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# A new technique for the measurement of the normal incidence absorption coefficient using an impedance tube and a single microphone with fixed position

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When using optical measurements of the sound fields inside a glass tube, near the material under test, to estimate the reflection and absorption coefficients, not only these acoustical parameters but also confidence intervals can be determined. The sound fields are visualized using a scanning laser Doppler vibrometer (SLDV). In this paper the influence of different test signals on the quality of the results, obtained with this technique, is examined. The amount of data gathered during one measurement scan makes a thorough statistical analysis possible leading to the knowledge of confidence intervals. The use of a multi-sine, constructed on the resonance frequencies of the test tube, shows to be a very good alternative for the traditional periodic chirp. This signal offers the ability to obtain data for multiple frequencies in one measurement, without the danger of a low signal-to-noise ratio. The variability analysis in this paper clearly shows the advantages of the proposed multi-sine compared to the periodic chirp. The measurement procedure and the statistical analysis are validated by measuring the reflection ratio at a closed end and comparing the results with the theoretical value. Results of the testing of two building materials (an acoustic ceiling tile and linoleum) are presented and compared to supplier data.

# 1 Introduction

Measuring the normal incidence absorption coefficients of acoustical materials in the laboratory is a well known standardized procedure. Two standardized methods for evaluating the normal incidence absorption coefficients of acoustical materials exist using the so-called Kundt's tube, also known as standing wave or impedance tube: the standing wave ratio [2] and the transfer-function method [3].

In the transfer function method, compared to the standing wave ratio, the microphone does not interfere with the sound field inside the tube due to its side-wall mounting. Problems can arise however, due to the limited number of microphone locations and the limitation of the separating distance between the microphones (according to [2] the spacing should be more than five times the diameter of the microphone). The optimal separating distance between the microphones, that produces good quality measurements, is also frequency dependent (i.e. decreases with an increase in frequency). Other possible problems include microphone phase mismatch and errors concerning the knowledge of the exact microphone and sample locations [4].

Since the early nineties a search for better test methods using the impedance tube [5] and new test methods using optical techniques to visualize sound fields, has lead to the publication of many articles. The existing optical techniques use TV holography [6] or scanning laser Doppler vibrometry [7, 8]. Until recently very few researchers use these optical visualization techniques to quantitatively determine the acoustical parameters of a material. In [1] optical measurements of the incident and reflected sound fields in a glass tube were used to estimate normal incidence absorption coefficients. The sound fields near the material under test are visualized using a scanning laser Doppler vibrometer (SLDV), which is a full field optical vibration measurement instrument.

In this paper we propose a method to determine confidence intervals when using the SLDV for measuring normal incidence absorption coefficients. Since data is obtained from hundreds of measurement points in one single scan and thousands of estimates for the reflection coefficient can be calculated, the quality of the measurement can statistically be determined. To obtain better accuracy different excitation signals are compared, such as a pure sine, a multi-sine (sum of harmonically related sines) and a periodic chirp. As shown further in Sec. 3.2 the multi-sine, constructed on the resonance frequencies of the tube, provides much more accurate results than the traditionally used periodic chirp.

The paper is outlined as follows: in Section 2 the sound absorption coefficient measurement procedure is described. Experimental results in different one-dimensional setups (e.g. rigid termination and two commonly used materials) are discussed in Section 3. Finally, as a conclusion, the merits and limitations of the discussed method are summarized in Section 4.

# 2 The measurement procedure

In the next paragraphs it will be explained what exactly the SLDV measurements are and how those measurements can be utilized to calculate the reflection and absorption coefficients by using the transfer-function method.

## 2.1 Experimental setup of the SLDV and theoretical background

Consider the setup as shown in Fig. 1, where the laser beam of a SLDV (a Polytec PSV300) is directed through a glass cavity onto a solid reflector, which has been covered with retro-reflective tape to increase the amount of reflected laser light.

It is shown in [1] that, under certain conditions, one can obtain quantitative acoustic pressure values from measured Doppler shifts $\triangle f(\theta, t)$. However, it will be shown that this is not necessary in order to obtain reflection and absorption coefficients.

