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# IN-SITU ACOUSTIC CHARACTERIZATION OF POROUS MATERIALS USING A PU-PROBE

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## ABSTRACT

The PU probe technique allows in-situ surface impedance measurements of porous materials with minimal sample preparation and measurement setup. However, the in-situ condition comes at the cost of multiple additional factors, such as the measurement environment and probe positioning, which can influence the results if not properly addressed. In this work, a sensitivity analysis is performed for two different materials, rockwool and melamine foam, with varying densities and sample thicknesses, aiming to provide a set of guidelines on how to perform measurements with the PU probe technique regarding sample size, methodology, and probe location. This technique is then compared with the current standardized procedures by converting all measured normal incidence sound absorption data into random incidence absorption coefficients of infinite lateral dimensions. Furthermore, the acoustically absorbent materials were inversely characterized using a minimization algorithm to estimate non-acoustical macroscopic parameters from the impedance gun and impedance tube normal incidence measurements. The results from both techniques were then compared with the macroscopic parameters determined with direct methodologies.

***Key Words—*** acoustic characterization, sound absorption, PU probe.

## 1. INTRODUCTION

Sound-absorbing materials play a crucial role in various applications, ranging from noise control to architectural acoustics, enabling us to enhance the sonic environment and improve our quality of life. The growing trends of urbanization and industrial development have made effective noise mitigation strategies a necessity as the environments where we live and work become increasingly noisier. The use of porous materials constitute a common and versatile solution, capable of efficiently absorbing sound energy across a wide frequency range. Current efforts are being focused on the development of sustainable and cost-efficiency materials, while providing good acoustic features [1].

To determine the Sound Absorption Coefficient (SAC), an indicator of how much energy is dissipated into thermal energy, reverberant chamber and impedance tube methods have been commonly used. The former method often demands large sample areas, which may not be feasible for the development of new materials, particularly considering economic constraints. In contrast, using an impedance tube for measurements could offer a more viable solution. However, this approach comes with its own set of limitations, such as the normal incidence restriction and the additional sample preparation and manipulation required. Free-field methods, developed in recent years, could become a solution to address these limitations.

The intention of this work is to study the influence of some factors that come into play when performing in-situ measurements and address these limitations using a model fitting algorithm. Then, a comparison with the standardized methods is performed, subdividing the results into normal and random incidence.

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## 2. ABSORPTION MEASUREMENT METHODS

The main methods regarding the measurement of the sound absorption coefficient are presented, along with their limitations. Free-field methods are further introduced.

### 2.1. Reverberation chamber

The reverberant chamber allows deducing a diffuse field absorption coefficient of a sample by the effect of the rate of decay of sound in a room, with and without the sample, assuming a perfectly diffuse field. It is thus commonly referred to as “Sabine's Absorption Coefficient.” The international standard ISO 354:2003 [2] specifies the measurement methodology, relying on Sabine's equation to obtain the equivalent absorption area of the sample.

In practice, it is difficult to achieve a perfectly diffuse field. Different rooms with different shapes and volumes may result in high levels of uncertainty as well as large discrepancies in the absorption coefficients compared to the theoretical random incidence sound absorption coefficient [3]. Additionally, the finiteness of the measured sample results in an increased absorption when measuring with this method due to the diffraction effects from the samples' edges, often leading to SAC values above 1 [4].

Furthermore, the measurement chamber must have a volume of at least $200m^3$. Additionally, large sample areas are required, varying between 10 and $12m^2$, depending on the volume of the reverberant chamber, which often may not be feasible during the research and development of new materials. The high cost of these conditions often limits their application, leading to the use of Impedance Tube measurements instead.

### 2.2. Impedance Tube

The impedance tube method, also known as the Kundt tube, is widely used because only small samples are needed. Several parameters can be retrieved using, for example, the transfer-function method standardized by ISO 10534-2 [5]. Unlike the reverberant chamber method, only plane waves at a normal incidence angle are considered. Therefore, the resulting absorption coefficient is addressed as the normal incidence absorption coefficient and cannot be directly compared with the one measured in the reverberant chamber.

