The adaptive secondary mirror for the 6.5m conversion of the Multiple Mirror Telescope: first laboratory testing results

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ABSTRACT

We present the first results of tests performed on a reduced size adaptive secondary prototype named P36. The full size unit, named MMT336, is ready to be assembled and it is planned to install it at the 6.5m conversion of the Multiple Mirror Telescope by the end of this year. The design of the final unit consists of: a convex thin deformable mirror whose figure is controlled by 336 electro-magnetic force actuators, a thick reference shell and a third aluminum shell used for actuator support and cooling. The force actuator response function is adjusted using both open and closed loop compensation to obtain an equivalent position actuator thanks to nearly co-located capacitive position sensors. The digital real-time control and the unit monitoring is done using custom-made electronics based on DSPs. The preliminary dynamical tests aimed at identifying the P36 mirror response function to obtain a proper dynamics compensation were successful. In fact two main results have been obtained: 1) an accurate identification of the feedforward matrix used to control the mirror 2) settling times of $\approx 0.5$ ms, well within the specifications. We also complement these lab results with results obtained from simulations of the full size mirror dynamics.

Keywords: adaptive optics, deformable mirrors, adaptive secondary mirrors, electromagnetic actuators, capacitive sensors

1. INTRODUCTION

The adaptive secondary for the MMT will be assembled in the next couple of months at Media Lario. All the mechanical parts are now ready, the glass parts are ready to be shipped from the Mirror Lab (Tucson, AZ) and the electronics parts are ready to be assembled. In order to do some test ahead in time a smaller version (P36) of the mirror has been built and its electronics is now being tested at Micogate. The mirror will be shipped to Osservatorio di Arcetri in a couple of weeks were a complete set of tests will be performed.

In this paper we mainly report on the very preliminary tests performed on this reduced size prototype at Micogate. We concentrated our effort in measuring the mirror dynamic response, in fact we were predicting an improvement in the mirror settling time due to the improved version of the control electronics. This has been confirmed by our first measurements that give a settling time of $\approx 500\mu$s versus a value above 1 ms obtained with a previous prototype.\textsuperscript{1} During these tests we could also get the impression of a much more reliable mirror operation with respect to the previous prototype. Only a few actuators presented minor problems and in general we found a very stable mechanics and electronics.

This paper is divided in the following sections: in Sec.2 we describe the MMT336 and its prototype P36 in terms of mechanics, electronics and control software. In Sec.3 we describe two of the three main procedures that need to be performed in order to allow the mirror operation, these are the optimal control law determination and the feedforward matrix estimation, the third important procedure, the capacitive sensor optical calibration, was already described elsewhere.\textsuperscript{1} In Sec.4 we report the preliminary results obtained with the P36 mirror and in Sec.5 we briefly report the current results obtained with a custom developed software that allows a complete dynamics simulation of the MMT336 mirror.

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Figure 1. (a) Exploded view of the design of the MMT36 unit. (b) View of the cold plate of the MMT36 unit. The circles indicate the actuator attachments. The cooling grooves are also visible.

2. MMT36 DESCRIPTION

In Fig.1 we show an exploded view of the adaptive secondary for the new Multiple Mirror Telescope called MMT36. Its general structure reflects the schematic design introduced several years ago and successively refined. The unit can be divided into four main components:

1. an intermediate flange bolted to the M2/39 mobile hexapod of the telescope that provides a mechanical interface and supports three electronics boxes;
2. an actuator support and cooling plate (cold plate) which is connected to the intermediate flange via a fixed hexapod. This plate is made of two separated aluminum disks with digged grooves (for cooling distribution) glued together;
3. a thick (50 mm) ULE glass plate (reference plate) with bored holes, attached to the cold plate through a second fixed hexapod and a central shaft;
4. a thin ULE glass shell (thin mirror) of 642 mm diameter and 1.6 mm thick with 336 magnets glued to it. This shell has a central hole of 55 mm to which a central membrane is attached to provide lateral constraint. When the mirror is not active its axial constraint is provided by the central membrane and a set of stops located at the inner and outer edge of the mirror.