Assume that we have $N$ measurements of the Doppler frequency shifts $\triangle f(\theta, t)$ (for $i = 1, \ldots, N$) at different laser angles $\theta$, performed with a SLDV. When using a periodic excitation of the tube with period $T$, both the Doppler shifts and pressure signals can be represented by a discrete set of Fourier coefficients $\triangle F(\theta_i, \omega_k)$ and $P(\theta_i, \omega_k)$ at frequencies $\omega_k = 2\pi/T$, which are obtained from the time domain signals, $\triangle f$ and $\dot{p}$, by applying an FFT. A relation between the two sets of Fourier coefficients can be derived, which will be used in Eq. 2 (for more details [1]).

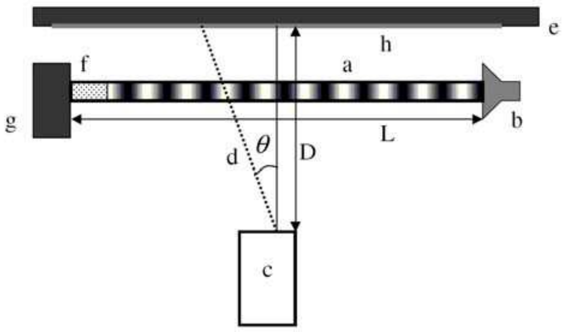

Figure 1: Experimental one-dimensional setup: (a) glass tube, (b) loudspeaker, (c) SLDV, (d) laser beam, (e) rigid block, (f) tested material, (g) rigid acoustic termination and (h) retro-reflective tape. [1]

When using the transfer-function approach to estimate the reflection coefficient $r$ starting from two pressure measurements at two arbitrary locations $x_1$ and $x_2$ on the tube (corresponding with laser beam angles $\theta_1$ and $\theta_2$), the following expression has to be calculated [3]:

$$r(\omega_k) = \left| \frac{H_{12}(\omega_k) - H_L(\omega_k)}{H_R(\omega_k) - H_{12}(\omega_k)} \right|, \tag{1}$$

with $H_L = exp(-jk_0(\omega_k)s)$ and $H_R = exp(jk_0(\omega_k)s)$, where $k_0(\omega_k) = \omega_k/c$ and $s = (x_1 - x_2)$. The following relation can be used to obtain $H_{12}$ from the measurements:

$$H_{12}(\omega_k) = \frac{P(\theta_2, \omega_k)}{P(\theta_1, \omega_k)} = \frac{\triangle F(\theta_2, \omega_k)}{\triangle F(\theta_1, \omega_k)}, \tag{2}$$

and therefore the reflection coefficients can be directly determined from the Doppler shift measurements.

In contrast to the classical transfer-function method that uses two microphones, or one microphone that can be placed in a limited number of positions, several hundreds of locations can easily be measured using a SLDV (in the experiments in Sec. 3, $N \approx 180$ to limit the duration of one single experiment). This means that for every combination of two measurement locations $x_l$ and $x_m$ for $l, m = 1, \ldots, N$ and $l \neq m$, a reflection coefficient $r_{lm}(\omega_k)$ can be computed using Eq. (1).
In order to limit the computation time and to guarantee that the pressure waves are still sufficiently correlated, only the ratios $r_{lm}(\omega_k)$ for which $x_m - x_l < s_{max}$ are calculated. This maximum distance between two measurement points can be derived from [3] as: $s_{max} < 0.776d$.

After the estimation of the reflection coefficient, the absorption coefficient $\alpha(\omega_k)$ is calculated by using the well-known relation $\alpha(\omega_k) = 1 - r(\omega_k)^2$.

## 2.2 Excitation signals

Since the introduction of the transfer-function method excitation signals such as periodic random noise or a periodic chirp (also called swept sine) have been used in most acoustic measurements to reduce the measurement time. The disadvantage of these broadband excitation signals is their lower signal-to-noise ratio (SNR) since all frequencies in a certain frequency band are excited simultaneously. A good alternative is the multi-sine, which is the sum of a number of harmonically related sinusoids with programmable amplitudes (Ch. 3 of [13]).

The multi-sine is the only periodic broadband signal that allows an arbitrary choice of the amplitude spectrum. To obtain a good SNR it is important to combine this with a reduction of the crest factor ($CF = Peak\ value/RMS\ value$) by making a proper choice of the phases. The crest factor minimization method used in this paper is based on [9]. This results in a CF of approximately *1.41* compared to the Schroeder solution with a CF of *1.78* [10].

Since (cylindrical) tubes resonate at certain frequencies, which have a higher SNR, a multi-sine was constructed on the resonance frequencies. These frequencies can be calculated using $f_n = n\frac{c}{2l}$. It will be shown in Sec. 3.2 that this results in much more accurate measurements.

