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Accurate structural identification for layered composite structures, through a wave and finite element scheme

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ABSTRACT

We present for the first time an approach for identifying the geometric and material characteristics of layered composite structures through an inverse wave and finite element approach. More specifically, this Non-Destructive Evaluation (NDE) approach is able to recover the thickness, density, as well as all independent mechanical characteristics such as the tensile and shear moduli for each layer of the composite structure under investigation. This is achieved through multi-frequency single shot measurements. It is emphasized that the success of the approach is independent of the employed excitation frequency regime, meaning that both structural dynamics and ultrasound frequency spectra can be employed. It is demonstrated that more efficient convergence of the identification process is attained closer to the bending-to-shear transition range of the layered structure. Since a full FE description is employed for the periodic composite, the presented approach is able to account for structures of arbitrary complexity. The procedure is applied to a sandwich panel with composite facesheets and results are compared with two wave-based characterization techniques: the Inhomogeneous Wave Correlation method and the Transition Frequency Characterization method. Numerical simulations and experimental results are presented to verify the robustness of the proposed method.

1. Introduction

Composites are widely used in modern industry, due to their low density and high dynamic and static performances. This goal has led to develop new sandwich structures and composite materials in general, with tailored properties and a wide range of possible configurations and topologies. However, the verification and Non-Destructive Evaluation (NDE) of the actual mechanical properties of the assembled layered structure remains a very much open engineering challenge. Experimental testing and system identification have played important roles in various fields such as civil engineering, mechanical engineering and aerospace engineering due to their versatile applications such as assessing system conditions and reconciling numerical predictions with experimental investigations [1–6]. In a broad context, ‘system identification’ refers to the extraction of information about the system behavior directly from experimental data [7,8]. Over the past decades, different system identification methods in the time domain [9–11], frequency domain [12,13] and time-frequency domain [14,15] have been proposed. System identification has been applied extensively in the field of structural dynamics and it has been proven to be useful in the analysis of the dynamic behavior of the structure. In the context of structural dynamics, system identification generally includes modal-parameter identification by extracting the modal data of a structural system such as its natural frequencies, damping ratio and mode shapes as well as physical-parameter identification by extracting useful information related to stiffness, mass and damping. Numerous approaches have been developed for system identification including stochastic subspace identification method [16], extended Kalman filter method [17] and Bayesian approaches [18–20] to cite a few of them.

The system identification approaches aforementioned are generally based on the measurement of structural vibration information. Nowadays however, several researchers have shown that propagating wave properties can have a high sensitivity to structural parameters than other structural responses. Therefore, sporadic but consistent efforts have been directed to extract a system’s structural condition using wave propagation information over the past decade [21,22]. However, it is worth mentioning here that rare work reviewed in [21,22] are dependent on the model. Though some efforts [23–25] have been devoted to inference the model parameters through wave propagation, they have not resulted in full-fledged applications. Therefore, there is

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Nomenclature

$\mathbf{M}$, $\mathbf{K}$	mass and stiffness matrices of the periodic waveguide
$\mathbf{D}$	dynamics stiffness matrix (DMS) of a waveguide's modelled periodic segment
$\mathscr{F}$	objective function to be minimized
$\mathbf{T}$	transfer matrix of the wave propagation eigenproblem
$\mathbf{f}$	forcing vector for an elastic waveguide
$\mathbf{p}$	vector of structural characteristics to be identified
$\mathbf{q}$	physical displacement vector for an elastic waveguide
$\mathbf{x}(t)$	logged signal vector as a function of time
ρ, h, E, G, ν	mass density, thickness and mechanical characteristics of each layer
L_x	dimension of a waveguide's modelled periodic segment
L, R, I	left, right sides and interior indices
U_0	amplitude of applied excitation signal
	wave phase velocity
c_g	wave group velocity
f_0	frequency of the applied excitation
k	wavenumber
l, l_{max}	index corresponding to layer number and total number of structural layers
m, m_{max}	index corresponding to each measured frequency and total number of measured frequencies
n_0	number of cycles for the Hanning windowed excitation
rf, fe	indices denoting wave characteristics obtained through measurements and the WFE scheme respectively
s	periodic segment positioning index
t	time
x_0, x_1	coordinates of the excitation and monitoring locations on the waveguide
$\Phi_q^{\omega,+}$, $\Phi_q^{\omega,-}$	grouped displacement eigenvectors for the positive and negative going elastic waves at frequency ω
$\Phi_f^{\omega,+}$, $\Phi_f^{\omega,-}$	grouped forcing eigenvectors for the positive and negative going elastic waves at frequency ω
$\boldsymbol{\phi}_q$, $\boldsymbol{\phi}_f$	displacement and forcing eigenvectors
β	arbitrary structural property
γ	propagation constant and eigenvalue of the wave propagation eigenproblem
ω	angular frequency

