Applied Acoustics 171 (2021) 107659

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Effect of the excitation signal type on the absorption coefficient measurement using the impedance tube

A.C. Corredor-Bedoya [a,1,*], B. Acuña [b,2], A.L. Serpa [a,3], B. Masiero [b,4]

[a] University of Campinas, School of Mechanical Engineering, Department of Computational Mechanics, Brazil
[b] University of Campinas, School of Electrical and Computer Engineering, Communications Department, Brazil

ARTICLE INFO

Article history:
Received 10 March 2020
Received in revised form 11 August 2020
Accepted 6 September 2020
Available online 26 September 2020

Keywords:
Impedance tube
Absorption coefficient
Random signal
Periodic signals

ABSTRACT

This work evaluates the effect of the excitation signal used when measuring the absorption coefficient on an impedance tube. This paper aims to offer some guidance on the selection of the excitation signal to perform sound absorption measurements using the impedance tube. Four possible excitation signals defined in ISO 10534-2 Standard were studied: two of them, random noise and two of them sine sweep signals. Some hypotheses tests were executed to assess the homogeneity of each measurement. The signal-to-noise ratio (SNR) was also computed to verify the measurement quality. The results show that the best performing approach was accomplished using a logarithmic sweep, giving more precise sound absorption curves with an SNR of 34.15 dB. Random signals reported similar SNR (greater than 30 dB) after executing an average with 100 repetitions.

1. Introduction

The sound absorption coefficient is one of the most critical properties required to design environments or acoustic barriers. Sound absorption is a frequency-dependent property, and, therefore, it is necessary to test the material along the complete frequency range of interest [1].

Sound absorption is described by the sound absorption coefficient, which ranges from 0.00 to 1.00, where 1.00 indicates a perfect energy absorption (without reflection), and 0.00 means that the material does not absorb any incident sound upon it, reflecting all its energy [2].

As shown in Fig. 1, when an acoustic wave hits a barrier, we consider that the incident energy is divided into three parts: the reflected energy, the dissipated energy, and the transmitted energy [3]. The sum of the transmitted and the dissipated energies is the absorbed energy. On the other hand, the difference between the incident and the reflected energies also equal the absorbed energy, i.e.,

$$E_a = E_d + E_t = E_i - E_r, \tag{1}$$

where E_a is the absorbed energy, E_d is the dissipated energy, E_t is the transmitted energy, E_i the incident energy, and E_r is the reflected energy.

The absorption coefficient (α) of a material is defined as the relationship between the absorbed energy (E_a) and the incident energy (E_i) at the material's surface [5], and is computed for frequency f as

$$\alpha(f) = \frac{E_a(f)}{E_i(f)}. \tag{2}$$

In practical applications it can be quite challenging to decompose a sound field into its incident and absorbed components. The absorption coefficient can be shown to be equivalent to the complement of the reflected energy, i.e.,

$$\alpha = 1 - |R|^2, \tag{3}$$

where R is the reflection factor, which contains all acoustical properties of the material [6]. The reflection factor can be related to the material's surface impedance Z [6] by

$$R = \frac{Z\cos\vartheta - Z_0}{Z\cos\vartheta + Z_0}, \tag{4}$$

where ϑ is the angle between the incident wave and the wall, and Z_0 is the characteristic impedance of the medium.

Even though there is not a general method to calculate the absorption coefficient, it is possible to predict it for a specific class

* Corresponding author.
[1] ORCID: 0000-0002-3060-7845
[2] ORCID: 0000-0002-3060-7845
[3] ORCID: 0000-0002-3060-7845
[4] ORCID: 0000-0002-2246-4450

https://doi.org/10.1016/j.apacoust.2020.107659

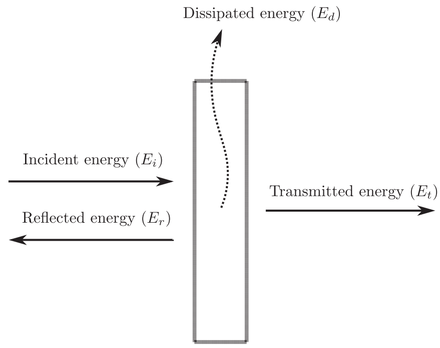

Fig. 1. Energy balance of the incident sound in a barrier. Adapted from [3,4].

of materials through experimental techniques [7,8]. Two of the best known and standardized methods are:

Reverberant room method [9], which measures the random incidence absorption coefficient to specify the performance of a material in room design.

Impedance tube method [10,11], also known as "Kundt tube", which measures the normal incidence absorption coefficient (α_n); this method has become widely used by developers of absorptive materials worldwide to build up an understanding of the material properties and to validate absorptive material models.

The impedance tube is the most common method to estimate the absorption coefficient since it does not use a great space and is cheaper than a reverberant chamber. The most common calculation method used with the Kundt tube is the so-called "impedance tube using the two-microphone method with transfer function" described in two standards: the ASTME1050 [12] and the ISO 10534-2 [11]. These standards establish acceptable conditions for conducting the measurement; however, they do not offer any guidance on how to select the excitation signal to be used. From the literature we note that commercial manufacturers and academics most often perform impedance tube measurements using broadband stationary random noise or maximum-length-sequence (MLS).

According to Horoshenkov et al. [13], the accuracy of the measurement using the impedance tube is influenced by four factors: the quality and homogeneity of the material samples, the environmental and operational conditions during the experiment, the quality of the setup, and the signal processing method. They tested some material samples using impedance tubes on seven laboratories and observed an influence of the mounting conditions and sample permeability on the measured data. Results with less dispersion were found for pseudo-random noise (PRN) and MLS, instead of random noise. They did not, however, include sine sweeps on their experiment.

