Non destructive and in situ acoustic testing of inhomogeneous materials

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Abstract: The surface impedance method based on the measurement of sound pressure and particle velocity at the surface is proven only on homogenous materials [1-6]. Many aerospace materials however (e.g. perforated jet engine liners and hollow spheres) are inhomogeneous and have far more complex geometries. The acoustic properties of these materials are likely to vary at each position. The properties of inhomogeneous materials are measured with the surface impedance method. First results will be presented of local impedance measurements, giving a reflection coefficient at each position. These local measurements will be averaged to obtain the effective impedance and reflection of the whole surface. This effective result is in good agreement with the PU Kundt's tube method that measures the average properties of a larger surface.

INTRODUCTION

There are a number of methods to determine the sound absorbing properties of materials in situ. However there seems to be no adequate method to measure small areas. Large samples of several square meters are required for the reverberant room method and the Tamura method [7]. The Kundt's tube method takes the average value of a smaller sample, typically 4 to 8 cm in diameter, but is not in situ and introduces the disadvantage of sample cutting and mounting problems. It is difficult to avoid sound leaks between the tube and the sample and at the same time not to clamp the sample which influences its acoustical behavior.

Many materials have no uniform structure and there is a need both for research purposes as for end of line control to assess the acoustical performance in more detail.

In this paper the results of a method will be presented to measure impedance very locally. The method is based on the already known PU free field surface impedance method [1-6]. Compared to traditional techniques, the method has the advantage to measure real time, broad banded, in situ without the need of an anechoic chamber or sample cut-out. The PU probe makes use of a unique true particle velocity sensor together with a pressure microphone. The ratio of sound pressure and particle velocity signal gives the acoustic impedance in one spot, so the reflection and absorption can be calculated.

A smaller probe is used to be able to decrease the distance to the sample and to decrease the measured area. To prove the correctness of this method initially a relative easy sample with a single quarter lambda resonator is measured. The impedance is scanned in a fine grid 3 mm above the surface of the sample and inside the resonator. After this a similar sample, with 3 resonators is studied and the reflection at each position is shown. Finally an actual sound absorbing aluminum foamed material is analyzed. All samples are also measured with the known Kundt's tube technique and results are compared.

1. STANDARD PU BASED FREE FIELD SURFACE IMPEDANCE METHOD

The PU surface impedance method is based on the ratio between sound pressure and the particle velocity close to the surface, see Figure 1. A pressure microphone and a particle velocity sensor (the Microflown) are combined in one so-called PU probe. In one position it is able to measure intensity or impedance in a single direction. With impedance (Z) measured, the reflection (R) and absorption (α) can be easily derived for higher frequencies, see formula (1), (2), (3). At lower frequencies the sound field becomes spherical and these results should be corrected [2],[5],[6],[8]. For the present study these corrections are not applied since the frequency of interest is in the relatively high range.

