



Identification of the anisotropic elastic and damping properties of complex shape composite parts using an inverse method based on finite element model updating and 3D velocity fields measurements (FEMU-3DVF): Application to bio-based composite violin soundboards

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ABSTRACT

Inverse methods have been used for decades to identify material properties, in parallel, or as a substitution for direct methods. Although it has proven a useful method for many types of materials and simple geometrical shapes, it has barely been used on complex shape parts. This is the main objective of the non-destructive method proposed in this study. The proposed inverse approach, based on both vibrational experiment data and Finite Element Model Updating (FEMU), is successfully applied to a violin soundboard made of flax-epoxy composite. Results show that, by minimizing the discrepancy between the experimental and numerical data, three rigidities and three loss factors can be determined simultaneously. The identified values of the constitutive elastic moduli and longitudinal loss factor are in agreement with those determined using quasi-static tests and dynamic mechanical analysis.

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1. Introduction

As the utilization of composite materials in research and industry has been continuously growing over the last three decades, numerous identification methods have been developed to identify the material properties of composite parts. The wide variety of shapes and applications of composite materials has driven to more and more sophisticated manufacturing processes and characterization methods. Both direct and indirect methods are classically used. Direct methods estimate the material properties from experimental data and fundamental mechanics theories. The second ones, also called inverse methods, are based both on experiments and models and a minimization procedure for the identification of the parameters. Each method has its advantages and drawbacks and some are not necessarily adapted to complex shapes and complex constitutive behaviour. Direct methods are generally destructive or at least with contact and have been traditionally used to measure the properties of a wide variety of materials. They are still considered as reference methods for the study of new materials and can be used to evaluate material properties even when they exhibit a complex behaviour, such as composites [1]. The growing

need for contact free methods for material characterization has led to the use of powerful experimental techniques, such as full-field measurements [2,3] and resonant ultra-sonic methods [4,5]. Some studies have successfully compared the results collected with such techniques to the ones obtained with standard static tests [6] and emphasized their capability and efficiency. Inverse methods based on both dynamic experimental data and Finite Element Model Updating (FEMU) can also be considered as a powerful method. The fitting of a numerical simulation with experiments using minimization methods [7] enables the determination of the properties of materials exhibiting a complex behaviour. This type of method is non-invasive, fast and easy to set-up. It requires a reduced preparation of the samples, compared to other traditional methods that require calibrated specimens. Moreover, dynamical responses, for example vibratory modes, are more representative of the global behaviour of the material when compared to static properties that are generally driven by local phenomena. These benefits have led to the development of numerically based identification methods over the last thirty years [8], as well as analytically based methods, to estimate both anisotropic loss factors and rigidities of composite plates [9]. The efficiency of the FEMU method in the case of non-standard specimen shapes has been assessed studying layered materials, and the impact of the grain angle on the material properties [10]. Sandwich structures have also been characterized using this validated method [11–13]. Many studies were focused on

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other types of structures or materials, like wooden beams [14], printed electric circuit material [15] and tonewood plates undergoing moisture content changes [16]. Only few studies concern different shapes, such as composite tubes [17]. More recently, in 2016, a review paper [18] made a list of the numerous works about the identification of material properties using vibrational approaches. This paper highlights the fact that, despite its potential, this method has mostly been applied to flat plate specimens and not complex shape parts. These parts, such as silicon carbide blades or composite corner reinforcements, are generally made of materials whose properties depend on the manufacturing process. The indirect methods deal with uncertainties, and stochastic methods for model updating have been proposed in [19,20] to quantify the sources of uncertainties due to the method. Nevertheless, stochastic methods need a large amount of experimental data and computations. As a conclusion of these different works, one remaining need is to use and validate FEMU method for 3D complex shaped parts which is the main purpose of this work. This study will focus on complex shapes and material behaviour to assess the efficiency of this method. The FEMU-3DVF method deals with a finite elements model and an experimental set-up constituted of an acoustic exciter (speaker) and a Doppler effect laser 3D vibrometer. This allows the determination, through the measurement of velocities at the surface of the specimen in the three material directions, of the dynamical response (operational modes) of the parts. The experimental data obtained are rich and detailed. The diversity of the resulting displacement fields of the specimen activate in a single experiment different material properties. The identification process requires an efficient method. This consists of the minimization of the discrepancies of the frequencies of the matched test-analysis modes. A preliminary sensitivity analysis is performed to determine which components of the compliance matrix of the constitutive law can be identified reliably, based on their influence on the computed modal basis. The parts studied in this work are half scale violin soundboards. Similar full-scale bio-based composite sandwiches made of flax fibre composite skins with a balsa core have been made as a substitute for bulk wood in the manufacturing of violin soundboard [21]. The bio-based composites are considered as an alternative to wood for the making of violin soundboard (spruce, *Picea abies*) [22]. The flax-epoxy composites show a lower variability than wood, and the cost of the materials used for bio-based composite soundboards is smaller than the cost of high quality tonewood. The sensitivity to relative humidity is also lower than for wood and thus it enhances the stability of musical instruments when undergoing climatic changes. Moreover, the loss factors of bio-based composite in the different material directions are closer to wood than glass or carbon fibre composites. Composite parts of violins are currently