The actuators locations are defined by the position of the magnets glued to the back surface of the thin mirror. Their coordinates are given in a spherical system of coordinates whose polar axis is defined by the optical axis (center of the pattern). As can be seen in Fig.1 the actuators are arranged in ten concentric circles, this circles are equispaced in the polar angle except for the last ring. For each circle the actuators are equispaced in azimuthal angle and have the same "phase" angle (as measured from the vertical axis) except for the second to last ring.

Electronics

The block scheme of the communication and control electronics is shown in Fig.2. The Adaptive Optics Wavefront Computer communicates via a fiber optic link to three mirror control electronics crates which are connected together in a daisy chain configuration. Each crate accommodates 16 electronics boards of which 14 are used to control the mirror. Each control board controls 8 channels (actuators) for a total of 112 channels per crate. Each actuator is controlled separately by a digital control whose schematics is shown in Fig.3. A DSP (ADSP2181) is connected to two ADCs and two DACs and implements the digital control for two actuators. The analog part of the control electronics consists of a driver for the coil actuator and an anti-aliasing filter for the ADC. The capacitive position sensor works
Wavefront Computer
Fiber optic comm. board
RX
TX
Crate 1:
- 14 control boards
  (112 channels)
- communication board
- housekeeping computer

Crate 2:
- 14 control boards
  (112 channels)
- communication board
- reference signal generator
- overcurrent protection

Crate 3:
- 14 control boards
  (112 channels)
- communication board

Inside M2 Hub

Figure 2. General electronics scheme

MMT336: 42 boards; P36: 5 boards

8x each board

BUS ⇔ DSP
‘bridge’ logic

½ DSP/channel

DAC
Current Driver

ADC
Signal Condit.

Voice Coil
Capacitive Sensor

Backplane board with parallel bus

Figure 3. Single channel electronics scheme
ADC conversion (5µs) + DSP computation (4.6µs) + delay to avoid cross-talk between coil and sensor (4.6µs)

DAC output here

DAC settling

DAC hold 25.6µs

ADC sampling (negative rail sample) (positive rail sample)

14.2µs 5µs 25.6µs

**Figure 4.** Timing diagram for the discrete time control

in a modulation-demodulation scheme in which the modulation is performed by a square wave signal at 40 kHz and the demodulation is performed by a synchronous detection done by the ADC and some timing electronics. The delay introduced by the digital loop can be estimated to be \( \approx 45 \) µs (see timing diagram in Fig.4).

**Software**

The software can be divided into four main parts:

1. the DSP code written part in C language and part in DSP Assembler;
2. a communication code written in C;
3. the engineering panel software written in C and running under WindowsNT OS;
4. a high level software written in IDL (Interactive Data Language), that allows to perform the required mirror calibrations and tests.

The DSP code is loaded on the DSP’s program memory at the booting from EPROMs mounted on the DSP boards and can be successively modified via software. It is a very flexible code that by periodically scanning some specific memory locations performs the required functions, it also handles the various interrupt requests. This software implements the local control law and low level system monitoring. The communication code runs on the Wavefront Computer (or any computer in which the communication board can be installed). This code allows to write in and read from both program and data memory of the DSPs, it operates in a DMA-like mode, with the possibility of issuing an interrupt request to the addressed DSPs. Three basic functions can be performed:

- **Wr_same** Transmission of data from the host to one/several DSPs, writing the same data to the same internal addresses of the addressed DSPs;
- **Wr_seq** Transmission of data from the host to one/several DSPs, writing different data to the same internal addresses of the addressed DSPs;
- **Rd_seq** Reception of data to the host from one/several DSPs, reading data from the same internal addresses of the addressed DSPs;

The engineering panel software can perform a wider set of operations by composing the three basic functions of the communication code. Finally the high level software allows to perform more complex tasks on the mirror like position sensors calibration, dynamic response measurements, feedforward matrix determination; it also allows an interactive operation as well as the execution of batch command files.
Figure 5. Diagram of the control law implementation. The functionality inside the box is performed by the DPSs. D is the current driver, A the actuator, M the mirror and S the position sensor.

