CONTACTLESS LARGE DEFORMABLE MIRRORS: ELT AO CORRECTOR TECHNOLOGY AVAILABLE NOW

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Abstract. We present our design of ESO E-ELT M4 deformable mirror and GMT Adaptive Secondary Mirrors unit. Both systems are based on our consolidated design of large deformable mirrors for 8-m class telescopes, successfully implemented on MMT and LBT and currently in advanced construction and testing phase for VLT and Magellan telescopes respectively. We describe the main features of the technology adopted: thin Zerodur mirror shell with contactless voice coil motors, co-located capacitive sensors to close a local position loop at each actuator, centralized control by force feedforward, embedded real time control and communication electronics. We then highlight how the same concept has been scaled up on the E-ELT M4AU and the GMT-ASM cases, adapting the technology to deal with thousands of actuators, while maintaining its intrinsic advantages: tolerance to actuators’ failures, mechanical decoupling and relaxed tolerances between correcting mirror and reference structure, large stroke, hysteresis-free behavior. For the next generation systems, we report the predicted performances based on the actual results attained on our 1-m class DMs currently in use: the LBT adaptive secondary for the GMT-ASM and the 330 actuators Demonstration Prototype for the E-ELT M4AU.

1. Introduction

The voice-coil based, contactless adaptive mirror has been conceived by Piero Salinari in 1993 [1]. His main goal was the development of an adaptive secondary for the Large Binocular Telescope, but it became clearly evident that the implementation of the new idea was very challenging, posing demanding requirements on several engineering fields. In fact, this technology involves multidisciplinary skills and engineering problems, from mechanics, to electronics, control systems, mechanics, fluid-dynamics and optical manufacturing.

In this paper we go though the main deployments of this technology on 6m- and 8m-class telescopes, like MMT, LBT and VLT, underlining the improvements introduced during the evolution. We also discuss the recent advancements in the design of the adaptive units for the GMT and the E-ELT extremely large telescopes, where the intrinsic advantages of this technique are particularly evident, presenting the results obtained in the frame of the feasibility and preliminary design of such units.

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2. Principle of operation

In our technology, a thin, continuous facesheet mirror is massively controlled in shape and position by a large number of voice coil motors. These are realized by gluing high efficiency magnets on the non-optical (rear) surface of the mirror. The actuators coils are facing the magnets, not being in contact with them. Since we are employing force motors, but ultimately the actuators have to be commanded in position, we need a measurement of the shell position, co-located with the actuator. This information is provided by contactless capacitive sensors measuring the gap between the thin shell and the massive and stiff reference body. The digital control loop is implemented by means of a high throughput, dedicated mixed signal electronics placed very close to the mirror assembly. This is required both by noise pick-up and signal integrity considerations, but also allows a great simplification of the cable harnessing, providing a very simple data and power system interface.

Fig. 1. Major components a contactless large deformable mirror (LBT672)

2.1. Contactless technology features

The contactless technology provides several intrinsic advantages. First, it is fault tolerant versus malfunctioning or complete inoperability of few actuators. In fact, faulty actuators can be disabled and the thin mirror will follow locally its 'unconstrained' shape. It has been demonstrated by simulation and by results obtained on the operating units [6] that the inoperability of about 5% of the actuators does not have any impact on the adaptive optics system performance.

Moreover, it provides large alignment tolerances, of the order of few tenths of millimeter, on the relative position between coil and magnet, ultimately between mirror and reference/supporting structure. This is a key aspect referring to large optics with size of the order of one meter and above, where the integration, installation and operational tolerances become particularly critical. Conversely, the adopted voice coil motor configuration is non-
optimal in terms of reluctance of the magnetic circuit, and this affects adversely also the thermal efficiency of the motor. However, both the magnets and the coils have been optimized to get the maximum efficiency out of this layout, so that the thermal print-through is well under control and not critical for the application.

