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COMPARATIVE ANALYSIS OF ACOUSTIC ABSORPTION TESTING METHODS FOR DIFFERENT LAYERS OF COTTON WADDING

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ABSTRACT

Sound-absorbing materials play a crucial role in various applications, ranging from noise control to architectural acoustics, enabling us to enhance the acoustic environment and improve our quality of life. Cotton wadding samples with four thicknesses and dimensions were investigated in the present paper. They were assembled in panels, including cylindrical (29 mm and100-mm diameter) and square (400*400mm²) samples. A comprehensive investigation into the differences observed when evaluating the acoustic properties of a multi-layered material using two standardized methods was carried out. Through a series of experiments, including impedance tube and in-situ absorption measurements, this study investigates the complexities of accurately estimating sound absorption characteristics in multi-layered materials. The experimental findings highlight the importance of selecting an appropriate evaluation technique for multi-layered materials, particularly in applications where acoustic performance is critical at lower frequencies.

Keywords: *acoustic characterization, sound absorption, in-Situ absorption measurements, Kundt's impedance tube.*

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1. INTRODUCTION

Enhancing the sound absorption properties of materials is crucial in acoustical engineering and materials science, contributing to improved quality of life [1]. The growing trends of urbanization and industrial development have made effective noise mitigation strategies essential as the environments where we live, and work become increasingly noisy. Noise pollution is emerging as a significant environmental hazard to public health worldwide. The rising number of cars, trucks, and two-wheelers has significantly contributed to high levels of vehicular noise. Additionally, poor urban planning and limited city space have resulted in constructing homes near railway tracks, airports, industries, and busy traffic routes. This situation presents a serious risk of exposing the general population to noise-induced health hazards [2,3,4]. Noise reduction is a significant concern for both the government and scientists. Measures to reduce noise can be implemented in three ways: addressing the sound source, improving the transmission path, and enhancing the receiver. Passive control methods, such as sound absorption and sound insulation materials that diminish noise propagation, have been widely used and proven effective [5].

A significant issue in acoustic testing is the considerable discrepancies often observed between the results produced by different methodologies [6-8]. These discrepancies can significantly impact accurately characterizing a material's acoustic properties, resulting in challenges when predicting and optimizing its performance in real-world applications.

Over time, various methods have been developed to measure sound absorption. Conventional techniques for measuring sound absorption include the impedance tube (or Kundt's tube) [9], and the in-situ surface impedance gun [10]. The impedance tube method is widely regarded as one of the most precise and repeatable techniques for measuring the standard incidence absorption coefficient, particularly on small samples. In contrast, the in-situ surface impedance technique has proven highly valuable, offering a complementary approach for characterizing acoustic absorption without requiring specialized testing facilities [11]. This method uses a sound intensity PU probe, providing a strong alternative to traditional microphone-based approaches. Its application across various industries, such as automotive [12], architecture [13], and road construction [14], demonstrates its versatility and effectiveness in assessing sound absorption.

Each of these techniques has specific strengths and weaknesses and combining results from multiple approaches is common. However, even for acoustic engineers, interpreting these results can be challenging, especially when different methods produce conflicting or inconclusive findings [11]. This section will discuss some well-known techniques. It is important to note that a thorough comparison of the two methods using various materials has not yet been conducted.

Studies [15-18] have demonstrated that, in some cases, the results from the in situ measurements can be quite similar to those obtained using Kundt's tube method, provided that the measurement conditions are consistent.

