Mechanical Systems and Signal Processing 103 (2018) 1–22

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Distributed microscopic actuation analysis of paraboloidal membrane shells of different geometric parameters

Honghao Yue [a], Yifan Lu [a,*], Zongquan Deng [a], Hornsen Tzou [b]

[a] School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, Heilongjiang Province 150001, PR China
[b] College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, PR China

ARTICLE INFO

Article history:
Received 17 August 2017
Received in revised form 20 September 2017
Accepted 1 October 2017

Keywords:
Paraboloidal membrane shell
Geometric parameter effects
Modal control
Microscopic actuation
Optimal actuator placement

ABSTRACT

Paraboloidal membrane shells of revolution are commonly used as key components for advanced aerospace structures and aviation mechanical systems. Due to their high flexibility and low damping property, active vibration control is of significant importance for these in-orbit membrane structures. To explore the dynamic control behavior of space flexible paraboloidal membrane shells, precision distributed actuation and control effectiveness of free-floating paraboloidal membrane shells with piezoelectric actuators are investigated. Governing equations of the shell structronic system are presented first. Then, distributed control forces and control actions are formulated. A transverse mode shape function of the paraboloidal shell based on the membrane approximation theory and specified boundary condition is assumed in the modal control force analysis. The actuator induced modal control forces on the paraboloidal shell are derived. The expressions of microscopic local modal control forces are obtained by shrinking the actuator area into infinitesimal and the four control components are investigated respectively to predict the spatial microscopic actuation behavior. Geometric parameter (height-radius ratio and shell thickness) effects on the modal actuation behavior are explored when evaluating the micro-control efficiency. Four different cases are discussed and the results reveal the fact that shallow (e.g., antennas/reflectors) and deep (e.g., rocket/missile fairing) paraboloidal shells exhibit totally different modal actuation behaviors due to their curvature differences. Analytical results in this paper can serve as guidelines for optimal actuator placement for vibration control of different paraboloidal structures.

1. Introduction

Many advanced aerospace structures and optical systems, such as reflectors, mirrors, antennas, rocket fairings and nozzles, belong to the category of double-curvature paraboloidal shell structures [1]. Due to weight restrictions in launching and space operation, these paraboloidal shells are mostly lightweight and flexible, which tend to exhibit prolonged oscillations and thus influence their precision and accuracy. Accordingly, precision control of structural vibration is of considerable importance not only to their stringent performance requirement, but also to their structural integrity and long-term reliability [2–4]. Accordingly, this study is to investigate the distributed actuation effectiveness of flexible membrane paraboloidal shells and to explore the optimal actuator placement on paraboloidal shell structures. Actuation characteristics of shallow and deep paraboloidal shells are evaluated respectively.

* Corresponding author.
E-mail address: yf.lu@hit.edu.cn (Y. Lu).

https://doi.org/10.1016/j.ymssp.2017.10.005
0888-3270/

Development of ''smart structures and structronic systems'' has demonstrated that various smart materials and control techniques can be applied to control static shapes and/or undesirable vibrations of structures and systems [5,6]. Distributed control of plate and shell structures based on the smart structure technology has been quickly developing in the last twenty years [7–12]. Among various smart materials and structures, the distributed control technique using piezoelectric actuators is widely investigated and applied to engineering systems, ranging from micro-/nano-devices to large aerospace structures. Distributed sensing and control signals of deformable plate membrane mirrors with different pretension forces were investigated by Lu et al. [13,14]. The equations of motion of a free-floating paraboloidal shell laminated with a piezoelectric actuator layer were derived and modal control effectiveness of the actuators was explored by Yue et al. [15]. Distributed control actions of thin cylindrical shells with various piezoelectric [16–18] and electro-optic photostrictive [19] actuators were widely investigated. Distributed modal voltages and their spatial strain characteristics of toroidal shells were investigated by Tzou et al. [20]. Static and dynamic behaviors of spherical and conical shells with piezoelectric actuators were also comprehensively studied [21–24]. Micro-control actions and distributed control effectiveness of segmented actuator patches laminated on hemispheric shells was evaluated by Smithmaitrie et al. [25]. Distributed modal voltage and micro-control characteristics of a simply supported paraboloidal shell were explored by Ding et al. [26,27]. Zhang and Yue et al. experimentally investigated the dynamic vibration control of paraboloidal membrane shells with different control strategies respectively [28–30]. Hu et al. studied the microscopic actuation and optimal actuator locations of parabolic cylindrical shells [31].