3. GENERAL PROCEDURES

Control law determination

To control the mirror a discrete time control law whose scheme is shown in Fig.5 is used. The control can be divided in two components, a decentralized closed loop control plus a centralized open loop control. It was shown experimentally¹ that this control can obtain good performances in terms of response time and external disturbances rejection provided that some level of damping is present in the mirror structure. Recently some more detailed analysis has been done in order to provide an accurate relationship between performances and two key parameters of the control strategy, i.e. the level of local damping and the control loop delay.⁴

The principle of operation of the control can be explained in an heuristic way by considering the mirror dynamics decomposed in its resonant modes. In order for the closed loop part of the control to apply the requested position command \( c_i \) (see Fig.5) the equivalent closed loop stiffness of the force actuator A must be higher than the natural mirror stiffness, this is only true for a reduced number of modes as the proportional gain \( k_p \) cannot be raised indefinitely for loop stability reasons. The open loop decentralized force component \( f_f \) serves the purpose of correcting the reduced loop gain for those mode whose intrinsic stiffness is higher than the maximum \( k_p \) applicable.

In practice the control law optimization i.e. the choice of a value for \( k_p \), \( k_i \) and \( k_d \) can be performed as a first approximation in the following way: once the mirror has been positioned with low loop gain to the requested working conditions (a specific thin mirror to reference plate gap), \( k_p \) is increased until a sustained oscillatory response is obtained, calling \( k_u \) the value of the proportional gain for which this happens and \( t_e \) the period of the oscillations, a nearly optimal set of gain can be derived as: \( k_p = 0.75 k_u \), \( k_d = 0.1 k_p \) \( t_e \), \( k_i = \frac{k_p}{0.825t_e} \) (Ziegler-Nichols method).

Feedforward matrix determination

The matrix \( K_{ij} \) relating the feedforward \( f_f \) to the position command \( c_j \) must be chosen to null the mirror static error in the absence of external disturbances, i.e. \( \lim_{t \to \infty} c_i - p_i = 0 \) when a force \( f_f = K_{ij}c_j \) is applied to the mirror. From which we derive that in statics also \( f_f = K_{ij}p_j \) must be valid. \( K_{ij} \) can be derived considering the statics of a thin shallow shell and the appropriate average functions corresponding to the finite size of the area where the force of the actuator is applied and annular area where the capacitive sensing is performed. In practice several effects like the glue bonding between magnets and mirror and the non uniform thickness of the shell make a finite elements analysis preferable to the direct analytical solution (see Fig.6). As it will be shown in Sec.4 the direct measurement of this matrix agrees very well with the finite elements analysis of the mirror influence functions.⁵

From the point of view of the mirror control the matrix \( K \) incorporates not only the mirror elastic properties but also the position sensor and force actuator calibrations and can be directly measured. This operation can be done in the following way:

- the mirror is held in the operating position in closed loop;
- a set of commands is sent to the mirror with the feedforward loop turned off
- the corresponding variations of positions \( \Delta p^{(k)} \) and forces \( \Delta f^{(k)} \) are recorded
Figure 6. Simulated influence function for actuator #0. Sensing areas for the actuators are also shown. The actuators are located at the center of the sensing areas.

- a least square estimate of K is performed.

The last point is briefly discussed. For every measurement set k we can write:

$$\Delta f_i^{(k)} = K_{ij} \Delta p_j^{(k)}$$  \hspace{1cm} (1)

By introducing the n by m matrices $F_{ik} = \Delta f_i^{(k)}$ and $P_{jk} = \Delta p_j^{(k)}$ where n is the number of actuators and m the number of data sets we can write:

$$F_{ik} = K_{ij} P_{jk}$$  \hspace{1cm} (2)

from which K can be derived with a least square technique provided that m be greater then n.

