On the Use of Condensation Models for Describing Highly Damped Multilayered Structures

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1 Introduction

Multilayered composite structures are of interest to many industries, such as aeronautics, aerospace and automotive, because of their high specific modulus. Nevertheless, reinforcement materials have low damping and improving the dynamic behavior of multilayered structures is an ongoing research area. Constrained layer damping treatment is a solution that increases damping and dissipates energy through shearing motion in the added viscoelastic layer. This method is suitable for high frequencies, but is not efficient at low frequencies and also lacks adaptability.

In [1], a shape memory polymer (SMP) was used as viscoelastic core of a sandwich structure. The mechanical properties of this SMP depend on frequency and temperature. It also exhibits excellent damping capacity over a wide frequency range at temperatures close to its glass transition temperature. The structure becomes adaptive, and can be "programmed" to reduce vibrations by controlling the temperature inside the core. However, the stiffness of the sandwich structure is compromised by the increase in temperature.

The combination of surface temperature fields enables the sandwich structure to maintain stiffness while reducing vibrations. In [2], heaters were distributed on a skin of a sandwich structure with SMP core. They can be controlled independently and many combinations of temperatures fields are possible. The selection of specific combinations was based on the evaluation of static and dynamic criteria, which were obtained from a finite element model (solid, 3D). While this strategy is suitable for small structures, it may become unfeasible for large structures due to the high computation time involved. This approach may also be inappropriate for reevaluating in short time the configurations according to different criteria. Instead of using the finite element model (solid, 3D) approach, reduced-order models based on plate theory are required to reduce computational time. However, the selection of a condensation model capable of determining the effective properties of highly damped structures remains a challenge.

2 Materials and methods

2.1 A sandwich structure with SMP core

A symmetrical sandwich structure with aluminum (Al) skins and SMP core is considered. The length is 0.7 m and width 0.5 m. All edges are simply supported and a point excitation is applied at its center. Table 1 contains the properties values. The loss factor $\tan(\delta)$ of the SMP depends on angular frequency ω and temperature. Figure 1 shows the frequency and temperature evolution of $\tan(\delta)$. Sandwich structures with SMP core have controllable properties, and some configurations are highly damped.

Table 1: Properties of the sandwich structure (SI units).

	h	ρ	ν	E	η
Al	0.0005	2700	0.33	$7 \cdot 10^{10}$	0.001
SMP	0.0022	990	0.37	$E'(\omega)$	$\tan(\delta(\omega))$

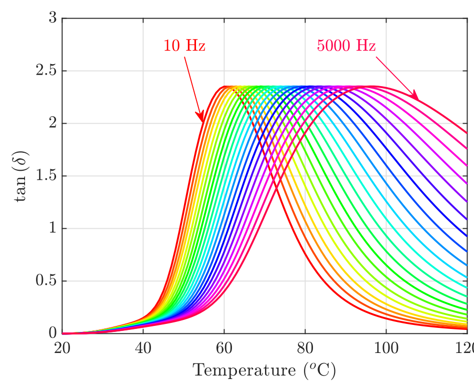

Figure 1: SMP loss factor $\tan(\delta)$. The SMP storage modulus E' is also affected by frequency and temperature (see [1] for details).

2.2 Calculation of effective properties

The bending (c_B), shear (c_T) and longitudinal (c_L) waves velocities propagating in a homogeneous and isotropic plate are related to the plate properties (thickness, density, Poisson's ratio and Young's modulus). The respective wavenumbers are $k_B = \omega/c_B$, $k_T = \omega/c_T$ and $k_L = \omega/c_L$. Dispersion relations can be determined with the General Laminate Model (GLM) [3]. The GLM considers rotational inertia and transversal shearing, membrane and bending deformations in composite plates with orthotropic orientation. The GLM also considers the frequency dependency of viscoelastic layers.

Table 2 gives the formulas used to calculate the effective properties of an equivalent (homogeneous and isotropic) plate. The effective properties are used in a Discrete-Kirchhoff plate finite element formulation [4]. The condensed finite element model intends to describe the dynamic behavior of the sandwich structure with reduced computational cost.

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Table 2: Effective properties of an equivalent (homogeneous and isotropic) plate that preserves bending, shear and extension wavenumbers.

