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Active structural acoustic control of an elastic cylindrical shell coupled to a two-stage vibration isolation system

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ABSTRACT

An analytical study of active structural acoustic control of an elastic cylindrical shell coupled to a two-stage vibration isolation system is presented. An analytical active–passive model is developed in order to attenuate sound radiating from the base shell structure, which consists of a rigid-body machine, an intermediate rigid mass, and a supporting cylindrical shell, all connected by a combination of passive and active isolators. Various active control strategies are considered and the corresponding optimal control forces are formulated, including (a) minimizing the vibratory power transmitted to the foundation, (b) minimizing the structural kinetic energy of the supporting shell, (c) minimizing the sum of the square accelerations at the isolator locations on the supporting shell, and (d) minimizing the acoustic power radiated from the supporting shell. Numerical results are presented and discussed in detail. The control performance of all control strategies and system configurations are evaluated and compared in terms of acoustic power radiating from the supporting shell. The effects of key system parameters, i.e., the number and location of the actuators, and the fact that the output forces from the actuators are limited in engineering applications, are also considered and discussed. Finally, some concluding remarks and general design principles for the active control system are also discussed.

1. Introduction

Vibration isolation of vibrating machinery on foundation structures has received considerable attention due to its significant value in extensive engineering applications, such as civil engineering, aerospace applications, and marine applications (especially with regard to ships and submarines). As a coupled system, the dynamic characteristics of an isolation system are far more complex than that of a single structure. The technique of power flow analysis, which essentially combines force and velocity into a single quantity, provides an efficient means of analyzing vibration isolation systems. The fundamental concept of power flow was proposed by Goyder and White [1–3], who used the rate of power flow to characterize the dynamic response of beams and plates. Subsequently, power transmission into the foundation structure was gradually employed to estimate the performance of an isolation system [4–6]. The characteristics of power flow from a vibrating machine to a supporting thin panel were investigated by Pan [7]. Li et al. [8] developed a coupled model and used a cylindrical shell as the elastic foundation structure. The study shows that the cross couplings may become important if the vibration isolators are substantially hard as compared with the stiffness or impedance of the supporting flexible structure, although their contributions are usually insignificant.

With the development of vibration isolation technology and increasing requirement for control of vibration and noise level, it was found that two-stage isolation systems exhibit much better vibration isolation performance compared to conventional one-stage isolation systems [9–12], especially at high frequencies. Therefore, two- and even multi-stage isolation systems have received an increasing amount of attention [13]. The results show that a two-stage isolation system can significantly reduce the power flow from the vibrational machine into the foundation structure. They can also protect equipments sharing the same foundation structure from being impacted by each other. With these advantages, two-stage isolation systems have been widely used in engineering applications. In recent years, floating raft structures have been developed for ships and submarines as advanced isolation systems. These aim to isolate the vibrations of the hosts and auxiliary machines and effectively reduce the structurally radiated noise [14–16]. Equivalent mobility power flow progressive approach is developed by Xiong et al. [17] to investigate the power flow behavior of a complex coupled system, which could significantly reduce the complexity of power flow analysis of complex dynamic coupled system. Subsequently, this method is applied to a floating sandwich raft isolation system by Choi et al. [18] based on a higher-order theory. However, most of