An additional key advantage of this technology is in the intrinsically hysteresis-free actuators: the position is controlled in closed loop on base of the capacitive sensor reading, that is by principle of operation unaffected by hysteresis effects. Moreover, the reference structure is not subjected to mechanical stress being supported by a quasi-kinematic mount.

Considering the dynamic aspects, it shall be remarked that the thin mirror has low mass and inertia when compared to the reference body and the actuators' plate. As a consequence, the supporting structure acts as an efficient mechanical low-pass filter, thus reducing the dynamic coupling between mirror and telescope structure. This allows to perform quite large motions, including field stabilization and chopping, without need of reaction masses to cancel out vibrations.

Finally, the accurate embedded metrology provided by the capacitive sensors allows using the mirror as a conventional rigid unit, without adaptive optics control loop. When operated in such mode, the controlled mirror can be used as any active optics system to compensate for slow aberrations. Moreover, during adaptive optics operation, the internal diagnostic measures directly the wavefront error. An additional important advantage linked to the embedded metrology is the capability of performing all dynamic performance tests and some long term stability test without needing an optical measurement. This autonomous testing capability is a dramatic advantage for the project planning and deployment, providing a way of clearly splitting the dynamic and functional tests with the optical ones.

All these aspects make this technology particularly suitable for large deformable correctors, as demanded by the current 8-10 meter class telescopes and even more by the next generation extremely large telescopes.

3. **How this technology evolved**

The concept and the fundamental pros of our technology have remained unchanged through the various systems already implemented, while some technological aspect has evolved either to deal with the size increase of the correctors or simply to improve performances.

After some fundamental initial prototypes, the first adaptive secondary ever built and used for telescope operation is the MMT336. Its 0.64m diameter, 1.9mm thick convex aspheric shell manufactured by MirrorLab (University of Arizona, Tucson) is controlled by 336 actuators. The unit has been electromechanically accepted in year 2000 and started operation at the MMT on mount Hopkins in 2002.
The second generation of adaptive secondary units is represented by the two LBT672 and the MAG585 units. The LBT units have 0.91m diameter, 1.6mm thick concave aspheric shell manufactured by MirrorLab (University of Arizona, Tucson) and are controlled by 672 actuators. Both systems are currently installed on LBT and started science operation. Magellan telescope adopts the same configuration, but the outermost ring of actuators is not used, so the number of actuators is 585 and the shell diameter is 0.85m. The unit passed recently the optical acceptance and will move to the Baade Magellan telescope before mid 2012. The generation step from MMT336 to the LBT and Magellan units implied several technology changes, partially motivated by size and performance considerations, partially by lessons learned on the first unit. The actuators thermal efficiency has been improved by a factor 2, thus reducing the overall power dissipation from 2.8W/act to 2.4W/act in typical operating conditions, thanks to an improved design of the actuator and to more efficient control electronics. We also improved the shell retention system when the unit is not operated by introducing passive bias magnets, co-located with each actuator, instead of an active open loop bias of the voice coil motors. Concerning integration and maintainability, the actuators harness has been completely redesigned to deal with the larger number of actuators, that can be now replaced from the front side once removed the shell. Additionally, the control electronics has been completely redesigned to deal with the larger computational throughput demanded by the doubled number of actuators. Besides the co-located and distributed real-time control tasks, the on-board electronics implements also the real-time reconstructor. This low latency, modular electronics, has then become the real-time computing platform for several adaptive optics systems. On LBT, besides the real-time reconstructor, the same electronic modules are deployed on the wavefront sensors and additional mirrors controls of FLAO, LBTi, Linc, Nirvana, Argos. It is also the real-time computational core of the Next Generation WaveFront Controller (NGWFC) operating on Keck I and II since 2006.

