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DYNAMIC CHARACTERISATION OF A HONEYCOMB SANDWICH STRUCTURE IN A WIDE FREQUENCY RANGE

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ABSTRACT

This paper deals with the experimental characterisation of a thick sandwich plate with a honeycomb core. Measurements were conducted by means of a 3D Laser Doppler Vibrometer with piezo excitation, allowing the assessment of the out-of-plane and in-plane displacements of the sandwich structure in a large frequency range (1-50 kHz). In addition, similar laser Doppler measurements were performed using a pump laser to excite the plate up to 300 kHz. Dispersion measurement results and equivalent mechanical properties (flexural rigidities) are obtained by using the wave fitting approach IWC (Inhomogeneous Wave Correlation). These results are compared to an analytical model based on the work of Guyader (JSV 1978). Through this experimental study, complex dynamic behaviours of the structure (shearing of the core, decoupling of the layers, dynamic evolution of the mechanical properties) are identified and analysed.

1. INTRODUCTION

Multilayered structures are widely used in industry nowadays. The characterisation of such structures requires an accurate knowledge of their complex dynamic behaviours.

Different experimental procedures exist for the characterisation of multilayer structures. At high frequencies, where modal analysis approaches become inappropriate, other techniques based on vibration field analysis have demonstrated their efficiency. Among them, wave fitting methods, such as IWC (Inhomogeneous Wave Correlation) developed by Berthaut et al. [1] or the Hankel fitting approach used by Roozen et al. [2], stand out. These techniques are global since they are applied on the total measured area. On the contrary, local approaches, such as the CFAT (Corrected Force Analysis Technique) [3] or the VFM (Virtual Field Method) [4], locally solve the equation of motion of the structure. In another recent approach, Margerit et al. developed a promising characterisation method using ESPRIT algorithm to extract complex wavevector for 1D [5] and 2D [6] structures in wide frequency range.

In this paper, a thick honeycomb sandwich plate is characterised in a wide frequency band using the IWC method. Dynamic mechanical properties are obtained by means of an equivalent methodology based on Love-Kirchhoff's theory. The experimental results, focused on the equivalent parameters as well as the dispersion curves of the structure, are compared to the predictions of an analytical model. The first section of this paper presents the experimental protocols used in this study. In a second part, the characterisation technique IWC, the analytical model as well as the equivalent methodology are described in details. Finally, the results are shown and analysed in the third section.

2. EXPERIMENTAL PROTOCOLS

The studied structure is composed of two aluminium skins separated with a Nomex honeycomb core. The thickness of each skin is 0.6 mm while the thickness of the core is 9 mm. The area of the plate is 0.73×0.52 m^2. Note that the honeycomb core involves that the mechanical properties of the three-layers structure are orthotropic. Two experimental protocols have been conducted on this sandwich.

2.1 Protocol (A)

In the first protocol, the plate is hung to a frame using elastics in order to tend toward free-free boundary conditions. A broadband chirp excitation is applied on the structure by means of a piezoelectric disc placed in the middle of the plate. The transverse (W) and in-plane (U and V) displacement fields of the structure are measured in the frequency range 1–50 kHz using a 3D Laser Doppler Vibrometer on a regular 2D mesh around the excitation. This mesh is parallel to the edges of the plates and is composed of 270×187 points with a spatial step $d_x = d_y = 2$ mm (see Fig. 1). We can also notice on Fig. 1 that the main axes of the honeycomb core (x', y') are oriented of an angle $\theta_T \approx 7^\circ$ as compared to the axes of the mesh (x, y). The structure is then considered anisotropic in the (Oxy) coordinate system. A damped rope is threaded into holes placed in the edges of the plate to locally increase the damping of the structure and attenuate the reflected waves. This procedure is used to improve the performances of the IWC method.

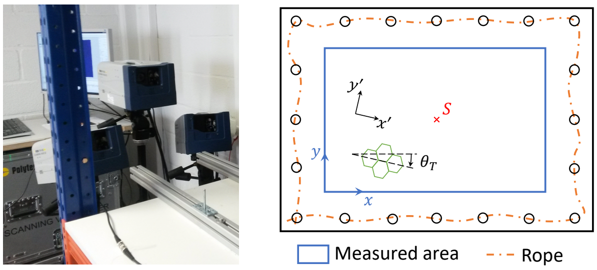

Figure 1: Measurement set-up of the protocol (A). 3D Laser Doppler Vibrometer (left). Sketch of the measured plate (right).