4. FIRST P36 RESULTS

The P36 has a reduced size with respect to the MMT336 (25 cm vs. 64 cm), in fact it consists of the first three rings of actuators of the final unit (for a total of 36 actuators). It also has a concave shape instead of convex for easier optical measurements. The mechanics of the P36, although reduced in size reproduces exactly the one of the final unit, the same is true for the electronics (only one DSPs crate was used). The tests on the P36 are in fact very significative and we plan to pursue them until the final unit is ready for testing. These first test were done at Microgate were the P36 was undergoing a set of electronics burn in tests. During these test it was not possible to perform any optical measurements, we also decided not to attach the central membrane to the thin mirror since this procedure is better done with a direct feedback from optical measurements.

Because of lack of optical measurements it was not possible to calibrate the capacitive position sensors and the same calibration curve (estimated from the sensor dimensions) was assumed for all the actuators. In the tests the mirror was first set to a nominal position in an isostatic configuration (three actuators in closed loop and the others in open loop) and then all the actuators were activated in closed loop. The estimated position of the thin mirror with respect to the back plate was 37.5 µm. Then the control gain (proportional part) was increased until stabilization of the loop was reached giving (Sec.3) $k_u \approx 1.05 \frac{N}{\mu m}$ and $t_u \approx 0.36 ms$, from these two values an "optimal" PD control was derived with $k_p = 0.8 \frac{N}{\mu m}$ and $k_d = 30 \frac{N}{\mu m}$. In these conditions three sets of 36 step position command responses (one per actuator) were recorded and the feedforward matrix shown in Fig.7 was estimated from this set of data (see Sec.3). Assuming no calibration errors it is possible to compare this matrix (called hereafter $k_m$) with $k_s$ the simulated one (see Sec.3). The results of the comparison is shown in Fig.8 and 9, for the matrix elements significantly different from zero a very good relative error is found.

Two main points can be noticed by comparing the matrix diagonal elements:

- the elements corresponding to the inner ring in $k_m$ are all below the relative elements in $k_s$ except for actuator # 5. This can be easily explained considering the defect in the aluminization of the back of the thin mirror in that area that tends to reduce the capacitive sensor area;
• in the central ring, actuator # 8 seems to be well above the average value of the others. This is due to some problem in the corresponding coil that results in a lack of efficiency.

Apart from these minor points the agreement between simulated and measured feedforward matrix seems to be very good, especially considering that we did not have the calibration of the capacitive sensors. Once the feedforward matrix was uploaded onto the DSPs a test of step responses with feedforward was performed. Several actuator step responses were recorded and were found quite similar with two main features, a very steep initial response (up to about 80 % of the command) followed by a slower exponential settling. The settling time measured as the time between the initial command was sent and the time when the mirror is within +/- 10 % from the final position is about 0.5 ms. This result is very encouraging and already better than the specifications.

We think that some improvement in the settling time may be possible. In fact by looking at the step responses decomposed on the modes (see Fig.12) associated with the feedforward matrix we noticed that the last "slower" part of the step response is caused by the low order modes that show an overdamped behaviour. This would suggest that a higher proportional gain was needed, although it is not possible to increase it over all the actuators it may be possible to increase it for some of the actuators thus changing the low order modes response from underdamped to critically damped.

5. MMT336 DYNAMICS SIMULATION

In order to provide an estimate of the MMT336 performances in terms of dynamical behaviour we developed a code that enables us to fully simulate the mirror dynamics. The mirror model is based on a modal decomposition of the thin shell off the plane dynamics:

\[ \ddot{q}_i + 2 \zeta_i \omega_i \dot{q}_i + \omega_i^2 q_i = f_{m_i} + f_{e_i}, \]  

where the index i runs over the modes considered, \( q_i \) is the modal amplitude, \( \omega_i \) and \( \zeta_i \) are the mode pulsation and damping coefficient and \( f_{m_i}, f_{e_i} \) are the modal control and external forces. In order to solve the Eq.3 some assumptions must be made for the damping coefficients \( \zeta_i \). Based on measurements already done for a similar system\(^1\) and on a simplified analytic solution for the mirror dynamics\(^4\) we model \( \zeta_i \) as:

\[ \zeta_i = \frac{\alpha}{\omega_i} + \beta \omega_i + \delta \]  

where \( \alpha \) takes into account the damping due to the air trapped between the thin shell and the back plate, \( \beta \) is the glass structural damping and \( \delta \) is a free parameter introduced to improve the fitting with experimental data. In
Figure 8. The absolute value of $k_m$ divided by $k_m - k_t$

