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Evaluation of damping loss factor of flat laminates by sound transmission

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ABSTRACT

A novel approach to investigate and evaluate the damping loss factor of a planar multilayered structure is presented. A statistical analysis reveals the connection between the damping properties of the structure and the transmission of sound through the thickness of its laterally infinite counterpart. The obtained expression for the panel loss factor involves all the derivatives of the transmission and reflection coefficients of the layered structure with respect each layer damping. The properties of the fluid for which the sound transmission is evaluated are chosen to fulfil the hypotheses on the basis of the statistical formulation. A transfer matrix approach is used to compute the required transmission and reflection coefficients, making it possible to deal with structures having arbitrary stratifications of different layers and also granting high efficiency in a wide frequency range. Comparison with alternative formulations and measurements demonstrates the effectiveness of the proposed methodology.

1. Introduction

Passive damping treatments are widely used in engineering applications to reduce noise radiation, the amplitude of vibrations and the risk of fatigue failure. In particular, viscoelastic laminates have found application in many areas of structural acoustics due to the high damping levels that can be attained when the cross-sectional properties of the laminate are appropriately chosen. A key requirement for determining the optimal cross-sectional properties of a given laminate is an accurate model of its dynamics.

Typically, at low frequencies, a finite element (FE) model provides a good description of the structural-acoustic behavior of the laminate. A Modal Strain Energy (MSE) analysis on the FE model can provide the loss factor of the structure in terms of the strain energy field of each mode [1]. At higher frequencies, the wavelengths of interest become small with respect to the lateral dimensions of the laminate and then the FE approach becomes impractical. Indeed, Statistical Energy Analysis (SEA) [2] is a more suitable method for estimating the high-frequency responses of a structure under acoustic or mechanical excitation. In order to model a subsystem in SEA, it is necessary to determine the dispersion properties and the Damping Loss Factor (DLF) of each propagating wave type of the subsystem. An approach for evaluating the DLF of a structure is to simplify a real world component down to an equivalent 3-layer beam or plate system. This was first suggested by Ross, Kerwin, Ungar (RKU) [3–5], involving a fourth order differential equation for a uniform beam under free-wave propagation with the sandwich construction of the 3-layer laminate system represented as an equivalent, frequency dependent, complex stiffness. Several authors have described extensions to RKU analysis by involving different displacement fields to characterize the response of more general laminates [6,7]. Typically, the assumption of a low-order displacement field is required in order to reduce analytical complexity.

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While simplified analytical models can provide physical insights into the behavior of certain laminates, the assumed displacement fields can often restrict the types of laminates that can be modeled. Numerical methods to investigate the damping of laminated panels have been developed by several authors [8–13]. By exploiting a plane wave expansion, the power dissipated by an isotropic poroelastic media within semi-infinite multilayered systems under arbitrary excitation has also been assessed [14]. The loss factor of more general laminates can be explored by involving a one-dimensional FE mesh to describe the cross sectional deformation of a linear viscoelastic laminate, also including a three-dimensional displacement field within the laminate [15]. However, the model is computationally expensive due to the inversion of large matrices as a result of an increasing number of elements in the cross sectional thickness. Regardless of the model adopted to describe the cross sectional deformation, a dispersion problem must be solved by determining, at a specific frequency, ω, and for a specific direction of propagation, a finite number of complex wavenumbers, k, related to the free waves traveling in the structure. The solution of the dispersion problem at discrete frequencies for a specific direction of propagation leads to a $k-\omega$ dispersion diagram where dispersion curves must be identified. Then, the damping loss factor, η_i, for the i-th curve can be evaluated by means of the related eigenvectors. However, the number of curves and their intersections rapidly grow with the frequency, making it more difficult to identify the curves. An alternative approach is to use an exact description of the through-thickness deformation of a laminate by means of a Transfer Matrix Method (TMM) [16]. The characteristic equation that describes free-wave propagation in a laminate can take the form of a nonlinear transcendental eigenvalue problem [17]. However, the computational burden and robustness of the root-tracking algorithms employed to determine dispersion solutions limit the usefulness of the approach.

The scope of this work consists in defining the DLF of a planar structure, averaged among all dispersion curves, by avoiding both the solution of the dispersion problem and the modal approach. We are avoiding the solution of a dispersion problem because i) identify dispersion curves at high frequency could be prohibitive and ii) take into account the damping of all the propagating waves may be impractical. On the other hand, we are discarding the modal approach because i) it could be computationally prohibitive even at relatively low frequencies and ii) materials characterized by frequency dependent properties cannot be easily taken into account. A theory producing the DLF of a multilayered planar structure and overcoming the limitations of the above discussed approaches is proposed. A statistical analysis reveals the connection between the damping properties of the structure and the transmission of sound through the thickness of its laterally infinite counterpart. The incident diffuse acoustic field prescribed by the statistical approach to evaluate the sound transmission ensures the excitation of all the propagating waves contributing to the damping of the medium, thus providing a mean loss factor for the structure. A TMM is used to evaluate the required transmission and reflection coefficients, making it possible to deal efficiently with structures having generic stratifications, possibly including in-plane periodic layers [18]. The wave approach on the basis of the TMM also avoids the need to set a specific kinematic model for the laminate, thus yielding high accuracy.

The DLF of a multilayered planar structure is derived in Section 2 by means of a statistical analysis on the sound transmission through the thickness of the structure. A number of applications are then discussed and compared with alternative formulations and measurements.

2. Layered systems

Let us consider a layered structure in which the i-th layer is characterized by hysteretic damping through the loss factor $\eta_i(\omega)$. The time-averaged power dissipated by the i-th layer, Π_i, when the structure is subjected to harmonic excitation at angular frequency ω, can be expressed as [2]

$$\Pi_i = \omega E_i \eta_i \, , \tag{1}$$

where E_i is the time-averaged total energy stored in the layer. The DLF of the layered structure, $\eta_s(\omega)$, concerns the overall time-averaged power dissipated by the structure, Π_{diss}, when a diffuse reverberant field exists within it, and can be expressed as [2]

$$\eta_s(\omega) = \frac{\Pi_{\text{diss}}}{\omega E_s} = \frac{\sum_{i=1}^{N} E_i \eta_i}{\sum_{i=1}^{N} E_i} \, , \tag{2}$$

where the total dissipated power, Π_{diss}, is the sum of the power dissipated by the N layers in the medium, and the total panel energy, E_s, is the sum of the energies in all layers. We propose to derive the total energy stored in each layer of a planar structure, E_i, by means of the transmission and reflection coefficients of the laterally infinite counterpart of the structure. Such a purpose draws legitimacy from the idea that the phenomenon of sound transmission through the thickness of the structure hides and carries the very same information as the dispersion problem for the medium. Such information are exposed by means of a statistical analysis of the sound transmission through the structure. The adopted statistical approach is here reliable at any frequency since an infinite extent is considered for the structure.

2.1. Statistical approach

Sound transmission through the thickness of a planar structure can be investigated by placing the structure between two rooms. In the context of SEA, two energy paths can be identified between the rooms. The first one links the rooms without involving the resonance of the interposed wall, and depends only on the specific mass of the wall, the so-called non-resonant path. A second path treats the interposed structure as a subsystem, so involving its strain energy, the so-called reverberant path.