Despite its advantages, this method requires careful sample preparation and manipulation at multiple sample diameters, which may be challenging for certain materials, such as lower-density porous materials. Moreover, differences between the sample and the actual implementation of the material may result in differences in acoustic properties.

### 2.3. Free-field methods

The free-field methods originated from a generalization of the Impedance Tube method, with the aim of measuring the acoustic impedance of ground surface [6]. Different approaches have been taken, using either pressure sensors (PP), particle velocity (UU), or a combination of both (PU). The PU method, which requires the measurement of acoustic pressure and particle velocity, measures the specific impedance near the surface of the sample. In a study comparing the three above-mentioned methods, the sample size was proved to have a major impact on the measurements, producing higher errors when testing smaller samples. The PU method was found to be the most stable against sample size, as well as to source height [7].

The integration of the PU Probe into a handheld setup, often termed an "Impedance gun," has facilitated research with this device. Nevertheless, numerous factors add complexity to measurements employing this device. Valid results from this setup are expected in a frequency range from 300Hz-10000Hz. The lower boundary of this range is primarily limited by the models needed for extracting the surface impedance and signal-to-noise ratio issues encountered at the pressure and particle velocity sensors [8].

## 3. METHODOLOGY

### 3.1. Materials studied

Melamine foam and rockwool were chosen for this study due to their availability and cost-effectiveness as sound-absorbing materials. Other materials with elevated costs were excluded as the reverberant chamber method requires a significant testing area. All main non-acoustic parameters for melamine foam were previously measured through direct experimental methods [9], being the flow resistivity $\sigma = 12200 \left[\frac{\mathrm{Ns}}{\mathrm{m}^4}\right]$, porosity $\phi = 0.98[-]$, tortuosity $\alpha_\infty = 1.01[-]$, characteristic lengths $\Lambda = 115\ [\mu\mathrm{m}]$, $\Lambda' = 115\ [\mu\mathrm{m}]$ and density $\rho = 9.6 \left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$. A single thickness of 50mm was available for this material.

Two thicknesses (50mm and 100mm) and two densities ($55 \left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$ and $70 \left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$) were considered for rockwool, from which only a reference range of flow resistivity was available from the manufacturer. Thus, additional flow resistivity measurements were performed using the alternating airflow method, following ISO 9053 [10] on the 50mm thickness samples, obtaining $\sigma_{PN55} = 20798 \left[\frac{\mathrm{Ns}}{\mathrm{m}^4}\right]$ and $\sigma_{PN70} = 30869 \left[\frac{\mathrm{Ns}}{\mathrm{m}^4}\right]$. These parameters enable the modeling of both melamine and rockwool materials using the equivalent fluid models.

### 3.2. Simulation with equivalent fluid models

To model sound propagation in porous media and thus calculate the relevant absorption coefficient, these materials can be modeled as equivalent fluid materials, where only the airborne wave propagates in the pores of the material. Several models have been developed through empirical and analytical approaches. The Delany-Bazley-Miki (DBM) is a well-known equivalent fluid empirical model, based on regression models and large number of Impedance Tube measurements on porous materials [11]. Assuming porosity and tortuosity near unity, this model can estimate the characteristic impedance $\tilde{Z}_{ca}$ and complex wavenumber $\tilde{k}_{ca}$, respectively, at a frequency f,

$$\tilde{Z}_{ca} = \rho_0 c_0 \left[1 + 5.50\left(10^3 \frac{f}{\sigma}\right)^{-0.632} - i8.43\left(10^3 \frac{f}{\sigma}\right)^{-0.632}\right] \tag{1}$$

$$\tilde{k}_{ca} = \frac{2\pi f}{c_0}\left[1 + 7.81\left(10^3 \frac{f}{\sigma}\right)^{-0.618} - i11.41\left(10^3 \frac{f}{\sigma}\right)^{-0.618}\right] \tag{2}$$

where $\rho_0$ and $c_0$ are the density and velocity of sound in air, respectively, and $\sigma$ the flow resistivity. As only the flow resistivity was obtained for the rockwool samples, the DBM was used for the modeling of this material.