Equivalent thickness	Equivalent density	Equivalent Poisson's ratio	Equivalent Young's modulus
$h_{eq} = \sqrt{12}\frac{k_L}{k_B^2}$	$\rho_{eq} = \sum_{i=1}^{3} \frac{\rho_i h_i}{h_{eq}}$	$\nu_{eq} = 1 - 2\left(\frac{k_L}{k_T}\right)^2$	$E_{eq} = \frac{12\rho_{eq}\omega^2\left(1-\nu_{eq}^2\right)}{h_{eq}^2 k_B^4}$

2.3 Damping estimation

Two techniques are used to estimate the structural damping loss factor η. In the first, the GLM is used to estimate damping by energy balance considering the characteristics of main propagating wave [3]. In the second, the Power Input Method (PIM) is used to compute the structural loss factor from dissipated power Π_d, kinetic energy E_c and strain energy E_d):

$$\eta = \frac{\Pi_d}{\omega\left(E_c + E_d\right)}. \tag{1}$$

The latter method is also used to obtain a reference solution using a full 3D solid element based model of the sandwich structure. Obtaining this solution is computationally intensive as a direct forced response is used and an average over several excitation locations is needed.

3 Results and discussion

Two high damping configurations (80°C and 65°C) are studied. In both cases, compared to the reference solution, the energy balance considering the main wave overestimates the structural loss factor, except at low frequencies, as shown in Figure 2. A much better correlation is obtained using the GLM computed forced response.

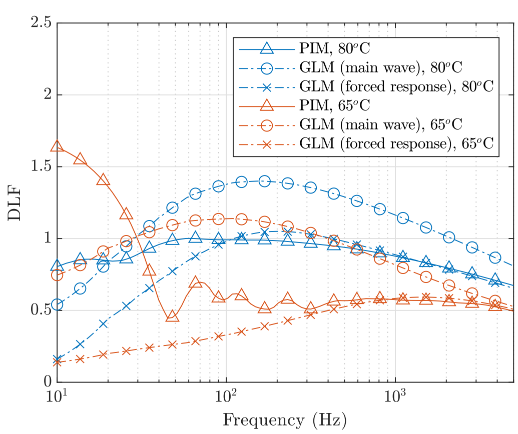

Figure 2: Structural damping loss factor (DLF) estimation: Power Input Method (PIM); GLM (energy balance, main wave) and GLM (forced response).

Systematic comparisons are presented between a reference finite element model (TET10 elements) of the sandwich structure and the equivalent plate (TRIA3). Figure 3 shows that for moderate damping the equivalent properties model is able to capture the response of the structure. However, it starts failing for the extremely damped configurations.

4 Conclusions

An equivalent plate model that preserves the dispersion relations of a highly damped sandwich structure with controllable properties is described. Estimating the structural damping loss factor for highly damped structures is an open research

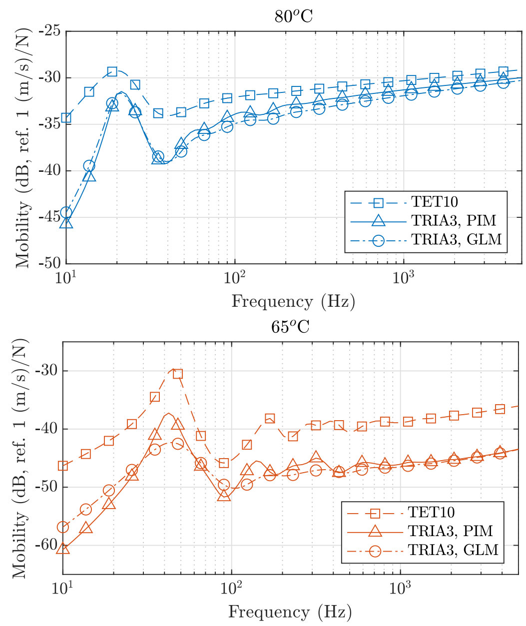

Figure 3: Point mobility: full 3D finite element model (TET10); and equivalent plate model (TRIA3) considering the effective properties and both damping estimates (PIM and GLM, main wave).

topic. For these cases, preliminary results indicate that the GLM can be used to adequately estimate the damping from the forced response. Overall, the equivalent plate model describes the dynamic behavior of the sandwich structure, but the discrepancies are still significant compared to a full 3D finite element model. By this approach, there is an important reduction in the computational cost (by one order of magnitude approximately). An accurate equivalent plate model allows to (re)evaluate in reduced time the configurations of the sandwich structure with SMP core for vibration control while maintaining stiffness.

Acknowledgments

The authors would like to thank ISITE-BFC (ANR-15-IDEX-0003), EUR EIPHI (ANR-17-EURE-0002) and the Natural Sciences and Engineering Research Council of Canada (NSERC) for their financial support.

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