Using near-field acoustic measurements to characterise mechanical and acoustic properties of lightweight building structures

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Abstract

The evaluation of the vibrational field on a certain surface has a great importance in noise control engineering applications. It can be helpful, both for noise reduction purposes, and diagnostic purposes, in product optimisation, or in order to characterise the mechanical properties of the vibrating structure. Accelerometers are still the most used sensors to measure vibration. However, contactless transducers, such as scanning laser doppler vibrometers (LDV), have been widely used recently, presenting several advantages. Near-field acoustic holography may represent a valid alternative to LDV, in order to reconstruct the vibrational field on a surface from sound pressure measurements performed with an array of microphones. This paper presents the preliminary results, of a ongoing project regarding the use of near-field acoustic holography to characterise the elastic and acoustic properties of a lightweight building structure. The used test rig allows to scan the sound pressure over the vibrating surface on a grid of points, using an array of microphones. The panel's dynamic response was used to evaluate its elastic properties. The reliability of this experimental approach was assessed by comparing the results with the ones obtained using miniature accelerometers. These elastic properties were finally used as input data to model sound transmission through the plywood panel using the transfer matrix method, investigating the accuracy by comparing the numerical results with the experimental sound insulation.

Keywords: near-field acoustic holography, building acoustics, mechanical characterisation, structural wavenumbers

1 INTRODUCTION

Nowadays, lightweight solutions are increasingly employed in building construction, as in many other fields of engineering, since they present several advantages compared to traditional massive systems. However, since these systems cannot rely on their mass to provide a satisfying sound insulation, it is necessary to properly design and optimise each building partition, in order to guarantee a comfortable indoor environment, providing an adequate acoustic performance [1, 2, 3, 4]. Several models have been proposed by different authors in order to accurately predict sound radiation from and sound transmission through building partitions [5, 6, 7, 8, 9, 10]. To this purpose, the elastic properties of the materials the considered partition is made of are required as input data by all the different vibro-acoustic simulation models [11]. Several experimental methods can be used in order to evaluate the mechanical characteristics of the different elastic or viscoelastic materials employed in building construction [12, 13, 14, 15]. Lately, wave correlation approaches have been successfully adopted in order to determine the experimental wavenumber dispersion relation, which can be used to evaluate the elastic and the damping properties of the investigated structure [16]. In order to apply such methods, the dynamic response of the investigated structure due to a broadband mechanical excitation needs to be measured along a line of equally distributed points. Measurements of the vibrational filed are commonly performed by using accelerometers attached to the surface of the vibrating structure. By using miniature transducers, it is possible to investigate a wide range of materials, even though contactless transducers are sometime preferred, in order to avoid any small influence of added masses on the dynamic response of very lightweight elements. Besides, the measurement performed by using accelerometers requires a great time effort in order to have a good spatial resolution. By using a scanning laser doppler vibrometer (LDV), having the possibility to automatically move the laser beam over the different grid points, the time required to measure the dynamic response over the entire surface can be drastically reduced. Moreover, it also allows to overcome the issue of the influence of added masses on the dynamic behaviour of the investigated structure. By using near-field acoustic holography (NAH) [17, 18] or very-near-field acoustic holography [19], it is possible to reconstruct the structural dynamic response from acoustic measurements, performed with an array of microphones. Such experimental approach can be used in order to measure the dynamic response of a given structure by using contactless transducer, as a valid alternative to optical-based approaches. The good agreement of NAH measurements compared to standard LDV was proven by Martarelli and Revel [20], also highlighting the advantages and disadvantage of these two methods.

In this study, a plywood panel was experimentally investigated, by using a test rig specifically designed to characterise the dynamic behaviour of lightweight building partitions. The dynamic response of the structure was determined by using an array of microphones as described in section 2. By using a wave correlation approach, the wavenumber dispersion relation, associated to a given propagation direction was evaluated. From the vibrational field measured over a line of points it was possible to evaluate the velocity of the structural wave propagating in that direction, which in the case of a point-force mechanical excitation, is strictly related to elastic properties of the investigated element. The reliability of the results has been determined by comparing the wavenumber dispersion relations and the elastic properties derived from sound pressure measurement with the results obtained form accelerometers, as discussed in section 3. The evaluated elastic properties were finally used as input data to model sound transmission through the plywood panel by using the transfer matrix method. The accuracy was investigated comparing numerical results with the experimental sound insulation. Finally, the possible future developments of this approach are discussed, since it offers several possibilities for a complete vibro-acoustic experimental characterisation of lightweight structures: for example the experimental evaluation of the damping properties, or the resonant radiation efficiency [21] of the investigated structure.