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Nomenclature

∇	gradient operator
δ	Dirac delta function
η_s	modal loss factor of cylindrical shell
η_J	damping loss factor of Jth isolator
θ	circumferential cylindrical coordinate
κ	shell thickness parameter
λ_m	modified axial mode number
μ	Poisson ratio
ρ	density of the supporting shell material
ρ_0	density of air
ζ	modal shape
σ_J	location of Jth low-stage isolator on shell
ω	angular frequency
χ	identifying number of the axis the control actuator provides the restoring force
-1	reverse of a matrix
$\mathbf{a}_i'$	simplified matrix for $\mathbf{a}_i$
A^2	sum of square accelerations
$A^2_{\min}$	minimum value of the sum of square accelerations
A_{mn}	even modal amplitude in axial direction
A'_{mn}	odd modal amplitude in axial direction
$\mathbf{b}_i'$	simplified matrix for $\mathbf{b}_i$
B_{mn}	even modal amplitude in circumferential direction
B'_{mn}	odd modal amplitude in circumferential direction
c_0	speed of sound in air
C_{mn}	even modal amplitude in radial direction
C'_{mn}	odd modal amplitude in radial direction
$\mathbf{d}_{Ac}$	displacement vector of rigid machine
$\mathbf{d}_{Bc}$	displacement vector of intermediate rigid body
$\mathbf{d}_{DJ,t}$	displacement of top of Jth active isolator
$\mathbf{d}_{DJ,b}$	displacement of bottom of Jth up-layer active isolator
EJ,b	displacement of top of Jth low-layer active isolator
$\mathbf{d}_{EJ,t}$	displacement of bottom of Jth low-layer active isolator
E	Young's modulus
E_k	structural kinetic energy of the supporting shell
$E_{k,\min}$	minimum value of the structural kinetic energy
h	thickness of cylindrical shell
H	complex conjugate of a matrix
(i)	imaginary part of a matrix
k_0	wave number
$\mathbf{K}_{DJ}$	stiffness matrix of Jth up-stage isolator
$\mathbf{K}_{EJ}$	stiffness matrix of Jth low-stage isolator
L	length of the shell
L_1	number of up-stage isolators
L_2	number of low-stage isolators m,p axial mode number
M	total mass of the shell
n	circumferential mode number
$\mathbf{p}_i'$	simplified matrix for $\mathbf{p}_i$
P_0	power flow into the supporting shell
$P_{o,\min}$	minimum value of power flow
P_s	distributed force in axial direction
P_θ	distributed force in tangential direction
P_r	distributed force in radial direction
$\mathbf{q}_0$	harmonic driving force vector
$\mathbf{q}_{DJ}$	force from Jth up-stage isolator
$\mathbf{q}_D$	force vector consists of elastic forces from up-stage isolators
$\mathbf{q}_E$	force vector consists of elastic forces from low-stage isolators
$\mathbf{q}_{EJ}$	force from Jth low-stage isolator
$\mathbf{q}_{EJ,s}$	the force vector acting on the supporting shell from low-layer active isolator
(r)	real part of a matrix
R	radius of the mid-surface of the cylindrical shell
$\mathbf{R}_{ADJ}$	force location matrix on the rigid machine for Jth up-stage isolator
$\mathbf{R}_{BDJ}$	force location matrix on the intermediate rigid body for Jth up-stage isolator
$\mathbf{R}_{BEJ}$	force location matrix on the intermediate rigid body for Jth up-stage isolator
$\mathbf{R}_C$	modal vector matrix for isolators
s	nondimensional axial cylinder coordinate
Δs	surface area of element of the shell
t	time
T	transposition of a matrix
$\mathbf{T}_{EJ}$	transfer matrix of the point σ_J of shell from the Cartesian coordinate to cylindrical coordinate
u_s	displacement in s direction
$\mathbf{u}_{DJ}$	control force vector of Jth up-stage actuator
$\mathbf{u}_{EJ}$	control force vector of Jth low-stage actuator
$\mathbf{u}$	control force vectors composed of up and low-stage actuators
$\mathbf{u}_n$	control force vector composed of real and imaginary parts of u
$\mathbf{u}_s$	displacement vector at any point on the shell
$\mathbf{u}_{n,opt}$	optimum control vector from actuators
v_s	displacement in θ direction
w_i	weight matrix
w_s	displacement in radial direction
W	acoustic power radiated from the supporting shell
$W_{\min}$	minimum value of the acoustic power
$\mathbf{x}_s$	vector of mode
$\mathbf{Z}_{Ac}$	impedance matrix of rigid machine
$\mathbf{Z}_{Bc}$	impedance matrix of intermediate rigid body

the existing studies on these systems are confined to passive vibration isolating systems.

In order to meet increasingly strict vibration isolation requirements, active control techniques provide an efficient way to improve the performance of vibration isolation systems for its greater adaptive capacity. An active isolation system could dynamically adapt to the characteristic parameters of the system or structure. Pan and Hansen [19] presented a study on active control of power flow from a vibrating rigid-body to a flexible panel through two active isolators. Their results showed that an active isolation system presents a better performance than a simple passive elastic system acting alone over a wide frequency range. Howard et al. [20] presented an analytical model to discuss the maximum achievable reduction of power flow into a supporting cylindrical thin shell with passive and active isolators. However, the aforementioned studies on active vibration isolation were confined to one-stage isolation systems. Based on a two-stage isolation system, an innovative active–passive analytical model of a floating raft isolation system was developed by Niu et al. [21]. In the study, the control efficiencies of three control types (machine control, raft control and full control) are compared in terms of power flow into the supporting plate. A generalized integrated structure-control dynamical system was investigated by Xiong et al. [22]. In their study, an analytical solution was developed to predict the dynamic responses at any point or in substructures of the coupled system. Three active control strategies, including multiple channel absolute/relative velocity feedback controllers, an existing passive control system and their hybrid combination, are examined in terms of power transmission.