A handheld device to measure the acoustic absorption in situ

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Abstract

This paper reports on the development of a handheld device to measure the absorption coefficient of acoustic materials in situ. The device is capable to measure the normal and oblique reflection coefficient in a 200Hz-20kHz bandwidth in situ, e.g. inside a car.

One novelty is that the probe is fixed to the source. This makes the setup easy to use and improves the accuracy because the calibration distance and the measurement distance is fixed.

It shows that a simple mirror source model gives the same results in the frequency bandwidth used as a far more complex F-term correction. The use of the mirror source model decreases the processing time so much that the measurements can be done virtually in real time.

The complete calibration and measurement procedure requires a few seconds and can be done handheld. It is a battery powered portable system with as data acquisition a simple USB soundcard.

Introduction

The Microflown is an acoustic particle velocity sensor that is invented at the University of Twente in 1994 [18]. In 1997 the sensor was commercialized. In this paper, the Microflown will be referred to as particle velocity sensor.

Over years the particle velocity sensor is used to determine acoustic impedance. The first application was the measurement of the acoustic impedance of a horn loudspeaker with a pu-method. In the throat of a horn loudspeaker a pressure microphone (p) and a particle velocity sensor (u) was placed and the impedance was successfully measured [2]. Afterwards, two particle velocity sensors (in stead of microphones) where used in a standard Kundt’s tube. This technique showed also that particle velocity sensors could be used to determine the acoustic properties of materials in a Kundt’s tube [3].

The acoustic impedance in the tube was determined by measuring the sound pressure and the particle velocity directly at one point in the tube [4]. Furthermore the ratio of intensity (I) over energy (E) was measured to calculate the reflection coefficient of the acoustic material. The basis of this method is that \( I=0 \) if the material is fully reflecting and \( I=cE \) (c is the speed of sound) if the material is fully absorbent.

At the University of Leuven the pu-probe was used to determine the specific acoustic impedance at the surface of an absorbing material [6]. With this method the disadvantages of the Kundt’s tube are avoided. Several disadvantages in the tube are the upper frequency limit, determined by the tube diameter, the fact that only the normal reflection coefficient can be obtained and that not all materials can be put in the tube. In this paper it is shown that material properties even change when put in the tube.

In [6] is proven that the acoustic reflection coefficient of materials can be measured broad band for both oblique and normal angles of incidence. The method is very fast, in 10 seconds the reflection coefficient for a certain angle of incidence can be obtained.

At the HAN University the so called mirror source technique [14] was investigated with mixed success. This completely different approach is based on a miniature point source and a velocity probe measuring extremely close to an acoustic material.

In this paper progress is reported.

The surface impedance technique is explored in more detail at several universities and companies [6]-[13]. At the HAN University the method is also investigated [14], [15]. In this paper the progress is reported.

Theory

The reflection coefficient \( R \) of an acoustic material is defined by the ratio of the incoming sound wave and the reflected one. If sound waves are plane the phase shift of between the sound pressure and particle velocity is zero or 180 degrees depending on the direction of the sound wave. The
sound pressure \((p)\) is scalar and the particle velocity \((u)\) is a vector value.

It can be shown that if the plane sound wave in one direction is given by the signal \(p+upc\), the sound wave in the opposing direction is given by \(p-upc\) \([1]\). The reflection coefficient is then given by:

\[
R = \frac{p-upc}{p+upc} = \frac{p}{u} - \frac{pc}{u} = \frac{Z-pc}{Z+pc} ; \alpha = 1-|R|^2 \tag{1}
\]

With \(p\) the density, \(c\) the speed of sound and \(\alpha\) is the absorption coefficient. Plane waves are found in a standing wave tube below a cut off frequency \(f_{c}=c/2d\), with \(d\) the inner cross section of the (square) tube. See further e.g. \([2]\), \([3]\), \([4]\), \([14]\).

Measurements in the free field are more complex because plane waves are practically impossible to create. If a source is relative close to the sample under test, spherical waves may be expected. If a special (monopole) source is chosen, the sound wave is exact spherical, and this makes a model to calculate the reflection coefficient possible. Several methods are possible to calculate the reflection coefficient from the measured impedance \([5]\), \([6]\), \([7]\), \([8]\), \([14]\), \([19]\).

