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Improved layer-wise optimization algorithm for the design of viscoelastic composite structures

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ABSTRACT

To combine lightness and rigidity in passive damping, elastic faces of visco-elastic sandwich structures are often made of laminates. These laminates are usually cross-ply, angle-ply, special orthotropic, antisymmetric or balanced laminates which are commonly called classical laminates. In the design of visco-elastic sandwich structures, one often seeks to maximize the loss factor of the structure and its rigidity. To achieve this, computations are often made for several combinations of laminate fibers' orientation angles. In this paper, the optimal design of composite laminates regarding the orientation angles is carried out by an improved layer-wise optimization algorithm (ILOA) by coupling a parametric non-linear eigenvalue problem resolution method (PANLER) with the so-called layer-wise optimization algorithm (LOA) to determine maximal frequencies and loss factors. The results are checked against a classical optimization algorithm.

1. Introduction

Visco-elastic sandwich structures are widely used in the industry (aeronautics, automotive, aerospace,...) to control noise and vibrations. In passive damping, visco-elastic sandwich structures are often made of a visco-elastic layer (called core) constrained by two rigid layers (called faces). Usually, materials used for the faces are isotropic. Composite materials and in particular classical laminates have a good ratio weight/stiffness which makes them suitable to meet the current lightness requirements for structures while having multifunctional abilities since each layer has some special properties that are required in some specific area. Mechanical characteristics of laminates depend strongly on their fibers' layers orientation. This also affects greatly the damping properties of the sandwich structure in which they are used. It is clear that laminates having the same number of layers and made with the same material but having different stacking sequences of fibers' orientation angle do not provide the same damping properties. It is therefore important for a designer to choose carefully the sequence of the laminate depending whether a better damped frequency or a better loss factor is needed for the structure. Studies are therefore done to propose to a designer some practice tools in it work. Thus Marcellin et al. [36] used genetic algorithm (GA) to determine the best stacking sequence and layers thicknesses for composite beams. Trompette and Fatemi [35] used a genetic algorithm to find the optimal number of cut for a viscoelastic sandwich beam. Araujo et al. [37] compared two algorithms (FAIPA and GA) for the optimal design of laminated viscoelastic sandwich plates. Hamdaoui et al. [38] performed multiobjective optimization of viscoelastic sandwich structures. The polar invariants of Verchery [10] are also very used and often combined with GA to design viscoelastic composite structures [11–14]. More recently, Chao et al. [39] performed multiobjective optimization of laminated viscoelastic composite structures including the material as design parameter using mixed-integer optimization. Other authors [1–4] used parametric analyses relying on incremental methods for varying fibers orientation angle in order to determine the angle that give the highest damping. Although the efficiency of these methods, they are usually expensive in computational time since they require solving many times a strongly non-linear frequency dependent eigenvalue problem. To reduce computational times, Narita [5] proposed a new optimization approach called layer-wise optimization algorithm (LOA) to maximize the natural frequency of laminated composite symmetric plates. The LOA is based on the physical consideration that the outer layer has more stiffening effect than the inner layer in the bending of plates and is more

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influential in determining the natural frequency. The LOA was thereafter successfully used to design rectangular and cylindrical laminated plates and beams for maximal fundamental frequency [6–8]. It has been also used to determine the sequence giving the structural optimal loss factor for the fundamental mode of laminated plates with visco-elastic layers [4]. However, despite its computational efficiency, the method still relies on incremental methods to determine the optimal laminates' properties for maximal loss factor and/or frequency. In an earlier study, Akoussan et al. [15] have developed a parametric non-linear eigenvalue problem resolution method called here PANLER based on asymptotic numerical method (ANM) and automatic differentiation to study the effects of fibers' orientation angle on damped frequency and loss factor for composite visco-elastic sandwich plates with complex constant Young modulus. The main advantage of the method relies on its ability to give a continuous description at minimum computational cost of the angle effect on vibrational properties avoiding the use of incremental methods. The PANLER method was successfully used to analyse the sensitivity of damped frequency and loss factor of symmetric visco-elastic sandwich thin beam and plate with laminated faces according to their layers thicknesses [16]. In this work, symmetric visco-elastic sandwich thin plates with laminated faces are considered. A finite element model based on Tsai and Pagano laminates invariants [9] is built. Then, the effects of the fibers' orientation angle of the laminated faces on the vibration characteristics of the structure is demonstrated by using the PANLER method [15]. It is worth noting that the PANLER method can handle one angle at a time. In order to perform optimal design of laminated faces with many fiber's orientation angles, the method is coupled with the LOA algorithm to yield the improved layerwise optimization algorithm called ILOA. The method is used to maximize the fundamental damped frequency and fundamental loss factor of the viscoelastic sandwich structure. The accuracy of the approach is checked against a standard genetic algorithm. The computational savings of the ILOA approach are pointed out establishing the efficiency of coupling LOA with the PANLER method.

