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Sensitivity analysis of the damping properties of viscoelastic composite structures according to the layers thicknesses

Komlan Akoussan [a,*], Hakim Boudaoud [b], El Mostafa Daya [a,c], Yao Koutsawa [d], Erasmo Carrera [e]

[a] Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux (LEM3), UMR CNRS 7239, UL, Metz, France
[b] Equipe de Recherche sur les Processus Innovatifs (ERPI), UL, Nancy, France
[c] Laboratory of Excellence on Design of Alloy Metals for low-mAss Structures (DAMAS), UL, Metz, France
[d] Materials Research and Technology Department, Luxembourg Institute of Science and Technology, 41, rue du Brill, L-4422 Belvaux, Luxembourg
[e] Department of Aeronautics and Aerospace Engineering, Politecnico di Torino, Corso Duca degli abruzzi, 24, 10129 Torino, Italy

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ABSTRACT

Damping properties of viscoelastic composite structures are related to the thicknesses of their layers. To design these structures, there is a need to know their damping properties sensitivities according to the thicknesses of their layers. This allows to evaluate errors committed in the design for a layer thickness variation or to predict the damping properties of other structures having the same dimensions (length and width) except the layers thicknesses. Sensitivity analysis conducted to date are limited to the first derivative approximation which reduces considerably the calculation accuracy and the convergence radius but are computation time consuming. In this paper, we propose a high order continuous sensitivity analysis of the damping properties of viscoelastic composite plates according to their layers thicknesses. This method allows to get the exact values of the optimal damping properties and the high order derivative. Two cases are considered herein: the variation of only the thickness of the core layer and the variation of the thickness of each layer the total thickness of the structure being constant. Results showed that the damping properties variation is not standard but related to the viscoelastic material, the fibers orientation of the laminated faces, the boundary conditions and the structure dimensions.

1. Introduction

Passive damping is an effective way to control vibrations and dissipate acoustic energies. For this, it is widely used in industries such as automotive, aeronautics and aerospace. Passive damping consists in using viscoelastic sandwich structures that are generally formed of two very rigid layers between which is confined one viscoelastic layer. The damping of these structures is due to the difference of deformation between the rigid layers and the viscoelastic layer which therefor is strongly deformed in shear. The very first work on vibration modeling of viscoelastic sandwich structures are analytical and are realized by Kerwin [1], Ross [2] and DiTaranto [3] on viscoelastic sandwich made with isotropic materials. Difficulties encountered in analytical modeling of viscoelastic sandwich structures have led to intensive use of finite element method [4–10,17,28,29].

Then works were gradually oriented towards modeling of viscoelastic sandwich structures made with composite materials. Indeed, composite materials offer advantages of a better rigidity and are lightweight compared to isotropic materials; this motivates their use in new constructions. So, Rikards [11] developed two finite superelements for vibration and damping analysis of viscoelastic sandwich beam and plate with composite layers. For beams, he considered each layer as simple Timoshenko's beam and as Mindlin–Reissner plate finite element for plate. Araújo et al. [18,20] used mixed layerwise theory for damping optimization of anisotropic laminate plates with viscoelastic core in finite element formulation. Adams and Maheri [12,13] investigated damping of angle-ply laminates made of unidirectional glass or carbon fiber layers and of fiber reinforced plates by using finite element analysis. Zhang and Chen [15] used commercial software ANSYS 7.0 3D finite element SOLID46 coupled with Modal Strain Energy method (MSE) for predicting the loss factor of laminated composite beams with integral viscoelastic layers. They took into account the frequency dependence of viscoelastic damping materials and the contribution of energy dissipation due to fiber-reinforced composites in their formulation. Recently, Li and Narita [21] extended to general boundary conditions works of Berthelot and Sefrani [14,16] who used Ritz energy method to determine

* Corresponding author.
E-mail address: komlan.akoussan@univ-lorraine.fr (K. Akoussan).

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the loss factor of multilayered plates and beams with or without viscoelastic core for very specific boundary conditions. Ferreira et al. [22] used a layerwise finite element model for the analysis of sandwich laminated plates with a viscoelastic core and laminated anisotropic face layers where the stiffness and mass matrices are obtained by Carrera's Unified Formulation (CUF) [50,51]. Arvin et al. [19] developed finite element formulation using high order theory for sandwich beam with composite faces and viscoelastic core by considering independent transverse displacements on two faces and linear variations through the depth of the core. They didn't neglect rotational inertia in their formulation. They showed also the effects of fibers orientation and the thickness of the viscoelastic core on the damping properties of the beam by incremental calculations. Akoussan et al. [23] used quadrangular finite element to study continuously effects of fibers orientation on damping properties of three layered sandwich plates with orthotropic faces and viscoelastic core having a complex constant Young modulus. They used asymptotic numerical method coupled to automatic differentiation for continuous study of these effects.