The so-called F-term correction \([5]\), \([6]\), \([7]\), \([8]\), \([14]\) can be used but it is time complex compared to a spherical model, see further section ‘F-term correction vs. spherical calibration’.

Another problem with free field measurements is that a monopole sound source generates a sound pressure field that is proportional to the frequency. In practice that means that it is difficult to generate a sound pressure field that is higher than the background noise at frequencies lower than 100Hz.

Most acoustic materials do not absorb at lower frequencies and therefore particle velocity close to the sample is also low. (Close to a fully reflecting plane the particle velocity is practically zero).

So at lower frequencies both the sound pressure and the particle velocity are low. This causes the proper measurement of the surface impedance to be very difficult at low frequencies.

Apart from the difficult measurement, the models to calculate the reflection coefficient from the measurement become more difficult for lower frequencies \([19]\).

**Measurement setup**

The measurement set up consists on a spherical shaped loudspeaker. The radiation impedance in front of the loudspeaker is studied in \([20]\). The radiation impedance in front of the loudspeaker is quite similar to a monopole. The loudspeaker mounted, mechanically decoupled to a grip. On the grip is a structure is mounted that holds the pu-match probe.

![Figure 1: The handheld device to measure the reflection coefficient of acoustic damping materials in situ](image)

The distance between the pu-probe and the loudspeaker \((h-h)\) is 17cm and 32cm in this investigation, see Figure 2. The measurement distance, that is the distance between the pu probe and the acoustic sample is called \(h\). This distance is chosen as small as possible and is typically 5mm in this investigation.

![Figure 2: Schema of the setup.](image)

**F-term correction vs. spherical calibration**

The F-term correction is required to calculate the reflection coefficient from an impedance measurement in a spherical sound field \([5]\), \([6]\), \([7]\), \([8]\), \([14]\). The method is very complex and requires an iterative procedure that is time consuming.

The ‘image source model with plane wave reflection coefficient’ that is reported in \([6]\) and \([19]\)
is used here to get a very simple measurement routine. It is assumed that the spherical reflection coefficient equals the planar reflection coefficient. It shows to give similar results for higher frequencies (f>100Hz) [19].

Several measurements are processed with a piston on a sphere calibration and the spherical surface reflection coefficient is converted with a F-piston on a sphere calibration and the spherical (f>100Hz) [19].

shows to give similar results for higher frequencies coefficient equals the planar reflection coefficient. It term correction to the planar reflection coefficient.

routine. It is assumed that the spherical reflection is used here to get a very simple measurement point source is given by Eq. (2):

\[ p(r) = i \rho c k \frac{Q}{4\pi r} e^{-ikr} \quad u(r) = \frac{Q}{4\pi} \frac{ikr + 1}{r^2} e^{-ikr} \]

The impedance in the free field is therefore given by Eq (3):

\[ Z_f = \frac{p(h_h - h) + p(h + h)}{u(h_h - h) - u(h + h)} \]

With Q the source strength, \( k \) the wavenumber, \( h_h \) the distance from the point source to the sample and \( h \) the distance from the impedance probe to the sample. The impedance close to an acoustic sample is given by Eq. (4):

\[ Z_{measure} = \frac{(h_h - h) + (h + h)}{(h_h - h) - (h + h)} \]

\[ = \frac{i \rho c k 4\pi(h_h - h)}{Q} e^{-i(k(h_h - h))} + i \rho c k 4\pi(h + h) e^{-i(k(h + h))} R \]

\[ = \frac{Q}{4\pi} \frac{ik(h_h - h) + 1}{h_h - h} e^{-i(k(h_h - h))} - \frac{Q}{4\pi} \frac{ik(h + h) + 1}{h + h} e^{-i(k(h + h))} \]

\[ = \frac{e^{-i(k(h_h - h))}}{(h_h - h)} + \frac{e^{-i(k(h + h))}}{(h + h)} \]

