Computers and Structures xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Vibroacoustic analysis of double-wall sandwich panels with viscoelastic core

W. Larbi *, J.F. Deü, R. Ohayon

Structural Mechanics and Coupled Systems Laboratory, Conservatoire National des Arts et Métiers, 292 rue Saint-Martin, 75141 Paris Cedex 03, France

A R T I C L E I N F O

Article history:
Accepted 22 September 2015
Available online xxxx

Keywords:
Sandwich plate
Double-wall
Viscoelastic
Vibroacoustic
Finite element
Modal reduction

A B S T R A C T

In this work, an original finite element modeling to investigate the effects of a viscoelastic layer on the sound transmission through double-wall sandwich panels is presented. This formulation is obtained from a coupled fluid–structure variational principle taking into account the frequency dependence of the viscoelastic material. The resolution approach is based on a reduced order model generated by a modal projection technique. The sound insulation of the panels is evaluated by computing its sound transmission factor using Rayleigh integral method. An efficient and inexpensive finite element for a sandwich plate with viscoelastic core is developed. Various results are presented in order to validate and illustrate the efficiency of the proposed finite element formulations.

1. Introduction

Double-wall structures are widely used in noise control due to their superiority over single-leaf structures in providing better acoustic insulation. Typical examples include double glazed windows, fuselage of airplanes, vehicles, etc. Different theoretical, experimental and numerical approaches have been investigated to predict the sound transmission through double walls with an acoustic enclosure. In [6,22,12], theoretical approaches are proposed for the derivation of the sound transmission factor of double panels of infinite size exposed to a random sound field as a function of frequency and angle of incidence. For a finite panels size, a theoretical study, based on Fourier series expansions, on the vibroacoustic performance of a rectangular double-panel partition clamp mounted in an infinite acoustic rigid baffle is presented in [35]. Experimental evaluation of sound transmission through single, double and triple glazing can be found in [28,29,33,11]. Regarding the numerical prediction approaches, several methods are available in the literature, such as the finite element method (FEM), the boundary element method (BEM), and the Statistical Energy Analysis (SEA). In [1], FEM is applied to study the viscothermal fluid effects on vibro-acoustic behavior of double elastic panels. The FEM is applied in [32] by the authors for the different layers of the sound barrier coupled to a variational BEM to account for fluid loading. In [9], the SEA is used for predicting sound transmission through double walls and for computing the non-resonant loss factor. For all these approaches, the choice of the numerical method is related to the computational cost and the frequency band to be treated.

By introducing a thin viscoelastic interlayer within the panels, a better acoustic insulation is obtained. In fact, sandwich structures with viscoelastic layer are commonly used in many systems for vibration damping and noise control. In such structures, the main energy loss mechanism is due to the transverse shear of the viscoelastic core. However, accurate modeling of structures with viscoelastic materials is difficult because the measured dynamic properties of viscoelastic material are frequency and temperature dependent. This motivated several authors to develop accurate numerical methods of modeling the effects of viscoelastic damping mechanisms which introduce frequency dependence. A review of these methods can be found in [34]. In the same context, many studies are dedicated to the development of sandwich finite element with viscoelastic core [14,7,3,31,4].

Concerning the application of these structures in noise attenuation, we can cite [15] where numerical and experimental results concerning the sound transmission through a single and a double laminated glass with Polyvinyl Butyral (PVB) viscoelastic interlayer are presented and compared. In [11], the measured sound transmission loss of multilayered structures is compared with transfer matrix method results (assuming infinite layers) and a wave based model (taking into account finite dimensions) to show the importance of the finite dimensions in a broad frequency range. The effects of viscothermal fluid in a laminated double glazing are investigated in [2] using a finite element approach.

* Corresponding author.

http://dx.doi.org/10.1016/j.compstruc.2015.09.012
0045-7949/

This work is based upon Larbi et al. [21] for vibroacoustic analysis of double-wall sandwich panels with viscoelastic core, but includes the development of an original finite element sandwich plate. In the first part of this paper, a non-symmetric finite element formulation of double-wall sandwich panels with viscoelastic core is derived from a variational principle involving structural displacement and acoustic pressure in the fluid cavity. Since the elasticity modulus of the viscoelastic core is complex and frequency dependent, this formulation is complex and nonlinear. Therefore, the direct solution of this problem can be considered only for small model sizes. This has severe limitations in attaining adequate accuracy and wider frequency ranges of interest. An original reduced order-model is then proposed to solve the problem at a lower cost. The proposed methodology, based on a normal mode expansion, requires the computation of the uncoupled structural and acoustic modes. The uncoupled structural modes are the real and undamped modes of the sandwich panels without fluid pressure loading at fluid–structure interface, whereas the uncoupled acoustic modes are the cavity modes with rigid wall boundary conditions at the fluid–structure interface. Moreover, the effects of the higher modes of each subsystem are taken into account through an appropriate so-called a priori static correction based on adding the static modes, defined as the deformation shape at every load, to the truncated bases. It is shown that the projection of the full-order coupled finite element model on the uncoupled bases, leads to a reduced order model in which the main parameters are the classical fluid–structure and residual stiffness complex coupling factors. Thanks to its reduced size, this model is proved to be very efficient for simulations of steady-state and frequency analyses of the coupled structural–acoustic system with viscoelastic damping and the computational effort is significantly reduced. As a next step, the sound transmission through double walls is investigated. When the normal velocity distribution of the panel is known, the acoustic pressure field generated in the outward direction of the two plates can be calculated with the so-called Rayleigh integral for two-dimensional sound radiation. For this purpose, it is assumed that the double wall panel is placed in an infinite baffle. The normal incidence sound transmission is chosen in order to evaluate the acoustic performances and the sound insulation of the double wall.

