Development and application of a new method for the in-situ measurement of sound absorption

Dr. Ir. Y.H. Wijnant, Ir. E.R. Kuipers, Prof. Dr. Ir. A. de Boer
University of Twente, Faculty of Engineering Technology
Structural Dynamics and Acoustics
P.O.Box 217, NL-7500 AE, The Netherlands
e-mail: y.h.wijnant@ctw.utwente.nl

Abstract
In many applications of noise control engineering, knowledge about the sound-absorbing properties of acoustically reacting surfaces is essential. Being able to measure sound absorption of surfaces in-situ, i.e. at the site but also for the actual sound source, would prove very useful for this reason and would eliminate the need for laboratory measurements. This paper will present a (patented) new method for the in-situ measurement of sound absorption. This method is particularly useful since the sound absorption can be determined without a priori knowledge about the actual sound field present near the structure under investigation. In the paper the theory behind the method will be described and some experimental results will be shown.

1 Introduction
1.1 Introduction

For the experimental determination of the sound absorption of a material sample or material surface, many methods exist, of which a few have become standard methods. For the experimental determination of the normal sound absorption coefficient of small material samples, two main laboratory methods exist; the Kundt’s (standing wave) tube, as described in part 1 of ISO 10534 [25], and the impedance tube method, as described in part 2 of this standard [26]. The latter is often referred to as the transfer-function method. Although these impedance tube methods are standard methods, significant variations in absorption coefficient have been observed due to mounting of the sample, sample size and structural coupling of the impedance tube to the driving loudspeaker, see e.g. [27]. In addition, only the normal sound absorption coefficient is determined. In case the diffuse absorption coefficient needs to be determined, the reverberation room method according to ISO 354 [24] can be used. With respect to this method, many examples have demonstrated significant influences of sample orientation, sample edge effects and the diffuseness of the sound field in the room.

For these and practical reasons, not surprisingly, significant research efforts have been put in the development of in-situ measurement methods. However, as pointed out in the overview of existing methods given below, most methods only yield accurate results in ’ideal’ acoustic fields, such as acoustic free-fields or semi-free-fields with a single sound source. In practice this condition can often only be realized in (semi-)anechoic rooms, posing an obvious restriction on the term ’in-situ’. An exception are the pulse-based methods, as described by [14, 15, 18]. However, one can imagine cases in which reflective surfaces are located near the surface under investigation influencing the measurement results.

As there are many cases in which one does not want or is not able to transfer the surface under investigation to an anechoic room, a method that would yield accurate results irrespective of the presence of reflective
surfaces or even multiple sources will certainly be of interest. In this paper, we present such a method, as described in patent [29], that can be used in any complex acoustic field.

The paper is structured as follows: first, an overview of existing measurement methods for the determination of in-situ sound absorption will be given, followed by the formulation of our research objective. In section two, the theory behind the new method and some examples are presented. Section three deals with experimental results for various 'sound absorbing' samples. Finally, we present conclusions and recommendations in section four.

1.2 Overview of methods for the in-situ determination of sound absorption

In this section, an overview of methods for in-situ determination of sound absorption will be presented. Usually, one is interested in the frequency dependent normal surface impedance as this characteristic can be implemented in acoustic simulations. Other important numbers, such as the plane wave reflection coefficient and the normal sound absorption coefficient can however only be derived from the measured surface impedance if a global assumption of the actual sound field is made.

Compact overviews of existing in-situ surface impedance measurement methods or 'reflection methods', as they are sometimes referred to, are given by Garai [15], Kruse [17] and Tamura [1]. In this section, a few established and well-known methods are discussed briefly.

Significant research efforts have been performed on 2-microphone transfer function methods, see [8, 9, 13, 16, 17]. These methods can be applied in sound fields that are free of reflections from structures other than the surface of interest. Hence, measurements have to be carried out in open spaces or in anechoic rooms. In some cases a lower frequency limit of 200 Hz can be reached, in others, 500 Hz. Diffraction effects are the dominant factor restricting the lower frequency limit.

