Mem. S.A.It. Suppl. Vol. 9, 475

Memorie della
Supplementi

Integrated modeling in an active optics system

P. Schipani and F. Perrotta

Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, I-80131 Napoli, Italy e-mail: schipani@na.astro.it

Abstract. In all the modern telescopes (medium, large, extremely large) the active optics is one of the most delicate systems. No assessed simulation tool exists, one of the reason is that the approach can be different for segmented or monolithic, medium or large mirrors, and so each telescope design staff usually develops its own simulation system. In this paper an integrated modeling approach is proposed, combining finite element analysis, dynamical systems simulation methods and optical performance analysis.

Key words. Integrated modeling - Active Optics - Finite Element Analysis - Simulation - Software

1. Introduction

The integrated modeling is emerging as a fundamental strategy for the telescopes design (e.g. Angeli et al. (2004), Roberts et al. (2003)). In the framework of the VST (VLT Survey Telescope) project several simulations have been carried out to analyze the active optics system behavior. Some of the main tasks were the calculation of the deformation imposed to the primary mirror applying a set of calibrated correction forces, the simulation of the dynamic response of the mirror (applying as input to the axial actuators a set of forces or a wind disturbance) the prediction of the effects of the gravity at different altitude angles. Many software tools were needed: a FEA tool (like Ansys or Nastran), a computational and simulation environment (e.g. Matlab + Simulink), a ray-tracing software (like Zemax or Code V). In the end the work has naturally converged towards an integrated modeling environment in which the computational environment is the core block. The idea is to use FEA to produce a set of differential equations representing a nodal system. Then the computational and simulation environment converts them to a modal representation and then to a reduced order space-state model, easy to be analyzed with the traditional control system theory and tools. Finally the ray-tracing software can give information on the impact of the deformations of the primary mirror on the performance of the whole telescope optical system.

2. Primary mirror axial control

The mirror shape is controlled by means of a set of axial actuators. The actuators must both support the weight of the mirror and compensate for undesired aberrations of the optical surface of the mirror. In order to simulate the dynamic behavior of the mirror it is necessary a mathematic model. The starting point is a FEA of the mirror, which produces the input data for all the possible representations (Fig.1).

Send offprint requests to: P. Schipani

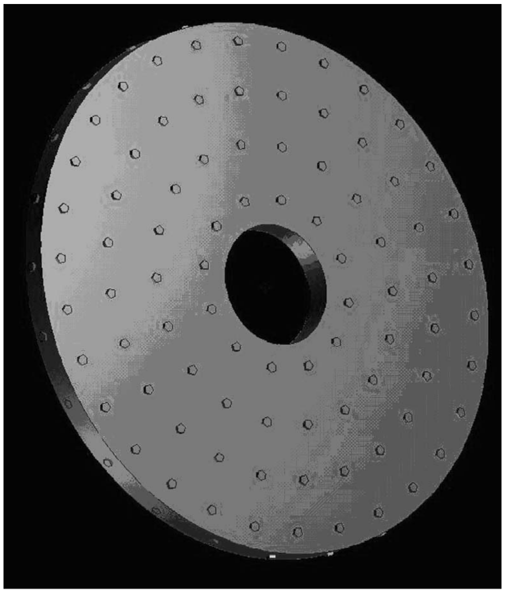

Fig. 1. 3D FEA mirror model and actuator locations

3. Mirror models

The mechanical structure of a telescope mirror can be analyzed through three different descriptions representing increasing levels of abstraction.