2 EXPERIMENTAL MEASUREMENTS

2.1 Experimental Setup

The used test rig is constituted by a steel frame, in which a small rectangular sample, with a surface area of approximately 1 m^2 ($L_x = 0.98$m, $L_y = 1.18$m), can be installed. Two moving parts allow the investigated plate to be held in place by clamping all the four edges, as shown in Figure 1(a). The height of the frame can be adjusted in order to place a shaker, representing the exciting source, underneath the panel. A two-direction sliding carriage, hosting 9 microphones, is mounted on the top of frame, as shown in Figure 1(a,b). The shaker needs to be encapsulated within a wooden box, internally lined with porous material in order to reduce the sound field generated by the shaker, which could influence the measurements. It was rigidly attached to the investigated structure, a 15 mm thick plywood board made of 5 thin plies with density $\rho = 400\mathrm{Kg/m}^3$, and driven with a 10 seconds exponential sine sweep from 20 Hz up to 6000 Hz. In order to evaluate the dynamic response of the investigated plate, the sound pressure was measured by using 9 PCB $1/2''$ microphones simultaneously, placed at a stand-off distance r from the radiating surface, as shown in Figure 1(c). The microphones were previously calibrated in amplitude, by using a B&K type 4231 sound level meter calibrator. By installing an impedance head between the shaker stinger an the panel's surface it was possible to obtained the input force and acceleration of each single measurement. All the acquired signals - force, acceleration and sound pressure - were then convolved with the inverse filter of the sine sweep to obtain the impulse responses (IR) of that particultar suorce receiver configuration [22], a well established experimental technique widely used in room acoustics [23]. In order to guarantee the same relative phase relationship between the signals acquired by non-simultaneous measurements, the IR associated to each input channel was aligned in time with a reference IR, represented by the force signal of the impedance head transducer, placed on the shaker's stinger. The complex spectra of the IRs were obtained by means of a fast Fourier transform algorithm.

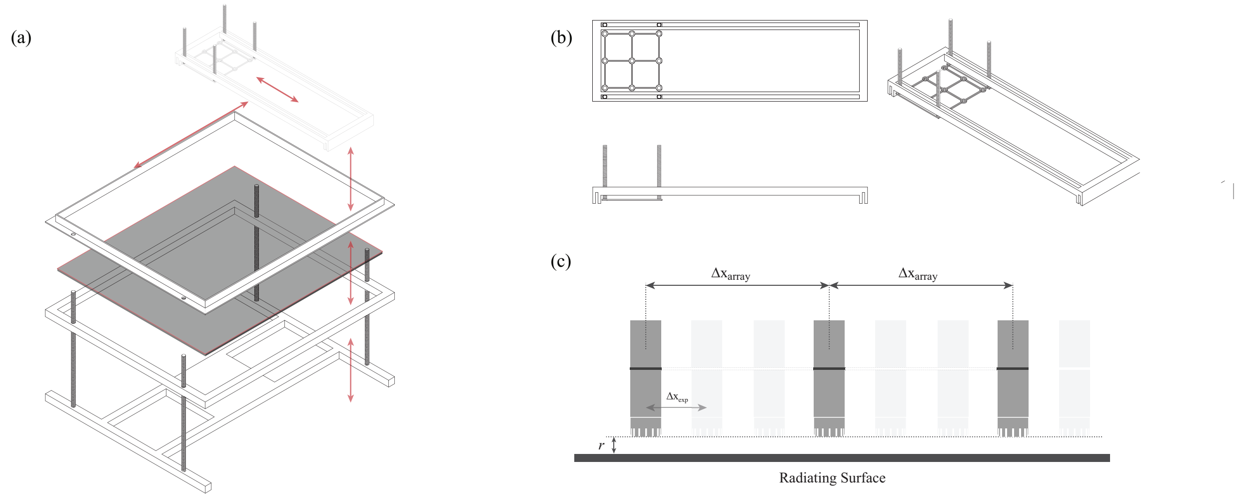

Figure 1. Test rig for the mechanical characterisation of lightweight panels: (a) exploded diagram of the testing frame and the scanning microphone carriage; (b) views of the the scanning microphone carriage; (c) digram of the sound pressure scanning system.