manufactured and studied, and the need of non-destructive characterization method is at the origin of the development of the FEMU-3DVF method. So, in this work, the capacity and performance of the proposed method is demonstrated at the scale of a violin soundboard made of bio-based composite, but the method is suitable for any given part with a complex 3D shape. In the following, the materials and methods used are fully described. The elastic and damping properties determined using FEMU-3DVF in the vibratory domain are compared to those obtained with quasi-static flexural tests and Dynamic Mechanical Analysis (DMA). A master curve built using DMA is used to compare the material properties at the same frequencies of solicitation that are used for the FEMU-3DVF method.

2. Materials and methods

2.1. Materials

The parts considered in this study are bio-based composite violin soundboards whose dimensions are half scale compared to standard sized soundboards. The soundboard of a violin is the top part of the body. It is traditionally hand carved to create an arch, and two f-shaped holes are cut symmetrically.

2.1.1. Composite violin soundboard manufacturing

The bio-based composite soundboards are manufactured by thermocompression of the flaxpreg T-UD[®] material, a pre-impregnated flaxtape provided by LINEO[®]. The areal weight of the reinforcements is 110 g/m². The resin that is used is the XB3515[®] and the hardener is the Aradur5021[®]. The manufacturing method is schematically represented in Fig. 1(a). The parts are made of sixteen flax layers aligned and stacked. The layers are compressed in a Teflon coated aluminum mould and cured for one hour and a half at the cure temperature of 130 °C. The mould is machined to the shape of the arch of the violin soundboards using a numerical control machine and computer aided design. A pressure equal to 3 bars is applied for a period of 1 h after 30 min of heating. The arched plate is cut using a Trotec Speed300[®] laser device. The bio-based composite violin soundboard is represented in Fig. 1(b). Two soundboards (called S_1 and S_2) were made, their dimensions are determined manually with a sliding calliper for length, width and thickness of the edges. A compass calliper is used to measure the inner thickness of the part. Their lengths, from bottom to top of the soundboards are 167 ± 0.05 mm. Their width, from left to right side on the lower part of the soundboard are 100 ± 0.05 mm. The thicknesses have been measured at twenty points and the mean value is taken for the making of the model. The fibre mass fraction of the composite material, M_{fibre} , is calcu-

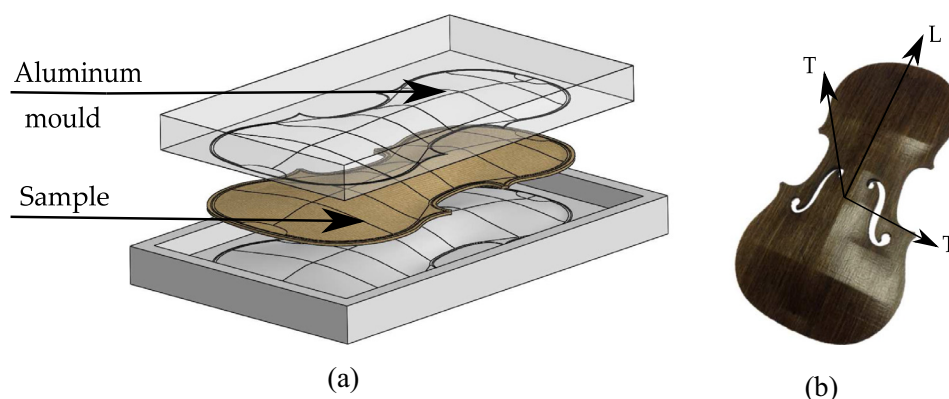


Fig. 1. Composite soundboard, (a) Manufacturing tool scheme, (b) specimen and material orientation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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