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Optimization of segmented constrained layer damping with mathematical programming using strain energy analysis and modal data

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ABSTRACT

A new method for enhancement of damping capabilities of segmented constrained layer damping material is proposed. Constrained layer damping has been extensively used since many years to damp flexural vibrations. The shear deformation occurring in the viscoelastic core is mainly responsible for the dissipation of energy. Cutting both the constraining and the constrained layer, which leads to segmentation, increases the shear deformation at that position. This phenomenon is called edge effect. A two-dimensional model of a cantilever beam has been realized for further investigations. An optimization algorithm using mathematical programming is developed in order to identify a cuts arrangement that optimizes the loss factor. The damping efficiency is estimated using the modal strain energy method. The Nelder–Mead simplex method is used to find the best distribution of cuts. In order to take into account geometrical limitations, the exterior point penalty method is used to transform the constrained objective function into an unconstrained objective function. As the optimization problem is not convex, a modal analysis is performed at each mode in order to identify initial cuts positions that lead to a global minimum. Over a large frequency range, the algorithm is able to identify a distribution of cuts that optimizes the loss factor of each mode under consideration.

1. Introduction

For many years vibration damping has been an important criterion in the design phase of many engineering applications. Large dissipation capabilities over a wide frequency range are desired. A common solution is to use a constrained viscoelastic material bonded to the vibrating structure. The damping material is applied in a sandwiched configuration. The inner surface is attached to the host structure and the outer surface is constrained by a stiff cover. With such configuration, the damping layer is mainly deformed in shear. The energy is dissipated into heat because of the relaxation process occurring in the long molecule chains [1,2]. Further improvement can be achieved by cutting the whole damping treatment. As a result, the number and the volume of high-shear regions is increased leading to a higher damping rate. Additionally, structural topology optimization can be a powerful tool to further improve the design of damping treatment.

1.1. Literature review

In 1959, Kerwin [3] published his observation that a stiff constraining layer, placed on top of the viscoelastic damping layer, can significantly increase the structural damping rate. Ungar and Kerwin [4] re-examinated the concept of loss factor applied for viscoelastic systems. Their main conclusion is that the stored energy can be estimated only if the energy storage and dissipation mechanisms are known. DiTaranto [5] determined the loss factor of a freely vibrating laminated beam having any possible boundary conditions using an analytical model. Mead and Markus [6] derived a mathematical expression for the transverse displacement of a three-layered sandwich beam with a viscoelastic core. They assumed different boundary conditions at one end of the beam such as no transverse displacement, no rotation, no bending moment, or no shear force. Rao [7] also presented a formula for the frequency and loss factor of a sandwich beam under the following boundary conditions: clamped–free, clamped–simply supported, clamped–clamped, simply supported–simply supported, and free–free. Plunkett and Lee [8] invented the concept of segmenting the constraining layer. Their study included experiments and derivation of a formula for optimum distance of their equidistant cuts arrangement. Kress [9] solved a shear-lag model for simulating segmented constrained layer damping treatment, similar to the investigation by Plunkett and Lee, with a transfer-matrix method. An illustration of the shear stress distribution over the whole length of the beam was given. A good agreement between simulations and measurements was observed. He also derived a simple formula for optimum spacing of his equidistant cuts arrangement that is different from the formula of Plunkett and

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Lee. Nevertheless, the effect of cuts were only investigated at the first bending mode of a cantilever beam. Torvik and Strickland [10] investigated a structure consisting of a base plate with a multiple-layer damping treatment with unanchored constrained layers, attached to one side of it. The constraining layers were segmented in two-dimensions. In the field of laminated composites, Mantena et al. [11] also investigated the optimal side length of constrained layer damping material. They considered various geometric arrangements of a load-carrying structure in terms of the clamping situation with special regard to the damping material. The main limitation of their work is that they focused their investigation on a single mode and considered just one segment. Alam and Asmani [12] sought optimal damping treatment design by considering as parameter damping material's thickness. Huang et al. [13] did a similar study. Kung and Singh [14] developed an energy-based approach of multiple constrained layer damping patches. They only looked at the effect of constrained layer damping patches at several modes separately. In the field of active vibration control, Lesieutre and Lee [15] performed a finite element analysis on segmented active constrained layer damping. Liu and Wang [16] investigated the distribution of passive and active constrained layer damping patches. In both papers, no length optimization of the damping treatment was performed. In the field of structural optimization, genetic algorithms were used by Trompette and Fatemi [17], and by Al-Ajmi and Bourisli [18] to optimize the segments' length. They were only able to identify a distribution of segments for a single mode and considered only one optimization technique. No comparison with other optimization methods on the efficiency of the selected algorithm to find the best solution was realised. As a general remark concerning all the papers above mentioned, the main limitation is that the different studies did not take into account a large frequency range. Additionaly, many of them just assumed either a fixed length for each segment or a fixed number of segments.