2.2 Material characterisation

The set of measured IRs can be used in order to evaluated several physical properties and acoustic descriptors of the investigated structure, such as its elastic and damping properties, its resonant radiation efficiency and the point mobility. The results presented in this paper are focused on the determination of the panel's elastic properties from sound pressure measurements. Many different techniques can be used to determine the elastic properties of a structure, based either on resonant methods [13], or on wave propagation analysis, performed both within the audible frequency range [24] and in the ultrasound domain [25]. However, the wave correlation approches [16, 26] are particularly suitable to the experimental setup presented in the previous paragraph. The wavenumber dispersion relation can be obtained by maximasing the correlation function between the structural dynamic response, measured along a line of equally spaced positions with a propagating wave. One of the most commonly used approaches is known as inhomogeneous wave correlation method (IWC) [27]. This method was applied in order to evaluate the elastic properties of the investigated plywood panel. The panel's dynamic response was evaluated from sound pressure IRs measured on a number of points in line with the excitation position, equally spaced at $\Delta x = 2.5$ cm apart, along the two principal directions. For each angular frequency ω the complex spectra $\tilde{w}(\omega, x)$ is correlated to an inhomogeneous propagating wave $\tilde{o}(x, k_r, k_i) = -\mathrm{i}(k_r + \mathrm{i}k_i)x$, by the function:

$$\mathscr{I}(k_r, k_i) = \frac{\left|\sum_{i=1}^{N} \tilde{w}(\omega, x_i)\, \tilde{o}(x_i, k_r, k_i)\right|}{\sqrt{\sum_{i=1}^{N} |\tilde{w}(\omega, x_i)|^2 \sum_{i=1}^{N} |\tilde{o}(x, k_r, k_i)|^2}} \tag{1}$$

The structural wavenumber is determined by maximising the function $\mathscr{I}(k_r, k_i)$ given in Eq. 1. The real part k_r of the complex wavenumber is strictly associated to the elastic properties of the panel, while its imaginary part k_i is proportional to the structural damping. Being interested in the panel elastic characteristics, rather then in its damping, the imaginary part has been neglected: $k_i = 0$.

3 RESULTS

The elastic properties of the investigated panel were determined by fitting the experimental wavenumbers, obtained from the wave correlation approach described in the previous section, with the analytical dispersion curve

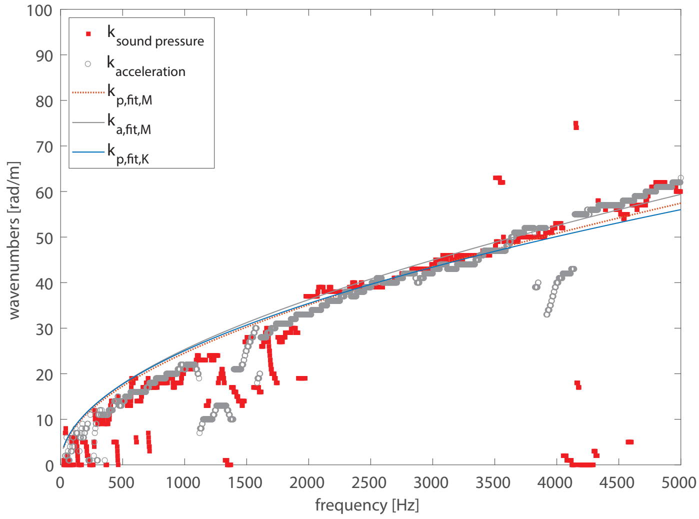

Figure 2. Comparison between the experimental wavenumber dispersion relation determined by using the wave correlation approach from sound pressure measurement k_p and acceleration measurements k_a, and between the curves obtained by analytical fitting $k_{i,fit,j}$.

derived from Mindlin's theory for thick plates.

