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Acoustic transmission properties of pressurised and pre-stressed composite structures

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ABSTRACT

This work was focused on the examination of the effect of the pre-stress, namely tension and pressure, on the wave propagation and acoustic behaviour of composite laminates. The dispersion characteristics of two dimensional layered and sandwich structures were predicted using Wave Finite Element Method (WFEM). The structures were examined in non-stressed and pre-stressed scenarios. After extracting the mass and stiffness matrix of a small periodic segment of the structure using commercially available Finite Elements software, a polynomial eigenvalue problem was formed, the solutions of which consisted of the propagation constants of the waves of the structure. This way the wavenumbers and eigenvectors of the out of plane structural displacements were extracted. These wave propagation magnitudes were then used to calculate important Statistical Energy Analysis (SEA) quantities, such as modal density and radiation efficiency. The effect of pre-stress on these quantities, along with its effect on loss factor of the structure were examined.

1. Introduction

Current research in most industries, such as aerospace and automotive, focuses on materials that offer low density along with superior dynamic and static performance. This goal has led to increasing use of sandwich structures and composite materials in general, whose high stiffness-to-weight ratio along with the tailoring of their properties that they offer make them quite appealing. This high stiffness-to-weight ratio they offer, though, comes with a significant cost in their vibroacoustical behaviour, being responsible for high noise and displacement resonant vibrations. Prompted by that, elevated quality and quantity of research is about modelling the behaviour of these materials, along with conventional ones, using time and cost efficient computational methods. These methods are used to reach the goal of enhanced stiffness, weight and vibration behaviour.

Classical publications [1,2] offer analytic formulas to predict the wave propagation characteristics of numerous different structures. Classical Laminate Plate Theory (CLPT) is one of them [3], being developed as an extension of the Kirchhoff–Love's theory for isotropic panels and can be applied on thin orthotropic plates. Additionally, First-order Shear Deformation Theory (FSDT) [4] is based on the transverse shear deformation of the panel and can be used for the prediction of the dispersion characteristics at higher frequencies. Many researchers have used this kind of classical theories producing satisfying outcomes, such as Leppington et al. [5,6] who modelled the radiation efficiency and the vibroacoustic response under a reverberant field. Others [7,8] have mathematically improved the existing equations and examined the vibrational behaviour of laminated plates. Kurtze and Waters [9] were the first to examine the wave dispersion of thick sandwich structures by developing an asymptotic model. In their assumptions, though, the core was called incompressible, which kept them from modelling the deformation of the panel in the thickness sense. Dym and Lang [10], using the kinematic assumptions of [11] developed a structural model for an infinite sandwich panel deriving the five equations of motion corresponding to the symmetric and antisymmetric motion of the panel. Sokolinsky et al. [12] developed a consistent theory (Higher-Order Shear Deformation Theory, HSDT) taking into account the core's shear deformation and Wang et al. [13,14] used it to construct a structural model of an infinitely long sandwich panel in which the vibroacoustic response within an Statistical Energy Analysis (SEA) context was calculated. Wave propagation has been major object of intense research with numerous numerical methods being developed the last decades. Finnveden in [15] examined hollow beam structures and presented a method of calculating the wave dispersion in them. In [16] the authors used Spectral Finite Element (SFE) to predict the wave propagation characteristics, overcoming the thresholds of CLPT.

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In [17] the phase constant surfaces of periodic composite and stiffened structures was examined taking advantage of the periodicity using Periodic Structure Theory (PST) and Finite Elements (FE). In this work, an expression for the computing of the radiation efficiency was presented and the STL was expressed through the radiation and mechanical impedances of the structures. In [18,19] the authors used a multi-layer analytical model based on Mindlin theory to calculate the dispersion characteristics of layered structures. In this work, though, the symmetric mode of motion was not naturally expressed. The same authors [20] came back presenting an approach for taking into account the symmetric wave motion for thick panels. Wave Finite Element Method (WFEM) was firstly introduced in [21]. Its main aspect is that it takes advantage of the periodicity of the structure and using existing classical literature's periodic theory [2] manages to examine a structure's wave propagation by modelling only a small periodic part of it using FE for its analysis. This way the calculation of the wavenumbers and eigenvectors is achieved with considerably lower cost of time than the previous ones. WFEM has been used in one dimension [22,23] and in two dimensions analyses [24] producing quite satisfying results. Using FE for the structure's modelling has given researchers the ability to broaden the potentials of the method, calculating loss factor [25] with the help of existing theories [26]. In addition to that, Manconi et al. [27] calculated the effect of the pre-stress on the loss factor and wavenumbers of structures using two dimensional WFEM. Chronopoulos et al. in [28] produced the wave dispersion characteristics using the WFEM by forming a dynamic stiffness matrix for a honeycomb orthotropic sandwich panel, the results of which were validated experimentally. Also, the same authors in [29,30] using WFEM and SEA computed the broadband vibroacoustic response of composite shells and thick layered panels. Another use of WFEM is the examination of the potential band gaps in periodic structures. Domadiya et al. [23] used WFEM to model two different periodic beams to examine the band gaps and had the results certified with actual experiments. Droz et al. [31] proposed a mathematically improved version of the WFEM and calculated the wave propagation and band gaps in a periodically stiffened plate.