still significant room for further exploration in system identification by integrating mathematical models of wave propagation. Many methods have been developed to perform material characterization in composites. On can cite the experimental method for the characterization of Nomex cores [26], or the vibratory identification technique proposed in Matter et al. [27]. Other methods based on numerical strategies were also developed in [28,29]. Recently, a Transition Frequency Characterization technique [30] was developed to perform material identification in sandwich structures, based on the so-called bending-to-shear conversion effect. However, such methods could not handle more complex topologies often encountered in transportation industry, despite the considerable progress made on the numerical wave-based models in this field.

The propagation of guided waves in sandwich structures has indeed been the subject of intense research in the recent years. Traditional analytical methods (i.e. classical plate theory, Mindlin type or first-order shear deformation theories) typically employed for modelling wave propagation in monolayers can only correctly capture the wave characteristics in the low frequency range for thick structures. In contrast, Finite Element (FE) based wave methods assume a full 3D displacement field and are therefore capable of capturing the entirety of wave motion types in the waveguide under investigation in a very accurate and efficient manner. FE-based wave propagation within periodic structures was firstly considered in the pioneering work of the author of [31]. The work was extended to two dimensional media in [32]. The Wave and Finite Element (WFE) method was introduced in [33,34] in order to facilitate the post-processing of the eigenproblem solutions and further improve the computational efficiency of the method, while the extension of WFE method for two dimensional structures was introduced in [35].

The principal novel contribution of this work is the development of a comprehensive methodology coupling periodic structure theory to FE in order to identify the characteristics of each individual layer of a composite structure through experimental measurements on the entire structure. The method is robust and can account for structures of arbitrary complexity. Both low as well as high frequency excitations can be employed for inverting the structural problem. It is shown that faster convergence can be acquired around the wave transition region [36,37] which is a specific type of wave conversion [38,39], occurring in sandwich structures subject to flexural vibrations. Both experimental, as well as numerical case studies are presented in order to validate the exhibited methodology.

The paper is organised as follows: In Section 2 the FE computational scheme for predicting wave propagation in multilayered structures is presented and targeted suggestions are made in order to effectively recover the structural and material characteristics for the structure under investigation. A Hilbert Transform is employed to measure the time of arrival of the wave pulses and subsequently the propagating wavenumbers. A Newton-like iterative scheme is eventually employed for minimising the formulated objective function and recovering the mechanical characteristics of each individual layer through solution of the system of eigenvalue expressions. In Section 3 several experimental and numerical case studies are presented for validating the exhibited identification approach. A periodic layered structure is modelled and multi-frequency single wave shots are excited and measured. The structural and material characteristics for each layer are then recovered. Conclusions are eventually drawn in Section 4.

2. An inverse wave and finite element methodology for structural identification

Mathematical modeling can provide a good understanding and form the basis of a characterization process for a mechanical system. Given the mathematical model, system identification can be implemented by fitting it to that from experimental testing. In the present paper, the primary focus is to improve structural models by measurements performed on the real structure using wave propagation measurement data. As a result, one can make inference about the parameters of a mathematical model based on the observed measurements.

An arbitrarily complex and periodic in the x direction waveguide is illustrated in Fig. 1. The structure may comprise an arbitrary number of layers which may be anisotropic. It is assumed that some of the structural characteristics are unknown (or even variable over time) and need to be evaluated through a non-destructive evaluation process. The identifiable properties include the thickness, density as well as the material characteristics of each individual layers. In the following, a wave and finite element scheme is employed in order to recover the required properties of the layered structure through the acquired propagating wave data.

2.1. Obtaining the reference wave characteristics

The required data to be extracted and later fed into the structural identification process are the wave phase speeds (or wavenumbers) of specific wave types propagating within the laminate under investigation. A number of methods can be employed for exciting and measuring