However, damping properties of viscoelastic sandwich structures are linked to many parameters. These parameters including mechanical characteristic (Young modulus, shear modulus, Poisson ratios, density) and thickness of each layer of the structure describe its mechanical behavior. So, as temperature which affected directly materials behavior mainly viscoelastic core, the thickness of the layer has also a great impact on the damping properties. To design viscoelastic sandwich structures having a given minimal damping power and some specific resistance, when layers mechanical characteristics are giving, it's necessary to find the thicknesses values by studying the direct impact of layers thicknesses. To date, two methods are used. The first is the discrete calculations which consists of determining damping properties of the structures for several different values of the thicknesses of layers. This method is too expensive in computation cost since elementary calculations such as Gaussian calculation, matrices assembling, boundary conditions applying and the resolution of the non linear complex eigenvalues problems are repeated each time. Not only is this method time-consuming it does not allow to determine the optimal values of the modeling parameters for the damping properties. Some work has been conducted in this perspective. Especially, the work of Teng and Hu [52] on viscoelastic beam in which they concluded that the thickness of the viscoelastic core seems to have a strong impact on the damping of the structure for low values of the core thickness, and this damping reduces significantly as the core thickness increases. Sher and Moreira [53] in their side have proposed a finite element method coupled to Modal Strain Energy (MSE) to study the effects of thickness/length ratio, core layer thickness, material modulus and boundary conditions on the loss factors of viscoelastic structures. Works [52,53] concerned viscoelastic structures made with elastic isotropic materials for the faces layers and viscoelastic isotropic layer for the core. Concerning viscoelastic sandwich structures with composite layers, there are very few work. Nevertheless, Arvin et al. [19] showed the variation of damping properties of three layered viscoelastic beam with orthotropic faces according to the core thickness. Another way to study layers thicknesses impacts on the damping properties of viscoelastic sandwich structures is the sensitivity analysis. Sensitivity analysis consists in approximating the response of modified systems. Sensitivity analysis can be performed through two main types of numerical procedures [44]: first by computing the analytical derivatives of the equilibrium equations or equations of motion with respect to the design parameters, when those parameters appear explicitly in such equations. In this case, the derivatives are considered to be exact; second by approximating the derivatives by finite differences, by computing the ratios of the response and parameter variations. This method is used in several works for performing sensitivity analysis of dynamic responses [44–47]. They reduce the computation cost compared to discrete calculation case, especially for highly complex industrial structures. The aim problem of this method is the choice of the magnitude of the parameter variation which is done arbitrary and two calculations of the equation is needed for each derivative estimate. Furthermore sensitivity analysis is limited to the first-order, as computations of high orders are much more involved and time-consuming. To avoid choosing arbitrary the convergence radius of the parameter, Lampoh et al. [48,49] used asymptotic numerical method coupled to automatic differentiation in sensitivity analysis where the parameter convergence radius is obtained through a precision value. However, sensitivity analysis are suitable to certain increase of the modeling parameter for a good precision. When the modeling parameter is describing a large range, several calculations are also needed for sensitivity analysis [47,48] making expensive computation cost. Current requirements for design and optimization impose to develop a model that provides a continuous sensitivities analysis of the damping properties of viscoelastic composite structures according to the layers thicknesses and the exact values of the thicknesses for the optimal damping properties. In this purpose, we propose finite elements formulations for a continuous sensitivity analysis of the damping properties of viscoelastic symmetric plate with isotropic viscoelastic core having frequency dependence Young modulus law and elastic laminates faces. Two cases of study are made: the first (First case) consists in considering constant the thickness of each laminate face of the structure and varying the thickness of the core layer. The second is consisting in considering constant the total thickness of the structure and varying the thickness of each layer to find the optimal thickness of the core layer (Second case). These formulations lead to the resolution of residual non linear complex eigenvalues problem having frequency dependence and the modeling parameter herein layer thickness. This resolution is done by coupling the asymptotic numerical method, automatic differentiation, homotopy technic and continuation for a low computation cost. We will show through this study that the variation of the damping properties is not standard but related to the viscoelastic material used for core, the fibers orientation of the faces composite layers, the boundary conditions and the dimensions of the structure. Different viscoelastic core will be used for making out the effect of the core layer mechanical characteristic on the damping properties.

2. Finite element formulation

Let us consider a multilayer symmetric sandwich thin plate with viscoelastic isotropic core and laminate 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 midplane of the viscoelastic 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

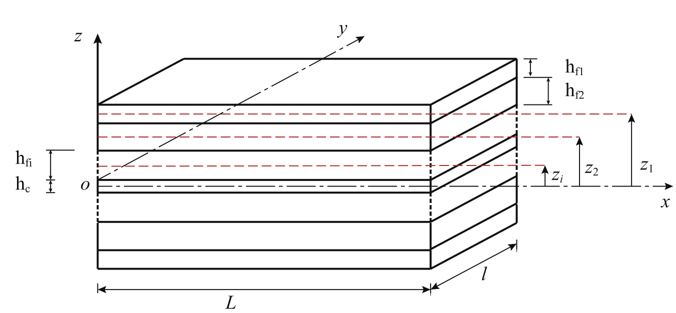

Fig. 1. Plaque sandwich with viscoelastic core and laminate faces.