The only kind of in-situ methods that have found their way into standardization are pulse-based methods, see the work by Garai [15], Mommertz [14] and Nocke [18]. Such methods separate the reflected waves from the surface of interest from those that are reflected by other surfaces. The applicability of the method lies in the frequency range of 250 to 8000 Hz, whereas the lower frequency limit requires a significant sample size. Newer work of Nocke [18] shows that by considering Fresnel zones, the frequency limit can be decreased at the expense of a very large sample size.

A well-known method for the measurement of reflection coefficients under normal- and oblique incidence is Tamura’s method [1]. By application of the spatial 2-dimensional Fourier transform, any incident- and reflected wave field can be decomposed into a set of plane waves. Accordingly, the plane wave reflection coefficients can be determined. The measurements are generally done in an anechoic room. The frequency range is 500-3000 Hz for practical sample sizes.

The availability of a PU-sensor, [12] has enabled the direct measurement of field impedances. In a number of papers [19, 12] methods for measuring the surface impedance for normal and oblique incidence are presented. The applicable frequency range is estimated at 300-5000 Hz. As in some other methods, the solution of Nobile and Hayek [7] is employed.

The difficulties that typically have to be dealt with when applying in-situ surface impedance measurement methods are the following:

- Low frequencies. At low frequencies, diffraction leads to inaccurate results. To cope with this issue, substantial sample sizes must be available and the data has to be acquired near the surface.

- Reflections. Many methods require a free field to ensure that the measurement is free of reflections caused by structures other than the sample under investigation. This requirement poses a serious restriction on the expression ‘in-situ’. Moreover, one needs a large and very-well designed anechoic chamber to obtain a sound field that is sufficiently free of reflections at low frequencies.
• Large incidence angles. For large angles of incidence, many methods fail to yield useful results.

• High surface impedance. Many methods perform well in case the samples consist of well-absorbing materials but have difficulties when the surfaces tend to be more reflective, see [16, 17].

• Non-locally reacting surfaces. Most theories of spherical- or plane wave propagation and reflection on which most methods are based, are only valid under the condition that the surface is indeed of the locally-reacting type.

Summarizing, it is recognized that a significant number of in-situ surface impedance measurement methods were developed. Some of them have become established standard methods. However, all of them are based on the a priori knowledge about the character of the sound field in the vicinity of the surface under investigation. Moreover, generally locally-reacting surfaces are assumed.

1.3 Objective

The objective of our research is to propose a reliable and accurate in-situ surface absorption measurement method for arbitrary lossless three-dimensional sound fields (complex geometries and/or multiple sources).

2 Theory and numerical examples

2.1 Theory

The (average) absorption coefficient of an area $S$ for a given sound field is defined as the fraction of the (time-averaged) incident sound power $P_{in}$ that is being absorbed by the area:

$$\alpha \equiv \frac{P_{in} - P_{refl}}{P_{in}} = \frac{P_{ac}}{P_{in}}$$

(1)

where $P_{refl}$ is the time-averaged reflected sound power and $P_{ac} = P_{in} - P_{refl}$ is the time-averaged nett power or active power flowing through $S$. The active power can be determined from:

$$P_{ac} = \int I_{ac} \cdot n dS$$

(2)

where $I_{ac}$ is the active intensity and $n$ is the surface normal unit vector. The component of the active intensity in the normal direction ($I_{ac} \cdot n$) can relatively easily be measured from the (complex) pressure $P$ and (complex) normal velocity $U \cdot n$:

$$I_{ac} \cdot n = \frac{1}{2} \Re \left( P U \cdot n \right)$$

(3)

where $\Re$ and $\overline{\cdot}$ denote the real part and complex conjugate, respectively. The incident power $P_{in}$ should follow from:

$$P_{in} = \int I_{in} dS$$

(4)

but, as stated in the introduction, the incident intensity $I_{in}$ can not be measured directly.