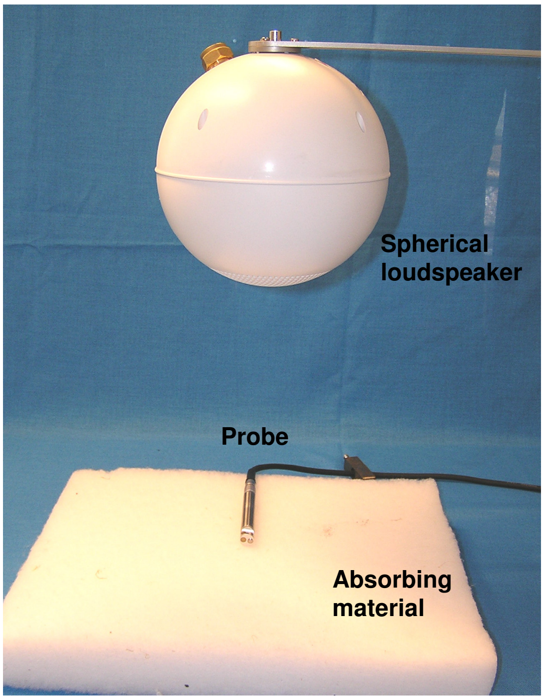


Figure 1. Standard free field surface impedance setup

$$Z = \frac{p}{u} \tag{1}$$

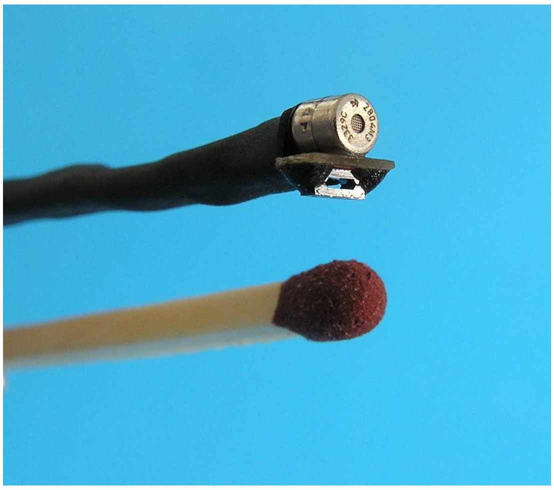
$$R = \frac{Z - \rho c}{Z + \rho c} \tag{2}$$

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

A spherical loudspeaker is used for calibration. Under relative anechoic conditions the PU probe is placed in front of it and the free field response is determined as described in [6],[8]. The same loudspeaker is used during the sample measurement. The probe is then positioned as close as possible to the material. The signals are measured with a regular 2 channel sound card. In order to avoid reflections and the need of an anechoic chamber a time window is applied during calibration and during the actual measurement.

2. SINGLE QUARTER LAMBDA RESONATOR

A very locally reacting sample is chosen to study the local deviation of impedance: a rigid plate with a single quarter lambda resonator, see Figure 2b. A tube 62 mm long with a 5.5 mm diameter is mounted in a 115 x 115 mm flat steel plate. This tube will predominantly absorb locally and only at one frequency when a quarter of the wave length equals the length of the tube (and at its higher harmonics). A miniature "PU match" probe is used to scan the surface and the inside of the resonator, see Figure 2a.



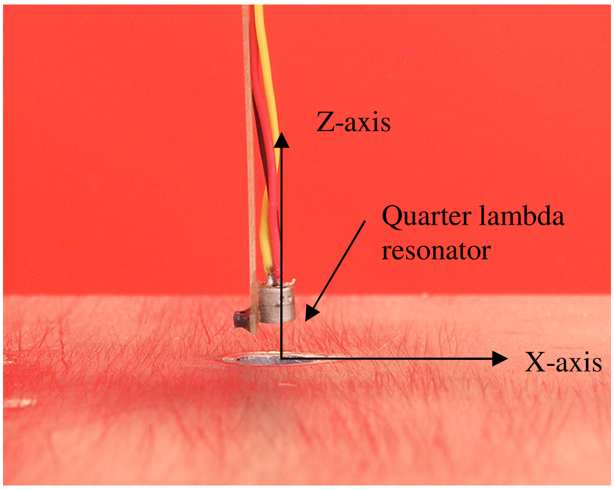


Figure 2a. Miniature PU match probe. A 1/10"microphone is combined with a particle velocity sensor.
Figure 2b. PU match impedance probe sensitive in the direction of the Z-axis on a quarter lambda sample

2.1 Movement over the surface (x-axis)

The probe is positioned 3 mm above the plate and is moved from directly above the tube (x = 0 mm), along the x-axis of the plate. The results are plotted in Figure 3 and Figure 4. The autospectrum is not an absolute value but the deviation in decibels normalized with the free field calibration. A value of zero dB will represent a free field condition.

Note that the impedance above the plate is mainly determined by particle velocity and pressure remains almost constant.

