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Vibration reduction for smart periodic structures via periodic piezoelectric arrays with nonlinear interleaved-switched electronic networks

Bin Bao, Daniel Guyomar, Mickaël Lallart*

Univ. Lyon, INSA-LYON, LGEF, EA682, F-69621 Villeurbanne, France

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ABSTRACT

Smart periodic structures covered by periodically distributed piezoelectric patches have drawn more and more attention in recent years for wave propagation attenuation and corresponding structural vibration suppression. Since piezoelectric materials are special type of energy conversion materials that link mechanical characteristics with electrical characteristics, shunt circuits coupled with such materials play a key role in the wave propagation and/or vibration control performance in smart periodic structures. Conventional shunt circuit designs utilize resistive shunt (*R*-shunt) and resonant shunt (*RL*-shunt). More recently, semi-passive nonlinear approaches have also been developed for efficiently controlling the vibrations of such structures. In this paper, an innovative smart periodic beam structure with nonlinear interleaved-switched electric networks based on synchronized switching damping on inductor (SSDI) is proposed and investigated for vibration reduction and wave propagation attenuation. Different from locally resonant band gap mechanism forming narrow band gaps around the desired resonant frequencies, the proposed interleaved electrical networks can induce new broadly low-frequency stop bands and broaden primitive Bragg stop bands by virtue of unique interleaved electrical configurations and the SSDI technique which has the unique feature of realizing automatic impedance adaptation with a small inductance. Finite element modeling of a Timoshenko electromechanical beam structure is also presented for validating dispersion properties of the structure. Both theoretical and experimental results demonstrate that the proposed beam structure not only shows better vibration and wave propagation attenuation than the smart beam structure with independent switched networks, but also has technical simplicity of requiring only half of the number of switches than the independent switched network needs.

1. Introduction

A periodic structure is composed of an assembly of identical elements connected in a repeating pattern. Examples of such structures can be found in many practical applications. Typically, they include rods [1,2], beams [3,4] or plates [5,6]. Due to their periodic nature, these structures may exhibit particular dynamic characteristics that make them acting as mechanical

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* Corresponding author.
E-mail address: mickael.lallart@insa-lyon.fr (M. Lallart).

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Nomenclature

L	inductance
C_0	capacitance of the PZT
U	voltage on the PZT
U_{diff}	voltage difference between two PZTs
t_i	duration of the closed state of the switch connected to one PZT
t_{id}	duration of the closed state of the switch connected between two PZTs
Q_e	electrical quality factor of the switch connected to one PZT
Q_d	electrical quality factor of the switch connected between two PZTs
V_M	piezoelectric voltage of the PZT before the inversion process
V_m	piezoelectric voltage of the PZT after the inversion process
V_{Md}	voltage difference between two PZTs before the inversion process
V_{md}	voltage difference between two PZTs after the inversion process
γ	inversion coefficient of the switch connected to one PZT
γ_d	inversion coefficient of the switch connected between two PZTs
u	displacement of the structure
$\dot{u}$	velocity of the structure
M_k	dynamic mass
K_E	short-circuit stiffness
C_L	structural damping
α	force factor
F	external force
$C_{equivalent}$	equivalent capacitance of two PZTs
ω	angular frequency
u_M	amplitude of the displacement of one PZT on the structure
u_{Md}	amplitude of the displacement difference between the displacement of one PZT and the displacement of the other PZT on the structure
$h(t)$	crenel function
$I(t)$	current flowing through the switch connected to one PZT
$I_{diff}(t)$	current flowing through the switch between two PZTs on the structure
$g(\omega)$	sin (ωt) in the frequency domain
E_p^E	elastic moduli of the PZT in short circuit
Z	electrical impedance of the shunting network
k_{31}	electromechanical coupling coefficient
N_g	number of interleaved unit cells
N	number of primitive periodic cells
γ_0	transverse shear strain constant
Y_b	Young modulus of the substrate
ν_b	Poisson's ratio of the substrate
s^E	mechanical compliance tensor of the piezoelectric material under constant electric field
ε^T	electrical permittivity under constant stress
d_{31}	piezoelectric charge constant
E_3	electric field intensity along x_3 direction
D_3	electrical displacement along x_3 direction
σ	sign of the piezoelectric constant which depends on the polarization of the material
T_{b1}	longitudinal stress of the substrate
T_{p1}	longitudinal stress of the PZT
S_1	strain along x_1 direction
t_p	thickness of the PZT
t_b	thickness of the pure beam
$\phi(x)$	angle of rotation of the normal of the mid-surface of the beam
u_3	vertical deflection of the neutral axis in the x_3 direction
x_c	neutral axis
$\aleph$	Timoshenko shear coefficient
G	shear modulus
E_b	elastic modulus of the substrate
E_p	elastic modulus of the PZT
E_e	equivalent elastic modulus of the beam section with the PZT
$M_{bending}$	bending moment
w_W	width of the bending beam
I_b	second moment of area of the pure beam substrate's cross-section
I_p	second moment of area of the PZT's cross-section
I_e	equivalent second moment of area of the beam section with the PZT
I_s	$=I_b$ referring to the substrate section or $=I_e$ referring to the beam section with the PZT
U_s	strain energy
T_k	kinetic energy
W_e	work produced by the external transversal load
Q_s	shear force
l	length of minimal finite beam element
A_c	cross-sectional area of the substrate
ρ	mass density of the material
q,m	distributed forces and moments along the length l, respectively
Q	electric charge on one PZT
L_p	length of piezoelectric beam element
n	number of finite beam elements
$p_{1,2,3,4}$	signs of piezoelectric constant which depend on the direction of polarization of the piezoelectric patches 1,2,3,4 in the periodic cell

filters for traveling waves [7–10]. Specifically, waves can propagate over the surface of periodic structures within particular frequency bands called pass bands, and within other frequency regions called stop bands, propagative wave may be attenuated in amplitude and/or shifted in phase. The bandwidth and location of those pass bands/stop bands are influenced by properties such as periodic element length, stiffness, acoustic impedance ratio, Young's modulus ratio and thickness. When

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