Distributed sensing signal analysis of deformable plate/membrane mirrors

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Abstract
Deformable optical mirrors usually play key roles in aerospace and optical structural systems applied to space telescopes, radars, solar collectors, communication antennas, etc. Limited by the payload capacity of current launch vehicles, the deformable mirrors should be lightweight and are generally made of ultra-thin plates or even membranes. These plate/membrane mirrors are susceptible to external excitations and this may lead to surface inaccuracy and jeopardize relevant working performance. In order to investigate the modal vibration characteristics of the mirror, a piezoelectric layer is fully laminated on its non-reflective side to serve as sensors. The piezoelectric layer is segmented into infinitesimal elements so that microscopic distributed sensing signals can be explored. In this paper, the deformable mirror is modeled as a pre-tensioned plate and membrane respectively and sensing signal distributions of the two models are compared. Different pre-tensioning forces are also applied to reveal the tension effects on the mode shape and sensing signals of the mirror. Analytical results in this study could be used as guideline of optimal sensor/actuator placement for deformable space mirrors.

1. Introduction

Circular thin plates are commonly used as key components for optical deformable mirror systems in space telescopes [1–5]. To further reduce the areal density and total mass of the optical system in space, the concept of thin film optics was proposed in recent years and series of membrane deformable mirror prototypes have been developed and tested [6–11]. These high-precision deformable plate/membrane mirrors used in space are usually lightweight and flexible and they often exhibit high flexibility, poor stiffness and low damping properties. Thus, undesirable external induced vibration can become a serious problem during operations, which lead to surface inaccuracy and even jeopardize relevant working performance. Precision sensing and control are therefore necessary to these high-performance optical mirror systems. This study is (1) to investigate spatially distributed microscopic sensing signals of lightweight circular plate/membrane mirrors, and (2) to evaluate the tensioning effects on different signal components of different modes. Sensor and actuator design criteria can be summarized from these results.

Due to the distinct direct and converse piezoelectric effects, piezoelectric materials are widely used in sensor and actuator applications where high accuracy and precision are needed [12]. Polyvinylidene fluoride (PVDF) polymeric materials, as an outstanding representative of thin-film piezoelectric materials, are lightweight, dynamically sensitive, and can be easily seg-
mented and shaped for distributed sensing and control of flexible structures. Accordingly, the distributed piezoelectric layer can serve as distributed sensors and actuators in sensing and control of optical deformable plate/membrane mirrors. Distributed sensing and control of various structures using piezoelectric materials have been investigated over the years [13–17]. Electromechanical sensing properties of flexible rings laminated with distributed piezoelectric sensors were investigated [18]. Static and dynamic control of a simply-supported non-linear circular plate with bimorph fully-covered piezoelectric layers were studied [19]. Modal sensing and actuating signals of thin cylindrical shells and panels were evaluated [20–23]. Sensing and active control of piezoelectric elastic spherical shells were explored and micro-sensing signals were obtained [24–26]. Micro-sensing characteristics and modal voltages of linear and nonlinear toroidal shells were achieved [27]. Distributed sensing and control of piezoelectric laminated conical shells with different actuator locations were analyzed [28,29]. Distributed modal sensing and actuation of thin-walled rotating paraboloidal shells with different boundary conditions were also studied [30–33]. Neural sensing signals and microscopic actuation of precision parabolic cylindrical shell panels were discussed [34,35]. However, investigation of distributed sensing signals on thin plates and membranes is insufficient.

In this study, dynamic governing equations of circular plate and membrane mirrors are presented first. Transverse mode shape functions of the pretensioned plate and membrane mirrors with clamped boundary conditions are derived respectively. Then, the microscopic signal generations of infinitesimal piezoelectric sensor distributed on two different models, i.e., the plate and membrane mirror models, are investigated. Details are described in following sections.

2. Modeling of a flexible thin deformable mirror

Based on the Kirchhoff-Love linear thin shell assumptions, the fundamental dynamic equations for a generic double-curved thin shell are [12,36]

\[
\frac{\partial}{\partial z_1} \left( N_{11} A_2 \right) + \frac{\partial}{\partial z_2} \left( N_{12} A_1 \right) + N_{12} \frac{\partial A_1}{\partial z_2} - N_{22} \frac{\partial A_2}{\partial z_1} + A_1 A_2 \frac{Q_{13}}{R_1} = \rho h A_1 A_2 \ddot{u}_1
\]

(1)

\[
\frac{\partial}{\partial z_1} \left( N_{12} A_2 \right) + \frac{\partial}{\partial z_2} \left( N_{22} A_1 \right) + N_{12} \frac{\partial A_2}{\partial z_2} - N_{22} \frac{\partial A_1}{\partial z_1} + A_1 A_2 \frac{Q_{23}}{R_2} = \rho h A_1 A_2 \ddot{u}_2
\]

(2)

\[
\frac{\partial}{\partial z_1} \left( Q_{13} A_2 \right) + \frac{\partial}{\partial z_2} \left( Q_{23} A_1 \right) - A_1 A_2 \left( \frac{N_{11}}{R_1} + \frac{N_{22}}{R_2} \right) = \rho h A_1 A_2 \ddot{u}_3
\]

(3)

\[Q_{13} A_2 = \frac{\partial}{\partial z_1} \left( M_{11} A_2 \right) + \frac{\partial}{\partial z_2} \left( M_{21} A_1 \right) + M_{12} \frac{\partial A_1}{\partial z_2} - M_{22} \frac{\partial A_2}{\partial z_1}
\]

(4)

\[Q_{23} A_2 = \frac{\partial}{\partial z_1} \left( M_{12} A_2 \right) + \frac{\partial}{\partial z_2} \left( M_{22} A_1 \right) + M_{21} \frac{\partial A_2}{\partial z_1} - M_{11} \frac{\partial A_1}{\partial z_2}
\]

(5)

Then the vibration equations of a circular thin plate/membrane deformable mirror can be simplified from Eqs. (1)–(5) with specified two Lamé parameters and two radii of curvature. The geometry of the mirror is defined in a polar coordinate system which is shown in Fig. 1, where r and \(\theta\) respectively define the radial and angular directions of the neutral surface and \(z_3\) defines the transverse direction of the mirror. The thickness of the mirror is \(h\) and the radius is \(a\). The two Lamé parameters of the mirror are \(A_1 = A_r = 1\) and \(A_2 = A_\theta = r\); two radii of curvature are \(R_1 = R_r = \infty\) and \(R_2 = R_\theta = \infty\). With the four parameters, one can simplify the double-curved shell dynamic equations to the dynamic equations of the mirror.

\[
\frac{\partial N_{rr}}{\partial r} + \frac{1}{r} \frac{\partial N_{r\theta}}{\partial \theta} + \frac{N_{rr} - N_{\theta\theta}}{r} = \rho h \ddot{u}_r
\]

(6)

\[
\frac{\partial N_{rr}}{\partial r} + \frac{1}{r} \frac{\partial N_{r\theta}}{\partial \theta} + \frac{2}{r} N_{r\theta} = \rho h \ddot{u}_\theta
\]

(7)

Fig. 1. Geometry of a thin deformable mirror.
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