## 2.3 Statistical analysis

The standard transfer-function (or two-microphone) method offers no information about the statistical reliability of the results. The possibility to perform a statistical analysis of this method has been researched previously in [11, 12].

Since in this measurement procedure thousands of measurement combinations are combined to hundreds of estimates for the reflection coefficient, it is possible to perform a statistical analysis of the data. By using the median of the results to obtain a more robust estimate of the reflection coefficient (by eliminating outliers), the variability can be calculated by computing the Median Absolute Deviation (MAD). The MAD calculates the average distance a data value is from the median and is given by [14]:

$$MAD(x) = median(|x - median(x)|), \tag{3}$$

with, in this case, $x$ the estimated reflection coefficients $r(\omega_k)$ calculated from Eq. (1).

This value is sometimes used as an alternative to the standard deviation (SD). The main advantage of the MAD is its resilience to outliers in a data set. In the SD, the distances from the mean are squared, so in the average, large deviations are weighted more heavily. In the MAD, the magnitude of the distances of a small number of outliers is irrelevant. As will be shown in Fig. 3 the hundreds of estimated reflection coefficients contain a relatively small number of (large) outliers, making the choice for the MAD instead of SD logical.
Furthermore, the MAD can be made comparable to the standard deviation by defining the normalized MAD:

$$MADN = \frac{MAD}{0.6745} \approx \sigma \tag{4}$$

with 0.6745 the MAD of a standard normal random variable [14] and $\sigma$ the standard deviation.

Using this MADN value it is possible to define a 95% confidence interval as 1.96 MADN.

In Sec. 3.2-3.3 these confidence intervals will be used to determine the reliability of the measurement method and to show the difference in quality between the different excitation signals.

# 3 Experimental results

The practical execution of the setup and some of its details will be discussed in the next paragraph. The results follow in Sections 3.2-3.4 (all measurements were processed using *Matlab*).

## 3.1 The measurement setup

In earlier experiments different diameters of glass tubes and different loudspeakers were used. In this paper the following glass tube/loudspeaker combination was used: a glass tube with an inside diameter of *32 mm* and a length of *500 mm* and an inexpensive loudspeaker (Visaton DTW 72).

An overview of the measurement setup is shown in Fig. 2. The SLDV was placed at a standoff distance of $N \approx$ *100 cm* from the glass tube.

The following experiments have all been carried out with different sound signals: pure sine waves at different frequencies, different multi-sines (sum of harmonically related sines) and a periodic chirp from *0-20 kHz*. Five complex averages were performed which resulted in an average signal-to-noise ratio of *20-40 dB*, depending on the applied sound level (see also Sec. 3.2).

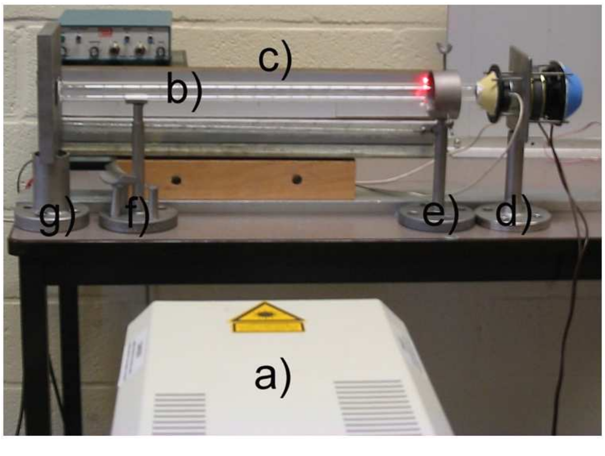

Figure 2: Overview of the measurement setup: a) SLDV, b) glass tube, c) rigid block with retro-reflective tape, d) loudspeaker support, e) fixed support, f) variable support and g) rigid end plate

## 3.2 Different test signals and their influence on the measurement quality

The reflection coefficient for a rigid reflector at the end of the tube is theoretically equal to *1.00*, so this makes it possible to determine the quality of the different sound signals and of our measuring procedure by comparing the test results with the theoretical value.
From the periodic chirp only the results at the resonance frequencies were used to calculate the reflection coefficients (better signal-to-noise ratio). A multi-sine was then constructed which only contains the same resonance frequencies. The following figure (Fig. 3) shows the distribution of the calculated reflection coefficients for 3 different test signals at *5 kHz* with a rigid reflector.

