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Comparison of *in situ* sound absorption measurements using single microphone and an array of microphones

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ABSTRACT

The sound absorption of materials is traditionally measured in laboratory condition with one of two methods: random incidence in a reverberant chamber (ISO 354) or normal incidence in an impedance tube (ISO 10534). Nevertheless, there are some materials that cannot be measured in the lab, e.g., road surfaces, which are recommended to be measured *in situ* with the use of a single microphone (ISO 13472). There are, however, other methods for in situ measurements, e.g. using microphone arrays or sound intensity probes. To better understand the advantages and disadvantages of different *in situ* measurement methods, in this work we compare the measurement results employing a single microphone (in an adaptation of the ISO 13472), an array of microphones and an impedance tube. The tested material was a PET-wool and the sound absorption coefficient was analysed in third-octave bands between 250Hz and 4000Hz.

In the experimental procedure of ISO 13472-1, the signal subtraction method was adopted. For the microphone array method, an apparatus was constructed employing four microphones and the median-based RELAX method for post-processing. Comparison of sound absorption results between the three methods showed statistically non-significant variations and indicate that both in situ methods evaluated have the potential to be applied in situations where the in situ method is necessary.

Keywords: absorption coefficient, in situ measurement, microphone array.
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1. INTRODUCTION

Environmental noise is harmful sound generated by human activities including road traffic, railways, air transport, industry, recreation and construction [1]. For instance, a survey applied in the Netherlands verified that road noise was rated as the most annoying source of noise (71%), followed by air traffic noise (13%) and neighbours' noise (13%) [2]. Furthermore, long-term exposure to road traffic noise in association with air pollution is credited to accelerate neurocognitive decline and development of dementia [3], [4]. Other studies indicate that transportation noise exposure may influence the occurrence of respiratory symptoms and exacerbate asthma in adults [5] and variation of blood pressure [6].

The presence of urban canyons may increase background noise levels perceived by pedestrians in up to 7.0 dB(A) in buildings with glass façade [7] and increases with traffic density [8]. However the application of absorbing materials in façades can decrease up to 5 dB the sound levels of street canyons [9], more specifically, a vertical greenery system provided 4.0 dB(A) attenuation in such environment [10].

For the effective analysis of street noise attenuation, it is necessary to determine the sound absorption coefficient of the building walls. The determination of this coefficient is, commonly, made following two standards: ISO 354 (2003) method of determination of sound absorption coefficient in reverberant chamber and ISO 10534-1 (1996) method of determination of sound absorption coefficient in impedance tube. Both methods have some disadvantages. The impedance tube has limitations on sample area. For the desired frequency range from 250 Hz to 4000 Hz a sample with a diameter of only 10 cm is commonly used. In the reverberant chamber method, the samples must be installed on the chamber walls and this, for fixed systems, is impracticable. For these situations, *in situ* measurement techniques are an attractive alternative as they do not require a special environment to be set up.

In situ techniques can be used in both indoor and outdoor conditions. When conducting indoor in situ measurements the reverberation and sample size are of major concern, while the meteorological effects are of major concern in outdoor conditions. Brandão, Lenzi and Paul made a review of in situ impedance and sound absorption measurement techniques, arguing that the main method used in this cases is the temporal separation method. For this method, the challenge is to determine how the acoustic wave will behave in between the microphone and the sample under measurement [13].

Londhe, Rao and Blough [14] used the in situ method described in [15] to measure the sound absorption coefficient of grass. This method is based on the signal subtraction technique between the incident and reflected signals. Only one microphone and one sound source is needed for this method. When compared to the impedance tube the results have good agreement in the range between 400 Hz and 3000 Hz. Lacasta et al. used this same in situ method for modular greenery barriers and the results were equivalent to the results found in the literature [10]. Bustamante also performed the in situ technique on two materials: mineral wool and gypsum plaster board and concluded that the results were satisfactory [16].

The use of microphone arrays is one of the most recent approach to measure acoustic impedance in situ. It makes use of spatial filtering to separate the incident and the reflected components of the wave field close to the material under test. The simplest configurations use a linear array [17], while more complex configurations use planar [18] or spherical arrays [19].

The objective of this paper is to compare the sound absorption coefficient measured in situ by a single microphone method, the microphone array method, and the impedance tube method. For a comparison of these methods, a commercially known material (PET-wool) was tested.