The incident intensity can however be determined if the sound field can be locally described by an incident and reflected plane wave. Hence it is assumed that the pressure and normal velocity near any measurement point in the area $S$ can be written as:

$$P = Ae^{-ikx} + Be^{ikx}$$

$$U \cdot n = \frac{1}{\rho c} \left( Ae^{-ikx} - Be^{ikx} \right)$$

(5)

(6)
where $x$ is a coordinate which is aligned with the normal direction $n$, $A$ is the amplitude of the wave traveling in the positive $x$-direction (the incident wave), $B$ the amplitude of the wave traveling in the negative $x$-direction (the reflected wave), $k = \omega/c$ is the wave number and $i = \sqrt{-1}$. $c$ denotes the speed of sound.

Choosing the origin of the coordinate system at the measurement position yields $P = A + B$ and $\mathbf{U} \cdot n = (A - B)/(\rho c)$. If $P$ and $\mathbf{U} \cdot n$ have been measured, the amplitudes $A$ and $B$ then follow directly from:

$$
A = (P + \rho c \mathbf{U} \cdot n)/2
$$

and

$$
B = (P - \rho c \mathbf{U} \cdot n)/2
$$

and the intensity of the incident wave and the intensity of the reflected wave are, respectively,

$$
I_{\text{in}} = A^2/(2\rho c)
$$

and

$$
I_{\text{refl}} = B^2/(2\rho c)
$$

The incident power can then obtained by integration of the incident intensity over the area of interest and the absorption coefficient is readily obtained. Note that only a local plane wave assumption has been made and hence generally $A$ and $B$ vary over the area of interest.

Another option, which is more practical from a measurement point of view, is to measure both the active intensity and (what we call) the total (gross) intensity. Obviously, the active intensity is the difference between the (time averaged) incident and reflected intensity. For the local plane wave assumption we can thus write:

$$
I_{\text{ac}} \cdot n \equiv I_{\text{in}} - I_{\text{refl}} = \frac{A^2 - B^2}{2\rho c}
$$

Instead of the difference between the intensities, we define the total intensity $I_{\text{tot}}$ to be the sum of the incident and reflected intensity. For the plane wave assumption this yields:

$$
I_{\text{tot}} = I_{\text{in}} + I_{\text{refl}} = \frac{A^2 + B^2}{2\rho c}
$$

$$
= \frac{1}{4} \left\{ \frac{(A - B)(A - B)}{2\rho c} + \frac{(A + B)(A + B)}{2\rho c} \right\}
$$

$$
= \frac{1}{4} \left\{ \rho c \mathbf{U} \cdot \mathbf{n} \mathbf{U} \cdot n + \frac{PP}{\rho c} \right\}
$$

Thus by measuring the pressure and normal velocity, we can calculate the active and total intensity. From these, one can determine $I_{\text{in}} = (I_{\text{tot}} + I_{\text{ac}} \cdot n)/2$ and $I_{\text{refl}} = (I_{\text{tot}} - I_{\text{ac}} \cdot n)/2$ within the area of interest and the absorption coefficient $\alpha$ follows after integration of $I_{\text{in}}$. Hence, one can conclude that measuring the cross- and auto-spectra suffices to calculate the average absorption coefficient of any surface.

After development of the theory given above, the work of Farina and Torelli [2] came to the authors attention. Their theory somewhat resembles the theory given above. In the method of Farina however, the absorbing sample should be large enough to avoid border effects, the source has to be placed in such a way that the incidence angle is known and at a certain distance from the surface, so that making the measurement close to the reflecting surface ensures that the incident wave is a plane wave. As a result, Farina’s method still relies on the global acoustic field and to the authors opinion these restrictions are almost never satisfied for an in-situ absorber/source combination. As such, the method can hardly be called in-situ. For the 1D case however, i.e. if the global field indeed consists of an incident and reflected wave only, the method of Farina and the proposed method closely resemble one another. Farina uses the time-averaged or mean energy density $w_0$, given by

$$
w_0 \equiv \frac{1}{4} \left( \rho \mathbf{U} \cdot \mathbf{U} + \frac{PP}{\rho c^2} \right)
$$
It is noted that the energy density $w_0$ multiplied with the speed of sound $c$ equals the total intensity $I_{tot}$ only if the normal vector $n$ coincides with the velocity vector. This is identically true in a 1D sound field but generally this is not the case.

