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Design optimization of damping material-inlaid plates for vibration control

Jin-Xing Shi, Rei Hirano, Masatoshi Shimoda *

Department of Advanced Science and Technology, Toyota Technological Institute, 2-12-1 Hisakata, Tenpaku-ku, Nagoya, Aichi 468-8511, Japan

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A B S T R A C T

Inlay structures composed of matrix and inlaid materials can be applied for vibration control in engineering structures, especially when the inlaid material has high damping property. In this work, we develop a shape optimization method of damping material-inlaid plates considering a frequency response problem in forced vibration. The squared displacement error norm of a designated evaluation point is used as the objective function and is minimized under an area constraint. In the shape optimization process, we carry out frequency response analysis to calculate shape gradient function, and then use the shape gradient functions in velocity analysis to update the shape or position of the inlaid material based on the H^1 gradient method. This process is repeated for determining the optimal shape or position of the inlaid material. The optimal results of numerical examples showed that the developed design optimization method of inlay structures could significantly reduce the squared displacement error norm of an arbitrary designated evaluation point at an arbitrary specific frequency.

1. Introduction

Inlay structures composed of matrix and inlaid materials were originally used in artworks based on the respect of the historic climate, e.g., wooden inlay bookcase cabinet [1] and Turquosie-inlaid Bronze sword [2]. As composite structures, inlay structures can perform more excellent behaviors by combining different properties of matrix and inlaid materials than a single matrix material. In recent decades, along with the development of the overall performance of microprocessors, Al-based interconnects have been replaced by inlaid Cu for electromigration (EM)-induced degradation, because the higher conductivity of Cu can improve the EM performance of interconnects [3–5]. Moreover, considering the different mechanical properties of the matrix and inlaid materials, inlay structures may also have potential applications in engineering structures to produce specific mechanical behaviors [6].

Vibration is such a mechanical behavior that deserves to be studied concerning inlay structures. In most cases, vibration of engineering structures is undesirable because it reduces efficiency, wastes energy, and even be harmful to human beings. Therefore, vibration control approaches are required in the dynamics analysis of engineering structures [7–10], and lead to frequency response problems [11]. Based on experiments or theoretical analysis, vibration damping of composite structures were investigated in some works [12–18]. Botelho et al. [12] investigated damping behaviors of fiber/metal composite materials by free vibration damping test. Bowyer and Krylov [14] studied vibration damping in glass fiber composite plates and panels containing acoustic black holes. Bae et al. [16] designed and fabricated a metal-composite hybrid wheel inlaid with a friction damping layer for enhancing the damping capacity and ride comfort. In particular, by inlaying high damping alloy in steel plates, Kanaya et al. [18] studied the structural damping behaviors of the inlay structures, and clarified the effects of inlaid position of the high damping alloy in the first vibration mode based on finite element method (FEM) and vibration test.

Up to now, design optimization plays an important role for vibration control of continua in frequency response problems. Ma et al. [11] developed an extended homogenization method for optimizing the layout and the reinforcement of an elastic structure in a frequency response problem. Shu et al. [19] performed a topology optimization for minimizing frequency response of continua based on the level set method. However, with regard to level set-based topology optimization of multiple materials, because there is no node exists on the boundary between dissimilar materials, it is difficult to evaluate the stress concentration at the interface boundary [20]. Hereby, a node-based optimization method is preferred for designing inlay structures. For optimal design of composite structures considering damping behaviors, there are also some works have been published [21–25]. Ansari et al. [21] proposed a novel

* Corresponding author.
E-mail address: shimoda@toyota-ti.ac.jp (M. Shimoda).