A sensitivity analysis was conducted by Maco et al. [19], on two different materials, rock wool, and melamine foam, with varying densities and sample thicknesses. The goal was to establish a set of guidelines for performing measurements with the in situ (PU probe) technique. The results obtained from both the in-situ impedance method and the impedance tube technique were compared at high frequencies. The findings indicated that the in-situ method (using a PU probe) provided more accurate results than the impedance tube method. A similar study was conducted in [20], which involved a comparative analysis of sound testing methodologies for multi-layered materials. This study revealed a significant discrepancy between the measurements taken with the impedance tube and those obtained from in situ methods, particularly at low frequencies. The alignment between the in-situ results and those from the reverberation chamber challenged prior assumptions, especially regarding the expected similarity between in-situ impedance measurements and those from the impedance tube for porous materials. Overall, the study underscores the importance of selecting appropriate evaluation techniques for multi-layered materials, as conventional methods may not adequately capture their complex acoustic behavior.

In another study by Peter Cats et al. [21], a preliminary comparison was made between PU probe-based in situ absorption methods and Kundt's tube method. It was found that similar results could be obtained for the examined samples using measurements from PU probes under normal incidence excitation as well as from Kundt's tube.

Despite advancements in the field, there is still a significant gap in understanding the most effective methods for evaluating the acoustic properties of complex, multi-layered materials, both porous and non-porous. This gap underscores a broader challenge: the need for a comprehensive approach that not only addresses the limitations of traditional methods, but also incorporates the strengths of newer techniques, such as the PU in-situ absorption method.

This study, a collaboration between Universitat Politècnica de Catalunya and University of Perugia, aims to try to fill this gap by conducting a comparative analysis of Cotton wadding with different layers. The evaluation will be carried out with two different measurement systems: an impedance tube (Kundt's tube, Brüel & Kjær model 4187) and an in-situ impedance measurement system from Microflown technologies. By comparing these methods directly, the research seeks to provide valuable insights into the selection of optimal tools for assessing acoustic properties, of different materials.

1. MATERIAL AND SAMPLES

The material used in this study is cotton wadding, a lightweight, fibrous textile primarily used in quilting and thermal insulation applications. This material consists of 100% cotton fibers, forming a porous and highly compressible structure, which makes it a potential material for sound absorption applications. To evaluate its acoustic properties, samples were prepared with different layer configurations, ranging from one to eight layers. Each sample was cut into circular specimens with a diameter of 29 mm and 100 mm, following the standard requirements for impedance tube measurements 10534-2 Standard [22]. The thickness of each configuration was carefully measured to assess its impact on sound absorption performance. Figure 1 displays pictures of the measurement with impedance tube.

The characteristics of the different layers of cotton wadding used in the comparison are summarized in Table [1].

Table 1. Description of the samples for acoustic measurement.

Sample	Sample size (mm)	Thickness (mm)	Pictures
1 Layer	300 x 300 mm^2 Φ 29 mm Φ 100 mm	1.5	
2 Layers	300 x 300 mm^2 Φ 29 mm Φ 100 mm	3.0	
4Layers	300 x 300 mm^2 Φ 29 mm Φ 100 mm	6.0	
8 Layers	300 x 300 mm^2 Φ 29 mm Φ 100 mm	12	

3. METHODOLOGY

3.1 Sound absorption testing methods

Over the years, several methods have been developed to measure sound absorption, each having its own unique strengths and limitations [23,24]. The results from these different techniques are often assessed from a broader perspective. However, interpreting these findings can be challenging for acoustic engineers, especially when different methods produce conflicting or inconclusive

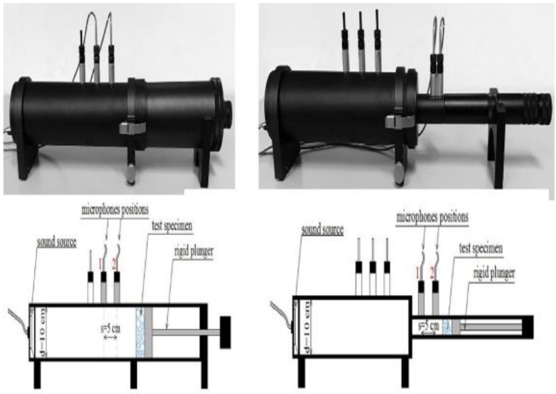

Figure 1. The Impedance tube: (a) absorption measurements configuration in large (left) and small (right) tube.

data. This section will provide a brief overview of the testing methods used in this paper.

