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Active force control of structure-borne sound based on robust optimization subjected to an irregular cavity with uncertainties

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ABSTRACT

This paper proposes a novel method of structure-borne sound analysis and active force control, which combines interval mathematics and robust optimization theorems, to achieve vibration damping and noise reduction for enclosed cavity systems with bounded uncertainty. By introducing the interference principle of sound wave, responses under control can be obtained by solving finite element equations of structural–acoustic coupling systems. Through synthetical considerations of parameter dispersion in practice, the interval quantitative model, which only needs limited sample data, is defined, and the interval Taylor extension approach is employed to further determine boundary rules of responses of structural vibration and acoustic noise. On this basis, a new interval-oriented robust optimization framework is established to seek the optimal secondary force to simultaneously minimize nominal and radius levels of sound pressure indexes at concerned space and frequency domains. A complicated engineering example of the 3-D bomb cavity is eventually presented, in which numerical and experimental results can demonstrate the usage, validity and effectiveness of the developed methodology.

1. Introduction

The vibro-acoustic coupling problem of the enclosed cavity/cabin has become an important issue in the design of aerospace craft [1–3]. Particularly for the military fighter, the high-level of vibration and noise may seriously affect the reliability of weapons and other equipment, and even lead to potential risks of sonic fatigue, structural fracture, stealth and missile ejection failure, etc. [4]. Therefore, it is of great significance to take interventions to suppress vibration and noise effects of such closed structures [2,5]. Currently, two main control strategies, called as the passive isolation and the active control, have been maturely developed. Compared to the operations of the passive control (it requires a great deal of damping material, which leads to a substantial increase in structural weight), the way of the active control can achieve better flexibility and economy. Consequently, active control techniques are becoming more and more popular in aerospace engineering [6,7].

Note that the main characteristic of the active control lies is the continuous external energy input that is applied to the real structure in accordance with the current state feedback [6,8]. Hence, tiny fluctuations in parameters may lead to significant deviations in the aspect of control effects, and may even directly cause system instability [9,10]. Indeed, the uncertain factors of controlled cavity structures are notable, impersonal and ubiquitous. In recent years, with the deep recognition of uncertainty analysis in structural mechanics, the robust optimization of active vibration control systems has aroused widespread public concern as well [11,12]. Singh [13] developed a robust optimization approach containing constraint matrices with uncertainties based on the general linear programming model. Sotiropoulos et al. [14] aimed at a nonlinear optimization problem with complex interval constraints, and a hybrid genetic algorithm was further proposed by the branch and bound method (a novel termination criterion based on the technique of shrinking search interval was adopted) to achieve global optimization. Liu et al. [15] proposed a new robust collaborative optimization (RCO) method by utilizing the policy of systematic uncertainty analysis (SUA). Its advantage lies in the higher-order moment descriptions for uncertain objective functions and constraints instead of the variation presentations in traditional RCO means. Hwang's [16] research aimed at performing robust design optimization by considering operational uncertainties to improve the performance of the coaxial rotor unmanned aerial vehicle that

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Nomenclature

Acronyms & abbreviations

DOF degree of freedom
FEM finite element method
min/max minimum/maximum value
UQ uncertainty quantification
coe the weight coefficient