2. MATERIAL AND METHODS FOR DETERMINATION OF ACOUSTIC ABSORPTION COEFFICIENT IN SITU

The material under this tests comparison is PET wool manufactured by Trisoft. The width of the material is 25 mm and each module has 1.00 m x 1.00 m. For the measurement, an external wall was covered with nine modules of the material, covering a total area of 3.00 m x 3.00 m. The superficial density is 0.7 Kg/m². As expected of fibrous material the high absorption performance is in high frequencies. For a reference, measurement of sound absorption coefficient were made with an impedance tube (Figure 1).

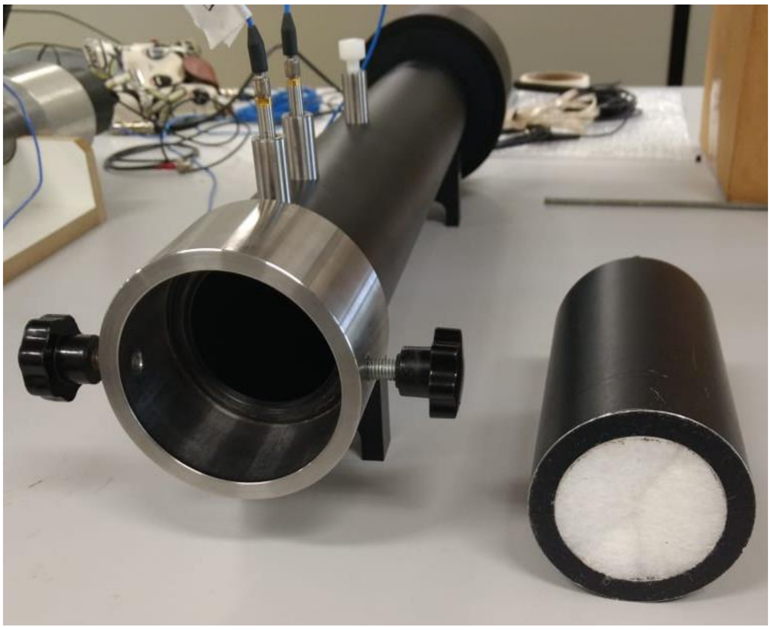

Figure 1*: Setup used for the measurement with an impedance tube.*

2.1. Single microphone method

The ISO 13472-1 defines two methods of signal processing to be used with in situ measurement of sound absorption coefficient with a single microphone: temporal separation and the signal subtraction techniques [15]. In both cases, it defines that the excitation signal used "shall consist of a repeatable short signal with a low peak-to-RMS ratio (…) such as maximum-length sequences (MLS) or short frequency sweeps". For this manuscript, the subtraction technique was preferred because it allows a longer sampling interval within a certain geometrical size of the system and the frequency sweep was used as excitation signal because of its robustness to system's non-linearity [20].

The test setup consists of a sound source, a microphone, an audio amplifier, an audio interface and a computer to acquire and process the signals (*Figure 2*). For the signal subtraction technique a second measurement in free field is needed. After the two measurements are concluded, the free-field signal is subtracted from the reflected signal, resulting in only the signal for the reflected path.

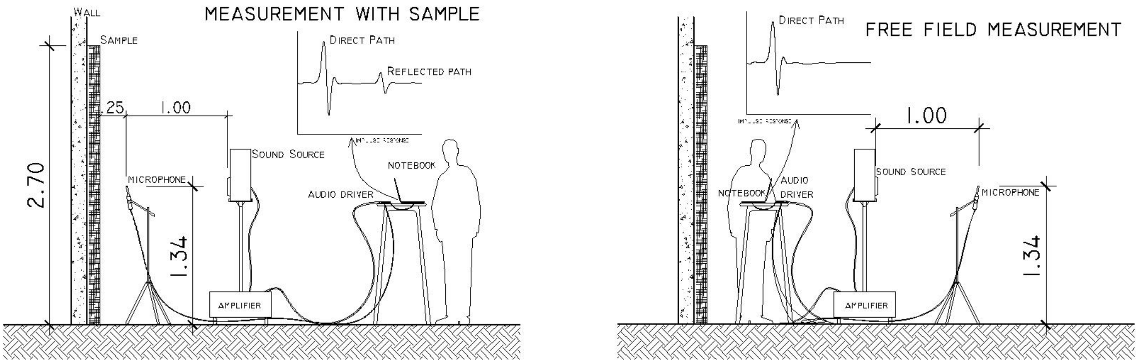

Figure 2: *Measurement set up of sound absorption coefficient according to ISO 13472-1 (2002)*