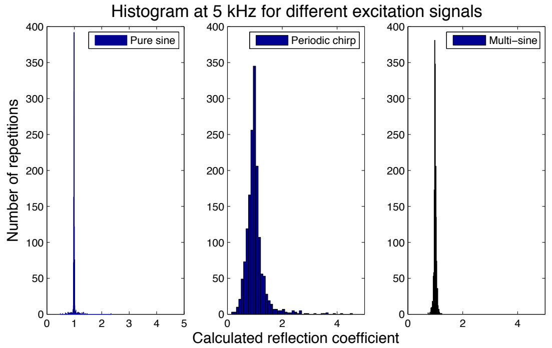

Figure 3: Histogram of the reflection coefficients excited by different excitation signals at *5 kHz*. From left to right: Pure sine / Periodic chirp / Multi-sine.

As can be seen, the calculated reflection coefficients obtained from the periodic chirp are spread much wider and contain more outliers (a slight skewness to the right with outliers up to $r = 4.5$).
The downside of measuring with pure sines, on the other hand, is the amount of time each measurement takes. Regardless of the used excitation signal the measurement time of one single scan remains the same. Obtaining results at $n$ frequencies would take $n$ times longer with pure sines than with a periodic chirp or a multi-sine, containing those $n$ frequencies.
A good alternative is therefore the use of a multi-sine, constructed on the resonance frequencies, combining the advantages of both signals.

In the following figures (Fig. 4 - 6) the median and 95% confidence intervals of the calculated reflection coefficients at the resonance frequencies of the used tube are shown. The grey dot shows the median of the results and the upper and lower red lines represent the 95% confidence intervals (as defined in Sec. 2.3).
The measurements at *1 V(olt)* were executed at a sound level of approximately *90 dB* inside the tube. The measurement at *0,2 V* reached a sound level of *75 dB*.

It is clear that the measurements executed with a multi-sine at *1 V* are the most reliable (smallest confidence intervals) and that even the measurements at *0,2 V* are still slightly better than the measurements executed with the periodic chirp at *1 V*. To obtain reliable measurements with the periodic chirp the sound level would have to be further increased to obtain a better SNR at the selected frequencies, risking the failure of the loudspeaker.

In the Figures 4 - 6 it is shown that the theoretical value of *1.00* is inside the confidence interval and that most measured results are, as could be expected, slightly lower than the theoretical value.

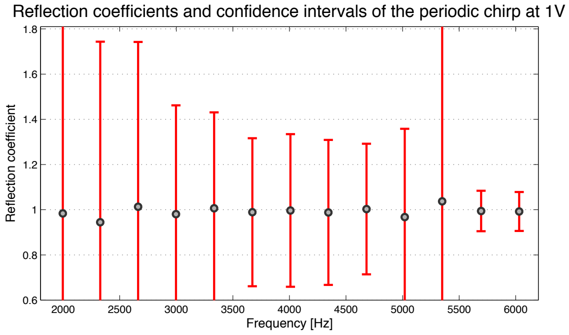

Figure 4: Confidence intervals at the resonance frequencies excited by a periodic chirp at *1 V*.

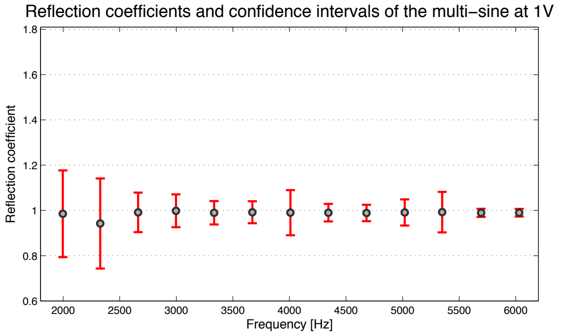

Figure 5: Confidence intervals at the resonance frequencies excited by a multi-sine at *1 V*.

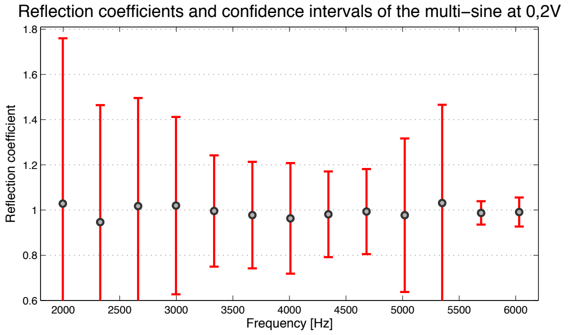

Figure 6: Confidence intervals at the resonance frequencies excited by a multi-sine at *0,2 V*.