The ratio of the measurement impedance and the free field impedance is given by Eq. (5):

\[ \frac{Z_{measure}}{Z_f} = \frac{e^{-i(k(h_h - h))}}{(h_h - h)} + \frac{e^{-i(k(h + h))}}{(h + h)} \]

With that the reflection coefficient can be derived Eq. (6):

\[ R = \frac{Z_{measure} - 1}{Z_f} = \frac{h_h + h e^{i2\pi}}{h_h + h} \]

When the \( Z_{measure} \) and \( Z_f \) are measured close after each other, all amplifier settings, AD settings, calibration of the microphone and microphone etc. are likely to be unchanged. As long as this is true, the values do not have to known as they will vanish in the ratio \( Z_{measure}/Z_f \).

Eq. (6) is similar to the expressions shown in [6] and [19] but here it is shown more clear what the consequence of a fixed source-probe distance is.

If Eq. (6) is observed for high frequencies \( (ik_h h >> 1 \rightarrow f >> 300Hz) \), the equation simplifies to:

\[ R = \frac{Z_{measure} - 1}{Z_f} = \frac{h_h + h e^{i2\pi}}{h_h + h} \]

If \( h_h >> h \), the equation is barely sensitive for the probe-sample distance h.

So for higher frequencies (f>300Hz, for a source-probe distance of 18cm), the reflection coefficient is measured accurate. This is important to realize, especially in respect to the paragraph below: ‘PU Kundt’s tube vs. free field measurements’. In that paragraph it will be shown that for certain materials the Kundt’s tube result is different than the free field measurements. The cause must be that the results in the Kundt’s tube are wrong. This is something that is known in literature [23].

**Method to get rid of (room) reflections**

In [21] a method was presented to get rid of room reflections in the calibration measurement. The method is based on calculating the impulse response of the measured transfer function \( Z = p/u \). The room reflections are later in time than the primary response and can be removed mathematically by setting the impulse response to zero by a window. Then the windowed impulse response is transferred to the frequency domain. This method works well for higher frequencies.

This time window method works well but requires setting the window limits. This is somewhat time consuming and the routine depends on the operator.
The calibration measurement \( (Z_{ff}) \) in a normal room (where some reflections occur) looks noisy in the frequency domain and the time window technique seems to eliminate this ‘noise’.

A moving average of the calibration measurement in the frequency domain is a far more simple routine and it produces similar result as the time window technique.

It shows that for highly reflective surfaces a standing wave occurs between the reflective surface and the loudspeaker. This reflection can also be eliminated with the moving average method.

**Moving average filtering**

In Figure 5 a measurement is shown of a calibration in a normal room and (red line) and the signal that was time windowed to remove the room reflections (black line). As can be seen, the black line follows the red line and is found in the middle. Many measurements have been done and this effect was always found.

![Moving average filtering](image)

Figure 3 (upper): A calibration measurement in an anechoic room (grey line) and in a normal room (black line). Lower: same measurement in an anechoic room (grey line). Black line is the moving averaged result of the calibration measurement in a normal room that was shown in the left plot.

Therefore a function ‘moving average’ was tested and found to have similar results. A calibration measurement was done in an anechoic room and repeated in a normal room to show this.

As can be seen in Figure 3, the calibration result in an anechoic room is a smooth line with some small ripples. The result in a normal room seems to be ‘noisy’. This ‘noisy’ signal is not because of a poor signal to noise ratio but due to the room reflections.

Because the room reflections have a random character, i.e. the reflections are from all possible directions with all possible phase shifts, the deviation from the anechoic calibration is also random. As long as the deviations are random (and thus the reflections are random), the moving average method will work.

At lower frequencies \((f<150\text{Hz})\) the method seems to break up and this is most probably caused by a dominant reflection (e.g. the ground reflection). For frequencies lower than 80Hz the method does not work, most probable due to the relative high background sound pressure levels.

**Software and data acquisition**

As data acquisition a standard, 16bit USB sound card is used (creative sound blaster). The measurements are processed with MATLAB version 2006r, the DAQ toolbox and the signal processing toolbox. The PC (1.8GHz, 2GB RAM) that was used runs with Windows XP.