2.2 Protocol (B)

The second protocol is similar to the one used by Roozen et al. [7] to characterize an isotropic sandwich. The plate is hung to a frame and the rope is kept. The structure is excited by means of a pump laser (Nd-YAG) with photo-acoustic impulses and its transverse displacement is measured up to 300 kHz using a monopoint Laser Doppler Vibrometer. The point of excitation moves along a line by means of a mirror and a scanning stage while the measurement point is focussed on a fixed position (see Fig. 2). With this set-up, two measurements are performed along lines parallel to the edges of the plates. A 1D mesh of 302 points defined by a spatial step of 0.5 mm is used for both measurements.

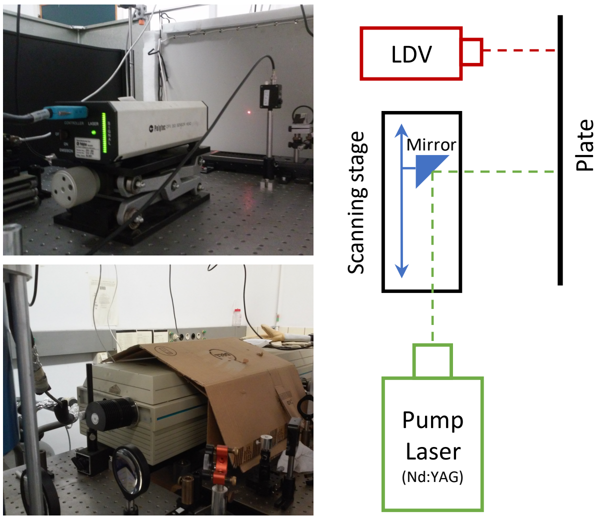

Figure 2: Measurement set-up of the protocol (B). Monopoint Laser Doppler Vibrometer (top left). Pump laser (bottom left). Sketch of the set-up (right).

3. CHARACTERIZATION TECHNIQUE AND ANALYTICAL MODEL USED IN THIS STUDY

3.1 Characterization method: IWC

The IWC method [1] assumes that the measured displacement field $w(x, y)$ of the structure is similar to a plane wave σ propagating in a direction θ and defined by a complex wavenumber k:

$$\sigma_k(x, y) = e^{-\mathrm{j}k(x\cos(\theta)+y\sin(\theta))}. \tag{1}$$

A correlation coefficient between the real and virtual displacement field is calculated for each angular frequency ω and direction θ as function of k:

$$\mathrm{IWC}(k) = \frac{\left|\sum_i \sum_j w(x_i, y_j)\sigma_k^*(x_i, y_j)\right|}{\sqrt{\sum_i \sum_j |w(x_i, y_j)|^2 \cdot \sum_i \sum_j |\sigma_k(x_i, y_j)|^2}}, \tag{2}$$

where the superscript $*$ denotes the complex conjugate. The value of k that maximizes the IWC coefficient is considered as the flexural wavenumber of the structure $k_\mathrm{f}(\theta, \omega)$.

3.2 Analytical model

The analytical model used in this study was initially developed by Guyader and Lesueur [8] for orthotropic multilayers and has been extended to anisotropic structures by Loredo and Castel [9]. The behaviour of each layer is described by a Reissner-Mindlin's displacement field taking into account the flexural, membrane and shearing effects. The transverse displacement is supposed to be constant for all layers, neglecting the deformation through the thickness. Continuity conditions between layers lead to equations of motion which are independent of the number of layers. An energetic aspect governed by Hamilton's principle is used to derive the equations of motion of the multilayer. A specific solution of this equation leads to the dispersion curves of the plate.