Vigran [6] proposed a ratio $F$, defined as the active intensity over the energy density multiplied by the speed of sound as a field index to detect deviations from ideal 1D sound field conditions. This ratio could be used to define absorption but, as stated above, the energy density multiplied by the speed of sound (which Vigran denotes as the apparent plane wave intensity) equals the total intensity $I_{tot}$ only if $n$ coincides with the velocity vector.

![Figure 1: Absorption coefficient $\alpha$ as a function of frequency for a tube with a baffled open end.](image)

### 2.2 Numerical examples

For validation, we first consider wave propagation in an impedance tube with a baffled open end. We assume the end impedance to be $Z = \rho c ((ka)^2/2 + i8ka/(3\pi))$ kg/(m²s), with $a = 0.025$ m the radius of the tube. The density is $\rho = 1.22$ kg/m³ and the speed of sound is $c = 343$ m/s. A unit pressure on the closed end surface has been assumed as a source. Below the cut-on frequency, the absorption coefficient for a baffled open end is readily obtained both analytically and numerically and is independent of the position in the tube at which the absorption coefficient is evaluated. Hence the length of the impedance tube is irrelevant in this case. As in latter examples the absorption coefficient can not be determined analytically, for consistency reasons, all presented results have been obtained numerically using the finite element package COMSOL.

In the 1D case, the absorption coefficient, as determined by the new method, is equivalent to the classical absorption coefficient. This is obvious; since the global sound field consists of two plane waves, also locally the sound field consists of two plane waves. Hence, the absorption coefficient for the impedance tube at any position along the tube, as shown in figure 1, equals the classically obtained absorption coefficient.

A second example is shown in figure 2(a). The setup consists of the impedance tube of length $L = 0.5$ m in which a sample containing a perforation has been inserted between $z = 0.2$ m and $z = 0.295$ m, see figure 2(a). The sample is made from an acoustically hard material. It consists of a cylindrical section of 30 mm with an inner radius of 40 mm, a conical section with a length of 28 mm and a second cylindrical section of 37 mm with an inner radius of 10 mm. The absorption coefficient can be determined at the various cross sectional areas (indicated by the $z$-coordinate shown) and has been calculated by the procedure given above: 1) 'measuring' the pressure and particle velocity in the $z$-direction in the cross sectional area, 2) calculating the active and incident intensity (based on the active and total intensity), 3) integrating over the cross sectional area to obtain the active and incident power and 4) evaluating the absorption coefficient. Figure 2(b) shows the calculated absorption coefficient evaluated at various $z$-coordinates.
It is obvious that, as is indeed observed to the right of the sample ($z > 0.32$ m), between the sample and the baffled open end, the absorption coefficient should equal the absorption coefficient for the baffled open end (as shown in figure 1). Progressing towards the source however (to the left), the absorption coefficient is seen to overall decrease; the sample increasingly blocks sound propagation and hence the absorption coefficient decreases. However, sound energy can propagate very effectively at the resonance frequencies of the system and hence peaks start to appear in the absorption coefficient curve at these frequencies. The new method thus allows to examine the transition in the absorption coefficient along the sample. From the graphs it is seen that the major change in the absorption coefficient only occurs in the second cylindrical section; the difference between the absorption coefficient before the sample, in the first cylindrical section and in the conical section is relatively small.