In a further study of the same group [14], the reproducibility of a test using the impedance tube was discussed regarding the ambiguity of the ISO 10534-2. Some potential measurement problems were: installation of the samples, instrument calibration procedures, number of samples to be measured for the material characterization, and the acceptability of a standard deviation on the tests conducted. In this case, most of the partners used white noise as the stimulus, while a fewer portion applied sweep and PRN. No relevant difference was observed due to the stimulus signal.

Espinosa et al. [15] made a comparison of the measured reflection coefficient using two different stimuli: Gaussian white noise and uniform white noise, finding consistency on both results. On their work, Suhanek et al. [16] made a comparison of three different stimuli on the impedance tube using the transfer function method and their results showed a smoother response using MLS and pink noise than with a periodic sweep. This result contrasts with the conclusion from Müler and Massarani [17], that "FFT techniques using [sine] sweeps as excitation signals are the most advantageous choice for almost every transfer-function measurement situation [as they] allow feeding the device under test with high power at little more than 3 dB crest factor and are relatively tolerant of time variance and totally immune against harmonic distortion.".

We note that authors do not usually explain their reasons for selecting the excitation signal used to measure the absorption coefficient with the impedance tube [18–20]. The higher signal to noise ratio perhaps influences this selection; however, this value is commonly not reported.

This paper is intended to provide aid in the selection of the excitation signal for the absorption coefficient measurement. We look for the excitation signal that offers higher precision and accuracy while keeping a reduced measurement time. Thus the exposition of the measurement system to external factors that may introduce experimental errors would be reduced.

2. Problem modeling

A impedance tube consists of a rigid wall tube with a loudspeaker in one end and a sample holder in the other; three microphone holes are located along the body of the tube, as shown in Fig. 2. The loudspeaker generates a plane wave that reaches the sample with normal incidence. Part of the energy is absorbed by the sample, while another part is reflected and returns along the tube. Due to the interaction between the two waves, a stationary sound wave is established in the tube. In Fig. 2 we see an example of the stationary pressure wave, with its maxima and minima distribute along the tube. Two microphones are used to measure the sound pressure at two different positions, which is then used to compute the cross spectrum or, equivalently, the transfer function between these two points. Finally, the results are computed using the transfer function method to obtain the absorption coefficient of the tested sample in the specified frequency [11].

The ISO 10534-2 Standard defines a guide to experimentally obtain the absorption coefficient α using the transfer function method. The Standard allows the use of random signals, pseudo-random sequence, or chirps (sine sweeps) as excitation signals [11] without specifying a preferred input for the two microphone technique; even though the Standard recommends the use of deterministic and pseudo-random signals with the one microphone technique.

3. Material and methods

An experimental setup was proposed to evaluate the advantages or disadvantages of using a chirp or random excitation signal. The two microphone technique was selected, using positions 1 and 2 of a commercial impedance tube (the BSWA SW 433, with a diameter of 60 mm). An LMS SCADA data acquisition system was employed as a signal generator and signal acquisition system. Post-processing was conducted in Matlab. Fig. 3 shows a schematic representation of the proposed experimental setup.

A tube diameter of 60mm theoretically allows its use up to a frequency of 3300 Hz. However, the tube's manual recommended a frequency band from 400 Hz to 2500 Hz. Therefore, we set up an upper frequency of 2560Hz for all excitation signals. The four different excitation signals compared in this experiment are listed below:

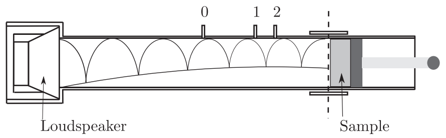

Fig. 2. Impedance tube scheme with an stationary wave. Based on [21].

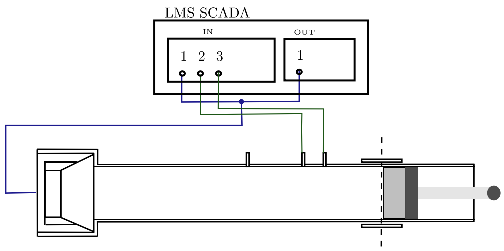

Fig. 3. Experiment configuration using an impedance tube with the two microphone technique and a LMS SCADA as the signal generator (OUT, channel 1) and processing equipment (IN, channels 1–3).

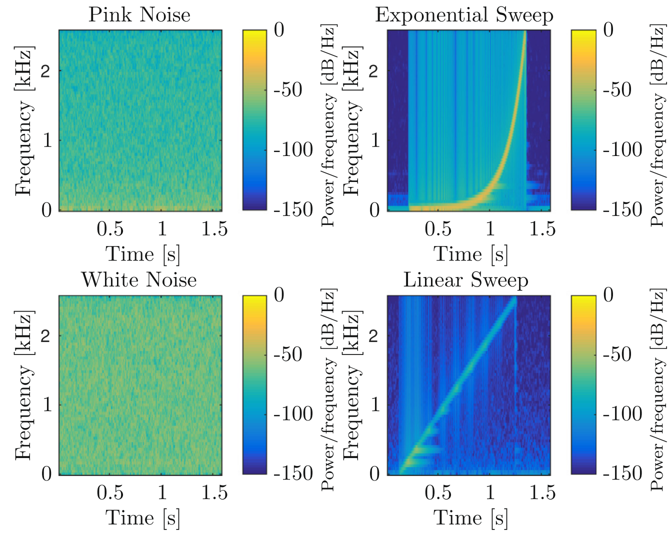

Fig. 4. Spectrogram of recorded stimulus signals during the measurement of the absorption coefficient in the impedance tube.

- White Noise (denoted as WN),
- Pink Noise (denoted as PN),
- Linear sine sweep (denoted as LS),
- Exponential sine sweep (denoted as ES).

Fig. 4 shows the spectrograms of a realization of each stimulus signal, i.e., how the spectral density of each excitation signal varies with time. The spectrogram of white noise is almost entirely uniform because all frequencies are continuously present with random amplitudes. The pink noise spectrogram shows that lower frequencies are predominant. The linear sweep spectrogram shows the linear relationship between frequency and time. Finally, the spectrogram of the exponential sweep shows how frequency increases exponentially with the time within a defined bandwidth.

