ABSTRACT

Several simulations of the deformable mirror of the LBT adaptive secondary unit have been run in the past, in order to determine the parameters able to achieve the best performances in the various static and adaptive operations of the mirror. The experience gained by those analyses allowed us to freeze the magnetic circuit design, the actuator geometry, and the thickness profile of the mirror. These choices, now included in the telescope preliminary design, are described in this paper, where the improvements of the new magnetic, mechanical, and thermal design are characterized.

1. INTRODUCTION

The results of the numerical simulation of first model of the deformable mirror (DM) of the Large Binocular Telescope (LBT) adaptive secondary unit, fully described in a previous paper (Del Vecchio and Gallieni, 2000), as well as the testing phase of the MMT adaptive secondary mirror (Riccardi et al., 2001), allowed us to freeze the final design of the LBT DM. After exploring two patterns derived from the one previously described (Del Vecchio and Gallieni, 2000), with 16 and 14 rings of actuators instead of 17, respectively, and varying the nominal thickness at center from 1 to 2 mm, a more effective pattern and a slightly different thickness profile have been selected (see Sect. 2). A finite element (FE) model reflecting that geometry has been set (Sect. 4), in order to evaluate the response (Sect. 5) of the DM to the gravity load, to a turbulent wavefront, and to several Zernike aberrations (the correction of the static, permanent magnet-to-magnet deformations is even easier with the current actuator pattern, due to the increased mean magnet-to-magnet distance), according to the method discussed in a previous paper (Del Vecchio and Gallieni, 2000). Furthermore, adopting a permanent magnet conceptually similar to the one described in a previous study (Del Vecchio and Gallieni, 2000), accommodating a bias magnet in its central hole, let us to achieve an higher efficiency, without increasing the total magnet mass, as discussed in Sect. 3. Finally, the power dissipation has been considerably improved by using heat pipes to convey the heat produced by the coils to the heat exchanger.

2. THE THICKNESS PROFILE

In the most general case, the equation of an aspherical surface is

\[ z = \frac{r^2}{R + \sqrt{R^2 - r^2 - r^2K}} , \]

where \( r \) is the distance from the optical axis, \( R \) is the surface radius of curvature at the vertex and \( K \) is the conic constant. The LBT DM radius ranges from \( R_i = 28 \text{ mm} \), the inner hole radius, and \( R_o = 455.486 \text{ mm} \), the outer edge radius.
Selecting \( R_b = 1994.968 \) mm as the radius of the back, spherical surface, and varying the thickness according to

\[
t(r) = 1.6 - 0.085 \left( 6\rho^4 - 6\rho^2 + 1 \right) \text{ mm}
\]

where \( \rho = r/R_o \) is the normalized distance from the optical axis, allows to obtain a front, aspherical surface whose parameters \( R \) and \( K \) in Eq. 1 are equal to 1974.126 mm and -0.734544, respectively, that match the optical specifications. The resulting thickness ranges from 1.516 mm at the outer edge to 1.642 mm at \( r = 321.986 \) mm.

3. THE ACTUATOR OPTIMIZATION

The efficiency of an electromagnetic actuator is defined as the ratio between the delivered axial force and the square root of the electric power. The efficiency of the toroidal, radially magnetized magnet adopted for the MMT DM (Del Vecchio et al., 1999) and analyzed for the LBT DM (Del Vecchio and Gallieni, 2000), decreases when increasing the air gap between the coil and the magnet. In the current design, that gap has been raised from .2 — the value adopted in the past — to .7 mm, in order to accommodate a .5 mm thick copper disk, able to improve the thermal conduction of the power generated by the coil towards the coil axis. Inside the coil, a commercial, low-cost heat pipe (see Fig. 1), in good thermal contact with the coil itself, allows to transfer to the heat sink the heat dissipated much more effectively than all the traditional heat conductors. Although the increased gap of this actuator implies a loss of efficiency, a modification of the magnet design can balance this disadvantage. Inserting an axially magnetized bias magnet in the inner hole of the radially magnetized magnet increases the magnetic flux density \( \vec{B} \) on one side of the magnet, and decreases it on the opposite side, as shown in Fig. 2. As a consequence, the efficiency of the current actuator is equal to .74 \( N \times W^{-1/2} \). This value is achieved with inner and outer radii of the radial magnet equal to 3.2 and 5.5 mm, respectively, and inner and outer radii and height of the coil equal to 3, 5.5, and 2.5 mm, respectively. The total magnet mass is still equal to .0025 kg.

4. THE NUMERICAL MODEL

The FE model has been set up by means of the Ansys code, used also for all the computations described in this paper. It consists of 43998 shell elements that model the glass, with the element thickness varying according to the optical design discussed in Sect. 2, and using the material properties of the Zerodur. The total number of nodes defining the glass is 26238. The locations are plotted in Fig. 3. The magnets, as well as their interfaces with the glass, have been simulated as in the antecedent models (Del Vecchio and Gallieni, 2000); according to previous simulations (Del Vecchio et al., 1999), the nodes belonging to the inner hole of the DM model are restrained in the radial and tangential directions, approximating the central, non-linear membrane described in a previous paper (Del Vecchio, 1997) as infinitely rigid in its plane and neglecting its out-of-plane stiffness. All the input and output displacements have been considered as radial in the spherical coordinate system centered at the point (0,0,0).
5. STATIC ANALYSES

As the current distance between two actuator ring is greater than the mean magnet-to-magnet distance of the MMT DM described in a previous paper (Del Vecchio et al., 1999), the performance of the DM can be evaluated by the response of the DM to the gravity load (Sect. 5.1) and two types of imposed deformations — Zernike aberrations and turbulent wavefronts (Sect. 5.2 and Sect. 5.3, respectively).

