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In-Situ Measurements of Normal Impedance and Sound Absorption Coefficient of Hard Materials by using a Laser Doppler Vibrometer

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ABSTRACT

Standard techniques to measure the sound absorption coefficient or the acoustic impedance of materials are the Kundt's tube and the reverberant room, albeit they are not practicable in-situ. In addition, these measurement methodologies involve extracting small or large samples of the material under test, which is not permitted for materials of historical importance. In this paper, the possibility of determining the normal acoustic impedance and the normal sound absorption coefficient based on direct in-situ measurements using a Laser Doppler Vibrometer (LDV) has been analyzed. Specifically, measurements have been conducted avoiding any contact on historical sandstones, bricks, and wood planks of the Greek-Roman Theater of Tyndaris located in Sicily (Italy).

1 Introduction

The standard methodologies for measuring the acoustical impedance or the sound absorption coefficient involve the use of a Kundt's tube or of a reverberant room, in line with the standard requirements [1], [2]. These techniques are considered invasive since they require samples of the material under test by cutting or coring a small or large portion of it. Furthermore, its practicality becomes difficult when the materials to be tested are of historical importance and stored inside protected buildings (e.g. museums), where the alteration or even the contact is not permitted. Similarly, the hard materials that can be found in archaeological sites, usually stones and marble blocks, are preserved such that the coring might not be feasible.

Other factors that contribute to the inconsistency of the acoustic results by undertaking impedance measurements with the Kundt's tube are the sample size, the diameter and the length of the Kundt's tube [3]–[5]. Another advantage of the on-site measurements is that the materials on site are installed and supported differently than what happens while the samples are tested inside a Kundt's tube; this affects the vibrational modes and resonances [5]. Although the reverberant room is indicated as an alternative methodology to the Kundt's tube, as outlined in the standard ISO-354 [2], the sound absorption coefficients are affected by other aspects, in particular the fact that ISO-354 measures the average random-incidence absorption, while the Kundt's tube measures the normal incidence absorption and impedance. Furthermore, the results obtained by the measurements conducted in a reverberant room can be affected by the room dimensions and diffusiveness, which reduces reproducibility of the results [6]. The other two biases involved in the reverberant room are the support and/or suspension of the test sample, that can affect the vibrational modes unless the site environment is faithfully reproduced, and the low frequency limit determined by the Schroeder cut-off frequency.

For materials whose alteration, contact or displacement is not allowed, an in-situ measurement technique without any contact represents the only possible approach.

In the literature, measurements of sound absorption coefficient and acoustic impedance without any contact with the test sample are widely debated [7]–[16]. A good review of different methods and techniques to measure sound absorption coefficient using in-situ techniques is presented in [7].

One of the methodologies that can be adopted for site measurements is the use of a pressure-velocity probe (PV probe) to gather the particle velocity and sound pressure data in relation to absorbent materials while the excitation signal is an artificial test signal [8]–[13].

A second technique used on site is the Laser Doppler Vibrometer (LDV), used to measure the vibration velocity of materials stimulated by a known sound pressure [14]–[16].

This paper deals with the possibility of determining the normal acoustic impedance and the normal sound absorption coefficient based on site measurements without having any contact with the test samples. Specifically, acoustic measurements have been conducted with a LDV on historical sandstones, bricks and wood planks placed within the Greek-Roman Theater of Tyndaris, located in Sicily (Italy).

2 Method

The proposed method involves the use of a loudspeaker to excite the selected material surface at a known distance using an Exponential Sine Sweep (ESS) or a white noise signal. A standard pressure microphone records the sound pressure close to the surface (but without any contact) and the LDV measures the vibration velocity of the surface near the microphone.

In the audible frequency range and for reasonably small source-sample distances (about one meter), the atmospheric absorption can be neglected.

It is well known that the sound absorption coefficient depends on the incidence angle of the impinging wave (relative to the normal of the surface), but since the purpose of this study is to focus on the principles of the measurement approach, in the following only normal incidence will be considered. In Figure 1, the experimental disposition is depicted.

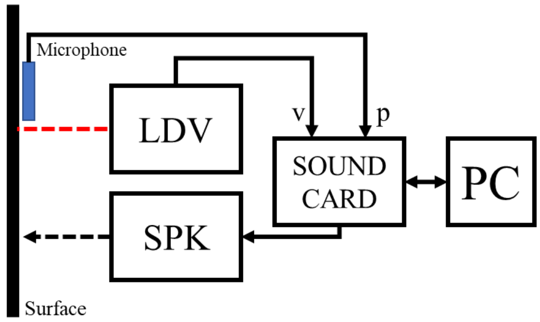

Figure 1. Experimental setup

After the microphone and LDV calibration (so that the amplitude of the velocity signal matches the amplitude of the pressure signal for a plane, progressive wave), the pressure and velocity signals are sampled by a USB audio interface and post-processed by a computer algorithm to obtain the normalized impedance and the sound absorption coefficient.