With the software it is possible to generate white noise on the loudspeaker and measure the response of the microphone and Microflown. The result is stored as .mat file.

The stored measurements are opened and processed with the main program, see Figure 4. First both signals are transferred to the frequency domain \((2^{14} \text{ points FFT})\). The transfer function of the free field calibration \((Z_f)\) and the actual measurement \((Z_{measure})\) are visualized in the upper two figures (left modulus and right phase). With ‘moving average’ smoothing the room reflections are cancelled. The values can be set in the upper right box and the result of the averaging is shown in the upper two plots. The averaging routine, and refresh of all windows is done within the second.

The middle two windows show the normalized impedance \((Z_f/Z_{measure})\) (left modulus and right phase). The figures are calculated from the averaged values \(Z_f\) and \(Z_{measure}\).

The lower two plots show the, with Eq. (6) corrected absorption and reflection coefficient in the left plot and the phase of the reflection coefficient in the right plot. The correction of Eq. (6) is only dependent on the measurement distance and the
source distance. These values can be set in the upper right box.

After setting the parameters and loading the calibration measurement it is possible to do an absorption measurement in real time.

**Measurement of a plane with R=1**

The measurement of a fully reflective plane is the most difficult scenario for this method. This is because the particle velocity level is low close to a fully reflective plane (see also paragraph below: 'Signal to (background)noise level'). Apart from that, the measurement is very sensitive for phase errors [22]. The only thing that is simple about a fully reflective plane is that the spherical reflection coefficient equals the planar reflection coefficient. The model that is used here is therefore valid.

In the measurement (at 4.5mm distance) of the impedance of the (80cmx80cm) reflective plane a ripple occurs, (see Figure 4 upper plots, red lines). This ripple is caused by standing waves between the reflective plane and the loudspeaker. The ripples can be removed by the moving average algorithm. It is our believe that a larger source-sample distance can reduce this effect. This is a point of further R&D.

A small monopole sound source is also tried. Such source is smaller that the one that is shown in Figure 1 so the reflections should be less. The monopole source is not used because the frequency response shows a high dynamic range (which makes measurements difficult at frequencies with a low sound emission) and this type of source makes the setup less portable.

**Figure 4**: Graphical user interface of the surface impedance method, here a fully reflective plate is measured.

**Figure 5 (Upper)**: A measurement result of a 80cmx80cm fully reflective plate (measurement distance h: 4.5mm 18cm source-sample). Black line without moving average smoothing red line: with moving averaging smoothing. Lower: An 80cmx80cm fully reflective plate measured at several probe-sample distances (source-sample distance: 18cm).

The measurement of a fully reflective plate shows within what limits the method works in worst case conditions. As can be seen in Figure 5 (red line), the error is relatively small in a frequency range from 200Hz up to 15kHz. Tests show that the ripples in the response are caused by a standing wave between the loudspeaker and the fully reflective plate.

The black line shows the measured reflection coefficient when the signals are not smoothed. All room reflections (in both calibration and measurement) are present and the effect of the standing wave between the reflective plate and the loudspeaker is not filtered.

It can expected that the measurement error will drop considerable if the material becomes less reflective.

The fully reflective plate can therefore be used as estimate for the maximal measurement error.

![Graphical user interface](image)

![Reflection coefficient vs frequency](image)
this example the measurement (Figure 5) error is in the order of 5% in a 200Hz-6kHz bandwidth for a 18cm source-sample distance.

Figure 5 Right shows the results of measurements with several probe-sample distances (source-sample distance: 18cm). As can be seen: The accuracy of the 2mm probe-sample distance is low for frequencies lower than 200Hz. This is caused by a poor signal to noise ratio. Measurements between 5mm and 10mm show good results.

**Signal to (background)noise level**

The signal to noise ratio (S/N) of a measurement is an important figure. If it is too low, the measurement becomes not valid.

The signals of the sound pressure and the particle velocity are measured in the free field and close (4.5mm distance) to a fully reflective plane and with the source switched off and on. The (1W) loudspeaker was driven maximal with pink noise at 17cm distance. The signals might be better if a swept sine is applied.

