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Interaction between two active structural paths for source mass motion control over mid-frequency range

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ABSTRACT

The interaction between two active structural paths is analytically and experimentally studied as part of a resonating source-path-receiver system, where each path consists of a piezoelectric stack actuator in series with an elastomeric (passive) mount. An analytical model of the system is first developed, and then an experiment is constructed to verify the feasibility. Good agreement is found between the model and experiment. A performance index to characterize the active path interaction for source mass motion control up to 1000 Hz is analytically defined; it considers the passive phase interaction (caused by system dynamics) between the active mounts and the resulting system motion. Two passive system parameters (rubber path structural damping and disturbance moment arm) emerge as key design variables that drastically change the performance index, and guidelines are developed for desirable path interactions. Limited experimental validation demonstrates that active source mass motion control is achieved at 400 Hz using piezoelectric stack actuators.

1. Introduction

Active mounts have been suggested for several engineering systems to primarily improve vibration isolation and resonance control, often with passive mounts used concurrently [1–13]. Conventional prime movers (e.g. automotive powertrains) generally have low frequency vibration excitations, and thus the primary mount function is to reduce the transmission of dynamic forces. Some recent hybrid electric powertrains also produce significant mid-frequency excitations (say from 100 to 1000 Hz) that amplify the source regime, creating significant structure-borne and radiated noise. Source mass motion control is thus needed to mitigate such unwanted noise [14–18]. Active mounts are still a viable solution, though different design perspectives need to be considered. In particular, the phase interaction (caused by passive system dynamics) between active mounts and the resulting system motion becomes more important as the frequency increases. This passive phase relationship may dictate the effectiveness of active control strategies (even at low frequencies), and it is the main thrust of this article.

Relevant literature on active vibration isolation focuses on control algorithms [1–13]. For instance, decentralized velocity control is studied in systems with multiple active mounts [1–7], though the active path interactions are not adequately addressed. Interactions among passive paths have been studied to some extent [19,20], but active paths are fundamentally different due to the applied force. Active path interactions are not of interest in single mount [8–11] or Stewart platform [12,13] applications, but such configurations may not be viable due to multi-axial forces or limited packaging space.

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Nomenclature

a	translational acceleration
A	constant coefficient for $\tilde{\Lambda}$
B	constant coefficient for $\tilde{\Lambda}$
c	viscous damping coefficient
C	constant coefficient for $\tilde{\Lambda}$
$\mathcal{C}$	matrix cofactor
$\mathbf{C}$	matrix of cofactors
d	disturbance moment arm
D	constant coefficient for $\tilde{\Lambda}$
E	constant coefficient for $\tilde{\Lambda}$
f	control force
F	control force amplitude
$\mathbf{F}$	control force vector
g	gravitational constant
H	dynamic compliance
$\mathbf{H}$	dynamic compliance matrix
i	square root of -1
I	mass moment of inertia
$\mathbf{I}$	identity matrix
k	stiffness
$\mathbf{K}$	stiffness matrix
ℓ	length
L	insertion loss
m	mass
$\mathcal{M}$	matrix minor
$\mathbf{M}$	inertia matrix
$\mathbf{O}$	null matrix
$\mathbf{q}$	generalized displacement vector
$\mathbf{Q}$	displacement amplitude vector
S	piezoelectric stack sensitivity
t	time
w	disturbance force
W	disturbance force amplitude
$\mathbf{W}$	disturbance force vector
x, y, z	Cartesian coordinates
α	constant value
β	phase corresponding to $\tilde{\Xi}$
ε	translational displacement
$\mathcal{E}$	translational displacement amplitude
η	loss factor
θ	rotational displacement
κ	dynamic stiffness
$\boldsymbol{\kappa}$	dynamic stiffness matrix
λ	ω^2
Λ	compliance numerator dynamics
ξ	translational displacement at mounts
Ξ	translational displacement amplitude at mounts
$\mathbf{\Pi}$	transformation matrix
ϕ	phase corresponding to $\tilde{f}$
χ	effectiveness of the control forces
Ψ	acceleration root mean square value
ω	circular frequency
Ω	resonance frequency
$\mathbf{\Omega}$	vector of resonance frequencies

Subscripts

$0,1,2,\ldots,n$	general indices
b	base
g	referenced to discrete inertia element coordinates
i	mount index
j	inertia index
m	mount
n	general index
$n \times n$	matrix of dimension (n, n)
r	receiver
s	source
t	transitional value
η	referenced to quadratic for transitional loss factor
λ	referenced to quartic for transitional frequency

Superscripts

a	after control forces are applied
b	before control forces are applied
B	referenced to constant $\tilde{B}_\lambda$
C	referenced to constant $\tilde{C}_\lambda$
D	referenced to constant $\tilde{D}_\lambda$
E	referenced to constant $\tilde{E}_\lambda$
T	transpose
x, y, z	referenced to Cartesian coordinates
$\dot{}$	$d(\ )/dt$
$\ddot{}$	$d^2(\ )/dt^2$
$\tilde{}$	complex valued
$\bar{}$	normalized parameter
$'$	relating to equations of motion formulation using mount displacements

Operators

$\lvert(\ )\rvert$	magnitude of complex number
$\angle()$	phase of complex number
$\langle\rangle_t$	time average
$\det(\ )$	determinant
$\mathrm{diag}(\ )$	diagonal matrix
$\mathrm{Im}\{\ \}$	imaginary part of a complex number
$\mathrm{Re}\{\ \}$	real part of a complex number

Reduction of mid-frequency structure-borne and radiated noise has been accomplished via active [14–18] and passive patches [21,22], reducing the structure surface velocity to minimize the radiated sound pressure or altering the radiating efficiency of the structure. Typically, the patches are bonded directly to the structure surface. Alternatively, active structural paths (mounts) could more effectively reduce the structure motion (and thus surface velocity).