1.2. Objective and content of the present work

The objective of the present work is to develop an optimization algorithm based on mathematical programming that enables to find a single cuts arrangement for optimum damping of all modes within a selected frequency range. Additionally, a new mode-shaped based technique is proposed for the initial conditions. It aims at facilitating the finding of the best design.

In Section 2, the finite element modeling is addressed. The material data and geometrical parameters are also presented. The method to estimate the modal loss factor is described in Section 3. A finite element analysis is performed on a cantilever beam with a segmented constrained layer damping in Section 4. It enables to observe high-shear deformation regions and to have a clear understanding of the phenomena under interest. The dissipated energy is also quantified. Section 5 discusses the efficiency of segmented constrained layer damping material with equally spaced cuts. In Section 6, the optimization method is described. The convexity properties of the objective function are analyzed to investigate whether the solutions are unique. Results are discussed for a single mode optimization and over a large frequency range in Section 7. In Section 8, a guideline for the enhancement of constrained layer damping material via segmentation is proposed as a conclusion.

2. Finite element modeling

2.1. Overview

The structure of interest is a cantilever elastic beam on which is bonded a constrained damping layer. The method used for the finite element modeling is illustrated in Fig. 1.

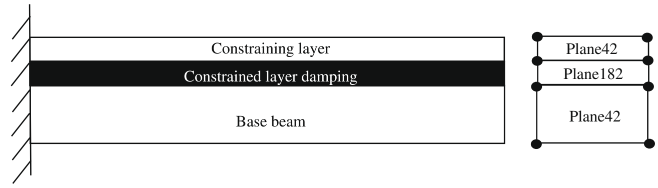

Fig. 1. Finite element model of a constrained layer damping treatment.

The beam and the constraining layer are modeled with two-dimensional structural solid elements called plane42 in ANSYS 11.0. The viscoelastic core is modeled with two-dimensional structural solid elements called plane182. All of these utilize two translations at each of the four nodes. An important feature of the plane182 element is the possibility to specify damping in terms of a loss factor as a function of frequency and temperature. It also has large strain capabilities. Therefore, the type of element is only used for the damping material. The thickness of each layer of the simulation model is given in Table 1.

The model includes details of a realistic clamping situation, as illustrated in Fig. 2a. The other model shown in Fig. 2b is oversimplified. It cuts off the influence of the realistic damping on the vibration behaviour and introduces artificial singular stress concentrations which increase with increasing the mesh density.

2.2. Mathematical model

The system under consideration involves a base beam to which is added a viscous elastic layer and a further metallic constraining layer. The whole system is assumed to be in a state of plane stress, i.e. all stresses with an index z vanish. At each node of each

Table 1
Thicknesses table.

	Thickness (m)
Beam	1×10^{-2}
Constrained layer	1×10^{-3}
Constraining layer	1×10^{-3}

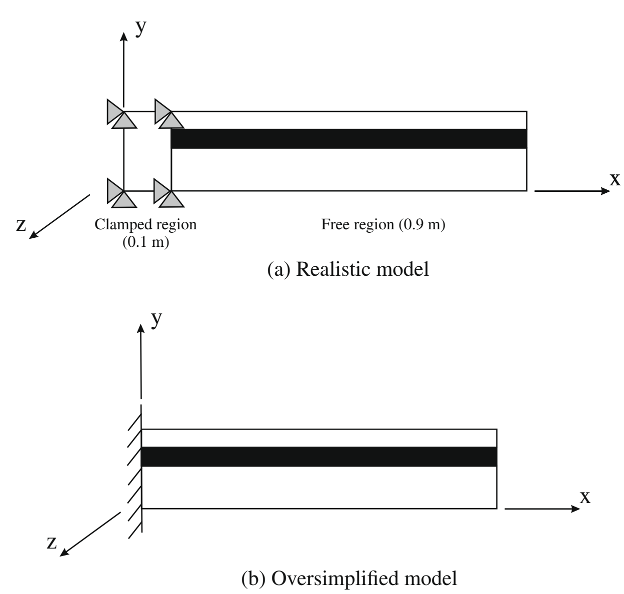

Fig. 2. Realistic and oversimplified models.