In the case of melamine foam, the availability of additional macroscopic parameters enables the modeling with the Johnson-Champoux-Allard (JCA) model, which is a more complex semi-analytical phenomenological model requiring the flow resistivity, open porosity, tortuosity, and viscous and thermal characteristic lengths to describe the visco-inertial and thermal effects, through the effective density and Bulk modulus [12],

$$\tilde{\rho}_e = \frac{\alpha_\infty \rho_0}{\phi}\left[1 + \frac{\sigma\phi}{i\omega\rho_0\alpha_\infty}\sqrt{1 + \frac{4i\alpha_\infty^2\eta\rho_0\omega}{\sigma^2\Lambda^2\phi^2}}\right] \tag{3}$$

$$\tilde{K}_e = \frac{\frac{\gamma P_0}{\phi}}{\left(\gamma - (\gamma - 1)\left(1 + \frac{8\eta}{i\Lambda'^2 N_p\omega\rho_0}\sqrt{1 + \frac{i\Lambda'^2 N_p\omega\rho_0}{16\eta}}\right)^{-1}\right)} \tag{4}$$

where $\gamma$ is the ratio of specific heats, $\eta$ the dynamic viscosity of air, $\omega$ the angular frequency, $N_p$ the Prandtl's number, and $i = \sqrt{-1}$. The characteristic impedance and complex wavenumber can then be obtained by

$$\tilde{Z}_{ca} = \sqrt{\tilde{\rho}_e \tilde{K}_e} \tag{5}$$

$$\tilde{k}_{ca} = \omega\sqrt{\frac{\tilde{\rho}_e}{\tilde{K}_e}}\,. \tag{6}$$

The surface impedance can be analytically calculated using the Transfer Matrix Method (TMM) which for a rigidly backed material of thickness d, is

$$Z_s = -i\frac{\tilde{Z}_{ca}}{\cos(\theta_t)}\cot\left(\tilde{k}_{ca}\cos(\theta_t)d\right) \tag{7}$$

where $\theta_t$ is the transmitted or refracted angle, obtained from the Snell-Descartes law. The absorption coefficient at an incidence angle $\theta_i$ can then be computed as

$$\alpha = 1 - \left|\frac{Z_s\cos\theta_i - \rho_0 c_0}{Z_s\cos\theta_i + \rho_0 c_0}\right|^2. \tag{8}$$

### 3.3. PU-probe sensitivity analysis

This analysis aims to provide answers regarding the minimum sample size, the calculation method and the receiver position. The results of both materials studied, melamine and rockwool, were then compared. To quantify the difference between the measured absorption coefficients, $\alpha_{meas}$, and the reference absorption curve from the Equivalent Fluid models, $\alpha_{ref}$, the mean relative error was calculated as

$$e = \frac{1}{N_b}\sum_{k=1}^{N_b}\left|\frac{\alpha_{meas,k^{th}band} - \alpha_{ref,k^{th}band}}{\alpha_{ref,k^{th}band}}\right|, \tag{9}$$

where $N_b$ denotes the number of one third-octave bands considered. The reference absorption curve was obtained through the JCA model, for melamine, and through the DBM model, for rockwool. The same error analysis was performed on the Impedance Tube measurements for comparison.

PU-probe measurements were conducted at normal incidence, employing a tripod setup with the probe positioned 5mm away from the sample's surface. The calibration followed the free-field calibration method. The sample sizes varied, ranging from sizes larger than 1m² to as small as 200x200mm². Measurements were taken at both central and at a “confidence region” [13]. Surface impedance was determined through both the Plane Wave Method (PW) and the Mirror Source Method (MS). The specific characteristics and distinctions of these methods are not covered within the scope of this paper. More detailed information on this matter can be obtained in [8].

### 3.4. Inverse characterization

An inverse characterization procedure is proposed to overcome the limitation within the lower frequency range of the PU-probe measurements. The validation of this procedure will be achieved by comparing the inverse parameters obtained with the experimental values.