5.1. Gravity

Two static analyses — with gravity applied along the optical axis and perpendicularly to it — have been run in order to evaluate the DM response when it is zenith and horizon pointing, respectively. The results, summarized in Tab. 1, show that the rms values of the actuator forces — .064 and .018 N at zenith and horizon, respectively — are low enough in terms of power dissipation, as discussed in a previous paper (Del Vecchio and Gallieni, 2000). The resulting displacement fields — 4.7 and 10.1 nm rms at zenith and horizon, respectively — are within the optical specifications.

5.2. Zernike deformations

5.2.1. Low orders

The Zernike aberrations $u_i$ of orders $i$ 1 to 28 have been imposed to the DM at the 672 actuator positions, in order to compute both the residues and the actuator forces as a function of the amplitude of the Zernike aberrations — defined as $u_i = C \phi_i(\rho) \, g_i(\theta)$ in the cylindrical coordinate system $\rho-\theta-z$, where $z$ is the optical axis and $\rho$ in the normalized radius, as defined in Sect. 2. The results of the response to the low-order Zernike aberrations — all the radial and tangential orders up to 6 — are plotted in Fig. 4 in terms of ratios between the rms values of the residues and the imposed displacements. Even the highest radial and tangential order input displacements give rms residue < 10% of the rms of the input. The ratio of the rms actuator forces and $C$ is < .07 N $\times$ $\mu$m$^{-1}$. The results of the most demanding low-order Zernike aberrations — i.e. the axisymmetric deformations $u = C \sqrt{3} \times (2\rho^2 - 1)$ (defocus), $u = C \sqrt{5} \times (6\rho^2 - 6\rho^4 + 1) \ (3$rd order spherical), and $u = C \sqrt{7} \times (20\rho^6 - 30\rho^4 + 12\rho^2 - 1) \ (5$th order spherical) — are summarized in Fig. 5, that shows the ratios of the actuator forces and the coefficient $C$ as a function of the actuator radius, and in Tab. 2, where the input displacements and residues, as well as their ratios, are listed.

![Figure 3. The actuator pattern.](image_url)
Figure 4. Ratio between rms of residues and input displacements of the Zernike aberration of index 1 to 28. The ratio is plotted as a function of the radial and tangential order of each Zernike order.

Figure 5. The ratios of actuator forces and the coefficients C as a function of the actuator radius for the low-order, axisymmetric Zernike aberration.
Table 2. Correction of defocus, 3rd order, and 5th order spherical aberrations. The input DM displacements, the DM residues, and their ratios are shown.

<table>
<thead>
<tr>
<th>aberration type</th>
<th>displ. [μm]</th>
<th>residue [nm]</th>
<th>ratio [%]</th>
</tr>
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<tbody>
<tr>
<td>defocus</td>
<td>max</td>
<td>0.173</td>
<td>3.043</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>-0.172</td>
<td>-12.088</td>
</tr>
<tr>
<td></td>
<td>ptv</td>
<td>0.345</td>
<td>15.051</td>
</tr>
<tr>
<td></td>
<td>rms</td>
<td>0.103</td>
<td>0.944</td>
</tr>
<tr>
<td></td>
<td>std</td>
<td>0.103</td>
<td>0.944</td>
</tr>
<tr>
<td>3rd order spherical</td>
<td>max</td>
<td>0.224</td>
<td>16.487</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>-0.112</td>
<td>-2.782</td>
</tr>
<tr>
<td></td>
<td>ptv</td>
<td>0.335</td>
<td>19.269</td>
</tr>
<tr>
<td></td>
<td>rms</td>
<td>0.104</td>
<td>2.536</td>
</tr>
<tr>
<td></td>
<td>std</td>
<td>0.104</td>
<td>2.505</td>
</tr>
<tr>
<td>5th order spherical</td>
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<td>min</td>
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<td>-13.303</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>std</td>
<td>0.103</td>
<td>9.187</td>
</tr>
</tbody>
</table>

Figure 6. Ratio between rms of residues and input displacements of some high-order Zernike aberration.

5.2.2. High orders

The Zernike aberrations of radial orders 9, 10, 13, 14, 17, 18, 21, 22, 25, 26, 29, and 30, each one with its relative minimum (0 or 1) and maximum tangential order, have been imposed to the DM, in order to evaluate its capability to correct high order deformations. Due to the (much) higher tangential density of the actuators than the radial density, the actuators can correct the higher tangential orders (much) better than the lower ones, as shown in Fig.6. The ratio of the rms actuator forces and $C$ ranges from .02 and .92 $N \times \mu m^{-1}$.

5.3. Turbulent wavefront

Adopting the method described in the past (Del Vecchio and Gallieni, 2000 and Del Vecchio et al., 1999) 100 wavefront deformations have been applied to the DM model, assuming the Kolmogorov turbulence spectrum of the atmosphere, with a Fried’s parameter of 100 cm at $\lambda = 2\mu m$. The average rms residue of the DM surface, equal to $\approx 49 \mu m$, is 2.8% of the average value of the rms uncorrected wavefront and 7.2% of average rms of the tip-tilt-removed wavefront, while the rms actuator force is .107 N, and the absolute values of the actuator forces are < .5 N.
6. CONCLUSIONS

The final design of the LBT secondary adaptive mirror is the result of the studies and tests performed on the correspondent unit of the MMT as well as the simulations run in the last year to determine the most critical parameters of the mirror. Three fundamental differences in the present design allow to enhance its performances. First, the new actuator geometry, even less dense than the ones studied and implemented in the previous designs, allows gravitational deformations still low in the static, intrinsically open-loop mirror response, and very good levels of corrections of both the Zernike aberrations and the turbulent wavefront. Furthermore, the implementation of the new magnetic circuit allows a much better heat removal without losing efficiency.

REFERENCES


