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Topology optimization of viscoelastic damping layers for attenuating transient response of shell structures

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ABSTRACT

This paper presents topology optimization of viscoelastic damping layers attached to shell structures for attenuating the amplitude of transient response under dynamic loads. The transient response is evaluated using an implicit time integration scheme. Dynamic performance indices are defined to measure the transient response. In the optimization formulation, three different types of the performance indices are considered as the objective function. The density-based topology optimization scheme is applied to find the optimal distribution of the viscoelastic material. The artificial densities of the shell elements of the viscoelastic layers are taken as the design variables. The constraint is the maximum volume fraction of the viscoelastic material. A sensitivity analysis method of the transient response is developed based on the adjoint variable method. Several numerical examples are presented to demonstrate the validity of the proposed method. The transient responses of the optimized structures are compared to those of the uniformly distributed structures to show the effectiveness of the proposed method. Also, the influences of the performance indices are discussed.

1. Introduction

Shell structures are widely used in civil, automotive and aerospace engineering applications. The structures are often excited by dynamic loadings such as impact, shock and seismic loadings. In general, the shell structures are thin and light. Therefore, the dynamic loadings cause severe undesired vibrations, which may lead to the considerable noise level, discomfort and damage of machines. Thus, the vibration control becomes crucial in designing shell structures. For the vibration control, passive damping treatment has been widely applied to attenuate the structural vibration. The passive method generally utilizes viscoelastic materials due to its simple implementation, low cost and relatively high damping capability. For the shell structures, a viscoelastic layer is attached to the base shell structure to provide damping capability against its vibration. However, a full-coverage damping treatment is not practical since it may add excessive mass to the base shell structure. Therefore, it can be achieved by partially covering the damping layer as patch-forms. The schematic illustration of the viscoelastically damped shell structure is shown in Fig. 1, which consists of the partially covered viscoelastic layer and the base shell structure. In order to find the best layout of the viscoelastic layer, the design problem may be formulated as a topology optimization problem.

Topology optimization is regarded as a powerful tool for developing novel conceptual designs. Since its introduction by Bendsøe and Kikuchi [1], topology optimization has also been applied to the design of damped structures e.g., rubber isolators [2], multi-material design [3,4], microstructure design [5,6], etc. In addition, it has been used in designing damped shell structures. Kim et al. [7] proposed a topology optimization approach to design optimal damping layouts for suppressing the resonance vibration of shell structures. The optimized damping layouts are also experimentally validated. Kang et al. [8] studied the optimal distribution of damping material of shell structures under harmonic excitations. This work was extended to simultaneous optimization of the damping and the host layers [9]. Topology optimization for minimizing sound radiation of shell structures was presented in Refs. [10,11].

The above-mentioned studies mainly focused on frequency responses of damped structures. However, transient responses should be considered when structures are excited by a suddenly applied loading. The topology optimization for time domain response has been also studied by many researchers [12]. Min et al. [13] developed a topology optimization approach to minimizing the dynamic compliance of elastic structures under dynamic loads. Zhao and Wang [14] investigated the model reduction method for the computational efficiency in dynamic response topology optimization problems. Dahl et al. [15] proposed a topology optimization method for structural wave propagation based on the transient response analysis. The equivalent static load (ESL) method was proposed by Refs. [16,17] for topology optimization in dynamic

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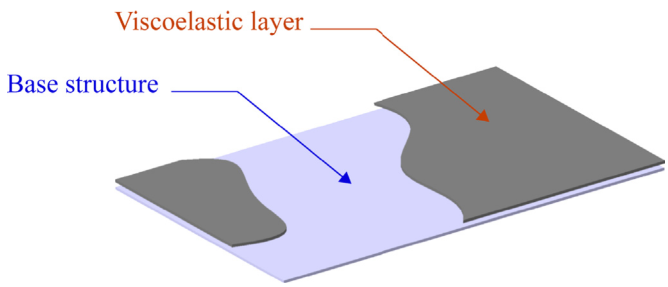

Fig. 1. Schematic illustration of shell structure with partially covered viscoelastic layer.

problems. Nakshatrala and Tortorelli studied topology optimization of elastoplastic systems [18] and multi-scale topology optimization [19]. Le et al. [20] studied topology optimization of material microstructure design for linear elastodynamic energy management. Yan et al. [21] studied optimal topology design of damped plate structures subjected to initial excitations. Also, the active vibration control of shell structures with piezoelectric actuators was proposed in Ref. [22].

The above studies of topology optimization for transient response consider only viscous damping. The viscous damping depends on the instantaneous velocity only. However, the viscous damping is rarely physically present in many dynamic systems [23]. Therefore, the viscoelastic damping, also referred to as non-viscous damping, should be considered in viscoelastically damped structures. There are few studies on the topology optimization of structures including viscoelastic material based on time domain analysis. James and Waisman [24] proposed a topology optimization approach considering creep deformation of the viscoelastic material to improve long-term structural performance. More recently, Yun and Youn [25] proposed a multi-material topology optimization approach of viscoelastically damped structures under time-dependent loading. These two studies only considered quasi-static responses while ignoring the dynamic or inertia effects.