An experimental investigation was conducted to characterize the sound absorption properties of a multi-layer sample consisting of 1 layer, 2 layers, 4 layers and 8 layers with an airflow resistivity 77600 Pa*s/m2. Different layers of this material were tested with different standardized methods, namely the Impedance Tube method (Brüel & Kjær, model 4206) [22]), as well as the in-situ PU method [11].

3.1.1 Impedance tube

The impedance tube method, commonly referred to as the Kundt tube, is widely used because it requires only small samples. The standard incidence absorption coefficient was measured using a two-microphone impedance tube (Brüel & Kjær, model 4206) and the transfer function method. This involved cylindrical samples with diameters of 29 mm, small tube for high frequencies between 5o Hz and 6400 Hz, and 100 mm, large tube for low frequencies covering a frequency range from 50 to 6400 Hz, in accordance with ISO 10534-2 standard [22].

In this method, the absorbed portion of the acoustic energy from a wave incident on the tested sample is evaluated in relation to the total incident energy; the unabsorbed portion is reflected back toward the source.

Despite its advantages, this method requires careful sample preparation and manipulation at multiple sample diameters, which may be challenging for certain materials, such as low-density porous materials.

Moreover, differences between the sample and the actual implementation of the material may result in differences in acoustic properties, especially because in the impedance tube the measurements are carried out at normal incidence, whereas in situ the incidence is random end sometimes diffused.

3.1.2 In situ impedance

In this section, the in-situ absorption methods that will be used are briefly introduced. A more detailed description of the methods can be found in [11]. The measurements can be performed in a broad frequency range (typically from 300 Hz up to 10 kHz) on small samples (typically 0.03 m^2 to 0.38 m^2 or larger) while hardly being affected by background noise and reflections [18, 25-29].
The free-field methods originated from a generalization of the Impedance Tube method. Their purpose is to measure the acoustic impedance of ground surfaces by assessing both acoustic pressure and particle velocity above the target material. This approach allows for the capture of the specific impedance near the sample's surface [11,30-32]. Measurements of the sound absorption coefficient were conducted in both laboratory settings and in situ, utilizing an impedance gun provided by Microflown Technologies [11,18,19,33].
The user must specify the measurement range and frequency resolution at which results are displayed (e.g., octave bands, third-octave bands, or narrow frequency bands).

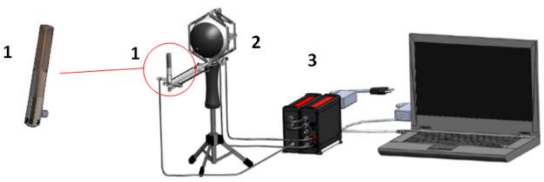

Figure 2. Measurement system assembly provided by Microflown Technologies.

While reflections from surrounding objects can potentially influence results, research has shown that in most relevant environments their impact on test outcomes is minimal, primarily due to the small distances between the sample and the P-U probe. Nevertheless, the impedance gun was calibrated [11] prior to conducting measurements. This calibration process involved pointing the impedance gun towards the best achievable free field conditions, far from any reflective surfaces.

Figure 3. Measurement systems used in the present investigation: in-situ PU method (Left), and impedance tube (right).

4. EXPERIMENTAL INVESTIGATION ON SOUND ABSORPTION

In the in-situ Absorption [19] measurements utilizing the Mirror Source model, each sample approximately is 0.4 m x 0.4 m in size. Measurements were taken by positioning a PU probe about 5mm above the sample's surface, at three arbitrary points (twelve total measurements).