The third, current generation represented by the VLT Deformable Secondary Mirror, is currently in final integration stage. The unit is has a diameter of 1.12m, with a 1.9mm thick aspheric shell manufactured by Safran-Sagem (France) and 1170 actuators. If features a highly lightweighted Zerodur reference body manufactured by Thales-SES0 (France). The unit implements several important improvements with respect to the LBT generation. The hexapod-
based fine positioning system is attached directly to the actuators' plate instead of being connected to an intermediate structure, and the electronic crates are mounted on the hexapod fixed flange. All this improves the overall stiffness increasing the 'pendulum' eigenfrequency of the system to 42 Hz. Concerning the electronics, the introduction of switching voice coil drivers enabled a dramatic reduction of power consumption, from 2.4 W/act to 1.2 W/act in typical operating conditions (1.1" seeing @ 500nm, 800 corrected modes). The computational throughput has been doubled to 150 billion multiply-and-add per second, to deal with the local and global control demand. Considering the severe operational and survival specifications regarding wind and earthquake, the unit has been equipped with a fully autonomous safety system that protects the thin shell by pulling it against the reference body when wind speed or acceleration limits are hit. The VLT DSM is currently fully integrated and the electromechanical tests will be completed by Q3/2012. Optical tests will be carried out at ESO premises in Germany under Microgate/ADS responsibility. Installation at the telescope is planned for Q2/2014.

4. Moving to the ELTs

The features described above make the contactless voice coil motor technology particularly suitable for the ELTs. Microgate and ADS have completed the feasibility study of the adaptive units for the Giant Magellan Telescope (GMT) and the preliminary design study of the European Extremely Large Telescope (E-ELT).

4.1. GMT Adaptive Secondary Mirror

The GMT telescope is based on a segmented gregorian design: seven circular primary mirrors, one on-axis and six off-axis are directly conjugated to a segmented secondary with identical layout.

The adaptive secondary segments have 1.06m diameter and a 2mm thick concave shell. The Phase A study, completed in August 2010 [8], covers all design aspects from mechanics, to control, simulation and optical specifications. By specific request of GMTO, the design has been largely based on existing units. In particular, the VLT DSM was taken as "our" state-of-the-art reference for the GMT ASM. Thanks to the segmented design, the individual segments are well aligned with the present technology and they don't pose particular challenges.

Each segment has 672 actuators. This number has been chosen upon the result of a trade-off analysis taking into account performance, reliability, development risks and costs. The actuator pitch is significantly larger than in the previous units, 36mm compared to the 'usual' 29–30mm. The verification of the impact of such change on system controllability and dynamic performance has been investigated by means of a sophisticated simulation code continuously developed along these projects by the Aerospace Department of Politecnico di Milano by a research group led by P.Mantegazza. The full-comprehensive simulation is based on a state space model including the structure (through a representative modal reduction derived from an accurate Finite Element Model), the control system with sensor and actuator noises and non linearity, and also the fluid-dynamic of the air trapped between the reference body and the thin shell. The results indicate that the different pitch can be managed by the
present control architecture leading to comparable results with respect to the present systems, with a following error of the order of 15nm rms wavefront in median seeing (0.65" in V).

Another significant difference with respect to the current systems is the strong aspheric shape of the off-axis units, that require both the inner face of the shell and the reference body to be figured aspherically. The off-axis units are significantly tilted. To simplify the holding structure design, we conceived an asymmetric hexapod that holds the adaptive units with the proper inclination. Moreover, specific design of the outermost actuators was needed to fit the regular actuators pattern up to the external diameter of the off-axis units.

The Phase A study comprehended also a comprehensive static and dynamic analysis of the whole unit, including top ring. The first pendulum mode is at 24.3Hz and the stability under gravity shows a displacement in the secondary plane of 0.5mm and a tilt of the unit of 23".