The parameters used to generate the random signals are described in Table 1. The first line represents the parameters used for an initial comparison maintaining the same parameters for the four signals. The second line shows the parameters used to generate the random signals in a second experiment that aimed at making a fair comparison of the signals results regarding the measurement time, as detailed in Section 3.2. The sine sweeps were generated in the frequency range of 0.256 Hz to 2534 Hz (corresponding to the 0.1% and 99% of the upper frequency), and sweep time of 70% of the acquisition time, i.e., an excitation signal of 1.12 s followed by 0.48 s of silence.

3.1. Experiment 1

One of the recommendations found in the ISO 10534-2 Standard [11] is to average the microphones' spectra to reduce errors due to noise. To evaluate the influence of averaging, a single execution measurement was conducted for all the input signals; then, tests with 100 and 1000 averages for random excitation, and with 10 and 30 averages for sine sweep inputs were performed. The test material, in all cases, was a sample of melamine foam with 25mm thickness and 60mm diameter.

Two processes were followed to obtain α, one for random noise and another for sine sweep signals. Even though the processing is similar in both cases, due to the stochastic nature of the pink and white noise, the use of averaging is mandatory, adding a processing effort to the signal processing equipment for this kind of excitation. Otherwise, for linear and exponential sweeps, a filtering process is required after the transfer function calculation (listed in Fig. 5 as H_{12}) to reduce signal noise in α. Fig. 5 shows the implemented algorithms for each case.

When using random signals, the microphones signal is divided into n blocks where n is the predefined number of averages. A Hann window is applied for each block before the frequency response function (FRF) is computed. After averaging the FRFs, the result is used to obtain H_{12}. Due to the phase mismatch of the microphones, a phase correction is executed, as explained in [11]. To conclude, before computing α, a Hann window of 512 samples is applied in the time domain to eliminate the influence of the background noise present in H_{12}.

When a sine sweep signal is selected, there is no blocking process. Instead of that, a uniform window is applied, and in sequence, the FRF and H_{12} are computed. After the phase correction, the signal measured with a sine sweep excitation was windowed with a Hann window in the same way as the random signal in order to allow a fair comparison (all results are plotted first with and without this step). Finally, the α is computed.

After windowing the impulse response (IR) obtained with the sine sweep signals ($H_{12}(t)$) the time-domain signal can either be kept with trailing zeros or be cropped (i.e., reduced in length). In this first experiment, the results were directly compared with the results obtained with the random signals, without cropping.

3.2. Experiment 2

In the second experiment, the windowed IR, when measured with sine sweep signals, was cropped to disregard the trailing zeros, random signals were not filtered on this case and new parameters were required to guarantee a fair comparison of the results. For this second parameter set, the test was repeated with 16 averages for random signals and a single execution for periodic signals.

3.3. Statistical analysis

To analyze the accuracy of the measured absorption coefficient, the 1/3 octave band α was computed as the mean of the measured values on each band and then, compared to the absorption coefficient given by the tube manufacturer. Two tests were performed: the first was a hypothesis test on the mean value of each 1/3 octave region, aimed to evaluate if the measured value on each frequency

Table 1
Sets of excitation signals parameters, where SL are the spectral lines or number of samples in the frequency domain, Fs is the sampling rate, Δf is the frequency resolution, N is the number of samples in the time domain, and T is the acquisition time.

	SL	Fs [Hz]	Δf [Hz]	N	T [s]
Experiment 1	4096	5120	0.625	8192	1.6
Experiment 2	256	5120	10	512	0.1

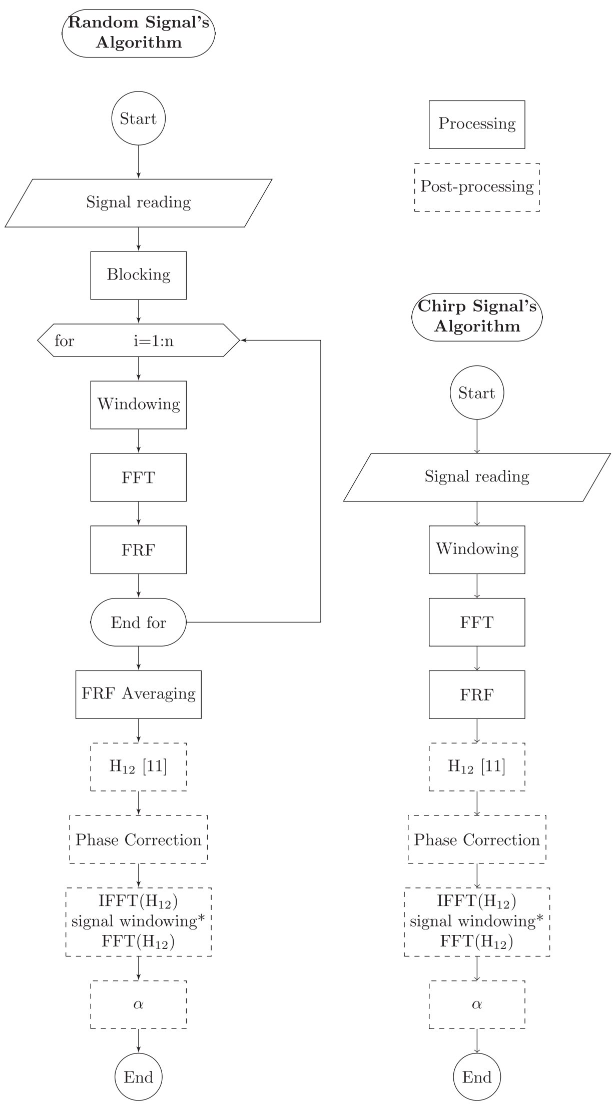

Fig. 5. Signal processing and post-processing algorithm for random and sine sweep inputs. *The windowed signal size is not reduced using the first set while it is reduced to 512 samples in the second set.

was statistically equal to the reference given by the tube manufacturer; the second one, a homogeneity test, studied each input signal separately and aimed to evaluate whether the set of measured values for the whole frequency range, using different amount of averages, had the same distribution.