The inverse methodology was implemented using MATLAB’s “fmincon” function within a Globalsearch optimization algorithm, solving for the global minimum of the objective function, defined here as the absolute error between the measured and the reference SAC from the equivalent fluid model,

$$F(f,h,\sigma,\phi,\alpha_\infty)=\sum_{fl}^{fu}\left|\alpha_{PU,Tube}(f)-\alpha_{ref}(f,h,\sigma,\phi,\alpha_\infty)\right|. \qquad (10)$$

Two reference models already described, DBM and JCA, were implemented in the algorithm to obtain the reference SAC. Search space bounds for the flow resistivity, porosity and tortuosity were defined, covering a wide range of porous materials (Table 1).

**Table 1.** Search space boundaries of the optimization variables.

| | $\sigma\left[\frac{Ns}{m^4}\right]$ | $\phi\,[-]$ | $\alpha_\infty[-]$ |
|---|---|---|---|
| Lower bound | $1x10^3$ | 0 | 1 |
| Upper bound | $1x10^5$ | 1 | 5 |

The model fitting frequency range's lower and upper bounds, $fl$ and $fu$, respectively, were defined from 100Hz to 5000Hz in the case of the impedance tube. For the PU Probe measurements, these limits are to be defined following the sensitivity analysis results.

### 3.5. Comparison between methods

By means of the proposed model fitting procedure, the retrieved characteristic impedance and complex wavenumber can be utilized to estimate the SAC in a virtual diffuse field using Paris equation [14]

$$\alpha_d = 2\int_0^{\pi/2}\alpha(\theta_i)\sin(\theta_i)\cos(\theta_i)d\theta_i \qquad (11)$$

This procedure was applied to both PU Probe and Impedance Tube measurements, by applying trapezoidal numerical integration, with $\Delta\theta=\pi/1000$, being $\alpha(\theta_i)$ calculated for incidence angles from 0 to $\pi/2$. This conversion was compared to London's simplified approach [15].

To correct for the excess absorption from the reverberant chamber measurements, the measured Sabine's absorption coefficient $\alpha_s$ is converted into a virtual infinite sample size by applying a sample size correction, estimated by the polynomial regression approach detailed in [16].

## 4. RESULTS

### 4.1. Sensitivity analysis

Presented below is an overview of the analysis conducted on both melamine and rockwool materials. For the sake of brevity, only the results pertaining to melamine foam are displayed. Greater deviations in the form of underestimated absorption at normal incidence were found mainly below 800Hz, resulting in increasing error as the sample size decreases (Figure 1). Above this frequency, good agreement to the reference curve obtained from the JCA model was found for all samples down to 200x200mm$^2$. Smaller samples showed a more pronounced underestimation, finding agreement only above 4kHz.

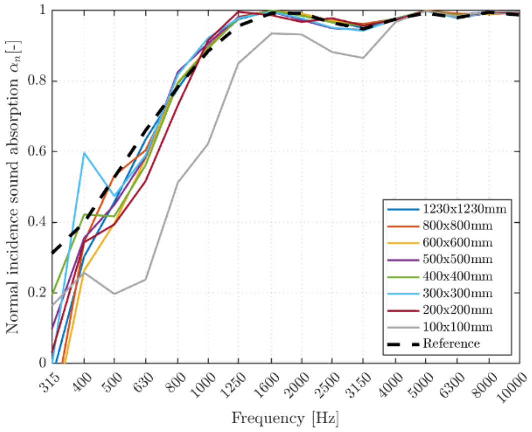

**Figure 1.** Sample size influence on the SAC from melamine using the PU-probe method

Figure 2 shows the calculated relative error over the working frequency range of the impedance gun. Below 800Hz, larger errors were obtained, largely surpassing those obtained by the Impedance Tube measurements. Nonetheless, independently of the sample size, from 800Hz to 10kHz the mean error from all sample sizes down to 200x200mm$^2$ was of 1% for melamine foam and of 2% for rockwool using the MS model in the center position. Given these results, further measurements on the remaining materials were performed with this configuration.