Figure 9. Comparison between measured (diamonds) and simulated (crosses) diagonal elements of the feedforward matrix
Figure 10. Step response for actuator #16. To the left the measured displacement for all the actuators is shown, together with the preshaped step command applied (solid line) and the +/- 10 percent window (dashed line). To the right the applied force over all the actuators is shown.

Figure 11. Step response for actuator #34. To the left the measured displacement for all the actuators is shown, together with the preshaped step command applied (solid line) and the +/- 10 percent window (dashed line). To the right the applied force over all the actuators is shown.
Figure 12. Step response for actuator #16 decomposed in the static modes basis. The x axis is time in ms and the y axis is the displacement in counts (1 count $\approx$ 2.6 nm).
Figure 13. Modal density (left) and modal damping (right, continuous line) used for the dynamics simulation of the MMT336. On the right (dashed line) the modal damping as obtained from a simplified analytical model (see Ref.4) and for a thin mirror to reference plate separation of 50 μm is shown.

Figure 14. Time evolution of the mirror simulation for actuator # 0. In the plot the time history of the turbulence (asterisks), the sampled turbulence (diamonds), the position command (triangles), and of the actual mirror position (squares) are shown.

Fig.13 we report the finite element model modal density and the modal damping coefficient used for the simulation. The modeling of the control force $f_{m}^{c}$ in Eq.3 requires to take into account the effect of the discrete control loop by introducing a transition matrix for the mirror dynamics between successive discrete control steps. The simulation done assumes that the AO system is operating in open loop, i.e. the error measured by the wavefront sensor (WFS) is sent to the mirror which "follows" the turbulence evolution without affecting back the WFS. Moreover the WFS integration time is assumed to be zero as it is the wavefront computer (WFC) delay time. This was chosen in order to establish the error due only to the mirror dynamics itself. Three rms errors averaged over the time evolution and over the actuators were evaluated (see Fig.14) for the case of a single layer with $r_{0}=1$ m @2 μm moving across the pupil at 50 m/s.

1. rms error between position command and actual mirror position (12.9 nm);
2. rms error between sampled atmospheric turbulence and mirror position (32.8 nm);
3. rms error between atmospheric turbulence evolution and mirror position (55.0 nm).

The first rms error measures the error due to the mirror time delay with respect to the preshaped command, the second the error between the non-preshaped command and the mirror position, the third depends heavily on the WFS sampling time and is the total error assuming a "perfect" WFS. It can be seen that these errors are all very small especially considering that a wind speed of 50 m/s was considered for the turbulence temporal evolution. No fitting error is taken into account as the average is taken over the actuators and not over the mirror surface.

6. CONCLUSIONS

The first results obtained with the 36-actuator prototype (P36) of the adaptive secondary for the 6.5 m conversion of the Multiple Mirror Telescope (MMT336) are very encouraging. Electrical measurements of the mirror step response show a settling time of \( \approx 500 \mu \text{m} \) for all the actuators. During the tests, performed at Micogate, we could also get the impression of a very reliable mirror operation that has been active for many hours a day for over one week. We now plan to move the mirror to Arcetri to perform a full set of measurements including direct optical measurements of the mirror static figure. We will start to build the MMT336 unit in the next few months, this will allow us to eventually operate some modifications indicated by the P36 experience. We plan to repeat the electrical measurements done on the P36 on MMT336 unit, then the unit will be moved to Tucson (AZ) for optical testing and final installation at the telescope.

REFERENCES