3.3 Equivalent methodology

In order to characterize the structure, we used an equivalent methodology [10] that we have recently extended for anisotropic structures [11]. This method determines, for a given frequency, the complex flexural rigidities D_{ij} of an equivalent anisotropic single layer plate under Love-Kirchhoff thin plate theory, in order to exhibit the same transverse displacement as the multilayer. It assumes that the flexural wavenumber $k_\mathrm{f}(\theta, \omega)$, identified with the IWC method or the analytical model, is solution of the dispersion relation of the equivalent thin plate, which is for anisotropic panels:

$$D_{11}c^4 + D_{22}s^4 + D_{12}c^2s^2 + D_{16}c^3s + D_{26}cs^3 = \frac{\rho h\omega^2}{k_\mathrm{f}^4}, \tag{3}$$

where $c = \cos(\theta)$ and $s = \sin(\theta)$. The D_{ij} coefficients are identified as function of frequency by means of a least square method detailed in the paper [11].

4. RESULTS

4.1 Flexural mode

This section focuses on the analysis of the flexural mode of the structure. The IWC method has been applied on

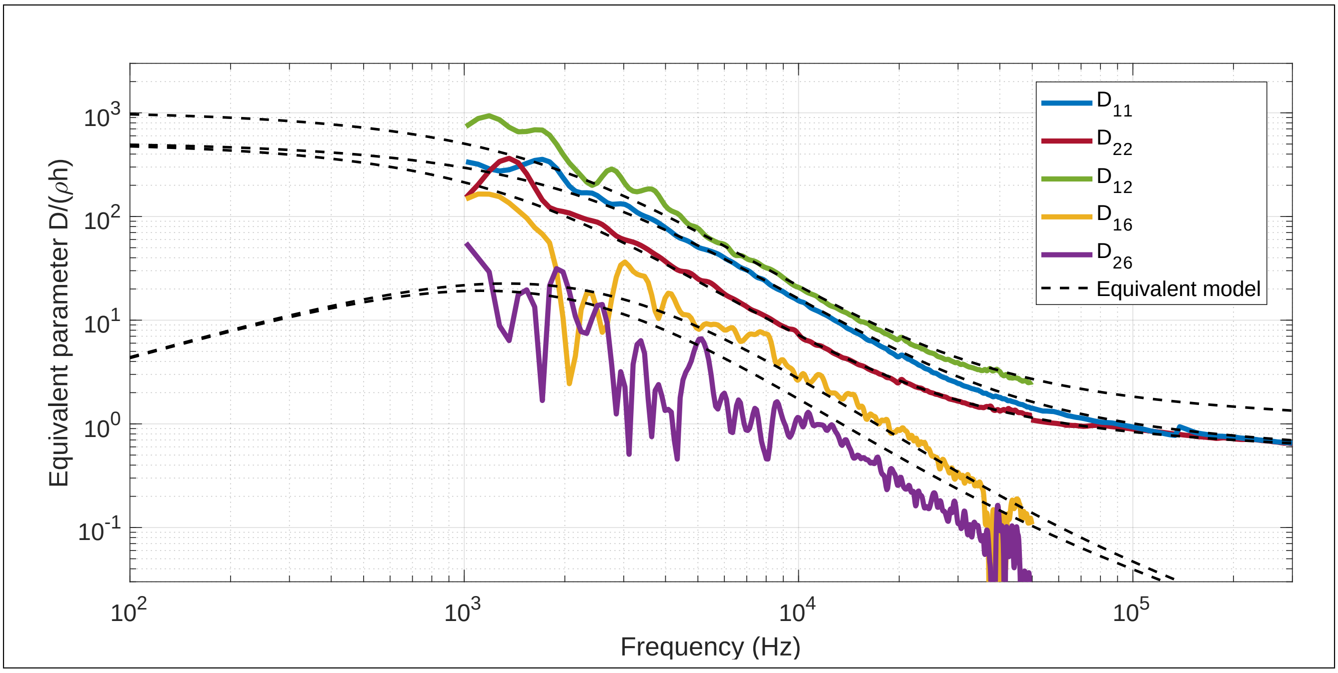

Figure 3: Comparison of the equivalent flexural rigidities experimentally identified with the IWC method and analytically estimated by the equivalent model.

the transverse displacement fields measured in both protocols (A) and (B).