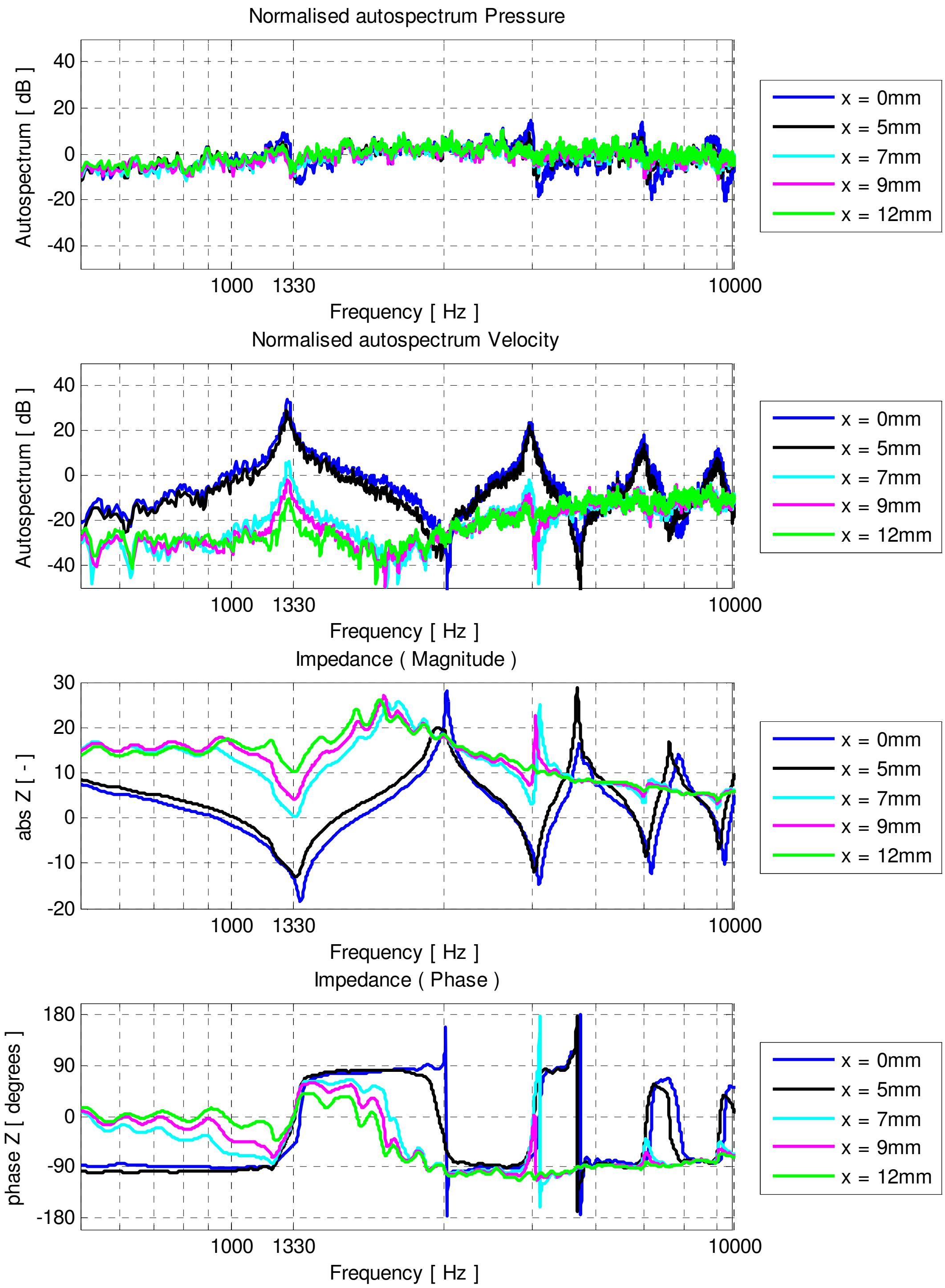


Figure 3. Autospectrum and impedance at 3 mm distance from the surface

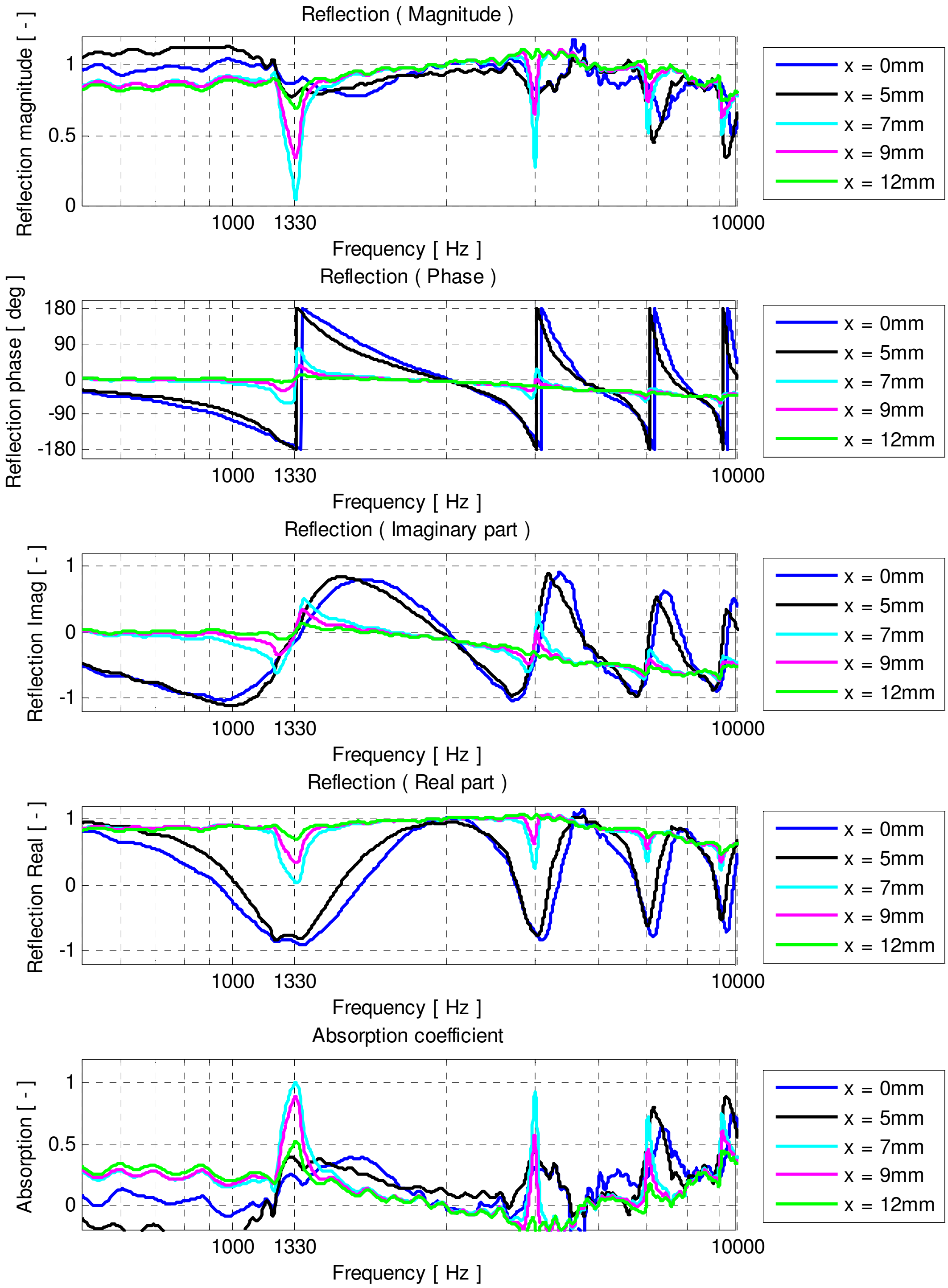


Figure 4. Reflection and absorption along the x-axis (distance from surface 3 mm)

In Figure 4 an interesting phenomenon can be observed at 1330 Hz. The absorption equals 100% near the resonator (x = 7 mm), but directly above the resonator there is nearly 100% reflection (x = 0 mm). Since the imaginary part is zero at that frequency we are allowed to look only at the real part. Above the tube the reflection is 1 but with negative phase, so -1. Inside the tube nearly all energy is reflected. As the reflection or absorption coefficient is calculated, the absolute value is taken and this information is lost.

Only directly above the tube the real part of the reflection equals -1 at 1330 Hz. If a larger area would be covered a more averaged value not equal to -1 would be measured. This means the spatial resolution of this method must be in the order of millimeters.

2.2 Movement in the resonator (z-axis)

Next the probe is moved in the z direction from inside the tube (z = -14 mm) to the surface of the plate (z = 0 mm) and further to above the plate (z = 6 mm), see Figure 5 and Figure 6.