## 3.3 Variability of the measurements

When calculating the 95% confidence intervals from the MADN-value, as defined in Sec. 2.3, at the different frequencies of the measurements discussed in the previous Section, the following results are obtained:

- ranging from 0.017 to 0.199 for the multi-sine (*1V*) at the resonance frequencies and 0.058 at *5 kHz*,
- ranging from 0.086 to 0.902 for the periodic chirp (*1V*) at the resonance frequencies and 0.390 at *5 kHz*,
- and 0.020 for the pure sine at *5 kHz*.

It is clear that these results confirm the use of the proposed multi-sine instead of a periodic chirp and that the calculated confidence intervals are a good estimate for the variability of the results and for the overall quality of the measurement.

## 3.4 Results for two building materials

In this Section the measurement results of two commonly used building materials are discussed: linoleum flooring and an acoustic ceiling tile.

### 3.4.1 Linoleum flooring

Linoleum has a very small absorption coefficient (*0.02-0.03* in the frequency range of *125-4000 Hz*). No acoustical data from the supplier (*Domo Belgium*) for comparison was available.

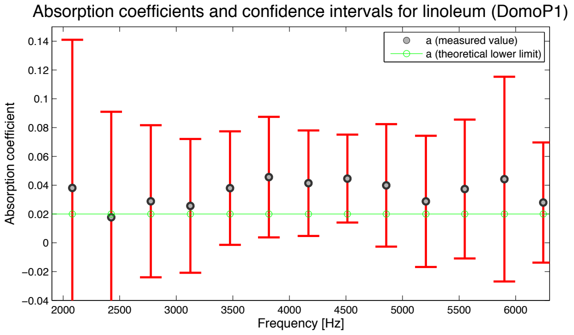

Figure 7: Absorption coefficients and confidence intervals for linoleum (Domo P1).

It can be seen on Fig. 7 that the differences between the lower limit and the measured values are small. The confidence intervals are of course quite large, since an error of the reflection coefficient has a great influence on the absorption coefficient (with $\alpha = 1 - r^2$).

### 3.4.2 Acoustic ceiling tile

Since this is a material with good acoustical qualities, data from the supplier (*Rockfon Belgium*) was available and was used for comparison. No high frequencies were tested, so only the values at *2* and *4 kHz* can be compared, which correspond very well with our results as shown in Fig.8.

It can be concluded that the presented measurement procedure provides satisfying results for materials with both high and low acoustical absorption coefficients. More measurements will be conducted in the following months to further substantiate these findings. Higher frequencies will also be tested using a tube with a smaller diameter.

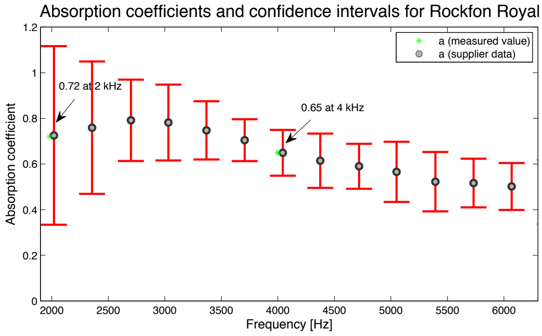

Figure 8: Absorption coefficients and confidence intervals for an acoustic ceiling tile (Rockfon Royal).

## 4 Merits and limitations

The use of a multi-sine (as proposed in Section 2.2) instead of a periodic chirp, combined with a statistical analysis of the acquired data leads to a very accurate measurement technique for normal incidence absorption coefficients. Using the large amount of data in determining the confidence intervals offers the possibility to calculate and visualize the variability of the measurement results. Without these confidence intervals it would be impossible to determine which test signal produces better results or to estimate the reliability at certain frequencies. As shown in the different validation experiments included in this paper, the absorption (and reflection) coefficient can be obtained with a very high accuracy.

The major limitation of this method is the need for a small, but good quality speaker, and the need for an extensive validation procedure. The method is also limited to materials with a texture, pattern or roughness that is substantially smaller than the diameter of the tube.

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