In this work, the sound source used was the same as in [21], the amplifier was a B&K model 2716, the microphone was a Behringer ECM 8000, and the audio interface was a Presonus AudioBox USB. The signal processing was made in MatLab with the freely available ITA toolbox[5]. The excitation signal used for the test was a logarithmic sweep with duration of 6 s and frequency range from 20 Hz to 20 kHz. According to the recommendation of [15], the measurement was repeated and averaged 50 times to obtain a stable impulse response function. In results, an analysis was made comparing 50 impulse responses measured in sequence (sound absorption coefficient named Alpha_50, in results), i.e. without interruption, and measured in 5 cycles of 10 measurements each (sound absorption coefficient named Alpha_10, in results) with interruption each cycles to minimize the background noise interference.

The sound absorption coefficient is determined as

$$\propto (f) = 1 - \frac{1}{{K_r}^2}\left|\frac{H_r(f)}{H_i(f)}\right|^2, \qquad \textbf{Eq1}$$

where $K_r = \frac{d_s - d_m}{d_s + d_m}$ is a geometrical spreading factor, d_s is the distance between the sound source and the sample, d_m is the distance between the microphone and the sample, $H_r(f)$ is the transfer function for the reflected path, resulted from subtraction, and $H_i(f)$ is the transfer function for the directed path, measured in free field.

The distances recommend in [15] are $d_s = 1{,}25$ m and $d_m = 0{,}25$ m. Considering these figures, assuming the speed of sound as 343 m/s and fixating the width of the temporal window as 5 ms the maximum sampled area radius is calculated to be 1,34 m. The signal-to-noise ratio was verified to be larger than 10 dB within each one-third-octave band between 250 Hz and 4 kHz. This method considers the part of the energy scattered as being absorbed; thus, the sound absorption coefficient may be slightly overestimated.

At post-processing, we first need to time align the measurement with sample and the free field measurement (Figure 3 shows the lack of alignment in the signals). A time shift $\Delta\tau$ with subsample resolution can be obtained by changing the phase of each coefficient, i.e., by multiplying it with a frequency-dependent factor $\exp(j2\pi f\Delta\tau)$. Windowing was also applied to eliminate spurious reflection from the signals. Lastly, the same method proposed by Bustamante in [16] was applied to calculate the sound absorption coefficient (Alpha_10 and Alpha_50).

[5]www.ita-toolbox.org

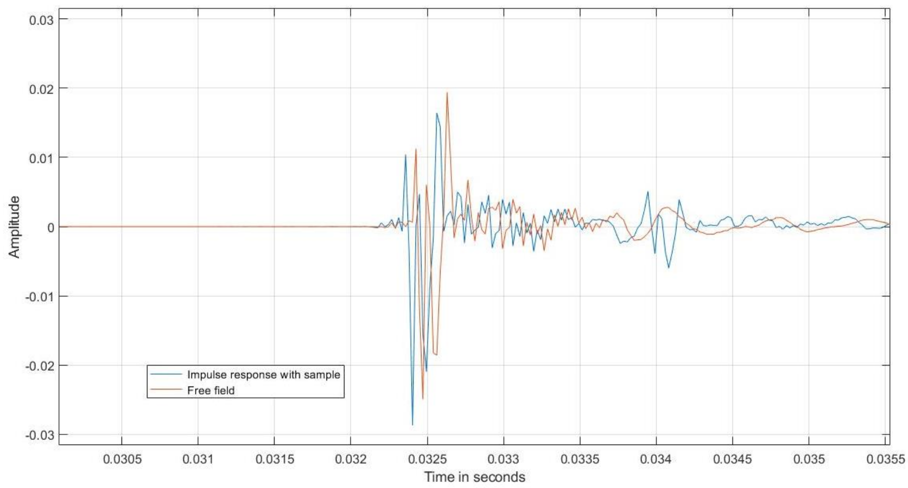

Figure 3: *Impulse responses with sample and in free field. Note delay between signals, this adjustment must be correct by the method described in annex G of ISO 13472-1.*

2.2. Array of microphone method

The combination of the signals extracted from a set of microphones distributed in space allows the realization of a *spatial filter*, also known as a *beamformer*, which can enhance the signal arriving at the array from a given direction while attenuating noise and interference arriving from other directions. The most common beamformer is the delay-and-sum (DAS) technique, which was used in conjunction with the RELAX algorithm, used to provide a sparse estimate of the sound sources.

