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Experiments on vibration control of a piezoelectric laminated paraboloidal shell

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

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ABSTRACT

A paraboloidal shell plays a key role in aerospace and optical structural systems applied to large optical reflector, communications antenna, rocket fairing, missile radome, etc. Due to the complexity of analytical procedures, an experimental study of active vibration control of a piezoelectric laminated paraboloidal shell by positive position feedback is carried out. Sixteen PVDF patches are laminated inside and outside of the shell, in which eight of them are used as sensors and eight as actuators to control the vibration of the first two natural modes. Lower natural frequencies and vibration modes of the paraboloidal shell are obtained via the frequency response function analysis by Modal VIEW software. A mathematical model of the control system is formulated by means of parameter identification. The first shell mode is controlled as well as coupled the first and second modes based on the positive position feedback (PPF) algorithm. To minimize the control energy consumption in orbit, an adaptive modal control method is developed in this study by using the PPF in laboratory experiments. The control system collects vibration signals from the piezoelectric sensors to identify location(s) of the largest vibration amplitudes and then select the best two from eight PVDF actuators to apply control forces so that the modal vibration suppression could be accomplished adaptively and effectively.

1. Introduction

Large optical reflector, communications antenna, rocket fairing, missile radome and other aerospace structures are typically made into the shape of thin-walled paraboloidal shells. To reduce the weight of the system, these structures are usually made of ultra-light and ultra-thin materials and therefore have generally low modal frequencies, small damping ratio and large flexibility. Since these kind of structures mainly work in outer space with scarcely any air resistance, their vibration endures once excited and this would not only jeopardize relevant instruments and equipment, but also lead to system or structural failures. Thus, in order to improve the performance and precision of the spacecraft, adaptive and active vibration control to the key structures are needed.

Since the piezoelectric effect was found by Jacques and Pierre Curie in 1880, piezoelectric materials have been used as sensors and actuators for plate and shell structures over the years. Bailey et al. [1] proposed the piezoelectric active damper in 1985. With distributed polyvinylidene fluoride (PVDF) piezoelectric film layers laminated on one side of a flexible

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* Corresponding author.
E-mail address: luyifanluyifan@126.com (Y. Lu).

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cantilever, the first modal damping ratio of the beam could be increased to 4.5 times. Also, it was investigated by Burke et al. [2] that vibration control could be achieved by changing the shape of PVDF actuators. A complete theory of distributed sensing and control of piezoelectric shells was presented by Tzou in 1988 [3]. Finite element method was employed combined with distributed sensing and control to analyze the dynamic performance of plate [4] and beam [5]. With piezoelectric lead zirconate titanate (PZT) ceramic and PVDF as patching on/ embedding in sensors and actuators, dynamic performance and theoretical model of piezoelectric structures were investigated and active damping control was achieved [6]. Tzou et al. carried out a multilayer actuator theory for distributed control of flexible shell structures [7]. With orthogonal winding piezoelectric sensors and actuators, Tzou developed a free modal control method for a flexible ring [8]. Relevant theories and applications of laminated composite cylindrical shells with sensor and actuator layers were discussed [9] and distributed piezoelectric elements were used to study the modal sensing performance of a rotational cylindrical shell [10]. A cylindrical shell controlled by completely/ partially distributed actuators and linear excitation was investigated [11,12]. Modal control force, excitation factor, feedback factor and control ratio of cylindrical shells with 4 distributed actuators under different deformation were studied [13]. Dynamic modeling and vibration control of spherical [14–16], composite spherical [17], conical [18] and toroidal [19,20] thin shell were also developed. Micro control and sensing action of smart structures was extended to nonlinear thick paraboloidal shell [21–23] by Tzou et al. The Newmark time integration method was used to calculate the dynamic response and negative velocity feedback control algorithm was used to control the dynamic response [24]. Dynamic modeling and active vibration control of a cylindrical shell with piezoelectric sensors and actuators was investigated [25]. The precision distributed control effectiveness of simple supported paraboloidal shells with laminated PVDF actuators was investigated [26]. Microscopic actuations of paraboloidal membrane shells and parabolic cylindrical shells were studied and optimal actuator locations were investigated [27,28].

Control methods and strategies are of importance to vibration control effectiveness. Although many modern control theories and strategies have been proposed in recent years, real-life engineering applications are still needed in practice. Positive position feedback (PPF) control, optimal control, fuzzy control, neural network control and adaptive filtering feedforward control are commonly used control strategies for current active vibration control. The PPF control method was introduced to control vibrations of large flexible space structures by Fanson and Caughey in 1985 [29]. It was applied by feeding the structural position coordinate directly to a compensator and then the product of the compensator and a scalar gain positively back to the structure. Neural network control was used in system identification and active control experiment. The result was compared with that of optimal control [30,31]. Adaptive neural network control was utilized in vibration control of flexible aerospace structure system where a back propagation (BP) algorithm and the stochastic optimization searching method were adopted [32]. An LMS (Least Mean Square) adaptive algorithm was applied to active vibration control of a broad band structure [33]. Directly adaptive algorithm [34], gain adjustment algorithm [35] and filtered-X-least mean square (LMS) algorithm [36] were studied respectively and employed in different structures. Nonlinear vibrations of laminated rectangular plates with free boundary conditions were discussed [37,38] and active control of a sandwich plate by collocated and the non-collocated PPF algorithm was developed respectively [39,40].

Due to the complexity of analytical procedures and unavailability of analytical solutions, this study focuses on an experimental study of the active modal vibration control of a flexible paraboloidal shell with free boundary conditions (BCs). Eight PVDF patches are laminated outside the shell as sensors and eight are inside as actuators to control the vibration of the first two shell modes. A parameter identification method is first used herein to establish the mathematical model of the control system. Controllers for the first order mode as well as the first and second order coupled mode of the paraboloidal shell are developed based on the positive position feedback (PPF) algorithm. Then, an experimental platform for adaptive modal control of precision paraboloidal shell is established and two from eight PVDF actuators could be selected by the control system to alleviate the oscillation caused by external excitations.

2. Positive position feedback control

Positive position feedback (PPF) was firstly proposed by Fanson and Caughey in 1982 and has been applied extensively to the low frequency vibrations of thin walled structures [29]. In the case of a second-order single-degree-of-freedom system, the modal displacement is processed by a second-order low-pass filter and, then, positively fed-back into the structure. The modal equations of the structure and the controller are respectively represented by

$$\ddot{\xi} + 2\zeta\omega\dot{\xi} + \omega^2\xi = \gamma\omega^2\eta \tag{1}$$

$$\ddot{\eta} + 2\zeta_c\omega_c\dot{\eta} + \omega_c^2\eta = \omega_c^2\xi \tag{2}$$

where ξ is the coordinate of the structure, η is the coordinate of the controller, ω and ω_c are the structural and controller natural frequencies, respectively. ζ and ζ_c are the structural and controller damping ratios, respectively. γ is a positive system scalar gain, i.e., $\gamma > 0$. The transfer function of the controller $C(s)$ becomes

$$C(s) = \frac{\gamma_c\omega_c^2}{s^2 + 2\zeta_c\omega_c s + \omega_c^2} \tag{3}$$

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