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Topology optimization of damping material for reducing resonance response based on complex dynamic compliance

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A B S T R A C T

In this research, we propose a new objective function for optimizing damping materials to reduce the resonance peak response in the frequency response problem, which cannot be achieved using existing criteria. The dynamic compliance in the frequency response problem is formulated as the scalar product of the conjugate transpose of the amplitude vector and the force vector of the loading nodes. The proposed objective function methodology is implemented using the common solid isotropic material with penalization (SIMP) method for topology optimization. The optimization problem is formulated as maximizing the complex part of the proposed complex dynamic compliance under a volume constraint. 2D and 3D numerical examples of optimizing the distribution of the damping material on the host structure are provided to illustrate the validity and utility of the proposed methodology. In these numerical studies, the proposed objective function worked well for reducing the response peak in both lower and upper excitation frequencies around the resonance. By adjusting the excitation frequency, multi-resonance peak reduction may be achieved with a single frequency excitation optimization.

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1. Introduction

Suppressing vibrations is one of the most important performance factors for mechanical devices subject to dynamic forces. Using damping materials is an important solution for this issue, and is especially effective for reducing the response peak. For example, sheet-like damping materials are often laid over metal plates in vehicle bodies to reduce the response to external loads. However, increasing the amount of damping material reduces the cost-effectiveness and increases the weight of the devices. Thus, there is growing demand for optimizing the shape and layout of damping materials.

Various methodologies for optimizing damping materials have been proposed. One of the early works on such optimization is the theoretical and experimental study of damping material layout for plates and beams by Plunkett and Lee [1].

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Numerical analysis, such as the finite element method (FEM), has been introduced for accurate analysis and detailed optimization in recent research. Chen and Huang [2] studied location and thickness optimization for damping materials based on a topographical optimization method. Zheng et al. [3] also studied location and thickness optimization for damping materials using a genetic algorithm. They extended this methodology to optimization of damping material layout on cylindrical shells [4]. Although these researches are limited to location optimization for a fixed shape of the damping material, some papers have studied distribution optimization of damping materials. Alvelid [5] proposed an original gradient-based method, while Chia et al. [6] used cellular automata to study this issue.

Topology optimization (TO) [7,8] is a methodology that achieves detailed optimization of device shapes, and has led to significant improvements in vibration characteristics of structures. Both maximization of the eigenfrequency [9–12] and reduction of the response in the frequency response problem [13–16] have been studied. However, these studies ignore the damping effect, whereas an optimization methodology for damping material distribution on a host plate has recently been proposed. Ling et al. [17] developed an optimization to maximize the modal loss factor based on eigenfrequency analysis. Kang et al. [18] proposed an optimization methodology based on frequency response analysis. They also extended their work to simultaneous optimization of the damping and host layers [19]. An experimental verification of these works has also been reported [20]. Fang and Zheng [21] studied the effect of modal sensitivity analysis on optimization of the damping material. Moreover, TO has been further extended to transient response optimization [22] and mode shape optimization [23,24].

Of these approaches, we focus on frequency response-based optimization, which is more straightforward than the eigenfrequency-based method when the excitation frequency can be predicted. A typical objective function proposed in previous research is minimization of the amplitude of the loading domain [18,19,21]. However, in actual mechanical design, the damping material is usually used to reduce the response peak at resonance near the excitation frequency rather than the response under the specified single frequency. Because the response amplitude is decided by the mutual effect of the mass, stiffness and damping of the vibration system while the response peak is affected only by damping in theory, the optimal solution obtained from this objective function will not always work well for peak reduction. Thus, an alternative criterion for the damping effect that can be used as an objective function in the peak reduction design problem is required.

On the other hand, the dynamic compliance proposed by Ma et al. [13,16,25], which was originally the scalar product of the force and amplitude vectors, is an effective objective function for optimization of non-damped structures. The advantage of dynamic compliance is that its sensitivity can be calculated without solving the adjoint equation as with static compliance [8]. Jog [26] re-defined dynamic compliance as the energy dissipated per cycle through damping. Although peak reduction optimization was not studied in this paper, the objective function can be used for this issue because it directly represents the damping effect.

Based on this research, we introduce a new objective function for optimizing damping material distribution on a host structure in peak reduction optimization by extending the original dynamic compliance into complex space. This paper is organized as follows. The complex dynamic compliance is first formulated as a criterion for the damping effect based on a discrete vibration system subject to a dynamic force. The proposed objective function is implemented using the solid isotropic material with penalization (SIMP) method for TO. The relationship between the physical properties of the material and the density function is defined. The optimization problem is then formulated as maximizing the complex part of the proposed complex dynamic compliance under a volume constraint. The optimization algorithm is constructed using the method of moving asymptotes (MMA) [27] as an optimizer. We finally provide 2D and 3D numerical examples to illustrate the validity and utility of the proposed methodology.

2. Criteria for damping effect

2.1. Design objective

Let us consider a vibration problem involving a thin plate structure composed of a host layer Ω_h and a damping layer Ω_d as shown in Fig. 1. The design target is optimal distribution of the damping materials in a damping layer on the fixed host layer. The damping and host layers are modeled as damped and undamped linear elastic bodies, respectively. The hysteretic damping model is introduced for the damping material. Thus, the stiffness of the material E_d including the damping effect is

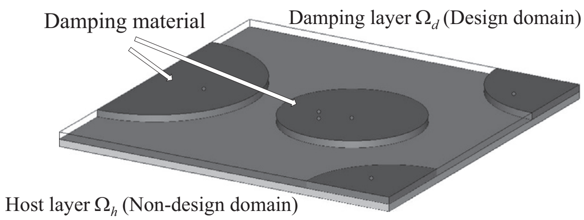

Fig. 1. An outline of the design target structure composed of the damping and host layers.

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