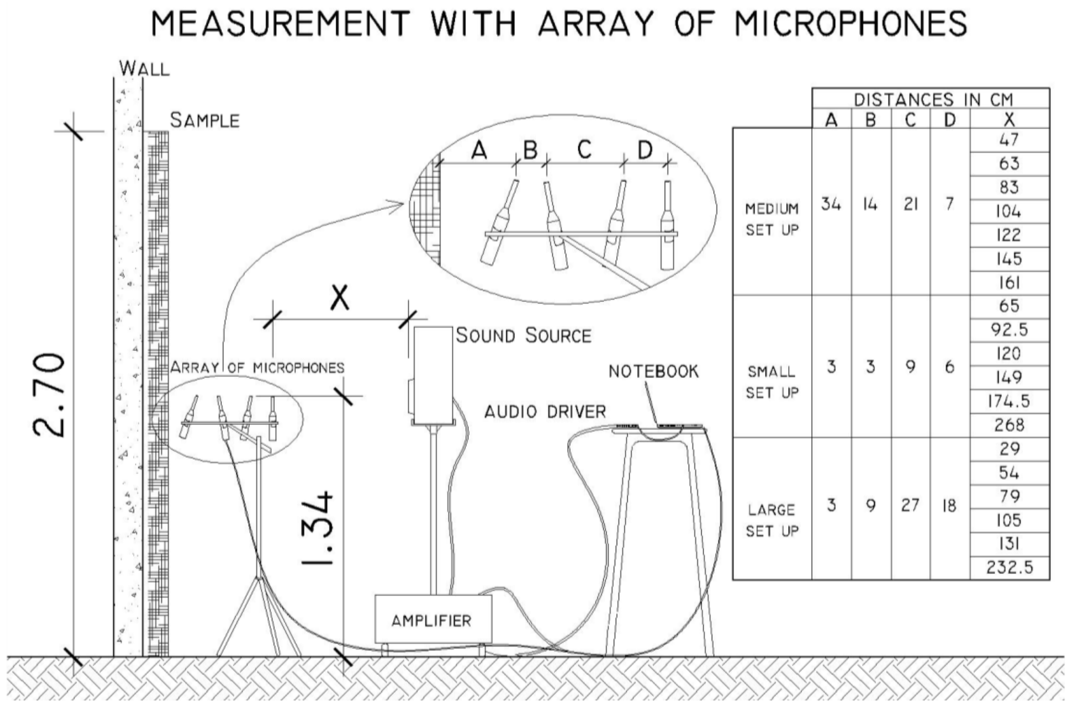

Figure 4: *Measurement setup of sound absorption coefficient using a microphone array.*

Since the microphones used for the array did not have matched frequency response, we first equalized their frequency responses. To do so, we placed the microphones with their membranes side by side and measured the transfer function between the loudspeaker (placed in far field) and the microphones. Assuming the microphones are close enough in order for the spatially sampled frequency response to be the same, we equalize the microphone from the relative difference from these measured frequency responses.

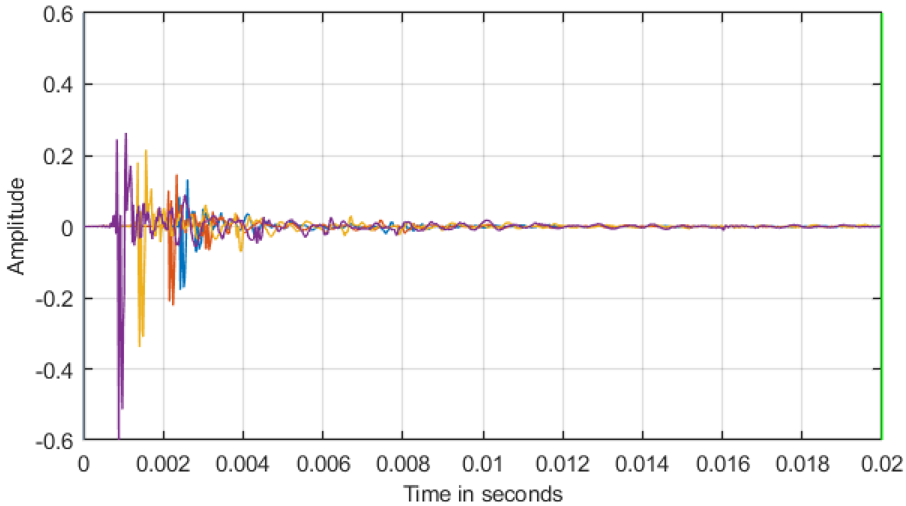

Figure 5*: Impulse response measured with loudspeaker placed 29 cm from the microphone array (large setup).*