Figure 6 shows the responses. In the left plot the pressure responses are shown. As expected, the pressure response increases about 6dB due to the reflective plate. Below 100Hz the S/N drops below 10dB in the free field and close to the reflective plate the S/N is 6dB better.

Figure 6 (left): Pressure signals and (right): velocity signals (PU match). Red lines: silent response, blue lines: pink noise on the loudspeaker and close to fully reflective plate, black lines: free field response to pink noise.

The velocity signal has a much better S/N in the free field. Below 100Hz the S/N drops below 40dB. However when the probe is positioned very close to the reflective plane the S/N drops below 15dB.

Conclusion is that for lower frequencies the S/N of the sound pressure signal becomes low due to the monopole radiation behavior and if the probe is positioned close to a reflective plane the S/N of the particle velocity is low due to the reflection.

**PU Kundt’s tube vs. free field measurements**

Five materials are measured in a Kundt’s tube. The material properties are first measured in a Kundt’s tube and then compared with the free field method.

A: 25mm Foamex

B: 25mm Foamex with reflective foil

C: 25mm Akotherm (white) D20/25 polyester wool 0.5kg/m²

D: 25mm Acusticab: 30 kg/m³ polyurethane foam with 0.025mm polyurethane film on top. At the back is a thin adhesive layer.

E: 1.2kg/m² felt that is used for automotive applications

The acoustic field in the tube is measured with a PU probe. First the probe is calibrated in the tube by measuring the response of the PU probe without an acoustic sample of the fully reflective end of the closed tube [14]. Then a sample is inserted, the impedance is measured and the reflection and absorption coefficient is calculated [6], [14].

After this, the free field absorption coefficient is measured and compared with the Kundt’s tube results. The red lines in Figure 8 show the free field response when the sample is still mounted in the tube (see Figure 7, left) and the blue lines show the free field response of a 60cmx60cm sample (see Figure 7, right).
Figure 7: Left: the acoustic samples are mounted in the tube and measured with the free field method with a PU match. Right: a large sample is measured.

As can be seen, the Kundt’s tube result matches the free field response if the sample is mounted in the tube. However the free field response of a large sample does not always match the response of a small sample mounted in a tube.

Figure 8: The acoustic samples are mounted in the tube and measured with a PU Kundt’s tube (black line); with the free field method (PU match) and the sample still mounted in the tube (red line); and a large sample in the free field (blue line).

It can therefore be concluded that the acoustic properties might change if a sample is cut and put in a tube. This is known for elastic porous materials [23].
Influence of the measurement distance

In this paragraph the effect of the measurement distance is shown. First a measurement of Foamex 1 is measured at 2mm and 10mm. Then in the software the distance \( h \), is varied in 1mm steps around the real measurement distance.

The 2mm distance is varied in the software from -3mm to +7mm. The result is shown in Figure 9, left. As can be seen: the influence is most when the reflection coefficient is high.

Same shows for the same material measured at 10mm. If the absorption is calculated for a distance varied from 4mm to 15mm, the results are influenced when the reflection coefficient is high.

Figure 9 (left): Foamex 1 measured at 2mm and the absorption is calculated for a variation of measurement distances (from -3mm to 7mm). Right: the measurement distance is 10mm and results are calculated from 4mm to 15mm. The middle line is the proper distance.

A large sample of Foamex 1 is measured at several measurement distances. These distances are also used for the processing. The results are shown in Figure 10. As can be seen, the measurements in a range from 2mm up to 20mm are consistent and when the distance is increased further, the results deviate.

The measurement results have a reflection coefficient higher than 1 which is obviously wrong. Why this error occurs is not clear especially because the measurements on a fully reflecting plate are not showing this error.

Foamex 1 is measured at several probe-sample distances. The physical distances are used in the software to convert the measurements into a reflection coefficient. As can be seen in Figure 10, as long as the measurement distance is smaller than 20cm, the results are comparable.

Figure 10 (left): Foamex 1 measured at several distances.

Measurement errors

The method shows to be sensitive for materials with a high reflection coefficient and especially at lower frequencies the results have a higher error.