$$k_M^4 - \left[k_L^2 + \left(\frac{k_S}{T}\right)^2\right] k_M^2 - k_K^4 + \frac{(k_L k_S)^2}{T^2} = 0 \tag{2}$$

where k_L and k_S represents respectively the longitudinal and shear wavenumber propagating in the plate, T is a coefficient to take into account that the shear stress is not constant over the panel cross-section and k_K is given by the Kirchhoff's dispersion relation for thin plates:

$$k_K = \sqrt{\omega}\sqrt[4]{\frac{12\rho h(1-\nu^2)}{Eh^3}} \tag{3}$$

Moreover, in order to evaluate whether the thin plate assumptions are verified for the investigated structure within the entire frequency range, the experimental wavenumeber were also fitted with Kirchhoff's dispersion relation, given in Eq. (3): were ρ is the panel density, h its thickness, ν its Poisson ratio and E the elastic modulus, which represents the fitting parameters.

In order to reconstruct the vibration velocity field from the sound pressure measured in the vicinity of the panel surface an adequate transfer function should be applied. However, as first approximation the wave correlation as been applied directly on the sound pressure IRs measured along a line of points. A first validation of the method is performed by comparing both the experimental and the fitted wavenumber dispersion relation obtained from sound pressure measurements, with the results obtained from acceleration measurements. As show in Figure 2, a good agreement is found between the two experimental data set. In both cases are evident some fluctuations, even though it is possible to accurately fit the experimental wavenumbers with the analytical dispersion relation, obtaining consistent curves. Moreover, a good agreement is also found between the dispersion relations obtained by the fitting procedure of the experimental data by using Eq. (2), $k_{p,fit,M}$, and Eq. (3), $k_{p,fit,K}$; proving that the thin plate theory is suitable to describe the plate motion within the investigated frequency range.

In order to asses the influence of the stand-off distance, the sound pressure IRs were measured both at 5 mm and at 20 from the panel's surface. As shown in Figure 3, no significant difference were found by comparing

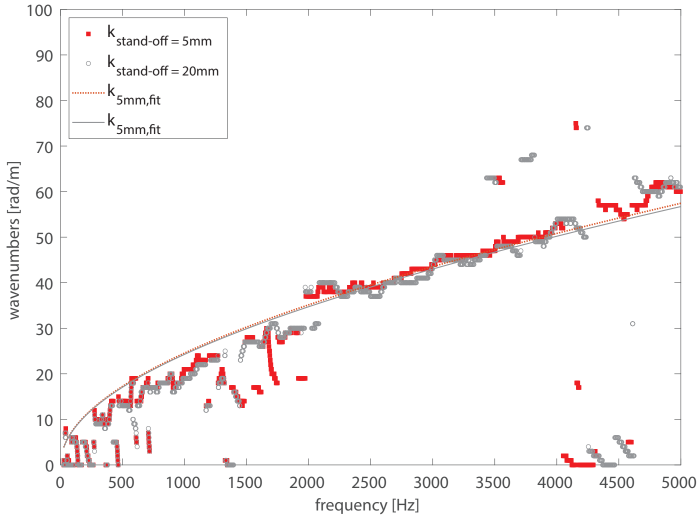

Figure 3. Comparison between the wavenumber dispersion relations determined by using the wave correlation approach from sound pressure measurements performed at 20 mm and at 5 mm from the panel surface.

the experimental and the fitted dispersion relation obtained from this two sets of measurements. However, in order to further investigate the influence of the stand-off distance it is necessary to analysis the reconstructed velocity field over the panel surface.

At this stage of the study, the main goal was to characterise the structure's elastic properties in order to determine the input data required for vibro-acoustic simulations. The structural wavenumbers were investigated along both the plate's principal directions, in order to take into account a possible orthotropic behaviour. The elastic moduli obtained from the three different set of measurements are reported in Table 1. A good trend was

Table 1. Elastic modulus of the plywood plate obtained from wavenumber fitting.