2. Computational model

2.1. Geometry

Let us consider a symmetric multi-layered sandwich thin plate with visco-elastic isotropic core and laminated faces as shown in the Fig. 1. The coordinate system (O, X, Y, Z) having the origin O at one corner is the global coordinates system such that the plane (O, X, Y) being the mid-plane of the visco-elastic layer. L, l and h_t denote the length, the width and the total thickness of the structure, respectively. The total number of layers of the structure is noted $\mathfrak{N} = 2n+1,\ n \geqslant 1$ and are numbered from top to bottom. The thickness of the visco-elastic layer is h_c, that of a layer numbered i of the laminate faces is denoted h_{fi}. The fibers orientation angle for ith layer of the laminated faces is denoted θ_i (Fig. 2).

2.2. Behaviour law of the laminated faces

The faces of the visco-elastic sandwich structures are made of laminate comprising orthotropic layers whose fibers are differently oriented in the global reference (O, X, Y, Z) of the structure and respectively denoted by the angles θ_i. Each layer of the laminated faces is assumed to be made with the same material (same matrix and reinforcing fibers). The behaviour matrix of the ith layer of the laminated faces is denoted Q_i in the structure reference system (O, X, Y, Z) and is calculated by the following (1) when considering plane stress hypothesis.

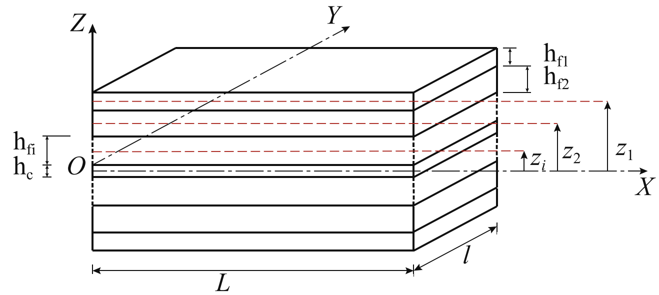

Fig. 1. Symmetric viscoelastic sandwich plate with laminated faces.

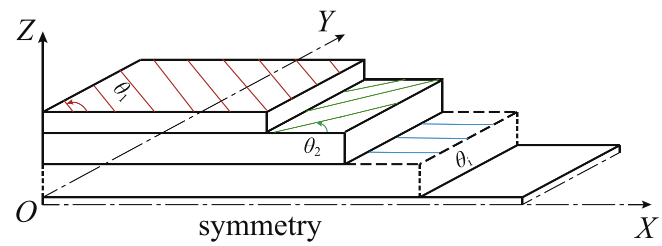

Fig. 2. The staking sequence of the symmetric viscoelastic sandwich plate.

$$Q_i = {}^tT_\varepsilon^i \, Q \, T_\varepsilon^i \tag{1}$$

where T_ε^i is the strain rebasing matrix whose expression is:

$$T_\varepsilon^i = \begin{bmatrix} \cos^2\theta_i & \sin^2\theta_i & \sin\theta_i\cos\theta_i \\ \sin^2\theta_i & \cos^2\theta_i & -\sin\theta_i\cos\theta_i \\ -2\sin\theta_i\cos\theta_i & 2\sin\theta_i\cos\theta_i & \cos^2\theta_i - \sin^2\theta_i \end{bmatrix} \tag{2}$$

In (1), the matrix Q represents the behaviour matrix of each layer of the laminate in the material reference system (O, L, T, Z). This matrix Q is expressed as a function of the mechanical characteristics of the composite material as follows:

$$Q = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \tag{3}$$

with

$$\begin{aligned} Q_{11} &= \frac{E_L}{1 - \frac{E_T}{E_L}\nu_{LT}^2}, \quad Q_{12} = \nu_{LT} Q_{22} \\ Q_{22} &= \frac{E_T}{E_L} Q_{11}, \quad Q_{66} = G_{LT} \end{aligned} \tag{4}$$

E_L, E_T, G_{LT} and ν_{LT} being respectively the longitudinal and transverse Young modulus, the shear modulus, and the Poisson ratio of the composite material. In [15] the fibers' orientation angle dependence membrane (C_m^i) and bending (C_f^i) stiffness matrices of the orthotropic faces whose fibers are oriented by an angle θ_i in the structure reference frame are given as follows:

$$\begin{aligned} C_m^i(\theta_i) &= A_1\cos^4(\theta_i) + A_2\sin^4(\theta_i) + A_3\sin^2(\theta_i)\cos^2(\theta_i) \\ &\quad + A_4\sin(\theta_i)\cos^3(\theta_i) + A_5\sin^3(\theta_i)\cos(\theta_i) \\ C_f^i(\theta_i) &= \frac{h_{fi}^2}{12} C_m(\theta_i) \end{aligned} \tag{5}$$

In (5), the $A_i, i = 1, 2, \ldots, 5$ are constant matrices obtained from the mechanical characteristics of the material through (4) (see Appendix A for their expressions). The behaviour matrices C_m^i, C_f^i are expressed as trigonometric functions of the variable θ_i which is the fibers' orientation angle of the layer i. However, this kind