)
Dynamical behaviour	x (global)		x (local)
Hysteresis and creep effect			x
Exchange of a PZT actuators			x
Reliability of the actuators		x (environmental stress)	x (mechanical stress)
Manufacturing credibility	x		

Table 1 : Risk assessment strategy

3. BREADBOARD 1, THE ACTUATOR

The actuator is an assembly of several pieces: The optical plate interfaces, the head actuator, the piezo-stack and the rear part. Pictures of the actuators are presented in Figure 1. The critical part is the piezo-stack made of 250 PZT layers of 0.8 mm each. The actuators are driven with a high voltage of +/-400 V. The actuators were manufactured by batch of 100, quantity foreseen for the final manufacturing of the 7217 actuators of the M4AM.

- Free stroke: If we apply a voltage V to each of the N layer of the stack, the displacement or the stroke S obtained is given by the charge coefficient d33 according to the following: $S = N.d33.V$. In this equation, the voltage V is given by the electronic drivers with a value of 400 V. The charge coefficient is also given by the piezoelectric material properties and has been measured at 330.10^{-12} $m.V^{-1}$. We can then see that only the number of layers matters for the displacement and not the thickness of these layers. We could then increase the number of layer to reach the stroke requested and reduce the thickness of these layers to limit the length of the actuator. Using this formula, we expect a free stroke of +/-33 µm. The measurement of the free stroke confirmed that value.
- Capacitance: The knowledge of the capacitance of the actuator is a critical issue since responsible of the power consumption of the high voltage drivers. The capacitance of the piezo stack parts is known applying

$C = N.K_{33}^{T}.\frac{s}{e}$ where s, K^T_{33} and e states respectively for the surface, the dielectric constant and the thickness of the PZT plates. Numerical application leads to a capacitance value of 129 nF. Measurements show a capacitance value close to 133 nF.

- Bending strength: Regarding the geometrical ratio of the actuators, we decided to check the bending strength of the actuators in order to estimate safety margin during polishing or global inclination of the mirror. Several actuators were broken in proper conditions and the value of 25 MPa obtained as a lower limit. The FEM analysis showed that highest constraints are obtained in non operating conditions for an ambient temperature of -5 °C and an inclination of the mirror close to horizon. Even in that case, the stresses in the PZT are close to 3.5 MPa.

Figure 1: Breadboarding of the actuators

4. BREADBOARD 2, THE LOCAL BEHAVIOUR OF THE MIRROR

The breadboard 2 is composed of 37 piezoelectric actuators mounted on an optical plate which contains integrated pistons. The meshing of the actuators is triangular with an inter actuator spacing of 29 mm. The rear part of the actuators is mounted on a structural base plate in Invar with the same process as expected for the final mirror. The dimensions of the breadboard are 205 x 205 x 310 mm^3 and the mass is 31 kg. The following view gives more details of the assembly:

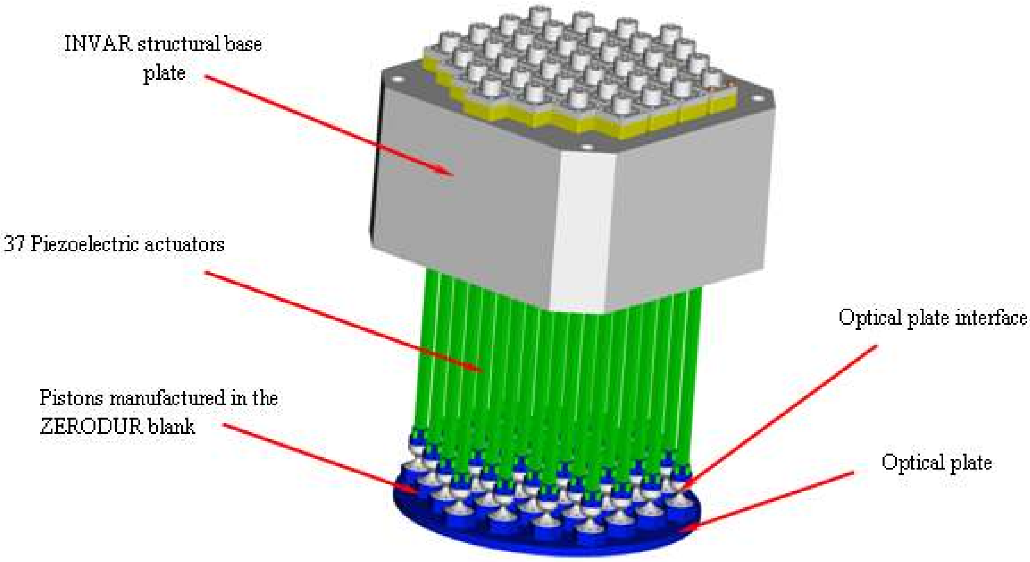

Figure 2: Breadboarding of the local behaviour of the mirror (CAD view)

The integrated pistons avoid the local defects (print through) by the displacement of the gluing interface between the optical plate interface and the optical plate as far as necessary from the clear optical surface. The thickness pistons are 9 mm and are machining in a zerodur® blank Ø 200 mm and thickness 15 mm. A sensitivity analysis by finite element model gave us the minimum thickness (13 mm) to reach the objective of a print through evolution lower than 0,3 nm/°C.

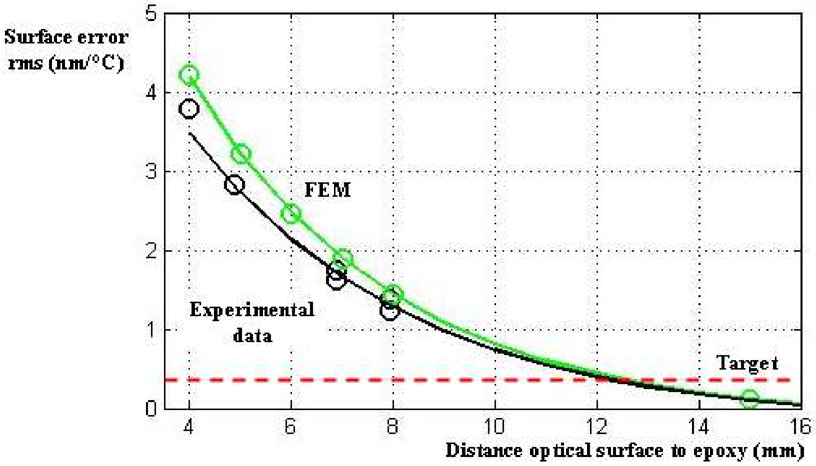

Figure 3: Sensitivity analysis of the print through effect with zerodur® glass thickness

Tests performed confirmed the expected value for print through rate below 0,3 nm/°C fully compliant with the requirement. The mechanical coupling was measured equal to 55 %. Thus the single stroke is predicted at 6µm but was measured at 4.8µm corresponding to a mismatch of 20 %. Fortunately, the total stroke measured corresponds to the theoretical one 33µm. Investigation are still under going to explain that behaviour.

As said previously, PZT are usually not best candidate for open loop operation because of hysteresis and creep effect. Those effects correspond to a parasitic migration of the electrical charge inside the piezo electric material when voltage applied. CILAS and University of Leonard de Vinci established a partnership to defined suitable hysteresis and creep compensation strategy for the M4AM. Both compensation effects were evaluated with this breadboard. With this strategy, the hysteresis effect is limited under an error of 200 nm rms on the wave front. The creep is corrected via an adjusted command with a reduction by a factor 5.