The porosity and airflow resistivity and absorption coefficient of sound-absorb cotton were measured by equipment directly (Figure 4). Airflow resistance is also a powerful tool to characterize sound absorption properties.
The airflow resistance has been determined with a Nor1517A airflow resistance measurement system which uses the alternating airflow method described in the standard ISO 9053-2:2020 [34].

Figure 4. Air flow resistance tool.

4.1 Results and discussion

Fiber type, material thickness, density, airflow resistance, and porosity are the key physical parameters influencing the sound absorption characteristics of nonwoven materials [35]. Figure 5 illustrates the specific airflow resistance (Rs) for samples with varying numbers of layers. The airflow resistivity, representing the specific airflow resistance per unit length, has been calculated as the slope of the linear fit, yielding a value of 77,600 Pa·s/m². This result indicates that as the material thickness increases, the resistance to specific airflow rises proportionally.

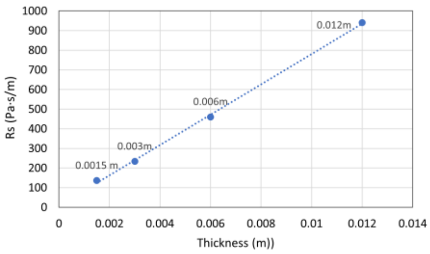

Figure 5. Specific airflow resistance as a function of thickness. The dotted line is a linear fit, the slope of which gives the value of the airflow resistivity of the material.

Sound absorption coefficient trends at normal incidence for the four samples vs. the frequency (range 100 - 6400 Hz), measured using the Impedance Tube and Impedance Gun, are shown in Figures 6 and 7, respectively. The small and a large Brüel & Kjær tube setup were used and later the measurements were combined to obtain sound absorption coefficient in the frequency range 50–6400 Hz.

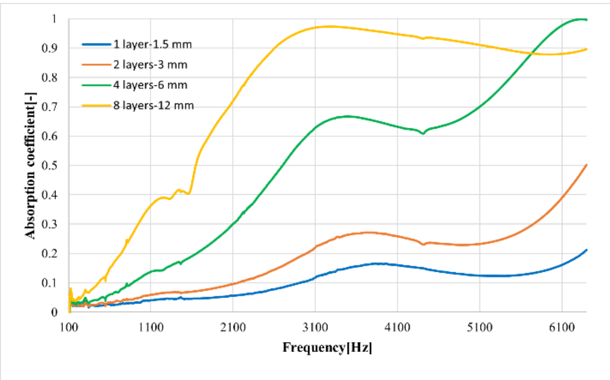

Figure 6. Sound absorption values of cotton wadding vs. frequency with Impedance tube.

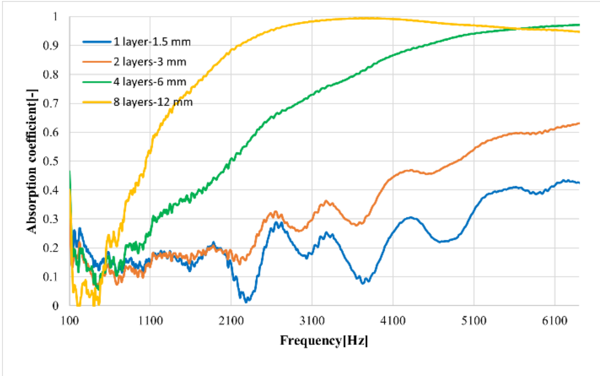

Figure 7. Sound absorption values of cotton wadding vs. frequency with Impedance gun.

Table 2. Values of sound absorption coefficient α, third octave bands with Impedance Tube.