$E_{x,p,20mm}$[Pa]	$E_{x,p,5mm}$[Pa]	$E_{x,acc}$[Pa]	$E_{y,p,20mm}$[Pa]	$E_{y,p,5mm}$[Pa]	$E_{y,acc}$[Pa]
2.29E+09	2.21E+09	1.96E+09	2.01E+09	2.06E+09	1.65E+09

found between the elastic moduli obtained from sound pressure and acceleration measurements, highlighting a soft orthotropy, with the elastic modulus along the $x-$direction slightly higher than the value determined along the $y-$direction. Even though the wave correlation performed on sound pressure IRs slightly overestimate the results compared to the data obtained from acceleration measurements. In order to evaluate the influence of such this deviation on the transmission loss (TL), these values were used as input data in a sound transmission simulation based on the transfer matrix method (FTMM) [28, 29]. In order to validate the numerical results, the sound insulation provided by the investigated panel was experimentally measured into the sound transmission test facility for small elements of Adler Evo acoustic laboratories, in Turin, Italy. Two sources were used to generate the incident sound field within the reverberant emission room, driven with a white noise signal. The sound pressure exciting the plate was measured by means of two rotating microphones, while, on the semi-anechoic receiving side, the radiated sound intensity was measured by scanning the panel's surface with a p-p probe. The plate TL was determined as:

$$TL = L_{p,1} - L_i - 6 \tag{4}$$

where $L_{p,1} = 20\log(p_1/p_0)$ is the sound pressure measured in the emitting room (dB re 20μPa) and L_i is

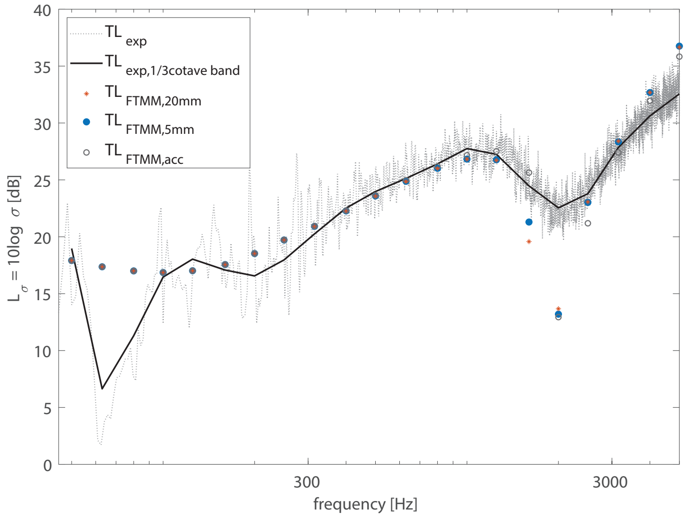

Figure 4. Comparison between the experimental transmission loss of the plywood panel and the numerical results calculated using as input data the elastic properties presented in Table 1

the sound intensity level measured on the receiving side (dB re 10^{-12}W). As shown in Figure 4 the FTMM results well approximate the experimental TL over the entire investigated frequency range, except in the very low frequencies where the structural resonances, which are not considered by this prediction method, govern sound transmission, and the critical frequency region when a greater contribution of the damping is shown by the experimental results. Comparing the three numerical curves, only small discrepancies are highlighted, with a maximum deviation lower than 3 dB in the 1600 Hz third-octave band.

4 CONCLUSIONS

In this paper, the early-stage results of a broader study, regarding the use of the near-field acoustic holography for the mechanical and acoustic characterisation of lightweight building structure, are presented. The reliability of this approach is investigated in order to provide a valid contactless alternative to vibration measurements performed by using a laser doppler vibrometer. The elastic properties of a plywood panel were evaluated from the structural wavenumbers propagating along a certain direction, determined by means of wave correlation approach, from the sound pressure IRs measured in the vicinity of the vibrating surface. The accuracy of this experimental technique was evaluated by comparing the results with the elastic properties obtained from acceleration measurements. The comparison showed a good agreement, with small discrepancies. In fact, the elastic modulus determined from sound pressure measurements only slightly overestimates the value obtained from acceleration measurements. However, when the elastic constants are used as input data to calculate the panel transmission loss, these deviations did not affect significantly the computed results. This was verified by comparing the panel TL compute using a model implemented within the transfer matrix method framework with the experimental sound insulation of the plywood plate.

Even tough the first stage of this study showed promising preliminary results, further investigations are required in order to assess the reliability of the presented methodology. The wave correlation approach should be applied to the velocity field reconstructed from the measured sound pressure, also considering the imaginary part of the structural wavenumber, other than the real one, in order to obtain information regarding the structural damping. Moreover, other quantities can be computed from the velocity field over the vibrating surface, such as the radiated sound power.

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