5. DEMONSTRATION PROTOTYPE

The demonstration prototype (DP) is made of a base plate in silicon carbide (manufactured by BOOSTEC), an optical plate (manufactured by SCHOTT) and actuators (manufactured by CILAS). Silicon carbide (SiC) is chosen for the base plate due to its exceptional specific stiffness value (around 130 Gpa/g/mm^3) compared to Zerodur® or aluminum. Moreover, the SiC exhibits a low CTE value close to 2,2 ppm/°C. The Zerodur® K20 was chosen because of its optical properties very close to the standard Zerodur® but with a CTE value well adapted to the SiC one. The actuators manufactured by CILAS are derived from the SAM technology (Stacked Array Mirror) and are those described in the §3.

The characteristics of the DP are recalled hereafter.

Characteristics	**Demonstration prototype**
Total number of actuators	852 with 172 active actuators and 680 dummy one
Meshing geometry	Square
Inter actuator pitch	24.5 mm
Stroke	60 µm
Overall size	Overall diameter=1.039 m

	Overall thickness=289 mm
Total mass	230 kg
Optical plate	Zerodur® K20, ϕ871 mm and thickness=4 mm
Base plate	Base plate made of invar and SiC SiC Base plate thickness=60 mm, diameter=878 mm Metallic base plate=11 mm, diameter=874.5 mm
Piezo stack	Hard PZT, length 200.5 mm and section=6x6 mm^2

Table 2: Characteristics of the demonstration prototype

In order to reduce the manufacturing cost, dummy actuators were used among the total quantity of actuators. Dummy actuators are very similar to active one but the piezo stack part that is responsible of the pushing and pulling capability is replaced by unpolarized bulk PZT material. The active actuators are integrated in dedicated areas in order to excite specific mode shapes (first Zernike modes) during the dynamical analysis.

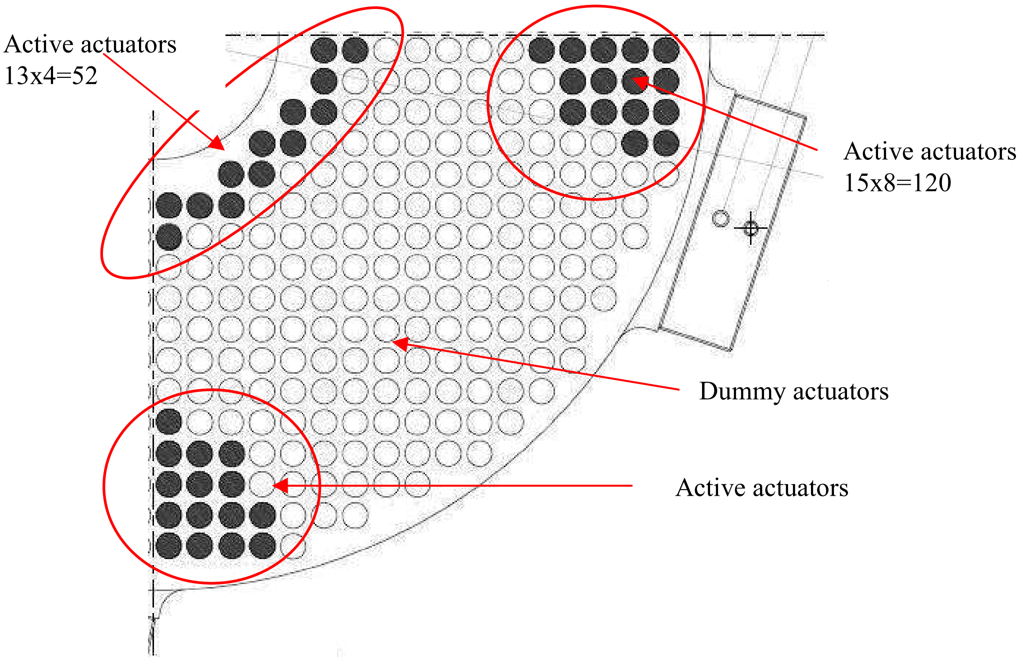

Table 3: Quarter of the base plate : The white holes will receive the 680 dummy actuators while the black ones will receive 172 active actuators

The first objective was to evaluate the critical issue of the manufacturing such as the machining of the base plate, the assembly of the base plate (invar and SiC), the integration of the actuators, the polishing capability…
The demonstration prototype was manufactured in time and helps us to put in evidence the critical steps for the final unit.