Aluminium skins	**Nomex honeycomb core**
$h = 0.6$ mm	$h = 9$ mm
$\rho = 2700$ kg.m^{-3}	$\rho = 170$ kg.m^{-3}
$E = 70$ GPa	$G_{xz} = 70$ MPa; $G_{yz} = 115$ MPa
$\nu = 0.3$	$\nu_{xz} = 0.12$; $\nu_{yz} = 0.2$

Table 1: Mechanical parameters of the layers used in the analytical model.

Fig. 3 compares the flexural rigidities identified by the IWC method and estimated by the model using the equivalent methodology. The D_{12}, D_{16} and D_{26} coefficients are not identified by the IWC method in the frequency range 50-300 kHz since the measurements of protocol (B) have been performed along the x and y axes only. Materials parameters of the layers used in the equivalent model are summarized in Table 1. Classical parameters have been chosen for the aluminium skins. Concerning the honeycomb core, we couldn't characterize this layer alone. We noticed that the results of the model are essentially driven by the shear modulus G_{xz} and G_{yz} as well as the mass density ρ of this layer. Different simulations have been performed varying these parameters around values obtained from literature [12]. Then, we selected the optimal parameters that minimize the differences between the flexural rigidities identified by the IWC method and the analytical model on the whole frequency band.

In low frequency range (0.1-1 kHz), the behaviour of the structure is essentially controlled by the flexural motion of the skins. The equivalent material properties are then isotropic ($D_{11} \simeq D_{22} \simeq D_{12}/2$ et $D_{16}, D_{26} \simeq 0$). In the mid frequency range (1-50 kHz), the dynamic behaviour is governed by the shearing effect of the core. It involves a decrease of the equivalent flexural rigidities since the thin plate theory only considers the flexural motion of the structure. The equivalent material properties are then anisotropic ($D_{11} \neq D_{22} \neq D_{12}$ and $D_{16} \neq D_{26} \neq 0$. At higher frequencies, a decoupling effect of the layers is observed and the dynamic behaviour is controlled by the flexural motion of one skin. The equivalent material properties in this frequency range become, again, isotropic.

The dynamic behaviour of the structure can also be observed in the wavenumber domain. Fig. 4 compares the correlation coefficient of the IWC method as function of k_x and k_y with the flexural wavenumber predicted by the model at 10 and 50 kHz. Similar conclusions can be established: the results of the model fit with consistency the maximum of correlation of the IWC method. The global behaviour of the structure is orthotropic at 10 kHz (non circular shape of the wavenumbers) and tends toward isotropy at 50 kHz (circular shape of the wavenumbers). We also notice that the orthotropy of the structure can be qualified of "elliptical". This special type of orthotropy is defined by the relation:

$$D'_{12} = 2\sqrt{D'_{11}D'_{22}}, \tag{4}$$

where the D'_{ij} coefficients correspond to the flexural rigidities in the main axes of the honeycomb (x', y').