This paper presents a topology optimization approach for designing viscoelastically damped shell structures subjected to dynamic loads. There have been no previous works that have dealt this problem in a systematic way. The shell structures are discretized with finite elements, and the transient response is evaluated using an implicit time integration scheme. Three different kinds of dynamic performance indices are defined to measure the transient response over a specified time interval. The optimization problem is formulated to find the optimal material distribution of the viscoelastic damping layer for minimizing the performance indices.

The remainder of this paper is organized as follows; in Section 2, the viscoelasticity and the transient response analysis are introduced. The finite element formulation and time integration scheme are presented. In Section 3, dynamic performance indices are defined. Then, topology optimization problem is formulated based on the density approach. The sensitivity analysis procedure is also presented. In Section 4, several numerical examples are presented, and the optimized results are discussed. Finally, concluding remarks are provided in Section 5.

2. Structural transient response analysis

2.1. Constitutive equation for the viscoelastic material

Viscoelastic materials exhibit both viscous and elastic characteristics. From the Boltzmann superposition principle [26], the uniaxial isothermal stress-strain relation for the viscoelastic material is given by

$$\sigma(t) = \int_0^t E(t-s)\frac{\partial \varepsilon(s)}{\partial s}ds, \tag{1}$$

where s denotes any arbitrary time between time 0 and t. This relation implies that the response of the material is influenced by the past history of motion. The time dependent relaxation modulus $E(t)$ is modeled using an analogy with the combinations of spring elements (for elasticity) and dashpots (for viscosity). There are large number combinations of springs and dashpots. Among them, the relaxation modulus is typically modeled by the generalized Maxwell model as illustrated in Fig. 2. The model consists of m different Maxwell elements (spring-dashpot elements) and a spring element arranged in parallel. The spring constants are denoted by E_∞ and E_j, and the viscosity in the dashpot is given by η_j. Defining the relaxation time of each Maxwell element as $\tau_j = \eta_j/E_j$, the relaxation modulus $E(t)$ is mathematically represented by using Prony series expansions as follows:

$$E(t) = E_\infty + \sum_{j=1}^{m} E_j e^{-t/\tau_j}. \tag{2}$$

The number of terms in the Prony series m is selected by designers to fit the material relaxation test data.

In the same manner as the uniaxial relationship, the constitutive equation for the three-dimensional case is defined as

$$\boldsymbol{\sigma}(t) = \int_0^t \mathbf{C}(t-s)\frac{\partial \boldsymbol{\varepsilon}(s)}{\partial s}ds, \tag{3}$$

where $\mathbf{C}(t)$ is the three dimensional constitutive matrix for the viscoelastic material. For the isotropic viscoelastic material assuming a constant Poisson's ratio, the constitutive equation becomes

$$\boldsymbol{\sigma}(t) = \mathbf{C}_\mathrm{V}\int_0^t g(t-s)\frac{\partial \boldsymbol{\varepsilon}(s)}{\partial s}ds, \tag{4}$$

where $\mathbf{C}_\mathrm{V}$ is the purely elastic constitutive matrix of the long term modulus E_∞ and the Poisson's ratio ν. The normalized relaxation modulus $g(t)$ (i.e., $g(t) = E(t)/E_\infty$) is defined as

$$g(t) = 1 + \sum_{j=1}^{m} g_j e^{-t/\tau_j}. \tag{5}$$

2.2. Transient response finite element analysis – spatial discretization

The damped shell structure is discretized with two-layered shell elements as shown in Fig. 3. The finite element nodes are placed on the reference surface, which is a boundary between the viscoelastic layer and the base structure. Then the mass matrix and the stiffness matrix can be obtained by combining the matrices of each layer.

The element mass matrices of both the structural material and the viscoelastic material are defined as

$$\mathbf{M}_\mathrm{S}^e = \int_{\Omega_e}\rho_\mathrm{S}\mathbf{N}^\mathrm{T}\mathbf{N}dV \text{ and } \mathbf{M}_\mathrm{V}^e = \int_{\Omega_e}\rho_\mathrm{V}\mathbf{N}^\mathrm{T}\mathbf{N}dV, \tag{6}$$

where ρ is the material density and $\mathbf{N}$ is the shape function matrix. Then,

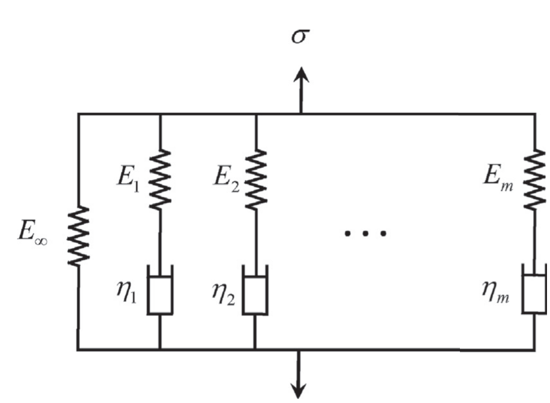

Fig. 2. Generalized Maxwell model.