We first need to compute the two main energetical quantities as a function of frequency, namely Sound Intensity $I(\omega)$ and Energy Density $D(\omega)$; the latter is usually dimensionally realigned to Sound Intensity by multiplying it for the sound speed c, so that both quantities are measured in W/m². These quantities are computed respectively, in frequency domain, from the Cross Spectral Density of the pressure and velocity signals (G_{AB}) and from the Auto Spectral Densities of sound pressure and particle velocity signal (G_{AA} , G_{BB}) as described in [17], [18]:

$$I = Re[G_{AB}] \qquad D \cdot c = \frac{G_{AA} + G_{BB}}{2} \qquad (1)$$

Impedance is the ratio of pressure and velocity, and is calculated as a function of frequency and normalized dividing by $\rho_0 \cdot c$:

$$z(\omega) = \frac{p}{v} \cdot \frac{1}{\rho_0 \cdot c} = \frac{G_{AB}}{G_{BB}} \qquad (2)$$

The sound absorption coefficient α can be calculated as a function of the dimensionless field descriptor $r_E = \frac{I}{D \cdot c}$:

$$\alpha(\omega) = \frac{2 \cdot r_E}{1 + r_E} = \frac{2 \cdot Re[G_{AB}]}{\frac{G_{AA} + G_{BB}}{2} + Re[G_{AB}]} \tag{3}$$

2.1 The proximity effect

Given that the distance between the sound source and the material surface is small, the plane wave hypothesis is not satisfied for the entire frequency range. In fact, at low frequency this hypothesis is no longer verified. So, it is necessary to correct the module and the phase of the calculated impedance based on the distance between the source and the surface of the material to be analyzed. The problem can be analyzed as follows.

For a spherical sound source, the D'Alembert equation can be written as in equation (4):

$$\frac{\partial^2 \Phi}{\partial r^2} + \frac{2}{r} \cdot \frac{\partial \Phi}{\partial r} = \frac{1}{c^2} \cdot \frac{\partial^2 \Phi}{\partial \tau^2} \tag{4}$$

where Φ is the potential of velocity $\vec{v} = grad(\Phi)$, r is the distance from the sound source, c is the speed of sound and τ is time.

Considering a pulsating sphere of radius R and in particular the condition of r > R, the D'Alembert equation can be easily solved. The sound pressure and the particle velocity are described by equations (5):

$$p(r,\tau) = \rho_0 c v_{max} \cdot \frac{j\,k\,R^2}{r\,(1 + j\,k\,R)} \cdot e^{j[\omega\tau - k(r-R)]}$$
$$v(r,\tau) = v_{max} \cdot \frac{R^2}{r^2} \cdot \frac{1 + j \cdot k \cdot r}{1 + j \cdot k \cdot R} \cdot e^{j[\omega\tau - k(r-R)]} \tag{5}$$

Where k is the wave number calculated as in equation (6).

$$k = \frac{\omega}{c} = \frac{2\pi f}{c} = \frac{2\pi}{\lambda} \tag{6}$$

The impedance of a spherical field is defined as the ratio of sound pressure and particle velocity, so using the solutions (5) of D'Alembert equation, it is possible to write the equation (7).

$$Z(r) = \frac{p(r,\tau)}{v(r,\tau)} = \rho_0 \cdot c \cdot \frac{j \cdot k \cdot r}{1 + j \cdot k \cdot r} \tag{7}$$

Equation (7) clearly shows that the impedance of a spherical field changes according to the distance from the source r. In Figure 2 and Figure 3 modulus and phase of the normalized impedance are represented as a function of $k \cdot r$.

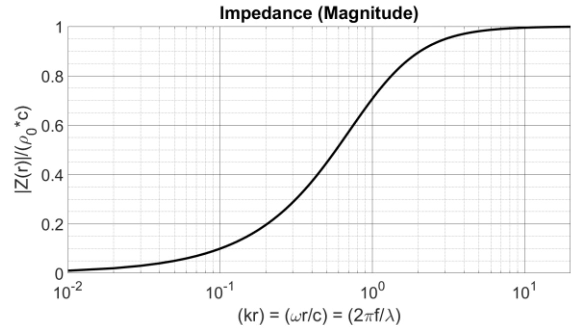

Figure 2. Normalized impedance magnitude

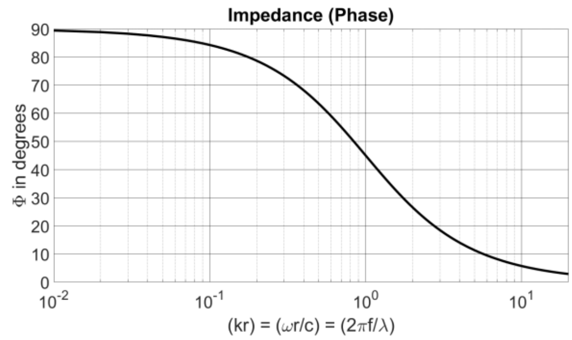

Figure 3. Impedance phase

The far field occurs when $r \gg \lambda$ and of consequence $k \cdot r \gg 1$, while when $k \cdot r \ll 1$ the near field occurs. Thus, Figure 3 shows that, reducing the source-microphone distance r, the phase shift between pressure and velocity tends to 90°.