3.1. Nodal representation

The nodal representation can be considered as the physical system, although it already has some level of approximation and abstraction through the choice of nodes. The associated coordinate system is defined through the displacements and velocities of physical nodes. The nodal model is a set of second order differential equations characterized by the mass (M), damping (D), and stiffness (K) matrices, the initial and boundary conditions for nodal displacements (q) and velocities, and the sensor outputs (y). The mass and stiffness matrices come from FEA analysis. Damping is not present in the finite element model but can be introduced modally to the state-space model. B_0, C_{0q} and C_{0v} are the input, output displacement, and output velocity matrices, respectively. The length of q is Nd, the number of degrees of freedom (DoF) of the system.

$$M\ddot{q} + D\dot{q} + Kq = B_0 u$$
$$y = C_{0q} q + C_{0v}\dot{q}$$

3.2. Modal representation

Unlike the nodal one, the modal coordinate system is defined through the displacements and velocities of structural modes. These modes can still be visualized as special shapes of the structure, but they are related rather to the whole system than to individual parts. The advantage of the modal representation is that it decouples the system differential equations. So after the derivation of the nodal model through FEA analysis, the next step is to convert it in a modal one, decoupling the equations of the model. This methodology is summarized in the following steps (Hatch (2001)):

- solve the undamped eigenvalue problem which identifies the resonant frequencies and mode shapes (eigenvalues and eigenvectors);

- use the eigenvectors to uncouple or diagonalize the original set of coupled equations, leading to N uncoupled single degree of freedom problems instead of a single set of N coupled equations;

- calculate the contribution of each mode to the overall response; this allow to reduce the size of the problem by eliminating modes that give little contribution to the system (e.g. high frequency modes have generally a little effect at lower frequencies and could be removed from the model, accepting some approximation).

The coordinate transformation that decouples the second order differential equations of the nodal model is:

$$q = \Phi q_m$$

where Φ is the eigenvector matrix of the system containing the eigenvectors as columns. Also the modal representation is a set of second order differential equations.

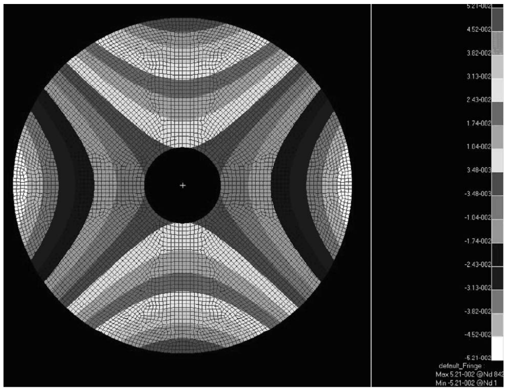

Fig. 2. Elastic mode: Symmetry 2, Order 1, displacements normal to mirror plane

3.3. Space-state representation

The state-space representation is a first order set of differential equations obtained describing the system by defining a state vector containing not just the displacements but also the velocities. The state-space model is commonly used in control engineering and expresses the basic control characteristics, the inputs, the outputs, and the dynamics of the system in a standard way. After FEA has produced a nodal representation, and after the conversion to a modal model, the final step is to go to a space-state representation. A space-state representation of a LTI (Linear Time-Invariant) system is a first-order matrix differential equation with constant coefficients:

$$\dot{x} = Ax + Bu$$
$$y = Cx$$

where u is the input and y is the output vector of the system, and the state of the system is characterized by the state variable x. A is the system dynamics matrix. To obtain a state space representation from the modal representation, a state vector including displacements and their speeds must be introduced:

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} q_m \\ \dot{q}_m \end{bmatrix}$$

4. Optical interfaces

Many optical routines have been written in Matlab to study the mirror aberrations. Assessed ray-tracing tools exist but they intrinsically do not deal with the mechanical properties of the mirrors but just with the optical properties. So it is possible to describe the aberrations of an optical system using the standard (or fringe) Zernike polynomials, but not to fit the aberrations to a set of natural vibration modes like the one in Fig.2 (Noethe (1991)). Since in the VST case the elastic modes are used to fit the wavefront and correct the mirror shape, an interface Matlab-Zemax has been written to generate mirror shapes through grid sags, in order to analyze the effect on the overall optical system of the deformations of the primary mirror at different altitude angles obtained by FEA in terms of elastic modes. Custom software has been needed to add missing capabilities to conventional ray-tracing, and to implement a bridge between FEA and ray-tracing.

References

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