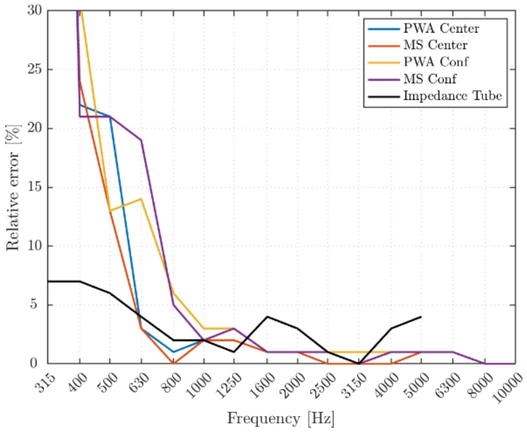

**Figure 2.** Relative error calculated from the JCA model for melamine foam

### 4.2. Inverse characterization

The parameters of the JCA model were inversely retrieved from Impedance Tube and PU Probe measurements using the proposed model fitting methodology. Following the results from the sensitivity analysis, the model fitting range for the PU Probe measurements was set from 800 Hz -10000 Hz.

**Table 2.** Inverse characterization results of melamine foam

| | Reference | Inverse Tube JCA | Inverse PU JCA |
|---|---|---|---|
| $\sigma\left[\frac{\mathrm{Ns}}{\mathrm{m}^4}\right]$ | 12200 | 11221 | 12381 |
| $\phi\,[-]$ | 0.98 | 1 | 0.94 |
| $\alpha_\infty[-]$ | 1.01 | 1 | 1 |
| $\Lambda\,[\mu\mathrm{m}]$ | 115 | 114 | 112 |
| $\Lambda'\,[\mu\mathrm{m}]$ | 116 | 114 | 112 |

The model fitting algorithm approximated the macroscopic parameters from both the Impedance Tube and PU Probe measurements, with a good resemblance to the parameters measured through direct methodologies (Table 2 - 3).

**Table 3.** Inverse characterization results of rockwool

| | Reference | Inverse Tube JCA | Inverse PU JCA |
|---|---|---|---|
| $\sigma_{PN55}\left[\frac{Ns}{m^4}\right]$ | 20798 | 19921 | 18640 |
| $\sigma_{PN70}\left[\frac{Ns}{m^4}\right]$ | 30869 | 28145 | 30802 |

### 4.3. Comparison between methods

Methods comparison is divided into normal and random incidence. Results are shown for samples of melamine of 50mm thick and rockwool PN55 of 100mm thick.

#### *4.3.1. Normal incidence SAC*

The measured normal incidence sound absorption curves from both Impedance Tube and PU Probe methods are presented next, alongside with the retrieved model fitted curve obtained from the PU Probe measurements.

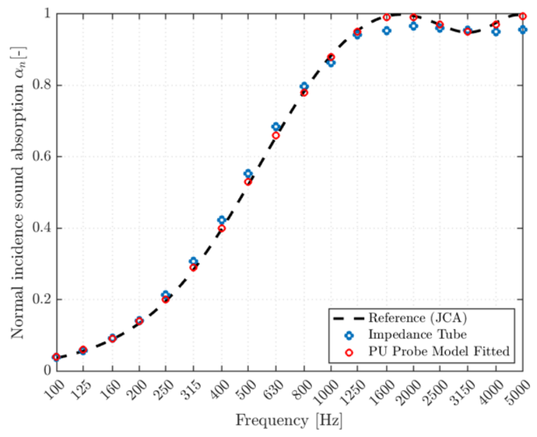

**Figure 3.** Normal incidence measurements of melamine, 50mm thick

Both experimental methods show a good agreement with the reference curves from the Equivalent Fluid Models, for both melamine foam (Figure 3) and rockwool (Figure 4) samples. As noted during the sensitivity analysis, below 800 Hz higher errors were found, which resulted in an underestimation of the absorption coefficient. The model fitting performed enabled to obtain comparable results down to 100 Hz from the PU Probe measurements.