An example of measured impulse responses between the loudspeaker and the microphones after equalization is presented in Figure 5. It is possible to observe that the impulse response from the loudspeaker is very long, resulting in its superposition with the reflected sound. To eliminate the influence of the loudspeakers eigenresponse, we first align the microphone's response using the GCC-PHAT algorithm. In the DAS beamforming, after aligning the signals, one should average all signals to estimate the incoming signal from that given direction. In this case, however, as we have only four microphones, this would result in impulsive noise caused by the reflected sound. To reduce this effect, we take the **median** instead of the mean value of the samples of the impulse response, as shown in Figure 6. Please note how the impulsive noise caused by the reflected sound is eliminated. The median signal is then used to equalize all channels, resulting in much more compact signals, with practically no superposition, as exemplified in Figure 7.

Now, with the equalized signals we apply a modified version of the wideband RELAX algorithm [21]. The algorithm was modified to be use a spherical wave propagation model instead of the plane wave propagation model used in the original algorithm. The spherical propagation model requires the distance between source and receiver that, in our case, is extracted from the time position of the maximum value from each impulse response. The modified RELAX algorithm is then able to separate the direct sound from the reflected sound, as shown in Figure 8 (time domain) and Figure 9 (frequency domain). The reflection factor is obtained by simply dividing the frequency response of the reflected sound by the frequency response of the direct sound. As we are using beamforming with a spherical propagation model it is not necessary to correct the measurement with the geometrical spreading factor presented in (1) as the beamformer does this automatically. Therefore, the absorption coefficient is obtained simply from $\alpha = 1 - |R|^2$.

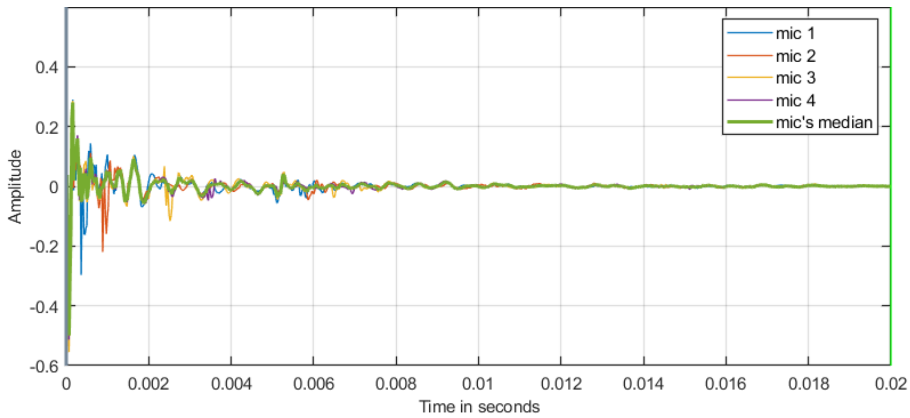

Figure 6*: Aligned impulse responses measured with loudspeaker placed 29 cm from the microphone array (large setup). In green, the median for each time simple. Note how the impulsive noise caused by the reflected sound is eliminated.*