In general. The reason can be found in: 1) wrong model, 2) bad signal to noise ratio, 3) wrong measurement distance, 4) wrong source behavior, 5) wrong calibration, 6) properties of the acoustic sample.

The model does not explain the measurement error: the measurement on a fully reflective plate has a higher accuracy than a measurement of Foamex 1. The measurements on a fully reflective plate show also that the signal to noise ratio is not the cause of this error; the measurement error is consistent.

If the probe sample distance is underestimated (so if at 1cm distance is measured but 7mm is used for the model), the measurements results resemble better the tube results. The physical reason for this under estimation (if any) is unknown.
The model that is used here assumes a loudspeaker with a monopole behavior. The real loudspeaker does have a behavior that only resembles a monopole. If the source-probe measurement distance increases to 30cm or more the behavior deviates less than 0.05dB and 1.5Degree from a true monopole source [20]. Increasing the source-probe distance to 30cm must improve the measurement if the deviation in behavior at close distances is the cause of the inaccuracy.

The properties of the acoustic sample can be the reason for the measurement error.

**Repeatability**

A group of six persons measured a sample of Foamex 1 by hand. They first calibrated the system by holding it in their hand and then measured twice. It is done without any training. The measurement distance was supposed to be 4mm and this value was used in the software. The setup was also fixed. Two measurements with a fixed position and calibration are also shown in Figure 11.

![Figure 11](image)

Figure 11 (left): Foamex 1 measured with the hand by several unskilled operators.

As can be seen, the measurements are consistent and the error is larger at lower frequencies in combination with lower absorption values.

**Influence of environment**

For this test 25mm Foamex is used and two source-sample distances are used: 17cm and 32cm. To check the influence of the acoustic environment several measurements were done:

- a large sample of 60cmx60cm was measured as reference
- a 30cmx30cm sample that was cut free
- a smaller (15cmx15cm) sample that was cut free
- a very small (4.5cmx4.5cm) sample that was cut free
- a very small (4.5cmx4.5cm) sample put in the end of a Kundt’s tube (see Figure 7)
- 60cmx60cm sample two reflective vertical planes (see, Figure 12, left)
- 60cmx60cm two reflective horizontal planes (see, Figure 12, right)

![Figure 12](image)

Figure 12 (left): two vertical reflective planes, (right): two horizontal reflective planes.

In Figure 4 the influence of several environments is shown.

The black line shows the response measured close (3mm) to the large reference sample. The green line, that almost overlaps, is the response if two horizontal planes are put over the acoustic
material with 8cm from the probe, see Figure 12 (right). It can be concluded that horizontal reflective planes do not influence the measurement much.

If the sample is cut to 15cmx15cm the response is similar except for a ‘dip’ around 2500Hz, see Figure 13 red line. See further ‘sample size’ below.

If the free field conditions are disturbed with two vertical planes 6cm from the probe, see Figure 12 (left), the response will alter into the blue line. It can be concluded that vertical obstacles do not influence the measurement much.

For comparison the kundt’s tube measurement is shown in yellow. It can be concluded that if the sample is cut and put in the tube, the properties of the material change: the maximal absorption is shifted from 1800Hz to 2500Hz.

If the size is reduced to 4.5cmx4.5cm, the complete shape alters: the maximal absorption increases in frequency. This effect is observed if the sample is free (red line) and, (black line) contained in a kundt’s tube holder (as shown in Figure 7). The small sample shows similarity with a measurement in a Kundt’s tube (purple line).

It can be concluded that the sample size is influencing the measurement. However it is most probable that the acoustic properties of the sample change and that the free field measurement is valid.

For comparison the kundt’s tube measurement is shown in yellow. It can be concluded that if the sample is cut and put in the tube, the properties of the material change: the maximal absorption is shifted from 1800Hz to 2500Hz.

If the size is reduced to 4.5cmx4.5cm, the complete shape alters: the maximal absorption increases in frequency. This effect is observed if the sample is free (red line) and, (black line) contained in a kundt’s tube holder (as shown in Figure 7). The small sample shows similarity with a measurement in a Kundt’s tube (purple line).