3.3.1. Test of the mean

According to Montgomery and Runger [22, p. 278], a hypothesis "is a statement about the parameters of one or more populations". In this case, one hypothesis should indicate that there is no difference between the absorption coefficient given by the manufacturer (α_r) and the measured one (α_m), while the other hypothesis indicates they are different, i.e:

H_0: $\alpha_r = \alpha_m$,
H_1: $\alpha_r \neq \alpha_m$,

where H_0 is the null hypothesis, and H_1 the alternative one.

To test whether the null hypothesis is true or not, the t-score was selected as the test statistic since the standard deviation of the population is unknown. A critical region was computed, following the procedure described in [22], with a significance level of 0.05 (the probability of rejecting the H_0 when it is true). H_0 is rejected when α_m lies outside the critical region; otherwise, the test fails to reject the null hypothesis and one could say that α_r and α_m are the same on that 1/3 octave band.

3.3.2. Homogeneity test

On the other hand, the homogeneity test evaluates n populations of interest, divided into k categories. In this case, the test was run for each input signal, with tree populations: the measured set of α with the different amount of averages defined in Section 3.1, each of them with seven categories or 1/3 octave bands. The test investigates whether or not the proportions in the k categories are the same, regarding the number of averages performed. The hypotheses were [22]:

H_0: The populations are homogeneous concerning the 1/3 octave bands,
H_1: the populations are not homogeneous concerning the 1/3 octave bands.

The decision is made considering the χ^2 statistic with $(n-1)(k-1)$ degrees of freedom and a significance level of 0.01. According to Table III in [22, p. 655], $\chi^2_{ref} = 26.22$ and the test fails to reject the null hypothesis for computed χ^2 lower than χ^2_{ref}.

The critical region and χ^2 were computed using the hypothesis test functions of R software [23].

3.4. Signal to noise ratio

The signal to noise ratio (SNR) is defined as the ratio of signal power to noise power [24]. The ISO 10534-2 Standard [11] mentions that SNR "shall be at least 10dB higher than the background noise at all reported frequencies." However, there is no explanation on how this measurement should be performed.

According to Huszty [25], there are various methods to compute the SNR using the room impulse response (RIR), and one possible representation of the RIR is the energy time curve (ETC). Obtained by presenting the RIR in decibels and normalizing it by the peak value, the ETC shows the decay of energy over the time, and has two parts: a noise-free decay, where the stimulus dominates the IR, and a flat part, where the background noise dominates the IR [25]. According to this reference, the SNR is computed as

$$\mathrm{SNR} = 10\log_{10}\frac{\frac{1}{N}\sum_{k=1}^{N}(s[k])^2}{\frac{1}{M}\sum_{k=1}^{M}(u[k])^2}, \quad (5)$$

where s is the noise-free signal with N samples and u is the background noise with M samples.

In practice, the noise-free decay is not simple to measure, hence the SNR can be approximated trough the noise power of the ETC, known as the peak to noise ratio (PNR)

$$\mathrm{PNR} = 10\log_{10}\frac{1}{\frac{1}{N}\sum_{k=1}^{N}(u_n[k])^2}, \quad (6)$$

where u_n is the second (flat) part of the ETC [25].

Following the SNR definition, PNR can not be considered the same as SNR; therefore, another way to measure the SNR is using the iterative truncation method. This method truncates the ETC at a point where the noise begins to dominate the IR and assumes the noise-free signal to be the first part of the ETC, and the background noise to be the second part [25]. Finally, SNR is computed using Eq. (5). In this work, both, PNR and SNR were computed to ensure the compliance of the standard requirement.

4. Results and discussion

4.1. Experiment 1

The results of the first experiment are summarized in Figs. 6 and 7. The figures are organized as follows: the first row shows the measured value of α using the four tested signals with only one execution, i.e., without averaging. The second row shows α as the average of a hundred repetitions for random signals and ten repetitions for sine sweeps, and the third row shows α computed for one thousand averages for white and pink noises and thirty for linear and exponential sine sweeps. The notation used to identify each plot includes two letters, which indicates the type of signal input, and a number which indicates the number of executions or averages, e.g., WN100 shows the α using white noise and 100 averages. Columns are organized to facilitate the comparison between signals with the same power spectral density (PSD), i.e., white noise alongside linear sine sweep – both signals have uniform PSD – and pink noise alongside the exponential sine sweep - both signals have a PSD inversely proportional to the frequency.

Also in Figs. 6 and 7, absorption results were plotted in 1/3 octave band using the standardized center frequencies from 500Hz to 2000Hz [3], and measured curves were then compared with a 1/3 octave reference value supplied by the tube manufacturer [21]. A hypothesis test was conducted, and a critical region with a significance level of 0.05 was plotted. The results indicate that, inside the critical region, the measured and the reference values of α can be considered the same.

Fig. 6 shows the results without the filtering process computed trough the IFFT block on Fig. 5. As observed, all signals with only one execution gave a noisy absorption curve. However, the 1/3 octave band could be computed for the whole frequency band only using periodic stimulus. With the addition of averages, the background noise was reduced, and the 1/3 octave band was plotted with the four selected stimuli.

Another way to reduce the background noise was windowing the H_{12} in the time domain. Results in Fig. 7 show the absorption coefficient curves obtained from the windowed IR. The plots WN1 and PN1 evidentiate the need for an average process associated with the excitation with random signals, otherwise some frequencies will not be excited.