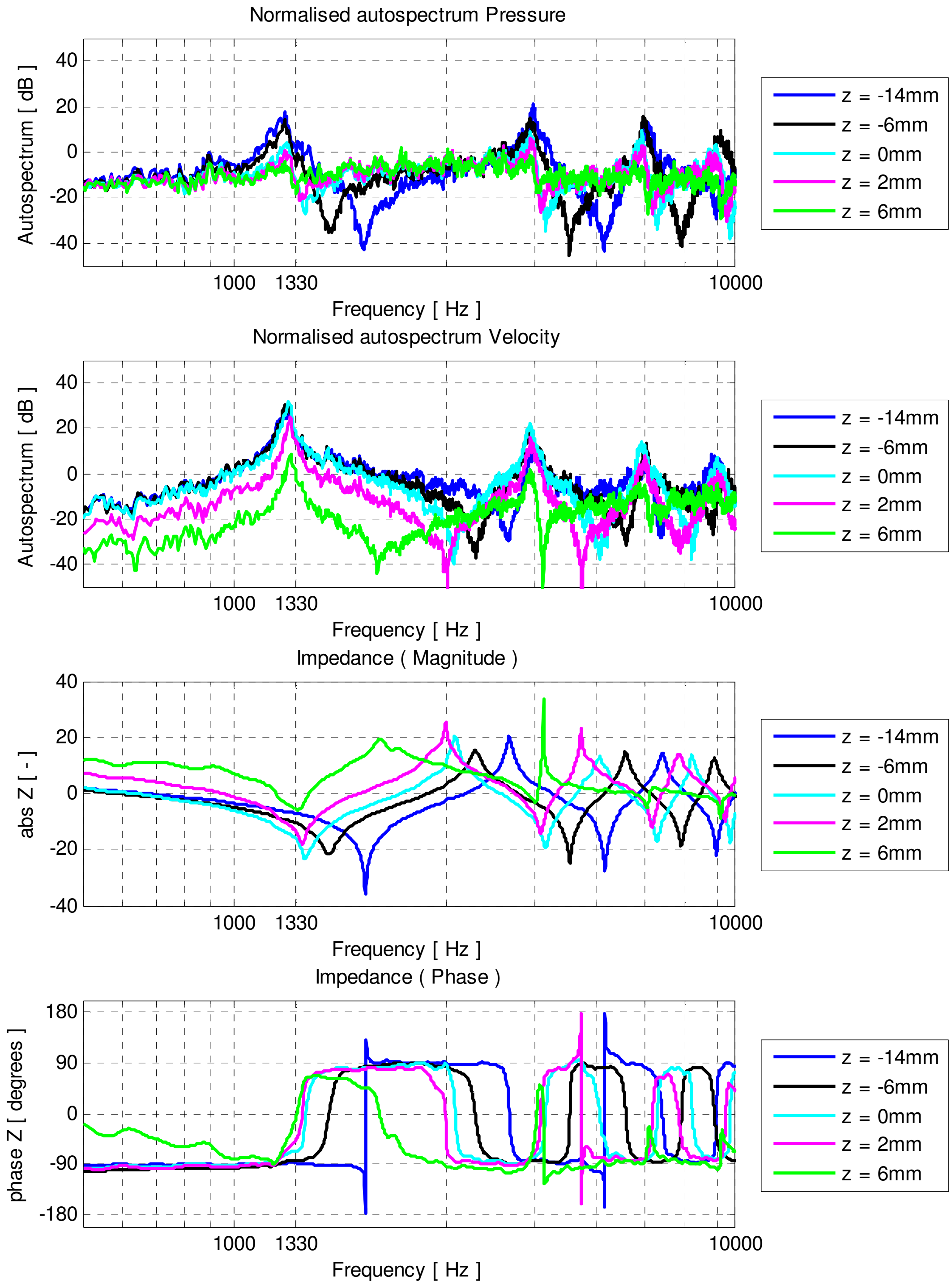


Figure 5. Autospectrum and impedance along the z-axis

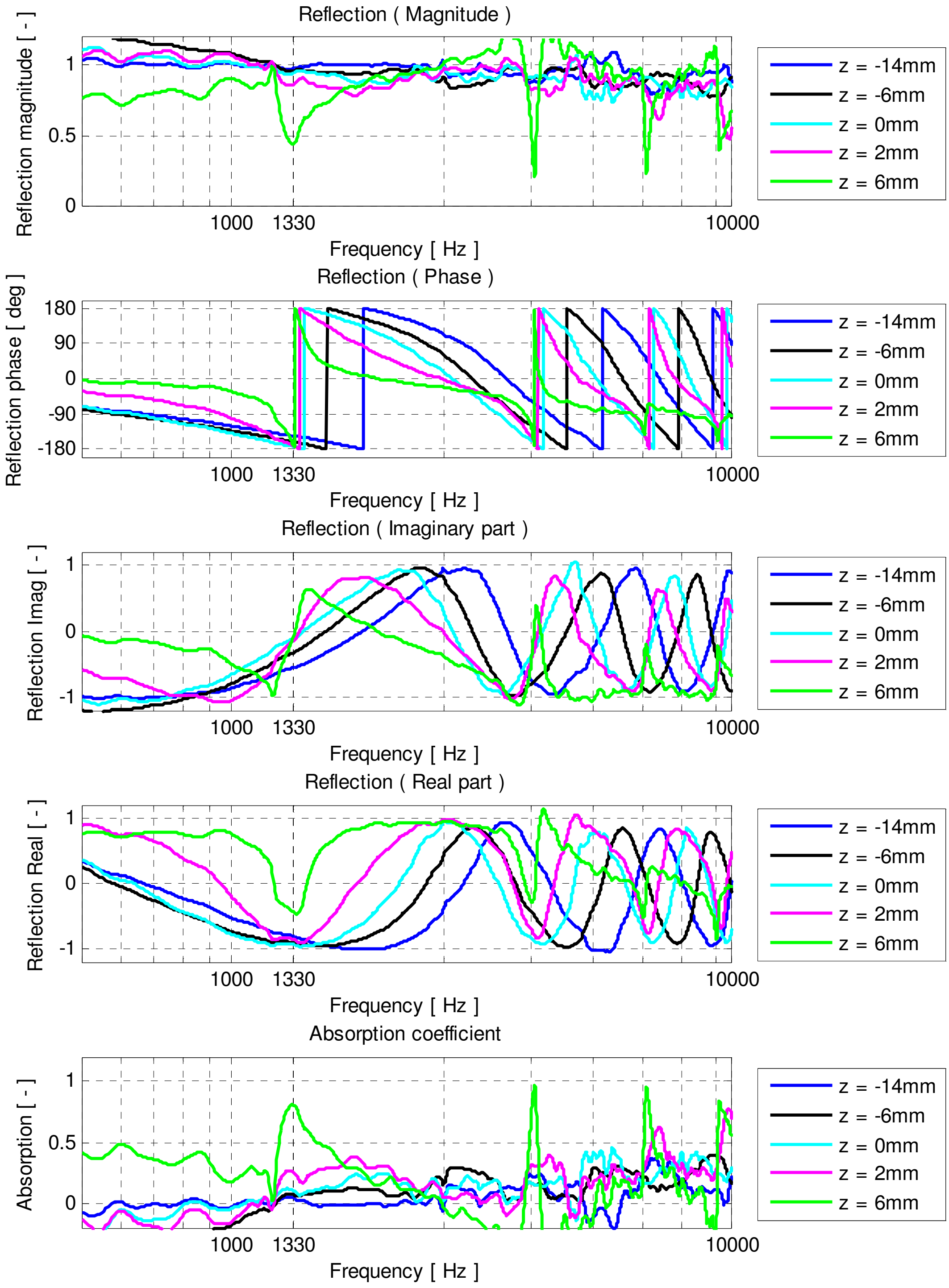


Figure 6. Reflection and absorption along the z-axis

The pressure doesn't change much outside the tube, while there is a large pressure variation inside the tube. This might explain why it is difficult to estimate impedance outside a tube based on pressure measurements only (e.g. Tamura method [7]). With enough dynamic range inside a tube it is possible to measure the impedance (Kundt's tube method).

2.3 Kundt's tube reference

As a reference the same sample is also measured with the PU probe Kundt's tube method [1], [4], [5],[6], see Figure 7. The Kundt's tube has a 46 x 46 mm square cross section and sound waves will travel only in one dimension below the cut-off frequency of 3500Hz. The plate with resonator can directly be mounted at the end of the Kundt's tube so there is no risk of re-positioning the sample or changing its acoustical properties.

Because the surface of the sample was only measured on several points with the free field impedance method it is not possible to reconstruct the effective absorption of the whole sample and to compare this directly with the Kundt's tube results.

The absorbing properties of a wall resonator are dependent of the ratio between the tube diameter and the distance between the tubes [9]. The measurement shows that one tube in a relatively large plate absorbs nearly all sound at one single frequency (1320 Hz). Nearly the same frequency as measured close to the tube with the local free field measurements (1330 Hz).