To correct the magnitude and phase of the calculated impedance it is necessary to convolve the velocity signal with the inverse Fourier transform of the last complex factor of the spherical wave impedance (eq. 7).

In the case of a completely absorbent surface, this brings back the velocity signal to be amplitude and phase matched with the pressure signal over the whole frequency range, resulting in a real value of the normalized impedance $z=1$.
When a reflecting material is present, the resulting value represents the normalized surface impedance for a normal plane wave impinging on the surface.
So, the correction of the nearfield effect corresponds to transforming the spherical wave in a plane wave. Hence the resulting values of z and α do not depend anymore on the source distance r.

2.2 Loudspeaker equalization

Every loudspeaker response is affected by peaks and valleys. These artifacts also influence the signals measured by the microphone and the laser vibrometer, altering slightly the results. In addition, the microphone for the pressure sampling is also affected by non-flat frequency response.
The technique described in [19] can be used to equalize the measurement chain: the loudspeaker and microphone selected for the absorption measurement setup can be equalized at the same time by using an ESS signal and a Kirkeby inverse filter.

3 In-Situ Measurements

To test the measurement method and the post-processing algorithm, a set of measurements on hard and reflective materials has been conducted at the Greek-Roman Theater of Tyndaris, represented in Figure 4. Specifically, the materials considered for the tests are the wood planks composing the cavea seats, the bricks used for the reconstructed arcs (Figure 5) and the sandstones of the remaining background wall (or skenè) shown in Figure 6.

Figure 4. Greek-Roman Theater of Tyndaris

Figure 5. Brick measurement

Figure 6. Sandstone measurement

For the in-situ measurements, a Montarbo MT160 loudspeaker has been used to excite the material. In order to measure the sound pressure, a Bruel & Kjaer type 4189 microphone has been used. The 4189 is a half inch prepolarized microphone designed for high-precision and high sensitivity free-field measurements over a frequency range of 6.3 Hz to 20 kHz. The Polytec VibroGO LDV has been used to sample the vibration velocity of the material. The used LDV is a portable and compact laser vibrometer capable of velocity, displacement, and acceleration non-contact measurement of surface vibrations. The LDV uses the principle of the heterodyne interferometer to acquire the characteristics of mechanical vibrations. In particular, the laser beam is pointed at the vibrating object and scattered back from it. The velocity of a vibrating object generates a frequency modulation of the laser light due to the Doppler effect. This frequency modulation is used to obtain velocity information.
Three different audio signals have been used, summarized as follows:

- A white noise with a time duration of 120 seconds,

- An Exponential Sine Sweep (ESS) of 30 seconds,
- A pre-equalized ESS of 30 seconds.

The pre-equalized ESS has been employed to compensate the loudspeaker frequency spectrum and obtaining a nearly flat spectrum. A Matlab script has been used to control and manage the whole measurement process. In addition, a USB audio interface (Zoom F8) has been used to record the pressure and velocity signals.

An additional Matlab script has been developed for post-processing. The elaboration of the pressure and velocity signals considers the analysis of the microphone calibration and LDV calibration with respect to the selected sensitivity range and the air temperature (C°) and relative humidity (%). The module and phase of the pressure and velocity signals have been corrected based on the distance between the loudspeaker and the material surface. This operation guarantees the correctness of the normal impedance values also at low frequencies, assuming a plane wave, despite the short distance between sound source and measured surface, as explained in chapter 2.1.

4 Result and Discussion

The previously described sound signals have been used to excite the materials, but only slight differences in results have been observed, as shown in Figure 7. It was noted that the use of the ESS signal allows obtaining a better repeatability of the measurements thanks to its good signal-to-noise ratio. The equalization did provide some improvement by extending the frequency range.

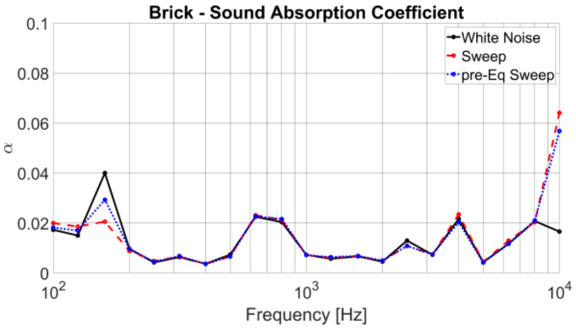

Figure 7. Comparison of the sound absorption coefficient measured with the three signals

In Figure 8 and in Table 1 the sound absorption coefficient in third octave bands resulting from the measurements are presented. Due to the loudspeaker frequency response, the analysis of the measurements has been restricted to the range 100 Hz – 10 kHz.