Regarding the test of the mean, all the measured coefficients lay inside the critical region. In consequence, the test fails to reject the null hypothesis, i.e., measured α should not be considered different than the reference α on any 1/3 octave band. Curves using white and pink noise as input with one execution were not taken into account due to the observed discontinuities.

The homogeneity test was run using R software [23]. The same tests were run with each set of stimulus signals, and results are summarized in Table 2. Using a significance level of 0.01, the reference χ^2_{ref} value with 12 degrees of freedom is 26.217, and the null hypothesis would be rejected when $\chi^2 > 26.217$.

The test results showed that there was not enough evidence to reject H_0 using WN, LS, or ES, meaning that the α results are homogeneous. However, we observe that χ^2 values are lower for deterministic signals than the obtained for white noise.

The statistical correlation coefficient (denoted here as *co*) was computed and shown in Table 3. A correlation coefficient near 1.0 indicates a strong relationship between the reference and the measured values of α [22]. The highest *co* value was observed for measurements using sine sweep signals with thirty averages. Due to the nature of the random signals, a lower *co* was expected

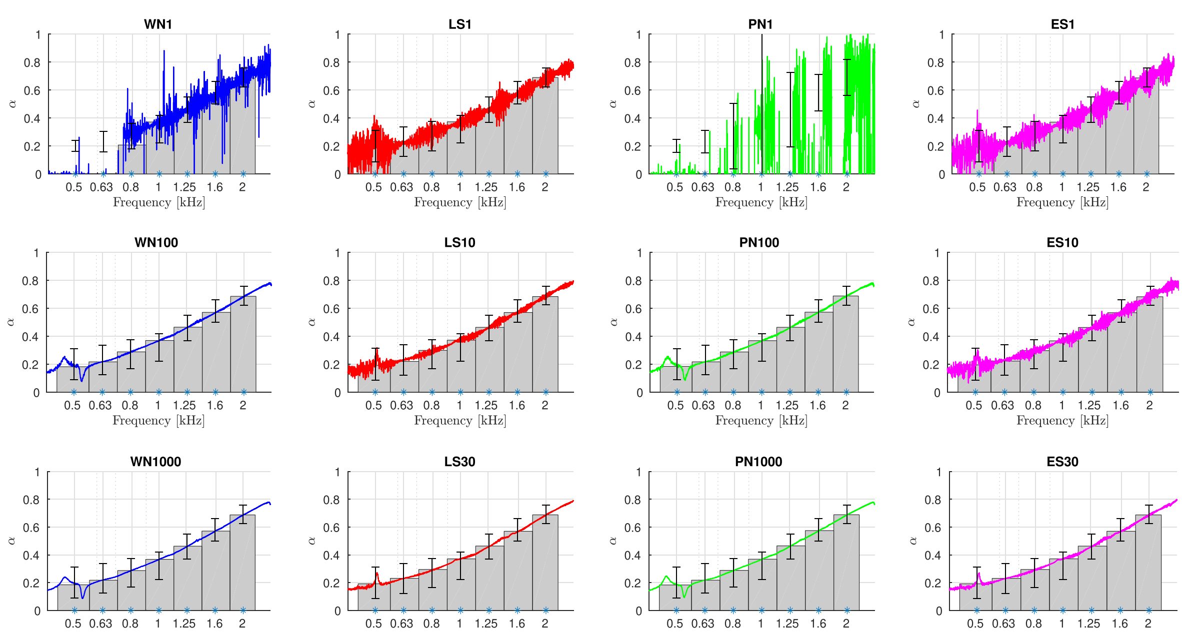

Fig. 6. α results of a 60 mm diameter and 25 mm thickness melamine foam sample using four different input signals from 400 Hz to 2500 Hz and in 1/3 octave bands with the computed critical region of the reference α. The two letters in the title of each subplot describes the signal type (WN, white noise; PN, pink noise; LS, linear sweep and ES, exponential sweep) and the numbers describe the number of processed averages. No filtering process was executed in the signal post-processing.

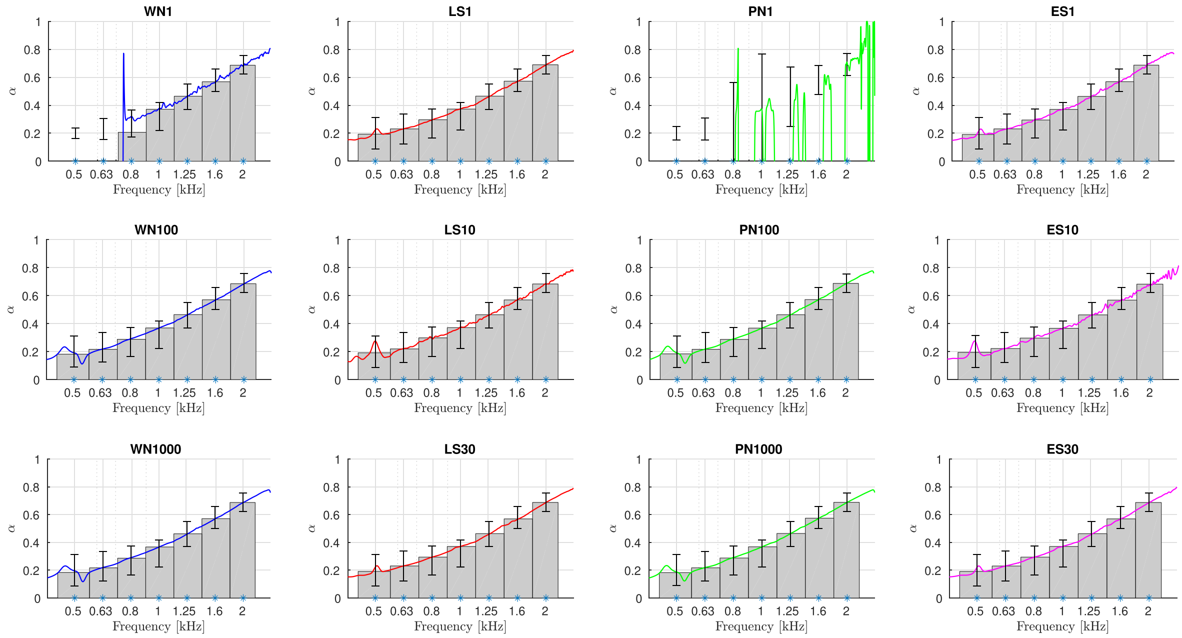

Fig. 7. Absorption coefficient of the melamine foam sample with a filtering process to minimize background noise. The labeling and distribution of the individual plots is the same as in Fig. 7.