In this study, the spatially distributed actuation behavior of piezoelectric actuators on free paraboloidal membrane shells is investigated. The modal control force induced by an arbitrary piezoelectric actuator patch is derived and the microscopic actuation effectiveness is investigated by shrinking the actuator area into infinitesimal. Geometric parameter effects on the microscopic actuation efficiency are taken into account. Paraboloidal membrane shells with two different height-radius ratios, i.e., the shallow and the deep shell, are discussed respectively. Deep/shallow paraboloidal membrane shells with different thickness are also investigated to reveal the influence of shell rigidity on modal control actions.

2. Modal control of paraboloidal membrane shell structronic systems

In this section, the governing control equations of a generic paraboloidal structronic shell laminated with a piezoelectric actuator layer are derived. Expression of the modal control force on a paraboloidal shell is formulated by modal expansion method.

2.1. Modeling of piezoelectric laminated paraboloidal membrane shells

A structronic system is composed of sensor, actuator, control electronics and elastic structures. Fig. 1 illustrates a generic paraboloidal structronic shell, i.e., an elastic shell laminated with an actuator layer, defined in a tri-orthogonal global coordinate system - *XYZ*. The neutral surface of the elastic double-curvature shell is defined in a tri-orthogonal curvilinear coordinate system (ϕ, ψ, α_3) where ϕ defines the meridional direction, ψ the circumferential direction and α_3 the transverse direction. $d\phi$ denotes an infinitesimal angular change in the meridian direction and $d\psi$ denotes an infinitesimal angular change in the circumferential direction. Furthermore, ''a'' is the radial distance and ''c'' is the meridian height at the pole. The Lamé parameters are $A_1 = b/\cos^3\phi$ and $A_2 = (b\sin\phi)/\cos\phi$. The meridional radius of curvature is $R_\phi = b/\cos^3\phi$ and the circumferential radius is $R_\psi = b/\cos\phi$, where constant $b = a^2/2c = 2f$, and f is the focal length. The actuator layer, with thickness h^a, is perfectly bonded on the shell surface. It is assumed that the actuator is made of bi-axially sensitive piezoelectric material, such that a transverse control voltage can introduce two in-plane normal strains applied to distributed actuation and control of shells.

Considering that shallow and deep paraboloidal membrane shells have distinct curvatures and characteristics which are utilized in different aerospace structures and systems, a shallow and a deep paraboloidal shell with a set of distributed actuator patches laminated on its outer surface is shown in Fig. 2(a) and (b), respectively.

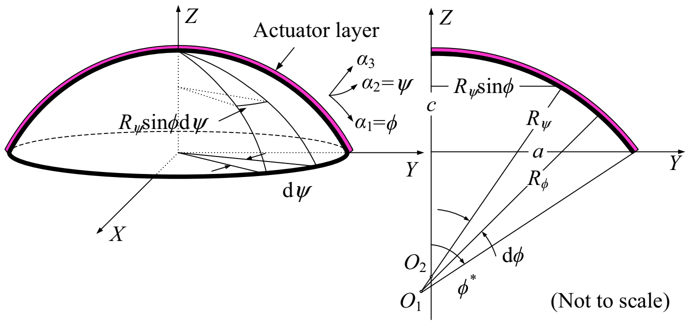

Fig. 1. A generic paraboloidal structronic shell with an actuator layer.