



Vibration control of a cylindrical shell with concurrent active piezoelectric patches and passive cardboard liner

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ABSTRACT

This article extends a recent publication [MSSP (2016), 176–196] by developing a Rayleigh-Ritz model of a thin cylindrical shell to predict its response subject to concurrent active and passive damping treatments. These take the form of piezoelectric patches and a distributed cardboard liner, since the effects of such combined treatments are yet to be investigated. Furthermore, prior literature typically considers only the “bimorph” active patch configuration (with patches on the inner and outer shell surfaces), which is not feasible with an interior passive liner treatment. Therefore, a novel configuration—termed as “unimorph”—is proposed and included in the model. Experiments are performed on a shell with active patches (under harmonic excitation from 200 to 2000 Hz) in both the bimorph and unimorph configurations to provide evidence for the analytical model predictions. The proposed model is then employed to assess competing control system designs by examining local vs. global control schemes as well as considering several alternate active patch locations, both with and without the passive damping. Non-dimensional performance metrics are devised to facilitate comparisons of vibration attenuation among different designs. Finally, insertion loss values are measured under single-frequency excitation to evaluate several vibration control designs, and to compare the effects of alternate damping treatments.

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1. Introduction

In a recent article [1], the authors developed a semi-analytical model to predict the vibration of a thin cylindrical shell subject to a homogenous cardboard damping liner. The motivation for the prior paper was the lack of physics-based analytical studies, despite the common usage of such damping liners for noise reduction in automotive drive shafts [2–5]. Aside from these empirical or computational studies, few other publications exist for lined shell systems outside of the recent article [1] and an experimental study by Koruk et al. [6]. The chief goals of this companion article are to extend the prior article [1] by proposing a semi-analytical model for a thin cylindrical shell with concurrent active (piezoelectric patches) and passive (distributed cardboard liner) damping treatments. Given a practical need for exploring lightweight vibro-acoustic treatments for vehicle applications [2–6], this article aims to develop a mathematical framework for the evaluation of vibration control strategies.

Abbreviations: IL, insertion loss; RMS, root mean square; SPL, sound pressure level.

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Nomenclature

a	radius	κ	order of problem (full or reduced)
A	surface area (for integration)	ν	Poisson's ratio
$\mathbf{A}$	system matrix	Ξ	control transfer function
$\mathcal{A}$	accelerance	Π	performance metric
$\mathbf{B}$	input matrix	ρ	mass density per unit volume
c	viscous friction coefficient	ϕ	Rayleigh-Ritz shape function
$\mathbf{C}$	viscous damping matrix	φ	phase between disturbance and control
d_{ij}	piezoelectric coefficient	Φ	shape function vector
$\mathbf{d}$	control-to-disturbance vector	ψ^2	mean-square value
$\mathbf{D}$	control-to-disturbance matrix	ω	angular frequency [rad/s]
e	exponential constant		
E	Young's modulus	Subscripts	
f	frequency [Hz]	0	motion location
F	force	a	acoustic measurement location
h	layer thickness	c	piezoelectric (control) layer or input
I	electric current	d	disturbance input
j	imaginary number, $\sqrt{-1}$	i	counting index for layers and modes
$\mathbf{K}$	stiffness matrix	k	counting index for shape functions
l	length	L	cardboard liner
M	moment	m	modal index (in x direction)
$\mathbf{M}$	mass matrix	n	modal index (in θ direction)
N	number (patches, shape functions, etc.)	o	orthogonal shape function set
p	sound pressure	s	shape function
$\mathbf{Q}$	generalized force vector	–	integrated quantity (underbar)
$\mathbf{q}$	shape function weighting vector		
r	radial coordinate	Superscripts	
t	time	α	arbitrary motion type (transverse, etc.)
T	kinetic energy	u, v, w	shape functions for different motions
u, v	lateral displacements (in x, θ direction)	$\sim$	complex valued
$\mathbf{u}$	input vector (control or disturbance)	–	normalized or dimensionless (overbar)
U	potential (strain) energy	$\rightarrow$	vector (in space)
V	voltage	$*$	complex conjugate
w	transverse displacement	T	standard matrix transpose
W	power (mechanical, electric, etc.)	H	Hermitian transpose
x	axial coordinate, endpoint, or location		
X	axial shape function	Operators	
α	conditioning parameter for performance metric	$ \cdot $	absolute value or magnitude (for complex number)
γ	coherence	$\ \cdot\ $	surface-averaged RMS value
Δ	change or shift in value	$\angle$	argument (angle) of complex number
ε	normal strain	H	Heaviside (unit step) function
η	loss factor	δ	Dirac delta (unit impulse) function
θ	circumferential coordinate, endpoint, or location	δ'	derivative of Dirac delta function
Θ	circumferential shape function		

Active patches have been used extensively for vibration control of shells, e.g. by Sonti and Jones [7,8] and Chaudhry et al. [9], who proposed the analytical models to predict shell response due to patch input. These investigators typically assume an active patch on both the inside and outside shell surface, termed as the “bimorph” configuration. Other experimental work using active patches or distributed actuators includes publications by Fuller et al. [10], Han and Lee [11], and Bailey and Hubbard [12], for instance. There is also a significant body of literature on active vibration control systems, as evident from literature review by Cabell and Fuller [13] and Kwak et al. [14]. However, relatively fewer publications have addressed combined active and passive control methods for thin shells [15], though prior methods have considered the active constrained layer damping approach in-depth [16–18]. Nevertheless, combined (yet independent) active and passive damping treatments have attracted only limited attention. For example, studies were published on a beam and a thin plate by Lam et al. [19] and Plattenburg et al. [20], respectively, but no similar studies seem to exist for cylindrical shells in terms of concurrent active and passive damping. Based on the above mentioned voids in the literature, this article intends to develop a refined model (as an extension of prior work [1]), for the novel “unimorph” configuration, using a single active patch, that would modify the existing bimorph theory [7,9]. Experimental evidence of the model refinements will be included, and a few vibration control strategies will be discussed.

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