In a third example we examine the absorption coefficient of a flanged duct (radius $R = 0.1$ m and length $L = 0.5$ m), shown in figure 3(a), which is closed at one end and open at the other. Off-center, at a radius of 0.06 m, the closed end contains a small hole (diameter $d = 0.005$ m). An acoustic source (which is assumed to be a pressure source) is put behind this hole. Note that, due to the hole, the model is not axisymmetric. The sound field close to the source is obviously three-dimensional. Above the cut-on frequency however, higher order modes will be excited and the sound field is three-dimensional throughout the domain. The cut-on frequency for the given duct is $f_c = 1.84c/(2\pi R) \approx 990$ Hz. Figure 3(b), showing the calculated active intensity vectors in a cross-section of the duct at 1000 Hz, illustrates this effect. The incident and reflected intensity for $n = (0, 0, 1)^T$ (the direction along the duct), as obtained by the proposed method, is given in figures 3(c) and 3(d). Note that the scale in the various arrow plots is different.

Based on the new method, figure 4 shows the calculated absorption at various positions in the duct (as indicated in figure 3(a)) in a frequency range which includes the cut-on frequency. From the figure it is clear that for positions within the tube, almost complete reflection is seen in the neighborhood of the cut-on frequency. The reflection reduces at the entrance of the duct (and hence the absorption coefficient increases).
(a) Cross-section of the duct. The source is on the left (z = −0.5 m, x = 0.06 m). The baffled open end is on the right (z = 0 m).

(b) Active intensity (I_{ac}).

(c) Incident intensity vector (0, 0, I_{in})^T.

(d) Reflected intensity vector (0, 0, I_{refl})^T.

Figure 3: Cross-section of a duct (L = 0.5 m, D = 0.2 m) and intensity vectors at 1000 Hz based on the direction n = (0, 0, 1)^T.

Figure 4: Absorption coefficient α as a function of frequency at the positions shown in figure 3(a).
Experimental results

In this chapter the results of various measurements will be presented and discussed, preceded by an explanation of the signal processing procedure. The first set of measurements are validation measurements to validate the theory for the simple one-dimensional case. The second and third set of measurements are performed in, respectively, a small sound absorbing room and a large diameter duct and serve as an illustration to apply the proposed method.

3.1 Signal processing procedure

To obtain the average absorption coefficient for a surface, the average active intensity and the average incident intensity need to be determined. The active intensity can be expressed in terms of cross-power spectral densities, as follows:

\[ I_{ac} = \frac{1}{4} (G_{pu} + \overline{G_{pu}}) \] (16)

where \( G_{pu} \) is the single-sided cross-power spectral density. Please note that the dependency on the surface normal vector is removed as the particle velocity is only measured in one direction, being the surface normal. \( G_{pu} \) is calculated from both microphone signals \( p_1 \) and \( p_2 \) as indicated by Jacobsen [4]:

\[ G_{pu} = \frac{1}{2\omega\rho\Delta r} (2Q_{12} + i(G_{22} - G_{11})) \] (17)

Where \( G_{11} \) and \( G_{22} \) are the single-sided power spectral densities of the pressure signals \( p_1 \) and \( p_2 \) and \( Q_{12} \) is the imaginary part of the cross-power spectral density \( (G_{12} = C_{12} + iQ_{12}) \). Please note that Jacobsen denotes power- and cross-power spectral densities with \( S \) instead of \( G \), indicating double-sided spectral densities.

The total intensity \( I_{tot} \), with the direction vector \( n \) set to the surface normal, is determined in terms of power spectra or power spectral densities by

\[ I_{tot} = \frac{1}{4} (\rho c G_{uu} + \frac{G_{pp}}{\rho c}) \] (18)

Where \( G_{uu} \) and \( G_{pp} \) are, see [4], as

\[ G_{uu} = \frac{1}{(\omega\rho\Delta r)^2} (G_{11} + G_{22} - 2C_{12}) \] (19)

\[ G_{pp} = \frac{1}{4} (G_{11} + G_{22} + 2C_{12}) \] (20)

The incident intensity can be calculated when \( I_{tot} \) and \( I_{ac} \) are known:

\[ I_{in} = \frac{I_{tot} + I_{ac}}{2} \] (21)

where, again, the multiplication with the direction vector \( n \) was removed from the original equation as presented in section 2.