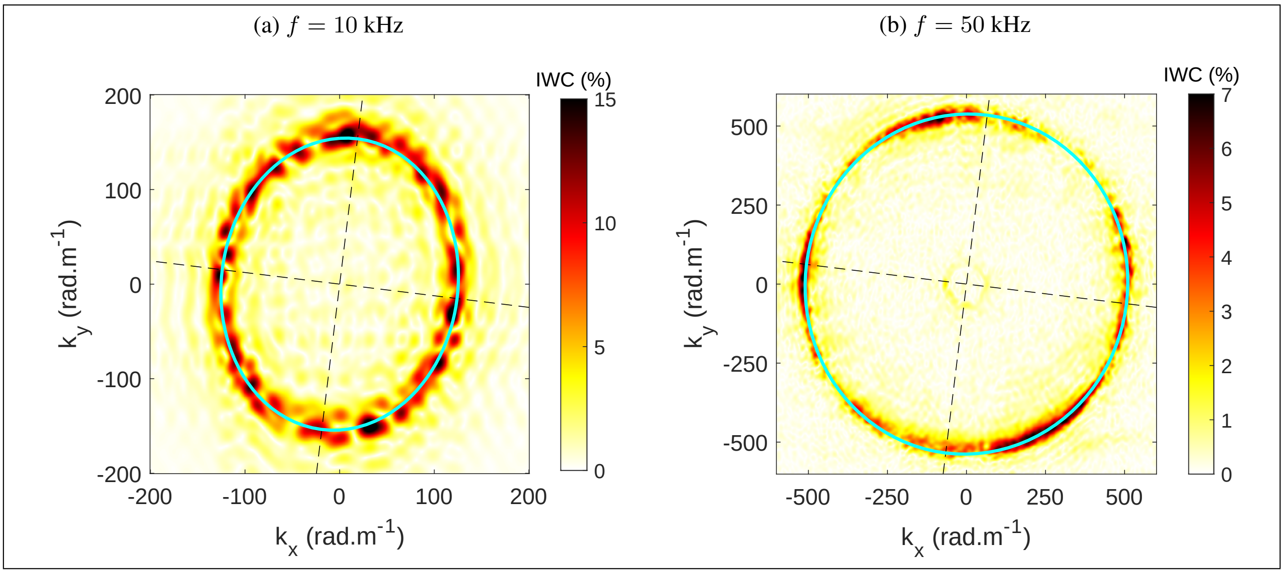

Figure 4: Correlation coefficient of the IWC method applied on the tranverse displacement field W in the wavenumber domain at 10 (a) and 50 (b) kHz. Analytical model (—). Axis of orthotropy (– –).

4.2 Membrane and shear modes

This last section deals with the analysis of the membrane and shear modes of the structure. The IWC method has been applied on the in-plane displacement fields measured in the protocol (A).

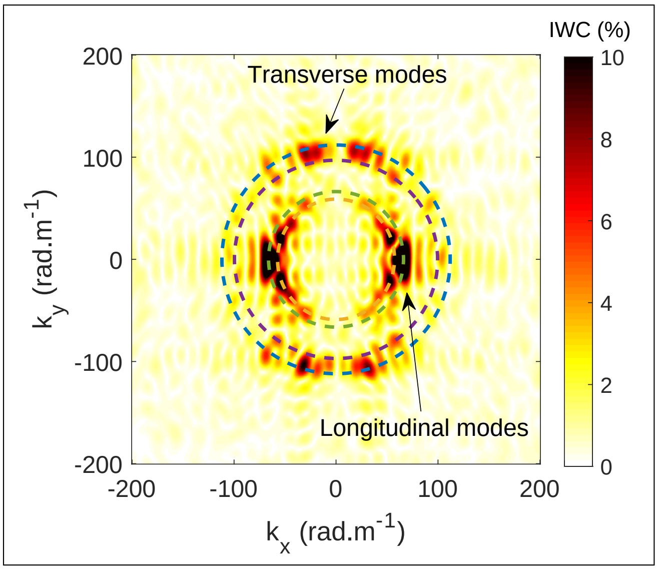

Figure 5: Correlation coefficient of the IWC method applied on the in-plane displacement field U in the wavenumber domain at 50 kHz. Analytical model (Membrane (– –), Transverse membrane (– –), Shear (– –), Transverse shear (– –))

Fig. 5 presents the correlation coefficient of the IWC method (applied on the U field only) in the wavenumber domain at 50 kHz. These results are compared to the dispersion curves estimated by the model. For the U field, the maximum of correlation corresponds to the longitudinal modes (waves propagating in the x direction) and the transverse modes (waves propagating in the y direction). For the V field (not shown here), the axes of the maximum of correlation are inverted. Each of these modes are well described by the model with dispersion curves corresponding to shearing and membrane motions.

5. CONCLUSION

In this paper, a honeycomb sandwich structure has been characterized by means of the IWC method in a wide frequency band (1-300 kHz). Frequency dependent equivalent material properties have been identified using the Love-Kirchhoff's theory. Through these results, the dynamic behaviour of the structure has been described: flexural motion at low frequencies, shearing of the core at mid frequencies and decoupling of the layers at high frequencies. The characteristics of the honeycomb core have been identified fitting the experimental results with the estimations of an analytical model. Membrane and shear modes have also been identified applying the IWC method on in-plane measurements. A perspective of this study could be to analyse the measurements with other techniques (such as the CFAT method [13] or the Hankel fitting approach) and compare the results with complete models (such as Lamb waves) which are not based on any kind of model assumptions. A further interesting research line is the application of CFAT procedure for determining local stiffness/damping values of composite plates [14]. Any abnormalities in these local quantities could reveal the presence of internal defects and damage.

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