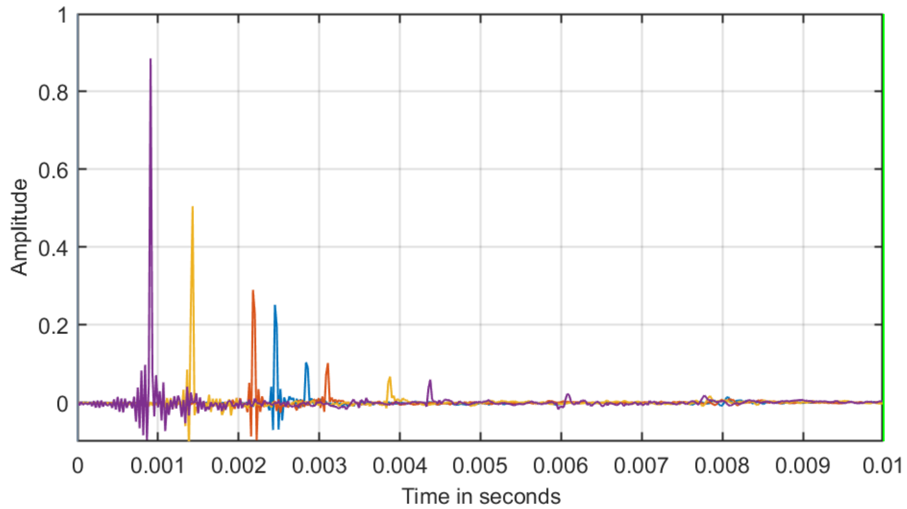

Figure 7*: Equalized impulse responses measured with loudspeaker placed 29 cm from the microphone array (large setup). Note how the direct and reflected sounds do not superpose.*

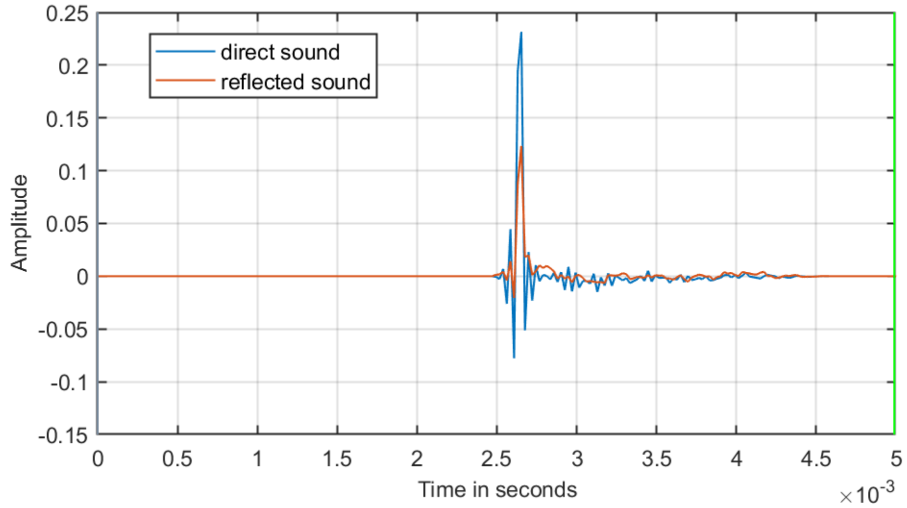

Figure 8*: Direct and reflected sound obtained with the modified RELAX algorithm.*

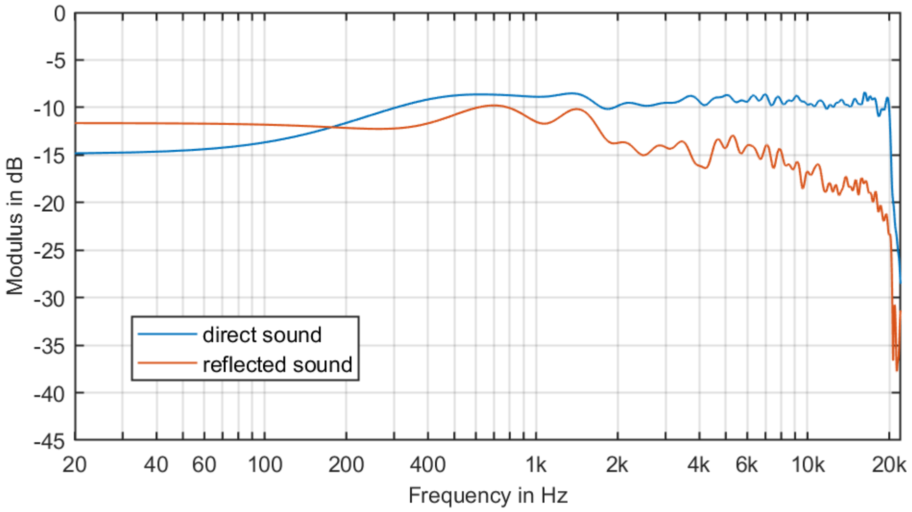

Figure 9*: Direct and reflected frequency responses obtained with the modified RELAX algorithm. Note that the loudspeaker does not have sufficient energy below 200 Hz, so response can´t be trusted below this frequency range.*

3. RESULTS AND ANALYSIS

We compare the results obtained with the one microphone technique and the microphone array technique with measurements of the same material made in an impedance tube.