In this paper the effect of pre-stress on wave propagation and acoustical behaviour of laminates was examined. Two-dimensional WFEM was used to calculate the Sound Transmission Loss (STL) of thick structures by accounting for their symmetric and antisymmetric wave motion. Both non-stressed and pre-stressed scenarios were examined. Equations from [30] were used to compute the reverberant field STL of the structures directly derived by their SEA properties. Finally, the loss factor of each structure was calculated.

The paper is organized as follows: in Section 2 the WFEM is described, along with the calculation of the loss factor and the pre-stressed stiffness matrix $\mathbf{K}_s$. In Section 3 the calculation of the main SEA quantities is presented. In Section 4 the analysis scenarios are presented, along with the numerical results. Finally, in Section 5 concluding remarks are written and in Section 6 some thoughts on future work are presented.

2. The two dimensional WFEM

2.1. Stress stiffening

In this work two different scenarios of pre-stressed structures were examined, as described in the next section. In these cases, pre-stress stiffness matrix $\mathbf{K}_s$ was calculated. Considering that a static analysis has been solved, the updated stiffness matrix $\mathbf{K}$ was calculated [32]:

$$\mathbf{K} = \mathbf{K}_0 + \mathbf{K}_s \tag{1}$$

where $\mathbf{K}_0$ the original element stiffness matrix and:

$$\mathbf{K}_s = \iiint \mathbf{G}^T \boldsymbol{\tau} \mathbf{G} \mathrm{d}x\mathrm{d}y\mathrm{d}z \tag{2}$$

where $\mathbf{G}$ is a matrix of shape function derivatives and $\boldsymbol{\tau}$ is a matrix of the current Cauchy (true) stresses $\boldsymbol{\sigma}$ in the global Cartesian system.

The updated matrix $\mathbf{K}$ was then used in WFEM to get the wavenumbers and eigenvectors of the pre-stressed structure.

2.2. Description of the WFEM

In this paper a laminate of L_x length and L_y width was examined. An FE model of a small segment of the laminate was created. This segment's length was dx, while its width was dy (Fig. 1). The segment was meshed using commercially available FEA software. The vector of degrees of freedom (dofs) $\mathbf{q}$ of the segment is given in terms of dofs by [24]

$$\mathbf{q} = \begin{bmatrix} \mathbf{q}_1^T & \mathbf{q}_2^T & \mathbf{q}_3^T & \mathbf{q}_4^T \end{bmatrix}^T \tag{3}$$

where T denotes the transpose and $\mathbf{q}_n$ is the vector of nodal dofs of all the elements nodes which lie on the nth corner of the element [24]. Following the same logic, the vector of nodal force is given by

$$\mathbf{f} = \begin{bmatrix} \mathbf{f}_1^T & \mathbf{f}_2^T & \mathbf{f}_3^T & \mathbf{f}_4^T \end{bmatrix}^T \tag{4}$$

Conventional FE methods is then used to get the $\mathbf{M}$ and $\mathbf{K}$ matrices of the segment. Assuming time-harmonic behaviour and neglecting damping we have

$$[\mathbf{K} - \omega^2\mathbf{M}]\mathbf{q} = \mathbf{f} \tag{5}$$

Using Floquet theorem for a rectangular segment and taking edge 1 as reference we get

$$\mathbf{q}_2 = \lambda_x \mathbf{q}_1, \quad \mathbf{q}_3 = \lambda_y \mathbf{q}_1, \quad \mathbf{q}_4 = \lambda_x \lambda_y \mathbf{q}_1 \tag{6}$$

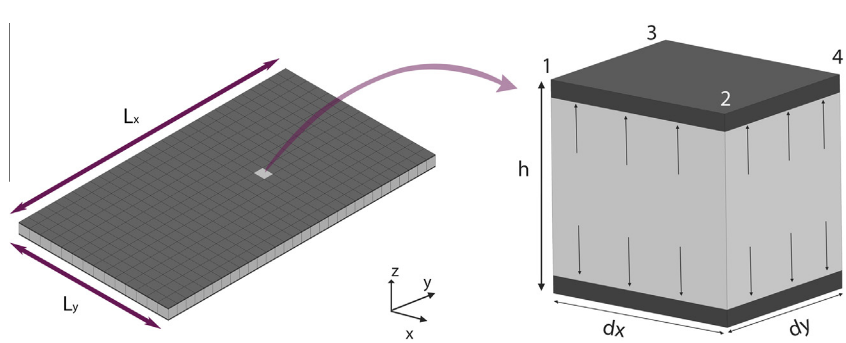

Fig. 1. Representation of the modelled internally pressurised periodic segment with its edges 1, 2, 3 and 4.