For 2- and 3-D sound fields, a spatial integration of the incident intensity is needed to calculate the absorption coefficient, see equation 1. This requires a sufficiently fine grid at which the incident intensity is accurately measured. This is somewhat less practical and hence, to be more efficient, we have adopted a scanning procedure, similar to the intensity scanning method of ISO 9614-2; the surface is manually scanned using...
the intensity probe and the incident power is approximately obtained by temporal averaging of the incident intensity. The scanning operation can be done under the assumptions that 1) every subregion of the scanned region is scanned equitemporally and 2) the lateral velocity of the intensity probe is sufficiently slow. In that case, averaged powers are obtained. Finally, the absorption coefficient $\alpha$ is calculated as the ratio of $P_{\text{ac}}$ and $P_{\text{in}}$.

### 3.2 Validation by means of an impedance tube

For the purpose of a first validation it was decided to perform a series of measurements with an intensity probe in a tube and to compare these with measurements using an impedance tube (of the same diameter) in combination with the well-known transfer-function method developed by Chung and Blaser [3]. The first sound absorbing sample is a sample having 20 different $\frac{\lambda}{4}$-resonators, see figures 5(a) and 5(b). This sample is referred to as the 'resonator sample' throughout this paper and has been analyzed in detail by Hannink and Kampinga [22, 28]. The second sample is an axisymmetric sample, see figures 5(a) and 5(c). The sample contains a slit of varying width and diameter. This sample will be referred to as the 'slit sample' and has been analyzed by Kampinga [28].

![Figure 5: The impedance tube samples.](image)

(a) Slit (left) and resonator sample (right).
(b) Slit sample.
(c) Resonator sample.

The impedance tube wherein the intensity probe is placed has an inner diameter of 50 mm. The length of the tube is 40 cm. The sound intensity probe is a B&K 2683 pp-probe consisting of a pair of phase-matched microphones in combination with the B&K Investigator 2260. The AC-outputs are fed into a National Instruments USB-4431 4-channel USB-powered front-end which is connected to a PC. The data acquisition process is controlled by MATLAB which is also used for signal processing. The whole setup is placed into a small sound absorbing room with dimensions 3x3x2.5m to exclude noise from exterior sources. A small loudspeaker is positioned at approximately 2 m away from the tube. The loudspeaker is driven with band-limited white noise from 20 to 4000 Hz. The measurement time is set to 30 seconds for sufficient averaging at a sample rate of 20 kHz. Anti-aliasing filtering is performed in the front-end by the AD-converter (delta-sigma principle) at the Nyquist frequency, being equal to 10 kHz. The sound waves in the tube are plane for frequencies below the cut-on frequency, in this case 4018 Hz. The reference impedance tube measurement is performed using an impedance tube with an internal diameter of 50 mm and a length of 40 cm. The excitation signal consists of repeating logarithmical sweeps and is generated by the software National Instruments LabView. LabView is also used for signal processing. Two KULITE microphones and two amplifiers are used for data acquisition.

In figure 6(a) the results of the new method and the transfer-function method are shown for the resonator sample. The agreement between both curves is very good. The transfer-function method (the reference) however shows some variations in the absorption coefficient curve above 2300 Hz. The measurement suffered
from a low signal-to-noise ratio here and could be improved. For the slit sample results shown in figure 6(b), the agreement between both curves is again very good, except for the absorption value at 700 Hz.

Further items that have been investigated are the influence of probe distance to the absorbing surface, the repeatability of a measurement, the position of the sound source and the type of signal with which the loudspeaker is driven. Although we do not present the results here, the new method performs very well on all of these items.

### 3.3 Experiment of a sound absorbing wall

The second experiment with the new method in a 3-D sound field is the measurement of the sound absorption of a wall of a sound absorbing room. The room is quite small, it is 3x3x2.5 m in size, but it is well insulated against exterior noise. The walls are not broadband sound absorbers, but are perforated absorbers that have high sound absorption in a frequency range around 1000 Hz. The floor of the room is covered with laminate flooring and cannot be considered as a fully reflective surface. A picture with details of the acoustic perforation is given in figure 7.