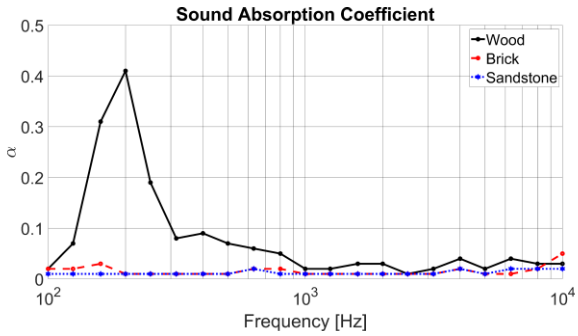

Figure 8. Measured sound absorption coefficient of the selected materials

Third Octave Bands	Wood	Brick	Sandstone
100	0.02	0.02	0.01
125	0.07	0.02	0.01
160	0.31	0.03	0.01
200	0.41	0.01	0.01
250	0.19	0.01	0.01
315	0.08	0.01	0.01
400	0.09	0.01	0.01
500	0.07	0.01	0.01
630	0.06	0.02	0.02
800	0.05	0.02	0.01
1000	0.02	0.01	0.01
1250	0.02	0.01	0.01
1600	0.03	0.01	0.01
2000	0.03	0.01	0.01
2500	0.01	0.01	0.01
3150	0.02	0.01	0.01
4000	0.04	0.02	0.02
5000	0.02	0.01	0.01
6300	0.04	0.01	0.02
8000	0.03	0.02	0.02
10000	0.03	0.05	0.02

Table 1. Measured sound absorption coefficient in third octave bands

In Figure 9, Figure 10 and Figure 11 the module and phase of the computed normalized impedance are represented for the three selected materials.

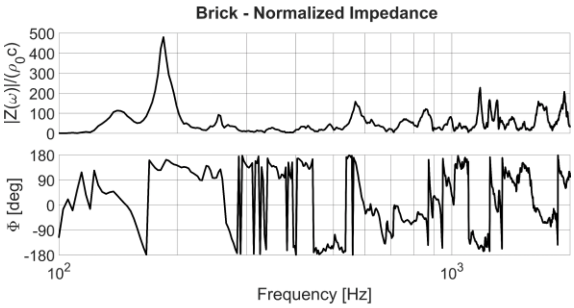

Figure 9. Magnitude and phase of the normalized impedance calculated for the brick

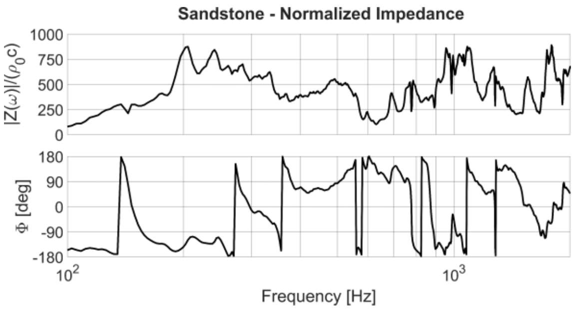

Figure 10. Magnitude and phase of the normalized impedance calculated for the sandstone

Figure 11. Magnitude and phase of the normalized impedance calculated for the wood

As expected, the wood used for the cavea seats is more absorbent at low frequencies than the other two materials. The absorption peak at 200 Hz may be due to the mounting structure of the wooden panels. In fact, the seat panels are mounted on a rectangular metal structure that supports the panel itself. This structure causes a vibrational resonance which results in an increase in the measured absorption.

Bricks and sandstones are acoustically very reflective materials which, despite their different composition, present a very similar low absorption in the whole measured spectrum, in the order of 0.01 – 0.02. Hence the usage of a modern material (bricks) during the restoration of the arches did not alter significantly the acoustical response of the theater.

5 Conclusions

In this paper, a new technique to determine the normal acoustic impedance and the normal sound absorption coefficient of hard reflective materials based on direct in-situ measurements using an LDV has been presented. A set of measurements on historical sandstones, bricks and wood planks of the Greek-Roman Theater of Tyndaris have been conducted.

The results are encouraging and demonstrate that the proposed method is feasible for in-situ measurements where the limitation of any contact with the material is a condition. A slight difference in the impedance and absorption coefficient values has been observed using the three audio signals; in particular, the use of an ESS signal is preferred for its good signal-to-noise ratio (S/N). Furthermore, the equalization did provide some improvement by extending the frequency range.

6 Acknowledgments

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