Freguency (Hz)	1 layer	2 layers	4 layers	8 layers
200	0.05	0.08	0.04	0.06
251	0.00	0.01	0.02	0.02
316	0.04	0.04	0.05	0.09
398	0.03	0.03	0.04	0.09
501	0.03	0.04	0.06	0.13
630	0.04	0.05	0.07	0.18
794	0.04	0.05	0.09	0.22
1000	0.04	.06	0.11	0.29
1258	0.04	0.06	0.13	0.35
1600	0.05	0.08	0.19	0.46
2000	0.05	0.10	0.28	0.68
2500	0.07	0.16	0.44	0.87
3150	0.12	0.26	0.63	0.97
4000	0.16	0.29	0.64	0.95
5000	0.15	0.28	0.71	0.91
αavg	0.06	0.10	0.23	0.42

Table3. Values of sound absorption coefficient α, for third octave bands with Impedance Gun.

Freguency (Hz)	1 layer	2 layers	4 layers	8 layers
200	0.21	0.18	0.15	-0.01
251	0.23	0.18	0.19	0.05
316	0.19	0.14	0.14	0.06
398	0.14	0.9	0.10	0.03
501	0.14	0.10	0.11	0.19

630	0.14	0.11	0.14	0.23
794	0.13	0.12	0.18	0.34
1000	0.13	0.12	0.22	0.47
1258	0.16	0.17	0.32	0.64
1600	0.14	0.17	0.32	0.75
2000	0.14	0.12	0.47	0.86
2500	0.14	0.26	0.63	0.94
3150	0.18	0.37	0.74	0.98
4000	0.18	0.39	0.85	0.99
5000	0.32	0.55	0.94	0.97
αavg	0.17	0.27	0.37	0.49

Table 4. Noise Reduction Coefficient (NRC) index of the investigated materials using impedance tube and impedance gun.

Sample	NRC-Impedance Tube	NRC-Impedance Gun
1 layer	0.03	0.16
2 layers	0.05	0.15
4 layers	0.12	0.25
8 layers	0.22	0.37

As observed in Figure 6 and 7, an increase in the number of layers leads to a higher sound absorption coefficient across most frequencies, as expected. Cotton wadding 12 mm-thick (8layers), and 6 mm- thick (4 layers) demonstrate high absorption properties when compared to the 2 layers and 1 layer. This effect becomes more evident at higher frequencies (above 3000 Hz), where the increase in the number of layers leads to a significant improvement in sound absorption. Also, the first peak of the absorption curve increases with thickness, and it is moved to lower frequencies, according to [36], due to the higher tortuosity of the thicker sample. In order to better compare the acoustic behavior of different layers of cotton wadding, the Sound Absorption Average (SAA) index was calculated as the average of the absorption coefficients across the twelve 1/3 octave bands from 200 Hz to 5000 Hz (Table 1 and 2). As the number of layers increases, the sound absorption performance improves significantly both in the measurements carried out with the impedance tube and with the impedance gun. For example, the SAA value rises from 0.06 for a single-layer sample to 0.42 for the eight-layers with impedance tube. Similarly, with the impedance gun, the SAA rises from 0.17 for one layer to 0.49 for eight layers. The Noise Reduction Coefficient NRC (arithmetic average of the absorption coefficient values in the one third octave band at the frequencies of 250, 500, 1000, and 2000 Hz) of samples with impedance Gun is higher than the one of materials with impedance tube. Moreover, NRC increased when thickness increased (see data in Table 3).

5. CONCLUSION

In this research, we studied the sound absorption properties of a commercially available natural fiber material (cotton wadding). We investigated the effect of material thickness and used two different measurement tools to evaluate its acoustic performance. The results demonstrated that both material thickness and airflow resistance significantly affect sound absorption performance.
By utilizing two different tools, the study provided complementary insights, more reliable and accurate findings. It was found that increasing the thickness of the cotton wadding improved sound absorption, while airflow resistance also played a crucial role in optimizing the material's performance. These findings contribute to a better understanding of the key factors influencing sound absorption in cotton-based materials. Additionally, the use of multiple tools allowed for a more thorough analysis, ensuring strong results.
Further research could explore additional variables or alternative different types of materials to improve sound absorption measurements reliability in a variety of applications.

6. ACKNOWLEDGMENTS

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