Figure 4: Demonstration prototype of the M4 AU

The first part of the experiment concerns the global thermal behaviour and the tri-metallic effect between the optical plate, the base plate made of SiC and Invar. The FEM predicted a curvature of 0.7 µm/°C on the whole aperture. To measure this effect, the DP wad installed with a Zygo interferometer in a cold chamber. The following picture gives a view of the experimental setup.

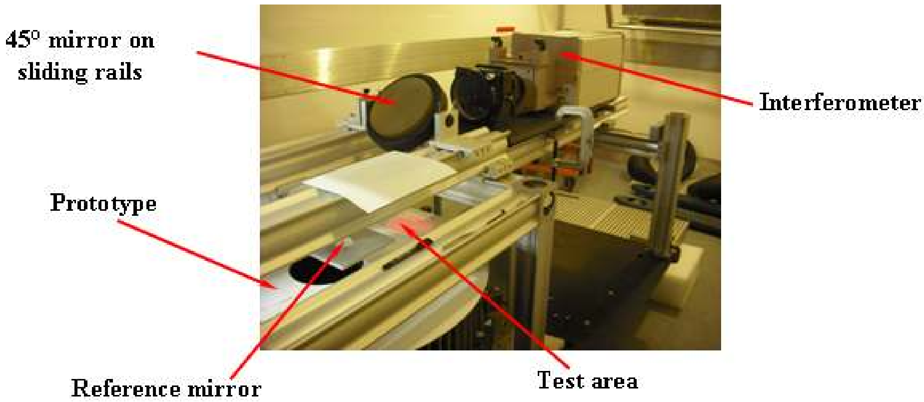

Figure 5: Demonstration prototype installed in the cold chamber for interferometric measurement

We measured a curvature of the surface bellow 250 nm for a diameter of the interferometer of 150 mm which corresponds to the expected effect.

The second part of the experiment consist of a experimental modal analysis in order to check the damping factor of each eigen modes and check also the eigen frequencies predicted by the Finite Element Model. The measurements were done in collaboration with the GEPI group of Observatoire de Paris-Meudon.

In order to obtain a behaviour closed to free-free conditions, the prototype was fixed on 3 elastic sandows. An impact hammer was used as source of excitation.

The experimental modal analysis was realized in 4 main steps:

1. Before the acquisition of the measures, a geometric model was first created with LMS software. This geometrical model contains all the coordinates of the measurement points and it is used to determine the excited mode shapes.
2. After the creation of the geometrical model, a calibration phase was realized to check the coherence of the measures and to define the acquisition parameters (frequency resolution, coherence of the AutoMAC matrix, tests of reciprocity, coherence of the excitation signal,…).
3. After the calibration phase, the acquisition of the optical plate and baseplate responses to the hammer excitation is then realized for all the measurement points; 2 tri-axes accelerometers were used (one on the baseplate and one on the optical plate). The excitation was repeated several times in order to realize the acquisition of all the measure points.
4. After the acquisition of all the measurement points, last step consists in the treatment of all the responses previously saved in order to determine the eigen mode (shape, frequency and damping factor). This analysis is realized with LMS software.

Results are the followings:

Mode shape description	**Measured eigen frequencies**	**FEM eigen frequencies**	**Measured damping factors**
Global flexion of the actuators (1st order) with rigid body rotation of the optical plate	73 Hz	69 Hz (-4%)	0.14%
Global flexion of the actuators (1st order) with rigid body translation of the optical plate + tilt baseplate	77 Hz	69 Hz (-4%)	0.20%
First astigmatism of the baseplate	238 Hz	76 Hz (-1%)	0.30%
Second astigmatism of the baseplate	346 Hz	248 Hz (+4%)	0.30%
Global flexion of the actuators (2nd order) with rigid body rotation of the optical plate	400 Hz	353 Hz (+2%)	0.13%
Global flexion of the actuators (2nd order) with rigid body translation of the optical plate Y axis	403 Hz	424 Hz (+6%)	0.12%
Global flexion of the actuators (2nd order) with rigid body translation of the optical plate X axis	404 Hz	426 Hz (+6%)	0.11%
Defocus of the baseplate	480 Hz	471 Hz (-2%)	0.83%
First trefoil of the baseplate	663 Hz	651 Hz (-2%)	0.37%
Second trefoil of the baseplate	735 Hz	730 Hz (-1%)	0.20%

Table 4: Comparison of the eigen frequencies predicted by FEM and the measurements

The measurements show very good correspondence with the model.

The third measurement consists of the validation of the state space model useful to predict the optical displacement in the dynamic frequency range as function of the command sent to the mirror.
With the use of the modal shape of the DP (eigen vectors of the DP), the general form of the equation of motion governing the dynamic equilibrium between the external, elastic, inertia and damping forces acting on a flexible structure such as the DP with a finite number of degrees of freedom is given by:

$$x\,(p) = \sum_i \frac{\Phi_i * \Phi_i'}{(\omega_i^2)(\,1 \;+\; 2\,\xi_i\, p \,/\, \omega_i \;+\; p^2/\,\omega_i^2)} * f\,(p) \;\Rightarrow\; x\,(p) = \sum_i \;\Phi_i * TFnm_i(p) * \Phi_i' * f\,(p)$$

With:

f : external forces,
x : motions

ξ_i : damping of the modal shape i,
ω_i : natural frequency of the modal shape i,
Φ_i : normalised modal shape i,

From the above formula, the structure of the DP model is constructed as shown below:

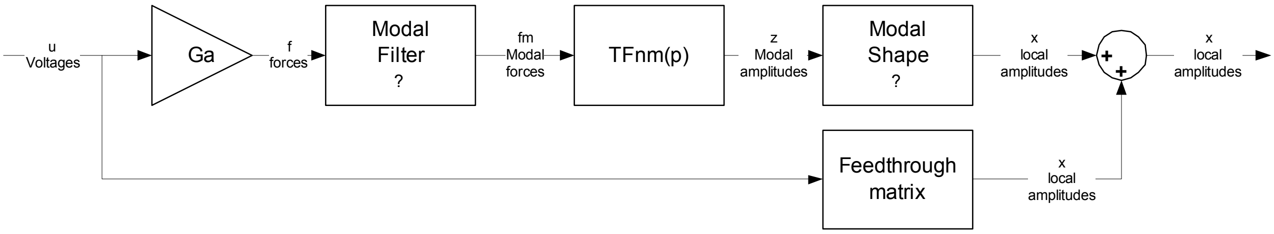

Figure 6: DP state space model

The D feedthrough matrix includes the elongation of the actuator due to the piezo electric effect according to the command voltage (sum of all the static contribution of all the not kept modes after reducing the model). Ga is a conversion factor that gives the equivalent force generated by the actuator when one volt is applied on it.

In order to reduce the model and to make its execution with MatLab possible, the model is simplified. Only the eleven lower frequency modes are used (rigid body modes are excluded) and the kept nodes (locations on the DP used for FEM simulation) are the ones located at the junction between the optical plate and the actuators where the actuator force is applied, the ones located at the junction between the base plate and the actuators where the actuator force is applied. So, as the DP includes 852 actuators, the reduced size of each mode used in the simulation is 2x852 = 1704 nodes.
A state space representation is used in order to implement easily such multiple input (voltage) multi output (local amplitude of each node according z axis) system.
The experimental setup is described in the next figure. The displacement was measured with an optical sensor (Keyence) with a resolution close to 10 nm. The real time computer allows measurement in sweep sin excitation from 40 Hz to 900 Hz at a sample frequency of 5 kHz. For each frequency, it computes the sine and the cosine part and stores them on the PC hard disk.