Roman symbols

V volume of the fluid domain of the cavity
$p(x, y, z)$ continuous sound pressure at any location (x, y, z)
N_i structural shape function
p_i nodal sound pressure
j imaginary unit
$\boldsymbol{K_a}/\boldsymbol{M_a}/\boldsymbol{C_a}$ acoustic stiffness/mass/damping matrix
$\boldsymbol{F_a}$ acoustic excitation vector
$\boldsymbol{p}$ nodal sound pressure vector
$\boldsymbol{K_s}/\boldsymbol{M_s}/\boldsymbol{C_s}$ structural stiffness/mass/damping matrix
$\boldsymbol{F_s}$ structural excitation vector
$\boldsymbol{u}/u_i$ nodal displacement vector/value of any concerned point
$\boldsymbol{K_c}/\boldsymbol{M_c}$ the coupling stiffness/mass matrix
n_{se} number of coupling elements
$\{\boldsymbol{n^e}\}$ the normal vector of coupling elements
$\boldsymbol{N_a}/\boldsymbol{N_s}$ the shape function of acoustic/structural FEMs
$\boldsymbol{F_s^0}$ primary force vector (the excitation term)
$\boldsymbol{F_s^c}/F_s^c$ secondary force vector/ single secondary force
$\tilde{\boldsymbol{p}}/\tilde{p}_i$ sound pressure vector/value of any concerned point under control
$\boldsymbol{p}_0$ the sound pressure term imposed by the primary force $\boldsymbol{F_s^0}$
$\boldsymbol{p_c}$ the sound pressure term imposed by the primary force $\boldsymbol{F_s^c}$
$\boldsymbol{p_c}$ the sound pressure term imposed by the primary force $\boldsymbol{F_s^c}$
$E_{\tilde{p}}$ the total sound energy of the cavity
c the sound velocity
$F_{\min}/F_{\max}$ minimum/ maximum value of F_s^c
$g(\cdot)/h(\cdot)$ the inequality/equality constraint
$\boldsymbol{a}/\boldsymbol{b}$ deterministic/interval vector of characteristic variables
$\boldsymbol{x}/x$ any interval vector/variable
$\boldsymbol{x^I}/x^I$ vector of interval number/interval set
$\underline{\boldsymbol{x}}/\underline{x}$ lower bound of $\boldsymbol{x^I}/x^I$
$\bar{\boldsymbol{x}}/\bar{x}$ upper bound of $\boldsymbol{x^I}/x^I$
R the real domain
$\boldsymbol{x^c}/x^c$ the mean value of $\boldsymbol{x^I}/x^I$
$\Delta\boldsymbol{x}/\Delta x$ the radius value of $\boldsymbol{x^I}/x^I$
e_Δ standard interval set
$\boldsymbol{M}/\boldsymbol{M^I}$ any implementation matrix/interval matrix
$\underline{\boldsymbol{M}}/\overline{\boldsymbol{M}}$ lower/upper bound of $\boldsymbol{M^I}$
$\boldsymbol{M^c}/\Delta\boldsymbol{M}$ the mean/radius value of $\boldsymbol{M^I}$
m/m^* dimension of the interval vector $\boldsymbol{x}/\boldsymbol{b}$
$f(\boldsymbol{x})/f^I(\boldsymbol{x})$ universal response function/interval form of $f(\boldsymbol{x})$
$\underline{f}(\boldsymbol{x})/\overline{f}(\boldsymbol{x})$ lower/upper bound of $f^I(\boldsymbol{x})$
$\boldsymbol{U^I}(\boldsymbol{b})/\boldsymbol{P^I}(\boldsymbol{b})$ vector set of $u_i(\boldsymbol{b})/\tilde{p}_i(\boldsymbol{b})$
$\underline{\boldsymbol{U}}(\boldsymbol{b})/\overline{\boldsymbol{U}}(\boldsymbol{b})$ lower/upper bound of $\boldsymbol{U^I}(\boldsymbol{b})$
$\underline{\boldsymbol{P}}(\boldsymbol{b})/\overline{\boldsymbol{P}}(\boldsymbol{b})$ lower/upper bound of $\boldsymbol{P^I}(\boldsymbol{b})$
$\underline{u_i}(\boldsymbol{b})/\overline{u_i}(\boldsymbol{b})$ lower/upper bound of $u_i^I(\boldsymbol{b})$
$\underline{\tilde{p}_i}(\boldsymbol{b})/\overline{\tilde{p}_i}(\boldsymbol{b})$ lower/upper bound of $\tilde{p}_i^I(\boldsymbol{b})$
$\boldsymbol{P_r}(\boldsymbol{b})/\boldsymbol{P_y}(\boldsymbol{b})$ real/ imaginary component of $\boldsymbol{P}(\boldsymbol{b})$
$\underline{\boldsymbol{P_r}}(\boldsymbol{b})/\overline{\boldsymbol{P_r}}(\boldsymbol{b})$ lower/upper bound of $\boldsymbol{P_r}(\boldsymbol{b})$
$\underline{\boldsymbol{P_y}}(\boldsymbol{b})/\overline{\boldsymbol{P_y}}(\boldsymbol{b})$ lower/upper bound of $\boldsymbol{P_y}(\boldsymbol{b})$
s the collocation dimension
$C_R(\xi)$ the Chebyshev basis function
$\boldsymbol{v}(\boldsymbol{\Theta}, \omega)$ the undetermined coefficient matrix
N the polynomials order corresponding to $C_R(\xi)$
$T_i(b_l, \omega)$ the surrogate model based on the set collocation theory
$\tilde{\boldsymbol{v}}(\boldsymbol{\beta_l^{node}}, \omega)$ the subset of $\boldsymbol{v}(\boldsymbol{\Theta}, \omega)$
$\tilde{\boldsymbol{C}}(b_l)$ the vector of $C_R(b_l)$
$b_l^{\min}/b_l^{\max}$ value of b_l for $\underline{\tilde{p}_i}(\boldsymbol{b})/\overline{\tilde{p}_i}(\boldsymbol{b})$
b_l^* solution of $\partial T_i(b_l, \omega)/\partial b_l = 0$
$\boldsymbol{b^{\min}}/\boldsymbol{b^{\max}}$ the solution set of $b_l^{\min}/b_l^{\max}$
$\tilde{p}_i^c/\Delta\tilde{p}_i$ the mean/radius value of $\tilde{p}_i$
$F_{s_0}^c$ the initial control force
$F_{s_1}^c$ optimum force under deterministic control
$F_{s_2}^c/F_{s_3}^c$ optimum force under interval/random robust control

Greek symbols

$\Omega_e/\Omega_r/\Omega_a$ flexible/rigid/sound absorption boundary of the fluid domain
ω angular frequency
ρ_0 density of the fluid in the acoustic field
Ω_{se} coupling region
$\boldsymbol{\alpha}/\alpha_i$ any deterministic parametric vector/parameter
$\delta x_l/\delta\boldsymbol{x}$ small perturbation quantity/vector
Γ integral solution set for $\boldsymbol{u}(\boldsymbol{b})$ and $\tilde{\boldsymbol{p}}(\boldsymbol{b})$
β_l standard interval variable corresponding to b_l
$\beta_l^{(k)}$ k-th collocation sample of β_l
$\boldsymbol{\Theta}$ the integral sampling set
$\boldsymbol{\beta_l^{node}}$ the subset of collocation combinations
ξ the changing variable of $C_R(\xi)$
Ω_l the solution set $\{\underline{b}_l, \overline{b}_l, b_l^*\}$

Superscripts & subscripts

e, i, k, l, R counting indexes
$\boldsymbol{a}/\boldsymbol{s}$ acoustic/structural part
I interval
c/r mean/radius value
$\boldsymbol{y}/\boldsymbol{r}$ real/imaginary part
U uncontrol
IR interval robust control
D deterministic control
RR random robust control