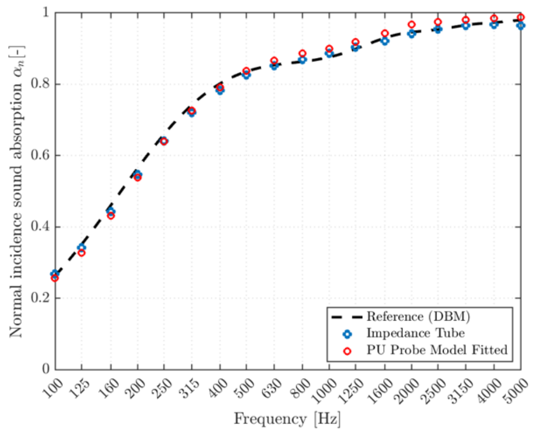

**Figure 4.** Normal incidence measurements of rockwool PN55, 100mm thick

#### *4.3.2. Random incidence SAC*

The model fitting methodology implementing Paris' equation enabled to obtain a broadband random incidence sound absorption curve for the PU Probe method, down to 100 Hz (Figure 5 - 6). Good agreement to the reference curve, using the reference macroscopic parameters, was found using this methodology from both Impedance Tube and PU Probe, for all materials tested. London's equation, assuming local reaction, yielded a fair approximation to the methodology proposed using Paris equation.

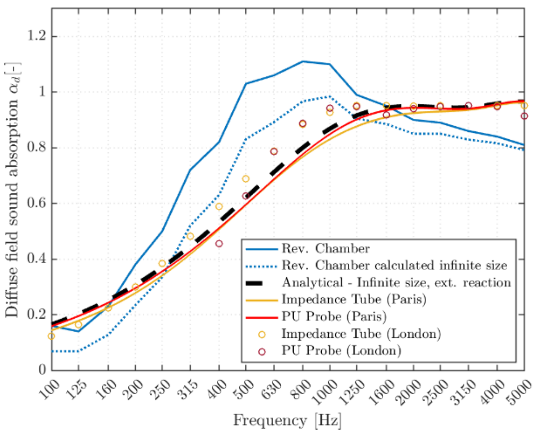

**Figure 5.** Comparison between all methods of melamine foam, 50mm thick

The sample size correction, calculated using the dimensions of the measured sample on the reverberant chamber, enabled the comparison to random incidence SAC from the Impedance Tube and the PU probe, as it reduced the excess absorption caused by the sample's edges. In comparison with the analytical curve, it is observed that the measured coefficients yield a similar behavior for all the materials tested, oscillating around the reference curve. The lack of diffusion found in the measurement chamber hindered the results from these measurements at higher frequencies.

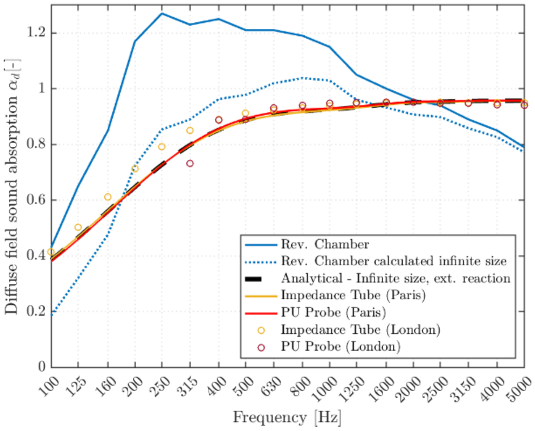

**Figure 6.** Comparison between all methods of rockwool PN55 100mm thick

## 5. CONCLUSIONS

This study highlighted the complexity and significance of various factors that come into play whenever performing in-situ measurements of sound-absorbing porous materials with a PU Probe. Below 800 Hz, the effect of sample size, sound field model and probe location proved to be significant on the measured absorption coefficient. Nonetheless, results showed to be very accurate at higher frequencies, yielding errors smaller than those obtained by the Impedance Tube, in reference to the Equivalent Fluid Models. Taking advantage of this, the model fitting procedure developed proved to be an effective solution to address the higher errors found in the low-frequency region, effectively obtaining broadband normal and random incidence SAC with samples as small as 200x200mm$^2$.

Excellent agreement was found between all measured and reference curves for both materials at normal incidence. In a diffuse field, despite the non-diffuseness found in the measurement chamber, the measured absorption after a size correction was found to be oscillating around the reference curve, from which good agreement between the Impedance Tube and the PU Probe techniques was found. The applicability of the proposed model fitting procedure should be further investigated in more complex systems, such as non-flat panels or materials with air gaps.

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