Table 2
χ^2 values of a test of homogeneity comparing the α results in the 1/3 octave band using three different amount of averages for the four excitation signals.

	WN	PN	LS	ES
χ^2	0.3844*	**	0.0004	0.0003

*α for WN1 in the 500 Hz and 630 Hz band were assumed as 0 since the χ^2 test requires positive values.
**PN test was not conducted due to the negative results on the PN1 α.

Table 3
Statistical correlation coefficient comparing the reference α supplied by the manufacturer, with the measured α.

	WN	LS	PN	ES
1 execution	0.9344	0.9932	0.0202	0.9936
10 means	–	0.9919	–	0.9932
30 means	–	0.9933	–	0.9933
100 means	0.9921	–	0.9929	–
1000 means	0.9930	–	0.9929	–

and further confirmed. There is not a significant difference in the correlation for the rest of the tested data.

In order to estimate the required amount of averages to obtain a correlation coefficient of 0.99 using random signals, a cubic interpolation was run using the Matlab *spline* function. Results show

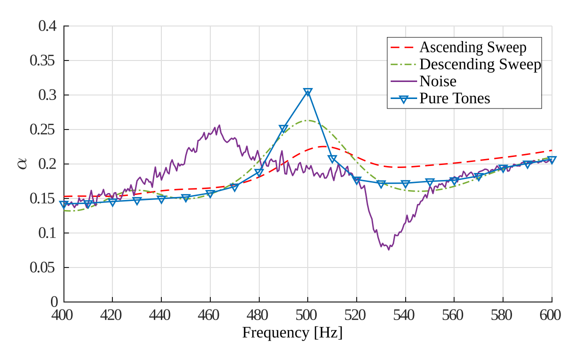

Fig. 8. Discontinuity on the α measurement system for 400 Hz to 600 Hz frequency band.

Table 4
Elapsed time in seconds* for α calculation, with white noise (WN), linear sweep (LS), pink noise (PN) and exponential sweep (ES) inputs.

Executions	Type	WN	LS	PN	ES
1	Processing	1.6	1.6	1.6	1.6
	Post proc.	0.0094	0.0103	0.0094	0.0096
10	Processing	–	16	–	16
	Post proc.	–	0.0104	–	0.0104
30	Processing	–	50	–	49
	Post proc.	–	0.0097	–	0.0097
100	Processing	162	–	156	–
	Post proc.	0.0097	–	0.0090	–
1000	Processing	1603	–	1603	–
	Post proc.	0.0090	–	0.0097	–

*Elapsed time measured using a linux desktop computer with Intel Core i7 870 processor and 8 GB RAM.

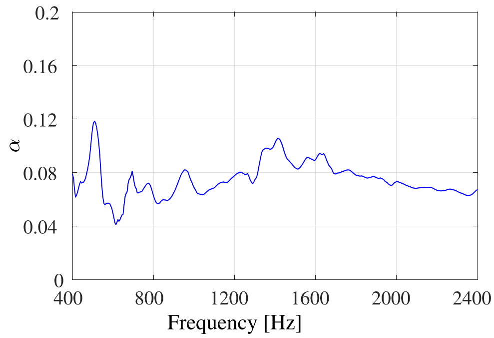

Fig. 9. Empty tube α measurement, from [26].

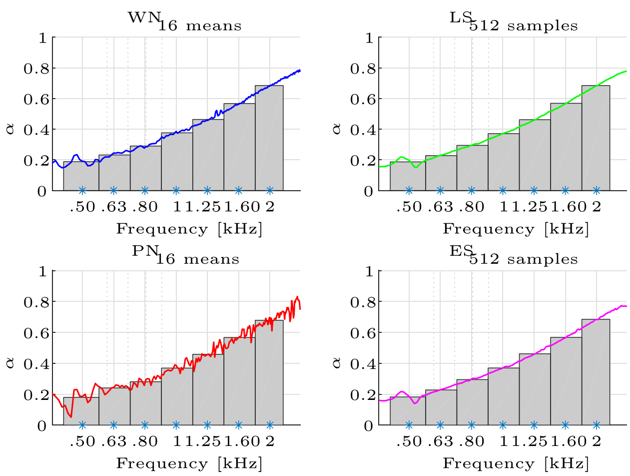

Fig. 10. Absorption coefficient α results for the second experiment. All curves present the same frequency resolution and were obtained with excitation signals of same duration.

that 96 averages were necessary to obtain $co = 0.99$ using white noise as input signal while 99 repetitions were required when using pink noise.

Computed absorption coefficient curves evidentiate the need for averaging when using random signals since a single execution did not stimulate the whole frequency range. An improvement in the curve quality was observed for α curves with random input and 100 averages. However, the best results for random excitation were found with 1000 averages, due to the stochastic nature of the excitation signal.

The elapsed time during measurement and post-processing are depicted in Table 4. We verify that the time required for post-processing can be neglected regarding the measurement time. Therefore, the use of sine sweep signals represented an advantage in the whole measurement time.