The described measurement is performed by scanning a 0.3 x 0.3 m region of the wall during a time interval of 30 s. The probe is operated manually, it is held perpendicularly to the wall surface while keeping the acoustic center of the probe at a distance of approximately 6 cm from the surface. The sound source is located behind the operator but is not centered at the middle of the measurement region. The sample rate and source signal are identical to those used for the validation measurements discussed before. Figures 8(a) and 8(b) show the narrow-band and 1/3-octave absorption curves obtained from two independent measurements.

The narrow-band absorption curves shown in figure 8(a) obtained by two independent measurements for the wall in figure 3.3 show a clear peak in the vicinity of 1000 Hz. Sound absorption is clearly lower at low frequencies and for frequencies above 1200 Hz. In the region with high sound absorption the variation between both curves is small whereas some absorption variations can be noticed for low and high frequencies. However, performing the same analysis for all one-third octave bands between 100 and 3000 Hz, the curves match quite well, see figure 8(b). A possible cause for the difference is non-equitemporal scanning of subregions but the variations remain small. It is concluded that the absorption curve obtained in this manner gives a good indication of the sound absorption of the wall in a quantitative sense.
Figure 7: Detail of the hole pattern of the wall; hole dia. 3 mm; hole spacing 10 mm

![Image of hole pattern]

Figure 8: Absorption curves obtained by scanning a rectangular region of the wall

(a) Narrow-band absorption curves, frequency resolution \( \Delta f = 4.88 \text{Hz} \)

(b) 1/3-Octave absorption curves

3.4 Experiment of a flanged duct in an anechoic environment

The third experiment deals with a large (dia. 20 cm) duct with a length of 50 cm as described in the third numerical example in section 2. This duct has a flanged open end at one side and is closed with a 10 mm thick aluminum plate at the other side. The closed end contains a small hole of a diameter of 5 mm (the sound source) to which a hose is connected. The other end of the hose is connected to a boxed loudspeaker. The loudspeaker is driven with band-limited white noise so that its spectral content was mainly limited to the frequency range 250-4000 Hz. The duct is oriented vertically so that the measurements can easily be performed by scanning the tube’s cross-section with the intensity probe. To ensure the correct position of the probe with respect to the duct longitudinal axis during a scan, the probe is fixed to a thin wire that was attached to the ceiling of the anechoic room, see figure 9.

Data acquisition is performed similarly as for the other experiments described in this section. The measurement is performed by scanning the duct’s cross-section during the measurement time of 30 seconds. Special attention is paid to scan all segments of the cross-section for an equally long time.
The whole measurement setup is placed into the aero-acoustic windtunnel facility of the University of Twente in order to match the acoustic free-field that was assumed in the simulation.

![Measurement setup](image)

Figure 9: Measurement setup

![Absorption curves](image)

(a) Results from simulation

(b) Results from measurements

Figure 10: Absorption curves obtained for the duct at $z = -0.4$, $-0.2$ and $0$ m.

Figure 10(b) shows the absorption curves for the three positions given in section 2, in the frequency range from 500 to 1500 Hz. The absorption curves obtained by measurements can directly be compared to those obtained by simulation in figure 10(a).

In the figure one can clearly recognize the dip in sound absorption at approx. 1000 Hz. At this frequency the first mode above the cut-on frequency is excited and a non-axisymmetric sound field is created. As in the simulation, the dip in the absorption curve reduces as the probe is moved towards the open end. By comparing both figures, it is concluded that a very good agreement between simulation and measurement is achieved.
4 Conclusions

In this paper, we present a (patented) new method to calculate and measure acoustic absorption in-situ. The method is based on a local plane wave assumption of the actual sound field and the incident intensity (and power) is efficiently obtained by means of measuring the active and total intensity. The method has been validated by means of impedance tube measurements, measurements in a larger duct and a small anechoic room. It has been shown that good agreement between numerical simulations and experiments is achieved.

References


