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Topology optimization of passive constrained layer damping on plates with respect to noise control

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Abstract. The square of normal surface velocity of a thin plate with a harmonic excitation is minimized by optimizing the topologies of attached passive constrained layer damping (PCLD) treatments. An extended solid isotropic material with penalization model for topology optimization is introduced based on a simple interface finite element modeling for viscoelastic layer of PCLD patch. For the purpose of illustrating the proposed method, a clamped square plate is used in the numerical study. Significant reductions of the objective functions are achieved by the optimal distributions.

Introduction

The decrease of sound radiation of the structures, such as machines, vehicles and domestic appliances, is gaining attention everyday as noise regulations around the world are getting stricter. Many of these structures involve thin plates or shells and these thin wall structures are always the main noise sources because of their small damping, low stiffness and large radiation surfaces. Continues efforts have been made to handle the problem, among of which passive constrained layer damping (PCLD) technology, utilized a high loss factor viscoelastic layer with its both sides constrained on by two stiff layers, has been widely used to reduce vibration and sound radiation levels of thin wall structures. Nowadays, it is very common for automakers to add PCLD patches to the structures like oil pans, front covers, valve covers, etc. to achieve low noise design. As the weight often plays a key role in the performance and cost in the product, it is essential to know where to place the PCLD patches in order to get the most reduction of sound radiation with a limited coverage rate.

During recent years, extensive efforts have been exerted to optimum design of PCLD patches, resulting in a large number of studies in the field. Lall et al. [1] carried out optimum design studies for the parameters of viscoelastic materials, e.g. the densities, thicknesses, and temperature, of a fully PCLD covered plate with objective functions as maximizing modal loss factor and minimizing displacement response. Marcelin et al. [2] used finite element method (FEM) and genetic algorithm (GA) to maximize the damping factor of a partially covered beam. The design variables were the dimensions and locations of the patches. Zheng et al. [3] studied the optimal layout of PCLD patches on a beam for minimizing vibration energy based on an analytical model and extended the work to a cylindrical shell then [4]. Alvelid [5] suggested a shape optimization method by adding the PCLD to the base structure piece by piece at permissible positions in a mosaique manner with the objective function as minimizing the square of the normal surface velocity (SNSV) of base structure.

The topology optimization can be thought of as how to redistribute the material in order to minimize/maximize the objective function for a given set of loads and boundary conditions. The idea of using topology optimization to design continuum structures was first introduced about twenty years ago by Bendsøe and Kikuchi [6] for minimizing the compliance of two-dimensional structure using a homogenization method. However, work on topology optimization of PCLD patches partially added on a base structure with respect to noise control has not been carried out up to now.

The paper focuses on the topology optimization method for finding the optimal distribution of the PCLD attached on a thin wall structure to reduce its sound radiation. The notion of interface element is adopted in our FE modeling. The SNSV is chosen as the objective function. A SIMP model is employed in topology optimization and is solved by the MMA algorithm [7].

Square of the normal surface velocity

When the plate is baffled and divided with equal area elements in the FE model, a suitable goal function can be defined as SNSV which can be expressed as

$$V = \mathbf{v}^H \mathbf{v} \tag{1}$$

where $\mathbf{v}$ is the normal velocity vector of elements of the base plate, and superscript H denotes the complex conjugate transpose. Furthermore, in order to get an effect over broadband frequency range, an integral criterion over the range is required. Actually, we approximately use a sum of Eq. (1) at some equidistant frequencies instead of integral in the frequency range of interest. That is

$$\hat{V} = \sum_j \left[\mathbf{v}\left(f_j\right) \right]^H \mathbf{v}\left(f_j\right) \tag{2}$$

This objective function is highly related to the sound radiation power and less computationally expensive as there is no need to employ BEM or Rayleigh's integral to get the radiated sound power of the structure.

Finite modeling of PCLD

In MSC/NASTRAN, the VEM layer is modeled with three-dimensional solid elements whose nodes are all at elements corners, and the base layer and the constraining layer are modeled with shell elements whose nodes are offset to one surface of the plate and coincident with the corner nodes of the adjoining solid elements. The coupling between the shell elements and the solid elements are handled by kinematic constraints. While, in practice, before PCLD treatments applied, the base structure is always predetermined with conventional shell elements, whose nodes are in midplane, e.g., within the automotive industry, conventional shell modeling is the dominating finite element modeling technique on the car "body-in-white" level. Thus, it is quite appropriate to use the existing conventional shell elements to take the investigation on the effect of PCLD treatments covered on a certain area of the base structure. As the case considered herein, the plate is already meshed by conventional shell elements and only part of the plate area is permitted to add PCLD. To handle this problem, the VEM layer is modeled using a special interface element with eight nodes, which can directly couples with the two stiff layers which is modeled with conventional shell elements. The detailed modeling method can be found from [5].