Regarding the observed discontinuity in all curves of Fig. 7 in the frequency range from 400Hz to 600 Hz we considered that it could be caused by a non-linearity in the measurement system. To test this assumption, we repeated the measurement using two other signals: a descending exponential sweep and a series of pure tones. Fig. 8 shows that a peak near 500Hz appears in all measurements with deterministic signals while a peak and a valley in different frequencies appear in measurements with random noise. Furthermore, we note that this resonance was also observed when measurements were performed with the empty tube (Fig. 9). We can, therefore, assume that the presence of this resonance is a systematic error due to the tube construction. We could not, however, determine the cause of the discrepancy between measurements with deterministic and random signals.

4.2. Experiment 2

The second experiment has as objective to compare input signals with the same time length. In this case, the IR, when measured with sine sweep signals, was cropped after 1/16th of its total duration, i.e., after 512 samples, thus eliminating the noise component. The parameters for the random signals were adjusted to have the same number of samples as the cropped IR and were repeated 16 times to achieve the same measuring time and frequency resolution with both types of signals.

Results in Fig. 10 show a noisy α for random inputs; however, the 1/3 octave band can be plotted despite the low amount of averages. A peak and a valley near 500 Hz were observed in the absorption results of all signals with periodic inputs, emphasizing the systematic error of the tube.

The hypothesis test was conducted, and, as observed in the previous measurements, there is not enough evidence to affirm that measured α is different from the manufacturer's reference for any of the excitation signals.

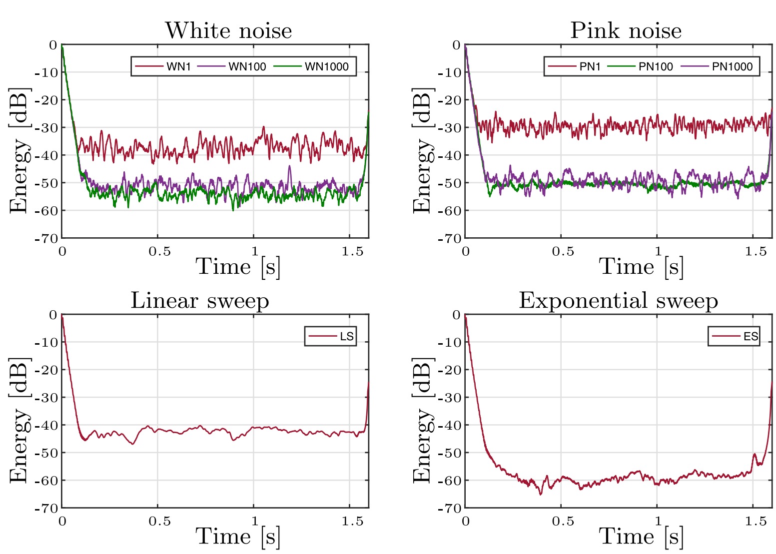

Fig. 11. ETC measured for the impedance tube using different excitation signals. White noise and pink noise were computed with 1, 100 and 1000 averages.

Table 5
SNR and PNR estimations from energy-time curves shown in Fig. 11 of white noise (WN), exponential sweep (ES), pink (PN) and linear sweep (LS).

	WN		PN		LS		ES	
Averages	SNR	PNR	SNR	PNR	SNR	PNR	SNR	PNR
1	29.76	40.86	27.31	35.61	31.09	55.74	34.15	61.82
100	32.90	55.93	32.52	54.95	–	–	–	–
1000	33.37	59.54	32.73	55.74	–	–	–	–

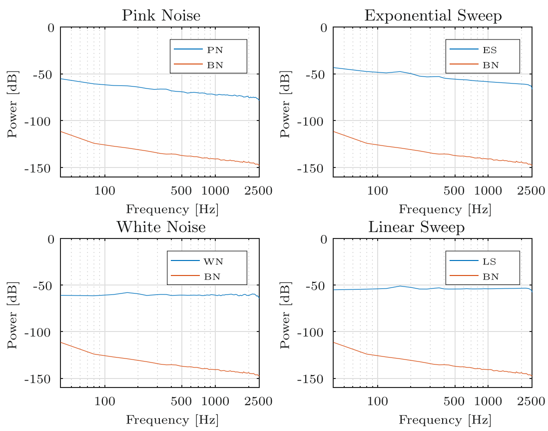

Fig. 12. Power Spectral Densities of recorded stimulus signals during the measurement of the absorption coefficient in the impedance tube.

4.3. Signal-to-Noise ratio (SNR)

To characterize the absorption coefficient in principle, any stimulus signal that provides energy through the frequency range of interest can be used in the impedance tube to perform the measurements. In practice, however, the excitation signal does impact the results as it provides different SNR values for the same level of background noise (BN) and the same amplitude of the excitation signal.

Fig. 11 shows the ETC of the system measured with different signals and different number of averages. These curves allow us to determine the PNR for every input signal, as observed in Table 5. We observe that the PNR obtained with random signals increase with the number of averages, in accordance with the results from Müler and Massarani [17]. It is important to highlight, however, that the highest PNR is obtained with the exponential sweep using only one execution, even when compared with 1000 averages of random inputs.

The SNR was computed trough Eq. (5) and results are summarized in Table 5. As observed, results for PNR were always higher than the SNR, and the highest value was always observed for the exponential sweep. The standard reference of an SNR higher than 10 dB was achieved using both methods, and the need for averaging with random inputs to obtain a higher SNR was confirmed.

We also compared the PSD of the background noise with the PSD of the used excitation signals. This comparison is depicted in Fig. 12. As observed, the background noise (BN) has a "pink" behavior, which implies that the SNR will remain constant over the frequency band using pink noise and exponential sweep despite the standard recommendation of using input signals with a flat spectral density.

5. Conclusions

An experiment to measure the absorption coefficient of a melamine foam sample with a 25 mm thickness and 60 mm diameter in an impedance tube with the two microphone technique was performed using four different excitation signals: white noise, pink noise, linear sine sweep and exponential sine sweep. The results for sine sweep signals (linear and exponential sweeping) were less noisy than results with random excitation even when presenting the signal only once. However, this result is achieved after the windowing the measured signal in a post-processing stage.