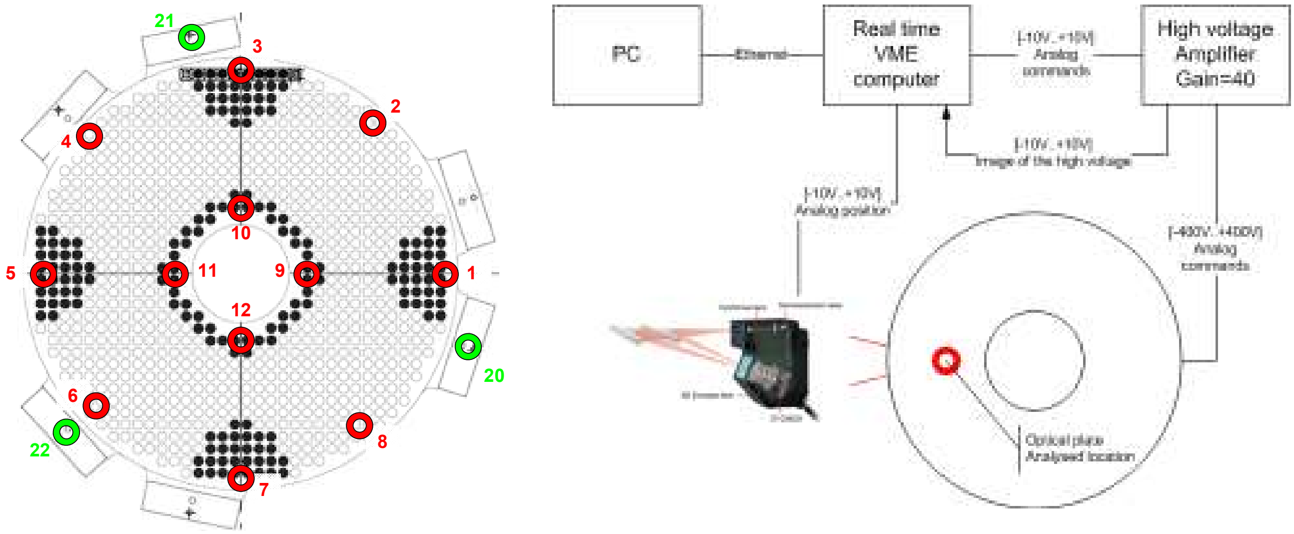

Figure 7: Left figure: In red, measure points and in green, interface points to hold the DP /
Right figure: Experimental setup for the dynamical analysis

The DP was dynamically excited using actuators in pseudo tip/tilt, a pseudo curvature or pseudo astigmatism configurations. The displacement of the optical plate was controlled for each case in twelve locations around the inner and external diameter of the mirror. An example of such a measurement is presented hereafter with the simulation provided by the MIMO model (see Figure 8).