SIMP model

A very popular and extremely efficient way for the topology optimization is to use the SIMP model. In the model, the continuous design variable called the "density" of the material is introduced to the model with some of penalty that steers the solution to a clear "black and white" design. The design problem is then formulated as a sizing problem on a fixed design domain. In the present study, the design domain is selected as the fully covered PCLD patch. The SIMP model of the structure is then expressed as followings

$$\left[K\left(\omega\right)\right] = \left[K_b\right] + \sum_{x=1}^{N_e} \rho_x^p \left[k_x\left(\omega\right)\right] \tag{3}$$

$$[M]=[M_b]+\sum_{x=1}^{N_e}\rho_x^p[m_x] \tag{4}$$

where $[K_b]$ and $[M_b]$ are the global stiffness matrix and mass matrix of the base layer, respectively. $[k_x(\omega)]$ and $[m_x]$ are the stiffness matrix and mass matrix of the xth element in global matrix of PCLD patch, respectively. For the single-sided PCLD (without base stiff layer) patch, the other side of the viscoelastic layer is directly connected to the base plate. The elements of single-sided PCLD patch include one layer of interface finite elements for viscoelastic core and one layer of shell elements for the top stiff layer. Though for double-sided PCLD patch, both sides of the viscoelastic layer is constrained by stiff layers. The base stiff layer of the patch is connected to the base plate. Thus, the elements of double-sided patch include the shell elements of both stiff layers coupled by one layer of interface elements for viscoelastic layer. Here, a simplification is made for double-sided PCLD patch in that the nodes of base stiff layer share the some location with that of the base plate, as we are primarily interested in the method of topology optimization, this modeling imperfection is not considered here. ρ_x ($0\le\rho_x\le1$) is the volumetric density of the viscoelastic material in element x and plays the role of the design variable in the sensitivity analysis. $\rho_x=0$ implies no material in the element and $\rho_x=1$ implies the element fully consists of the materials. p is the penalization power and $p\ge3$ is usually required to obtain true "0-1" designs. N_e denotes the total number of the elements. Then, the dynamic equation of the structure has the form

$$[M]\ddot{\mathbf{X}}+[K(\omega)]\mathbf{X}=\mathbf{L} \tag{5}$$

where $\mathbf{L}$ is the mechanical load vector, $\mathbf{X}$ is the nodal displacement vector, M is the mass matrix and K is stiffness matrix which is complex and frequency dependent due to the properties of viscoelastic meterials. The nodal solution of the dynamic function can be obtained from Eq. (5). The normal velocity of each element can be set equal to the average of the normal velocity of the four nodes of the element, and then the values of the objective functions can be readily determined. To perform the optimization with respect to minimization of sound radiation, a complete optimization model of the problem can be described as follows:

$$\begin{aligned}&\text{Find: } \rho_x, x=1,2,\ldots,N_e\\&\text{Min: } \hat{V} \text{ or } \hat{W}\\&\text{Subject to: } \sum_{x=1}^{N_e}\rho_x V_x-\beta V_0\le0\\&\qquad[M]\ddot{\mathbf{X}}+[K(\omega)]\mathbf{X}=\mathbf{L}\\&\qquad0<\rho_{\min}\le\rho_x\le1, x=1,2,\ldots,N_e\end{aligned} \tag{6}$$

where V_x and V_0 are the volume of the element x and the admissible design domain, respectively. β, referred to as volume fraction, is the maximum total fraction of the viscoelastic materials and $\rho_{\min}$ is introduced to prevent any possible singularity of the dynamic equation.

Numerical example

A square aluminum base plate is analyzed in the section. The model is the same as one of the numerical examples in Ref. [5]. The volume fraction is set up to 0.3 and MMA approach is chosen as the optimizer here.

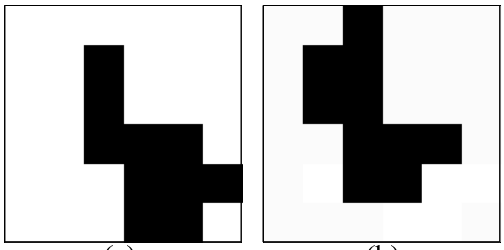

Fig. 1 Distribution of the PCLD patch: (a) result of present paper; (b) result of Alvelid.

Comparing with Alvelid's result for the case covering 600-800 Hz, see Fig.1, We can see that 6 out of 10 elements have the same location. The SNSV is compared in the frequency range for the two methods shown in Fig. 2. It is shown that the peak value of the present modified distribution is 3.4 dB lower than that of the Alvelid's.

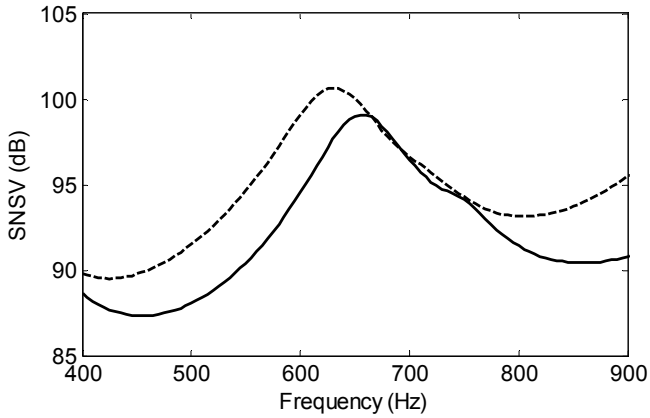

Fig. 2 Comparison of the SNSV for the modified result from Fig. 1(a) (solid line) and the result from Fig. 1(b)(dash line).

Summary

Topology optimization of PCLD patches distributed on a flat plate has been presented in this paper for minimizing SNSV. Numerical examples demonstrate the capability of the topology optimization of finding the optimal PCLD distribution for noise control and significant reductions of the objective function are achieved.

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