In one microphone method, sound absorption coefficients of impedance tube and measurements (Alpha_10 and Alpha_50) have a similar global trend to increase the absorption with the increase of the frequency. However, Alpha_50 is smoother than Alpha_10, which has a drop in 1250 Hz and 2500 Hz (Figure 10). Both measurements obtained a deviation less than 10% in when compared to the figures measured with the impedance tube.

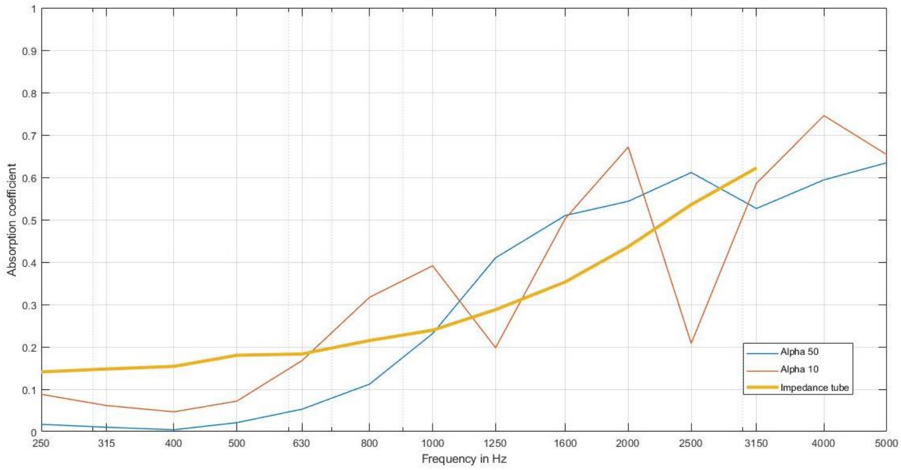

Figure 10: *Comparison of sound absorption coefficient measured with the single microphone methods (50 averages and 5 times 10 averages) compared to the same sample measured with an impedance tube.*

In comparison of methods, Alpha_10’s curve has best fit in range of 800 – 1600Hz in comparison of all setups of microphones’ array. The Alpha_50’s results have fitted a range of 1250 – 2000 Hz and 6350 Hz for all setups. Both measurements have the best approximation of small setup coefficients (Figure 11 - c). In all measurements, a range of 315 – 500 Hz was close to impedance tube’s sound absorption coefficient. The majority of array method’s curves have more absorption than impedance tube, i.e. this method slightly overestimated the sound absorption.