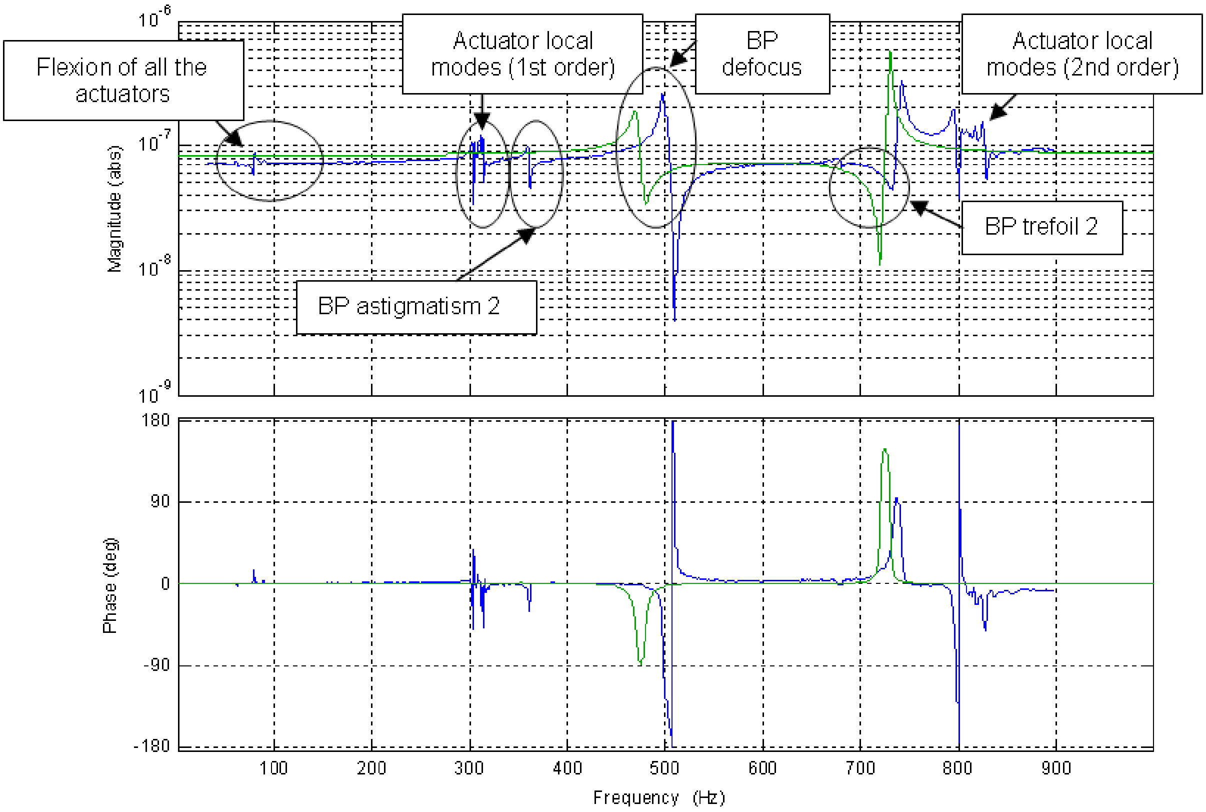

Figure 8: Transfer function of the DP for pseudo focus actuation (in green the plot from the model, in blue the measured transfer function)

We found a good correspondence between the model and the experimental in most of cases with the following restrictions.

1. The model do not include the local modes of the actuators near 300 Hz and 800 Hz (too many modes)
2. Some modes are not predicted such as the pseudo astigmatism 2 and trefoil 1. Study is under going for explaining this behaviour.

The most troublemaker modes inside the close loop are the tilt and tip modes (near 76 Hz). Thanks to the return of experience, we are currently building the model of the whole M4AU.

6. CONCLUSIONS

In the framework of the preliminary study of the M4AU, CILAS has developed breadboards and a demonstration prototype to mitigate the risks of the project.

The demonstration prototype is dedicated to the study of the global behaviour and also demonstration of the manufacturing capability in the large. Thanks to this prototype, all the manufacturing steps of the mirror where studied and evaluated in detail. The manufacturing of such a mirror in a short deadline (18 months) confirms the simplicity of the technology. The dynamical analysis performed will be very useful to predict the dynamical behaviour of the final mirror.

Two major breadboards were manufactured and tested: Actuators and a local representation of the mirror containing 37 actuators. Those breadboards confirmed the main advantages of the mirror (stroke, print through…) but allow to bring to light that some of the classical limitations can be improved in open loop (hysteresis, creep…)

CILAS and its partners have successfully passed the conceptual design review and the test review of the demonstration prototype. The next milestone corresponds to the preliminary design review (PDR) planned to be held mid July 2010. The work done for more than 2 years now confirmed the attractiveness of adaptive mirror based on piezo-stack actuators.

ACKNOWLEDGEMENTS

This work has been made in a framework of a contract with the European Organisation for Astronomical Research in the Southern Hemisphere (ESO).

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