The correlation coefficient confirmed that at least 100 averages must be performed when measuring with pink or white noise, while only one execution of the linear or exponential sweep is required. Therefore, the processing time for periodic signals is approximately 100 times faster than when using random signals as input, which implies an improvement on the test speed.

Results comparing the measurements in Table 2 did not reveal a significant difference in the use of random or periodic stimuli. Nevertheless, we verified that the random signals must be averaged at least 100 times to provide an SNR of approximately 33 dB, similar to that obtained with the exponential sweep signal (34.1 dB). Note that both random signals and sine sweeps can comfortably provide the value of 10 dB SNR recommend by the ISO 10534-2 [11].

A measurement discrepancy was observed in the region of 500 Hz in both experiments, which could not be explained and will be further investigated.

This analysis was executed with only one system mounting, i.e., only one sample of melamine foam and only one impedance tube equipment. Different instrumentation, as well as material samples, could bring different SNR and absorption responses. We recommend to perform this analysis with every system.

CRediT authorship contribution statement

A.C. Corredor-Bedoya: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **B. Acuña:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft. **A.L. Serpa:** Conceptualization, Methodology, Validation, Resources, Writing - review & editing, Supervision, Funding acquisition. **B. Masiero:** Conceptualization, Methodology, Validation, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was financed in part by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil* (CAPES) – Finance Code 001. Also, we would like to thank Matheus Araujo for the contribution in the early stages of this work, developing the Matlab function for the H_{12} phase correction.

References

[1] Simmons HL. Olin's construction: principles, materials, and methods. John Wiley & Sons; 2011.
[2] Dunn F, Hartmann WM, Campbell DM, Fletcher NH. Springer handbook of acoustics. Springer; 2015.
[3] Barron RF. Industrial noise control and acoustics. Marcel Dekker, Inc.; 2001.
[4] Bistafa SR. Acústica Aplicada ao Controle do Ruído. 1st ed. São Paulo, SP: Edgard Blücher Ltda; 2006.
[5] Gonçalves MC, Margarido F. Materials for construction and civil engineering. Springer; 2015.
[6] Kuttruff H. Acoustics, an introduction. Taylor & Francis; 2007.
[7] Cox T, D'Antonio P. Acoustic absorbers and diffusers. 3rd ed., Boca Raton: Taylor & Francis, CRC Press; 2017, 2016. doi: 10.1201/9781315369211..
[8] Drábek P. Comparison of two internationally recognized methods for determining the sound absorption coefficient. In: MATEC Web of Conferences, vol. 125. EDP Sciences; 2017. p. 02030..
[9] ISO 354:2003. Acoustics. Measurement of sound absorption in a reverberation room; 2003..
[10] ISO 10534-1. Acoustics. Determination of sound absorption coefficient and impedance in impedance tubes. Part 1: Method using standing wave ratio; 1996..
[11] ISO 10534-2. Acoustics. Determination of sound absorption coefficient and impedance in impedance tubes. Part 2: Transfer function method; 2001..
[12] ASTM E1050-98. Standard test method for impedance and absorption of acoustical materials using a tube, two microphones, and a digital frequency analysis system; 1998..
[13] Horoshenkov KV, Khan A, Bécot FX, Jaouen L, Sgard F, Renault A, et al. Reproducibility experiments on measuring acoustical properties of rigid-frame porous media (round-robin tests). J Acoust Soc Am 2007;122(1):345–53. https://doi.org/10.1121/1.2739806.
[14] Pompoli F, Bonfiglio P, Horoshenkov KV, Khan A, Jaouen L, Bécot FX, et al. How reproducible is the acoustical characterization of porous media? J Acoust Soc Am 2017;141(2):945–55. https://doi.org/10.1121/1.4976087.
[15] Espinosa JC, Ceniza CR, Violanda RR. Acoustic absorption coefficient of polyethylene using two-microphone transfer function method. Asia-Pacific J Sci Math Eng 2019;5(1):29–32.
[16] Suhanek M, Jambrosic K, Domitrovic H. Student project of building an impedance tube. J Acoust Soc Am 2008;123(5). https://doi.org/10.1121/1.2934823. 3616–3616.
[17] Müller S, Massarani P. Transfer-function measurement with sweeps. J Audio Eng Soc 2001;49(6):443–71.
[18] Niresh J, Neelakrishnan S, Subharani S, Prabhakaran R. Performance testing for sound absorption coefficient by using impedance tube. Res J Appl Sci Eng Technol 2015;11(2):185–9.
[19] Piana EA, Roozen NB, Scrosati C. Impedance tube measurements on the DENORMS round robin test material samples. In: 26th International congress on sound and vibration, Montreal, Canada. p. 3663–70.
[20] Koruk H. An assessment of the performance of impedance tube method. Noise Control Eng J 2014;62(4):264–74. https://doi.org/10.3397/1/376226.
[21] BSWA Tech. User's Manual – Impedance Tube Tests System; 2010..
[22] Montgomery DC, Runger GC. Applied statistics & probability for engineers. 3rd ed. Wiley; 2002.
[23] R Foundation. The R Project for Statistical Computing; 2019.https://www.r-project.org/..
[24] Kieser R, Reynisson P, Mulligan TJ. Definition of signal-to-noise ratio and its critical role in split-beam measurements. ICES J Mar Sci 2005;62(1):123–30. https://doi.org/10.1016/j.icesjms.2004.09.006.
[25] Huszty C, Sakamoto S. A note on the definition of signal-to-noise ratio of room impulse responses. Acoust Sci Technol 2012;33(2):117–20.
[26] Zanoni G. Acoustical characterization of double porosity materials using mineral wools. Master thesis. University of Campinas, Brazil; 2018..