

Active Optics of Large Segmented Mirrors: Dynamics and Control

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DOI: 10.2514/1.44041

This paper examines the active optics of future large segmented telescopes from the point of view of dynamic simulation and control. The first part of the paper is devoted to the modeling of the mirror. The model has a moderated size and separates the quasi-static behavior of the mirror (primary response) from the dynamic response (secondary or residual response). The second part of the paper is devoted to control. The control strategy considers explicitly the primary response of the telescope through a singular value controller. The control-structure interaction is addressed with the general robustness theory of multivariable feedback systems, where the secondary response is considered as uncertainty. This approach is very fast and allows extensive parametric studies. The study is illustrated with an example involving 90 segments, 270 inputs, and 654 outputs.

Introduction

MONOLITHIC mirrors of diameter larger than 8 m are difficult to manufacture [1]. As a result, all future large telescopes will be segmented. Currently, telescopes of 30 m and more are under design [2,3], involving several hundreds of segments. Figure 1 shows the primary mirror (M1) of a European extremely large telescope (E-ELT); it has a diameter of 42 m and consists of 984 aspherical segments; every segment is equipped with three two-stage position actuators, controlling the piston and the two tilts, and six edge sensors measuring the position of the segment with respect to its six neighbors. The motion of the position actuators is transmitted to the segment through a whiffle tree. Overall, there are 2952 position actuators \mathbf{a} and 5604 edge sensors \mathbf{y}_1 .

Modeling for control and controlling large complex active structures such as telescopes poses several challenges:

1) Finite element techniques classically used in structural modeling tend to use a very large number of degrees of freedom that reflect the complex geometry of the structural components. The size of the control model (used in the control design and to evaluate the control-structure interaction) must be drastically reduced while preserving the main features of the system, statically and dynamically. The control model must give access to all actuator inputs, sensor outputs, and optical performance metrics, and it is essential to preserve the kinematic relationship between the position actuators and the quasi-static position of the segmented mirror (primary response).

2) The control algorithm must be simple enough to be implemented in real time (in spite of the large number of inputs and outputs), provide enough gain in low frequency to achieve performance, and enough roll off outside the bandwidth to reduce spillover. A reliable lower bound for the stability margin should be evaluated from the control model, and, if possible, the critical mode(s) for stability should be identified. The control model should allow extensive parametric studies and sensitivity analysis. These challenges have only been partially covered by the existing literature [4–9].

The objective of this study is threefold:

1) To develop a representative numerical model of the segmented mirror and its supporting truss that can be used for control design and robustness evaluation; this model should have a minimum

complexity to allow extensive parametric studies and control-structure interaction. In a later stage, we intend to also use it for wind response calculation and optical performance evaluation.

2) To implement a control strategy based on the primary response of the mirror and two sensor arrays, the edge sensors measuring the relative displacements of adjacent mirrors and the normal to the segments.

3) To examine the interaction between the controller and the structural dynamics with various multivariable robustness tests in the frequency domain, where the secondary response is considered as uncertainty, and evaluate the requirements in terms of frequency and damping for the supporting truss to guarantee the performance, control bandwidth, and an appropriate stability margin for the control system.

The system can be represented schematically as in Fig. 2. The position actuator is represented by a force \mathbf{F}_a acting on a spring k_a that is taken as the stiffness of the whiffle tree; the force is related to the unconstrained displacement by $\mathbf{F}_a = k_a \mathbf{a}$. The position actuators rest on a supporting truss carrying the whole mirror. The disturbances \mathbf{d} applied to the system come from thermal gradients, changing gravity vector with the elevation of the telescope, and wind.

Figure 3 describes the temporal and spatial frequency distribution of the various layers of the control system involved in the wave front correction of a large telescope [10]; the spatial frequency is expressed in terms of Zernike modes. In general, adaptive optics operates on a smaller deformable mirror and the amplitudes are small, typically a few microns. Our discussion is focused on M1; the amplitudes to be corrected by the active optics are typically several hundred microns [11].

Currently the control strategy envisaged by the European Southern Observatory (ESO) for cophasing the segments [6,12] assumes that the supporting truss is rigid and that the natural frequency of the whiffle tree (connecting the actuators to the segments) is well above the bandwidth of the control system (which is realistic). In this case, the behavior of the segmented mirror is assumed quasi-static and the kinematic relationship between the actuator displacements \mathbf{a} and the edge sensors output \mathbf{y}_1 is simply

$$\mathbf{y}_1 = \mathbf{J}_e \mathbf{a} \quad (1)$$

where \mathbf{J}_e is the Jacobian of the edge sensors of the segmented mirror. Here we assume that the edge sensors are sensitive to the relative displacements normal to the segments only. The pseudoinverse of the Jacobian \mathbf{J}_e^+ is best obtained by singular value decomposition (SVD)

$$\mathbf{J}_e = \mathbf{U} \mathbf{\Sigma} \mathbf{V}^T \quad (2)$$

where the columns of \mathbf{U} are the orthonormalized edge sensor modes, the columns of \mathbf{V} are the orthonormalized actuator modes, and $\mathbf{\Sigma}$ contains the singular values on its diagonal. The control system works according to Fig. 4, called SVD controller [5]. \mathbf{d} is the

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