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Nomenclature

$(\bar{\bullet})$ variation
$(\bullet)' = (\dot{\bullet}) - (\bullet)_{,i}V_i$ shape derivative
$(\dot{\bullet})$ material derivative
$(\bullet)_{,i} = \partial(\bullet)/\partial x_i$ partial differential notation
$a^{\lambda}(\cdot,\cdot)\,(\lambda = A, B)$ virtual work in terms of rigidity
$b^{\lambda}(\cdot,\cdot)\,(\lambda = A, B)$ virtual work in terms of inertia
$\left\{C^{M}_{\alpha\beta\gamma\delta}\right\}(\alpha,\beta,\gamma,\delta = 1,2)$ elastic tensor with respect to the bending moment
$\left\{C^{N}_{\alpha\beta\gamma\delta}\right\}(\alpha,\beta,\gamma,\delta = 1,2)$ elastic tensor with respect to the membrane force
$\left\{C^{Q}_{\alpha\beta}\right\}(\alpha,\beta = 1,2)$ elastic tensor with respect to the shear force
C_{Θ} admissible function space satisfying the constraints of shape variation
$d(\cdot,\cdot)$ squared displacement error norm
F external force
$\boldsymbol{G}$ shape gradient function
G_{Γ}, G_D shape gradient density functions
$h^{\lambda}(\cdot,\cdot)\,(\lambda = A, B)$ virtual work of the traction on Γ_{AB}
$H^1(S)$ Sobolev space of order 1
I moment of inertia
j unit imaginary number
k shear correction factor
$l(\cdot)$ virtual work in terms of external load
L Lagrangian functional
$\boldsymbol{M} = \{M_\alpha\}\,(\alpha = 1,2)$ bending moment
$\boldsymbol{N} = \{N_\alpha\}\,(\alpha = 1,2)$ in-plane force
$\boldsymbol{n}^{\lambda} = \{n^{\lambda}_{\alpha}\}\,(\lambda = A, B)\,(\alpha = 1,2)$ unit in-plane normal vector of material λ
Q shear force
$\mathrm{Re}[\cdot]$ real part of the complex number
s iteration history of shape variation
S mid-plane of the inlay plate
S_s mid-plane of the inlay plate after shape variation
$S^{\lambda}\,(\lambda = A, B)$ mid-plane of material λ
$S^{\lambda}_{s}\,(\lambda = A, B)$ mid-plane of material λ after shape variation
S_D designated evaluation point
$\hat{S}$ area constraint value of material B
S^B_0 initial area of material B
t thickness of the inlay plate
$\boldsymbol{u} = \{u_i\}\,(i = 1,2,3)$ displacement vector
$\boldsymbol{u}_0 = \{u_{0\alpha}\}\,(\alpha = 1,2)$ in-plane displacement vector
U admissible function space satisfying the Dirichlet boundary conditions
$\boldsymbol{V} = \{V_n\}\,(n = 1,2,3)$ design velocity field
$\boldsymbol{V}_0 = \{V_{0\alpha}\}\,(\alpha = 1,2)$ in-plane design velocity field
V_3 out-of-plane design velocity field
w out-of-plane displacement
$\hat{w}$ target out-of-plane displacement
(x_1, x_2, x_3) local coordinate system
(X_1, X_2, X_3) global coordinate system
$\boldsymbol{X}$ position vector in global coordinate system
$\boldsymbol{X}_s$ position vector in global coordinate system after shape variation
$\mathbb{R}$ a set of real numbers
χ damping ratio
ε a small positive number
$\{\gamma_\alpha\}(\alpha = 1,2)$ shear strain vector
κ curvature of Γ^{g}_{s}
$\kappa^{\lambda}\,(\lambda = A, B)$ curvature of Γ^{λ}
$\boldsymbol{\theta} = \{\theta_\alpha\}(\alpha = 1,2)$ rotation angle vector
$\rho^{\lambda}\,(\lambda = A, B)$ density of material λ
ω angular frequency
Δs an infinitesimal amount
Γ boundary of S
Γ_s boundary of S_s
$\Gamma^{\lambda}\,(\lambda = A, B)$ boundary of material λ
$\Gamma^{\lambda}_{s}\,(\lambda = A, B)$ boundary of materials λ after shape variation
Γ^{g} boundary subjected to external forces and moments
Γ^{g}_{s} boundary subjected to external forces and moments after shape variation
Λ Lagrange multiplier of area constraint
Ω domain of the inlay plate

level set method to optimize both the shape and location of the damping patches on plate structures simultaneously with minimum usage of the constrained layer damping patches. Kameyama and Arai [22] clarified the damping behaviors of symmetrically laminated plates using theoretical analysis, and proposed a lay-up optimization method of the laminated plates for damping behaviors. Hamdaoui et al. [23] presented an optimal design approach for a sandwich beam by choosing the most suitable material for high damping and low mass. Based on a posteriori approach, Kalantari et al. [24] presented a multi-objective robust optimization of carbon/glass fiber reinforced hybrid composites under flexural loading. However, few works in terms of design optimization for vibration control of inlay structures in frequency response problems can be found.

Using the H^1 gradient method, which is a node-based optimization method, Wu et al. [25] carried out shape design optimization of linear elastic continua considering viscous damping in frequency response problems. In a previous study, we utilized this optimization method to design the interface shapes of sandwich structures in terms of the compliance minimization problem [26]. In this study, we aim to extend this optimization method for designing inlay plates in order to reduce the amplitude of vibration at specific frequencies. The rest of this work is organized as follows. In Section 2, we derive the governing equation of plate structures in a frequency response problem. Shape variation and formulation of the frequency response problem concerning inlay plates are introduced in Section 3. In Section 4, we develop the shape optimization method for designing inlay plates in the frequency response problem, and present the schematic of shape optimization

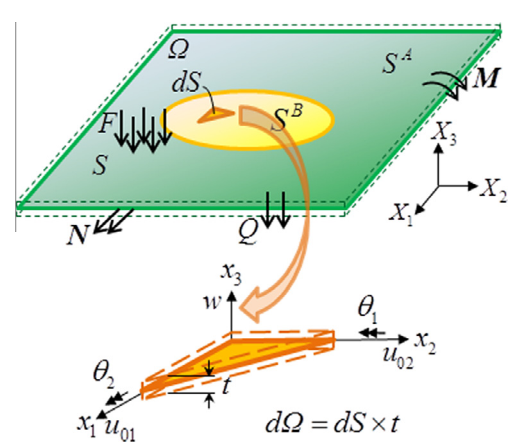

Fig. 1. Schematic diagram of an inlay plate.