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Optimal locations and orientations of piezoelectric transducers on cylindrical shell based on gramians of contributed and undesired Rayleigh–Ritz modes using genetic algorithm

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ABSTRACT

In this study, the active vibration control and configurational optimization of a cylindrical shell are analyzed by using piezoelectric transducers. The piezoelectric patches are attached to the surface of the cylindrical shell. The Rayleigh–Ritz method is used for deriving dynamic modeling of cylindrical shell and piezoelectric sensors and actuators based on the Donnel–Mushtari shell theory. The major goal of this study is to find the optimal locations and orientations of piezoelectric sensors and actuators on the cylindrical shell. The optimization procedure is designed based on desired controllability and observability of each contributed and undesired mode. Further, in order to limit spillover effects, the residual modes are taken into consideration. The optimization variables are the positions and orientations of piezoelectric patches. Genetic algorithm is utilized to evaluate the optimal configurations. In this article, for improving the maximum power and capacity of actuators for amplitude depreciation of negative velocity feedback strategy, we have proposed a new control strategy, called "*Saturated Negative Velocity Feedback Rule* (SNVF)". The numerical results show that the optimization procedure is effective for vibration reduction, and specifically, by locating actuators and sensors in their optimal locations and orientations, the vibrations of cylindrical shell are suppressed more quickly.

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1. Introduction

Vibration reduction of structures is one of the most important challenges that many of researchers have paid attention to it in recent years. Active vibration control is one of the techniques that are used for decaying structural vibrations. Many materials, such as piezoelectric materials, shape memory alloys, electro-strictive materials, electro-magneto-strictive materials, electro- and magneto rheological fluids, etc, can be used for suppressing vibrations. The application of piezoelectric materials has become popular because of low weight, high strength, high stiffness, high frequency response, and easy implementation [1,2].

One of the most applicable structures is structural shells on which vibration control is important. For example, main structure of submarines and aircraft, pipelines, etc, are structures in which thin cylindrical shells are used. Salahifar and Mohareb [3] proposed a super-convergent finite element for the steady-state analysis of circular cylinders under general

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Nomenclature

$[A]$	system matrix
A_a, A_{se}	area of actuators and sensors
B^m, B^b	strain–displacement matrices
$[\hat{B}]$	control matrix
$c_{ij}^P, h_{ij}, \beta_{ij}$	elastic, coupling and dielectric permittivity constants of piezoelectric
$[\hat{C}]$	output matrix
D_x, D_θ, D_z	electric charge density components
E, v	Young's modulus and Poisson's ratio of structural material of shell
E_x, E_θ, E_z	electric field intensity components
G_c	gain of amplifier
G_{Con}	matrix of control gains
H, KE	potential energy and kinetic energy
h_P	thickness
H_r	matrix of eigenvectors
K_{Con}	matrix of control gains
K_S, K_P	stiffness matrices of cylindrical shell and piezoelectric patches
$[k_u]$	disturbance matrix
L_S, R	radial and length of shell
l_x, l_θ	length and width of piezoelectric patches
M_S, M_P	mass matrices of cylindrical shell and piezoelectric patches
N, N^{Re}	number of contributed and residual Rayleigh–Ritz modes
N_η	matrix of admissible shape functions
q_{se}, q_a	electrical generalized coordinates
r	generalized displacement vector
R_S^i, R_D^i	strain and electric charge density transformation matrices
R_τ	prescribed traction transformation matrix
$S_{xx}, S_{\theta\theta}, S_{x\theta}$	strain components
$T_{xx}, T_{\theta\theta}, T_{x\theta}$	stress components
t	time variable
u, v, w	axial, circumferential and radial mid-surface displacement
$\overline{u}$	vector of mid-surface displacements
V_a, V_{se}	external voltage applied to actuators and sensors
V_S, V_P	volumes of structure and piezoelectric patches
w_e	external work
$(W_1^C)^{ii}, (W_1^{Re})^{ii}$	energies that are required for controlling contributed and residual modes
$(W^{Co})^{ii}, (W^{Re})^{ii}$	maximum energy outputs from the $[\hat{C}] \in R^{N_s \times 2(N+N^R)}$th contributed and residual Rayleigh–Ritz mode
x, θ, z	axial, circumferential and radial coordinates
χ	state vector of control system
φ^{se}	open circuit sensor voltage
$\eta_{ij}^u, \eta_{ij}^v, \eta_{ij}^w$	mechanical generalized coordinates
κ_{se}	assembled matrix for sensor patches
Λ	diagonal matrix of eigenvalues
$\lambda, \tilde{\lambda}$	weighting constants of fitness functions
μ_a, μ_{se}	fitness functions
Θ_a, Θ_{se}	coupling matrices of actuators and sensors
ρ_S, ρ_P	mass densities of structure and piezoelectric patches
τ	prescribed traction
ω_i	natural frequency associated with ith contributed Rayleigh–Ritz mode
ω_i^{Re}	natural frequency associated with ith residual Rayleigh–Ritz mode
Ψ_a, Ψ_{se}	inverse of the capacitance matrices of actuators and sensors
ζ	damping ratio matrix

harmonic forces based on thin shell theory. Sainsbury and Masti [4] presented studies on the damping of right circular cylindrical shells that are partially coated with passive constrained viscoelastic patches. Callahan and Baruh [5] presented a symmetric modal analysis method to solve free vibration problem for a thin cylindrical shell. Jou et al [6] discussed the vibration and damping analysis of orthotropic cylindrical shells with a constrained layer damping. Static and dynamic analysis of cylindrical shells have been studied by Kumar et al. [7], Alibeigloo and Nouri [8], Saviz and Mohammadpourfard [9], Alibeigloo [10], etc.

One of the earliest researches in the field of active vibration control of cylindrical shells was related to the magnetic resonance image (MRI) equipment [11]. Kwak et al. [12] presented the dynamic modeling, active vibration controller design and experiments for a cylindrical shell equipped with piezoelectric sensors and actuators. Active vibration control of a cylindrical shell, partially covered with a laminated PVDF actuator (LPA) was studied by Zhang et al. [13]. In the previous works, the piezoelectric sensors and actuators were located in random locations. In fact, when the sensors were located at random locations, the modes under control were not observed properly. In the same way, when the actuators were located at random locations, the maximum mechanical energy could not be transmitted to those modes. Thus, the control methodology did not work properly. Li and Yang [14] initially offered exact solutions of the dynamic responses of a fully coupled hybrid piezoelastic cylindrical shell with piezoelectric shear actuators (PSAs), and then modeled an active vibration control for a simply-supported laminated cylindrical shell with piezoelectric shear sensor and actuator layers using negative velocity feedback control strategy. In this study, they did not establish constitutive relations for both the piezoelectric devices and the cylindrical shell. Yiqi and Yiming [15] analyzed the nonlinear dynamic response and active vibration control of a piezoelectric functionally graded plate.

In [7], a negative velocity feedback control algorithm was used to actively control the dynamic response of a structure. In design process of smart structures for obtaining a good control performance, such location of sensors and actuators are important. Therefore, the patches should be placed such that they could have the highest efficiency. So far various methods for finding the optimal location of piezoelectric patches have been proposed by researchers [16–18]. Qiu [19] developed an

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