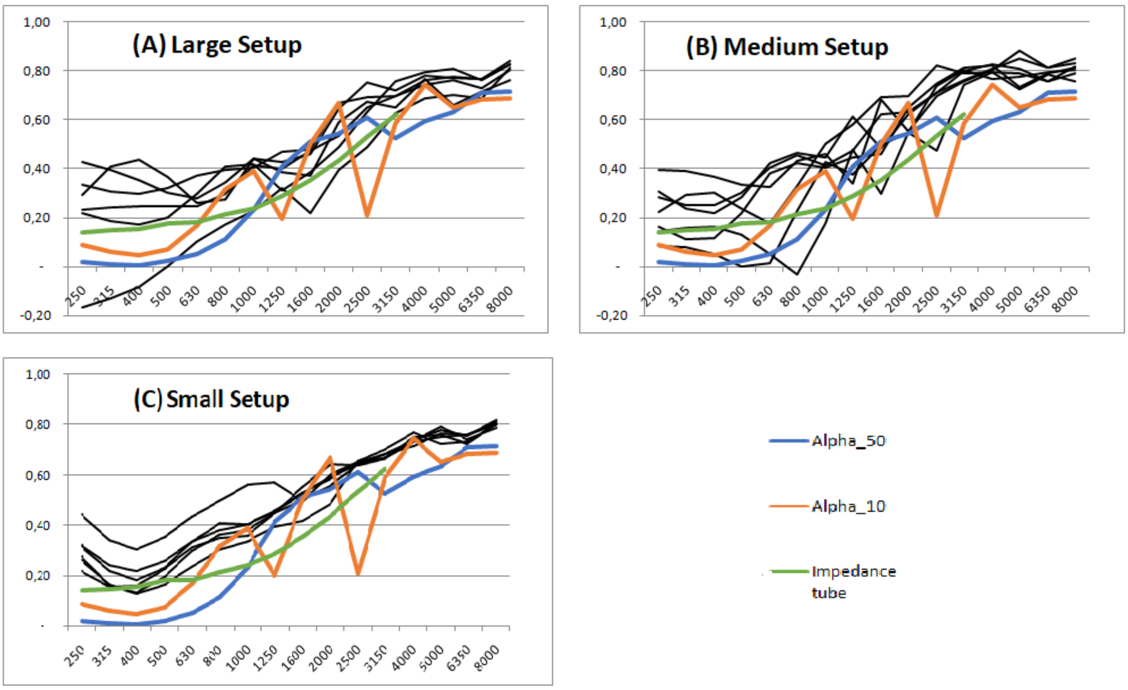

Figure 11: *Comparison of in situ and impedance tube methods for determining the sound absorption coefficient.*

In Figure 12, the results of the absorption coefficients measured with all microphone array configuration and loudspeaker distance are compared to the absorption coefficient measured with the impedance tube. We verify that the global trend of increase with frequency is kept; however, there is a systematic mismatch that we suspect can be caused by the inherent difference of the two methods, as the impedance tube is dealing with a plane wave while the in situ measurement is dealing with a spherical wave. Besides that, the difference in sample size and sample installation can play a significant role in these verified discrepancies.

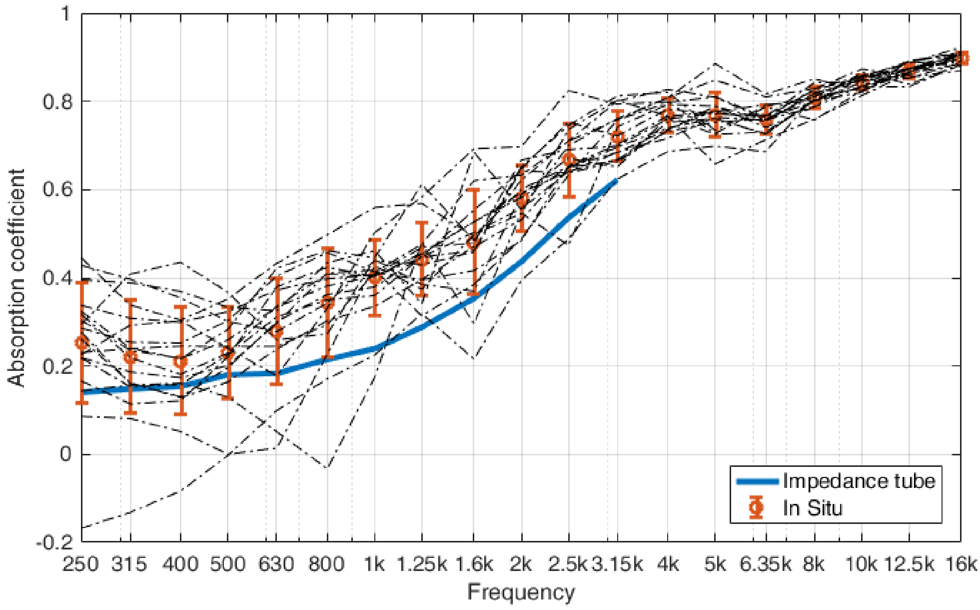

Figure 12*: Absorption coefficient of a PET wool measured in situ with a four microphone linear array and the modified RELAX method (thin lines and mean and standard deviation in orange) compared with the absorption coefficient of the same material measured with an impedance tube (blue thick line).*

4. CONCLUSIONS

We observed that the general trends for results of sound absorption coefficient measured by *in situ* method behave as expected, showing an increase with frequency. The measurements with a single microphone show large oscillations in the measured curve. This is probably due to the use of time windows that result in a “smeared” frequency spectrum. On the other hand, we propose an adapted median-based RELAX method which minimizes the use of time windowing and results in spectra with smaller oscillations. The results obtained with both in situ methods agree in general trend with the result obtained with the impedance tube, even though a systematic increase in absorption values measured in situ can be observed. These results corroborate the validity of using in situ methods when is not possible to determine an absorption via conventional methods.

5. ACKNOWLEDGMENTS

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