4.2. E-ELT M4 Adaptive Unit

In the frame of the E-ELT design, ESO has assigned two identical competitive contracts for the Phase B study of the M4 adaptive unit. One of the contracts has been granted to a group led by Microgate with ADS, Safran-Sagem and Istituto Nazionale di Astrofisica - Osservatorio di Brera being partners of the design team. The study has been successfully completed in 2010. During 2011, the preliminary study has been adapted to the new telescope design with 39m primary mirror. In our current design, the 2.44x2.40 m elliptic flat mirror is referenced to a monolithic reference body and controlled by 5910 actuators, 5245 of which being in the optical path. The size of the monolithic reference body and the large number of actuators forced us to reconsider the present 'typical' configuration, introduction deep modifications while still keeping the same operating principle. In the M4 design, the reference body acts also as supporting structure for the actuators and control system. The actuators are grouped into bricks comprehending typically ~30 actuators. On each brick, we have implemented all functions required by the local control loop. Capacitive sensor acquisition, voice coil drivers, digital control, power supply and communication are all hosted on the brick, which structure also acts as 'cold plate' removing the heat generated locally. To reduce power consumption, reduce size and also improve control performances all digital functions are performed by a
single FPGA. According to this concept, the brick is a Line Replaceable Unit with very clean and simple interfaces. This improves dramatically the maintenance concept: bricks can be substituted without removing the thin shell. Moreover, being the system tolerant against single actuator failures, the brick replacement, if necessary, might occur only at scheduled maintenance. The baseline design foresees a carbon fiber reference body, with a backup solution in aluminum, while the initial solution made based on a silicon carbide structure has been abandoned because of the manufacturing issues of such a big structure. The reference body fine positioning is obtained by means of a very large and stiff hexapod designed on base of the successful hexapod delivered by ADS for the FermiLab DeCAM project on the Blanco telescope. A rotating stage allows to reposition the unit in order to feed the two Nasmith foci. In this way the hexapod stroke can be limited with great benefit in terms of stiffness and accuracy. This structure performs very well both dynamically and statically. The first pendulum mode is at 40.7 Hz and the stability under gravity shows a displacement in the secondary plane of 0.14mm and a tilt of the unit of 2.5".

In the frame of the Phase B study we have developed and successfully tested a quite large prototype with 330 actuators, being fully representative of the final implementation. The prototype reference body is a cut-out of the final reference structure, and the bricks were designed and implemented to be compatible with the final unit. The prototype has been extensively characterized electromechanically and optically. The following error measured using the internal metrology amounts to 32nm rms wavefront without field stabilization tip-tilt (specification: 60nm, goal 43nm), and 58nm rms wavefront including all contributions. The tip-tilt residual amounts to 1.8mas, slightly above the specified 1.4mas, but it has been obtained in 'blind' open loop operation.

The optical tests demonstrated 18nm rms WF flattening over two independent shell segments. The thermal stability tests confirmed that the wavefront remains stable within 60nm rms over an ambient temperature variation of 3°K, exceeding the one of a typical night. The same environmental fluctuation has been also applied to verify the co-phasing stability. Apart from a very limited area close to the metal membranes that hold the mirror, and that are much stiffer than the final ones, we measured a stability of 100nm rms wavefront (specification: 250nm).

Fig. 4. E-ELT M4 adaptive unit, M4 demonstration prototype and optical tests results
These test results are fully supporting our baseline design, that is based on a segmented solution with six identical 2mm thick petals.

5. Conclusions

The contactless, voice-coil based technology has been successfully deployed in the adaptive secondary mirrors of 6m and 8m class telescopes, providing significant advantages with respect to other correctors. The technology has been developed in cooperation by research institutes and industrial partners, to which the implementation and deployment has been completely handed over. This allowed achieving the quality standards required by the complexity of the system, so that now it is sufficiently mature to be part of the infrastructure of large observatories.

Several aspects make the voice coil based, contactless mirrors a suitable choice for the next generation of large adaptive correctors for the Extremely Large Telescopes, as demonstrated by the results obtained on our E-ELT M4 prototype.

6. References