The second part of this work is devoted to the development of an efficient finite element sandwich plate. The model is based on the layerwise theory with a first order shear deformation in each layer. The skins are described according to the Kirchhoff–Love theory with a correction which takes into account the rotational influence of the transversal shearing in the core. A Mindlin model is used to describe the displacement field of the core. A four nodes finite element layered plate, with seven degrees-of-freedom (dof) per node, is then developed. The in-plane displacements and the rotations of the core are discretized by conforming bi-linear Lagrange shape functions, while the transverse displacement and rotations of the skins are discretized by non-conforming cubic Hermite shape functions. This choice is proved to be efficient compared to other FE models and well adapted to structural–acoustic applications.

In the last part, numerical examples are presented in order to validate and analyze results computed from the proposed formulations.

2. Finite element formulation of the coupled problem

2.1. Local equations

Consider a double-wall structure shown in Fig. 1. Each wall occupies a domain Ω_{Si}, $i \in \{1,2\}$ such that $\Omega_S = (\Omega_{S1}, \Omega_{S2})$ is a partition of the whole structure domain. A prescribed force density $\mathbf{F}^d$ is applied to the external boundary Γ_t of Ω_S and a prescribed displacement $\mathbf{u}^d$ is applied on a part Γ_u of Ω_S. The acoustic enclosure is filled with a compressible and inviscid fluid occupying the domain Ω_F. The cavity walls are rigid except those in contact with the flexible wall structures noted Σ. It should be mentioned that fluid loading on the source and receiving side of the double panel is neglected in this work. The harmonic local equations of this structural–acoustic coupled problem can be written in terms of structure displacement $\mathbf{u}$ and fluid pressure field p [19]

$$\mathrm{div}\boldsymbol{\sigma}(\mathbf{u}) + \rho_S \omega^2 \mathbf{u} = \mathbf{0} \quad \text{in } \Omega_S \tag{1}$$

$$\boldsymbol{\sigma}(\mathbf{u})\mathbf{n}_S = \mathbf{F}^d \quad \text{on } \Gamma_t \tag{2}$$

$$\boldsymbol{\sigma}(\mathbf{u})\mathbf{n}_S = p\mathbf{n} \quad \text{on } \Sigma \tag{3}$$

$$\mathbf{u} = \mathbf{u}^d \quad \text{on } \Gamma_u \tag{4}$$

$$\Delta p + \frac{\omega^2}{c_F^2} p = \mathbf{0} \quad \text{in } \Omega_F \tag{5}$$

$$\nabla p \cdot \mathbf{n} = \rho_F \omega^2 \mathbf{u} \cdot \mathbf{n} \quad \text{on } \Sigma \tag{6}$$

where ω is the angular frequency, $\mathbf{n}_S$ and $\mathbf{n}$ are the external unit normal to Ω_S and Ω_F; ρ_S and ρ_F are the structure and fluid mass densities; c_F is the speed of sound in the fluid; and $\boldsymbol{\sigma}$ is the structure stress tensor.

2.2. Constitutive relation for viscoelastic core

In order to provide better acoustic insulation, damped sandwich panels with a thin layer of viscoelastic core are used in this study (Fig. 1). In fact, when subjected to mechanical vibrations, the viscoelastic layer absorbs part of the vibratory energy in the form of heat. Another part of this energy is dissipated in the constrained core due to the shear motion.

The constitutive relation for a viscoelastic material subjected to a sinusoidal strain is written in the following form:

$$\boldsymbol{\sigma} = \mathbf{C}^*(\omega)\boldsymbol{\varepsilon} \tag{7}$$

where $\boldsymbol{\varepsilon}$ denote the strain tensor and $\mathbf{C}^*(\omega)$ termed the complex moduli tensor, is generally complex and frequency dependent ($*$ denotes complex quantities). It can be written as:

$$\mathbf{C}^*(\omega) = \mathbf{C}'(\omega) + i\mathbf{C}''(\omega) \tag{8}$$

where $i = \sqrt{-1}$.

Furthermore, for simplicity, a linear, homogeneous and viscoelastic core will be used in this work. In the isotropic case, the viscoelastic material is defined by a complex and frequency dependent shear modulus in the form:

$$G^*(\omega) = G'(\omega) + iG''(\omega) \tag{9}$$

where $G'(\omega)$ is know as shear storage modulus, as it is related to storing energy in the volume and $G''(\omega)$ is the shear loss modulus, which represents the energy dissipation effects. The loss factor of the viscoelastic material is defined as

$$\eta(\omega) = \frac{G''(\omega)}{G'(\omega)} \tag{10}$$

which alternatively allows writing Eq. (9) as

$$G^*(\omega) = G'(\omega)(1 + i\eta(\omega)) \tag{11}$$

The Poissons ratio ν is considered real and frequency independent. The loss factor of Young's modulus E^* is the same as that of the shear modulus, which leads to:

$$E^*(\omega) = E'(\omega)(1 + i\eta(\omega)) \tag{12}$$

where $E'(\omega) = 2G'(\omega)(1 + \nu)$.

Please cite this article in press as: Larbi W et al. Vibroacoustic analysis of double-wall sandwich panels with viscoelastic core. Comput Struct (2015), http://dx.doi.org/10.1016/j.compstruc.2015.09.012