It can be concluded that the sample size is influencing the measurement. However it is most probable that the acoustic properties of the sample change and that the free field measurement is valid.

Figure 13: Influence of acoustic environment. Black: large reference sample, red: smaller sample cut free; dark blue: with two horizontal reflective planes as shown in Figure 12 (right).

Sample size

In Figure 14 the influence of the sample size is shown. The reference 60cmx60cm sample is shown in light blue. If the sample size is reduced to 15cmx15cm, a deviation of the response is seen at 2500Hz (dark blue line). More deviations are seen if the size is reduced to 15cmx15cm and the deviation seen at 2500Hz increases (green line).

Figure 14: Influence of sample size. Left: source sample distance 32cm, right the distance is 17cm.

Influence of horizontal reflective obstacles

Two reflective horizontal plates are put on the 60cmx60cm reference sample to check what their influence is, see Figure 12 (right). As can be seen in the graph below (Figure 15), if the reflective planes are 8cm away from the probe that the response is not affected.
Figure 15: Influence of horizontal reflective planes. Left: source sample distance 32cm, right the distance is 17cm.

Influence of vertical reflective obstacles

Two reflective vertical plates are put on the 60cmx60cm reference sample to check what the influence is, see Figure 12 (left). As can be seen in the graph below (Figure 16), if the reflective planes are 6cm away from the probe that the response is not affected much.

Figure 16: Influence of vertical reflective planes. Left: source sample distance 32cm, right the distance is 17cm.

Measurements under an angle

Absorbing materials are usually measured in a Kundt’s tube because such measurement set up is relatively easy to use in practice. However this method determines the reflection coefficient only in the normal direction.

If materials are locally reacting (their properties do not change with measurement angle) the Kundt’s tube can be used to characterize. However most practical acoustic materials are not locally reacting.

In [6] the measured impedance must be corrected with a cosine of the measurement angle. However if the same ‘trick’ is used as is described in Eq. (6), that is taking the ratio of the measured surface impedance $Z_{measured}$ and the free field impedance $Z_{ff}$, then the cosine theta factor does not have to be used.

The pu-probe is rotated to the desired angle and calibrated in this orientation. Then the sample is measured with the pu-probe normal to the surface. Eq. (6) can then be used to calculate the reflection coefficient from the measured values.

At lower frequencies the measurements clearly deviate from real values as they are negative. The coherence however is high from 200Hz upwards. At higher frequencies (f>1kHz) the measured values are more realistic. No explanation is found for the low frequency deviation yet.
Measurements in a car

A sample of 15cmx15cm Foamex 1 is prepared with a reflective plate behind it to be used as a piece of material with known properties. This sample is now placed in several positions in a car with the doors open and closed.

As can be seen in Figure 19, the measurement results are consistent and not influenced by an open or closed door. The foot area seems a difficult place to measure: the results deviate at lower frequencies.

Conclusion

A fast, simple, portable, handheld measurement method is demonstrated that is able to measure the acoustic reflection coefficient in situ for both normal and oblique angles.

The PU method based on a PU match works in a frequency bandwidth higher than 200Hz. The lower limit is caused by the low sound pressure level that the loudspeaker emits at low frequencies. If the reflection coefficient is high, the particle velocity level is also too low below 200Hz.

The maximal measurement error can be measured easily by a measurement of a fully reflective plate. The measurement error increases when materials are highly reflective. Measurements on acoustic materials show a larger error than was expected with the fully reflective plate. The cause of that is still unknown.

The method shows not to be very sensitive to acoustic obstacles close by. Roughly speaking, reflective obstacles should be more than 10cm away from the setup.

The PU match is a bit fragile. There is a real risk that the Microflown sensor wires are damaged when measuring close to (hairy) acoustic damping materials. When a measurement distance of 1cm is used, the measurements are still accurate and the risk of damaging is reduced.

A larger source-sample distance increases the accuracy at lower frequencies and decreases the coherence. A too large source-sample distance (let’s say 1 meter) would make the set-up difficult to use in a car; it seems that a distance of 30cm to 40cm would be optimal. This is a point of further R&D. A probe-sample distance of 1cm seems to get good results.
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