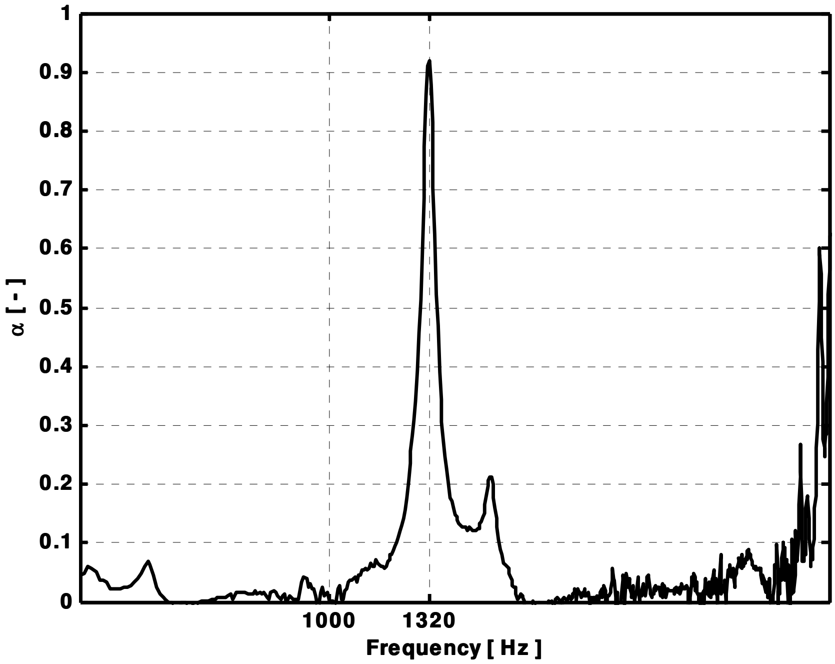


Figure 7. Kundt's tube absorption of one quarter lambda resonator

3. THREE QUARTER LAMBDA SAMPLE

3.1 Local impedance measurements

The entire surface of the same sample, but now with three quarter lambda tubes is measured 3 mm from the surface with a 5 x 5 mm grid (81 measurements), see Figure 8. Each tube will cause the sample to absorb at its particular resonant frequency.

Because each segment of the sample is observed, the combination of these measurements represents the behavior of the total sample. The result can then be compared with the Kundt's tube.

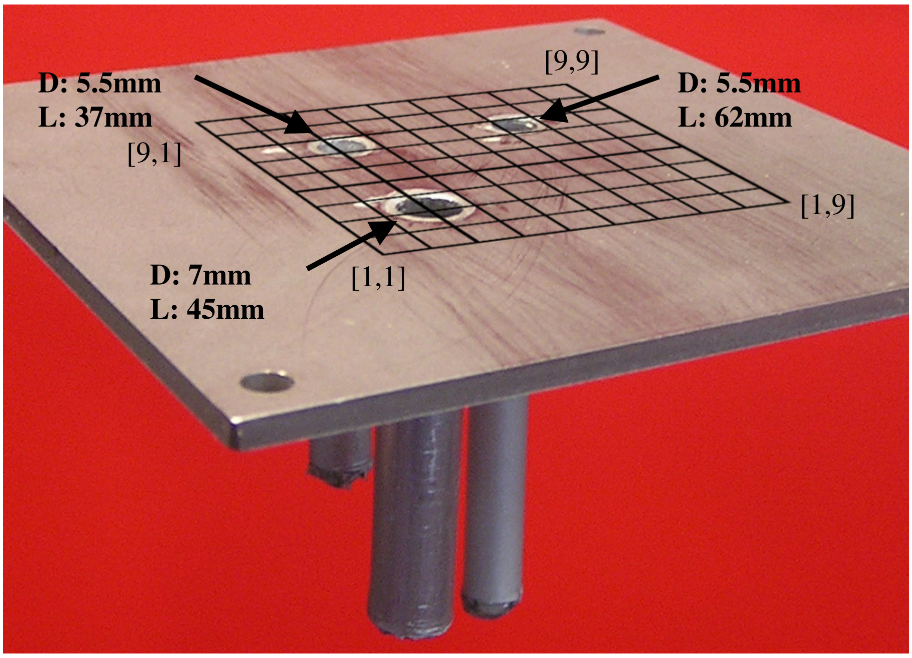


Figure 8. Measurement grid of a sample with three quarter lambda resonators

In Figure 9, Figure 10 and Figure 11 the results are plotted at the 1st resonant frequency of each tube at respectively 1330, 1841 and 2218 Hz. Here it is shown that the real part of reflection goes to -1 above the corresponding tube. At that position the absolute reflection is 1and absorption is zero.

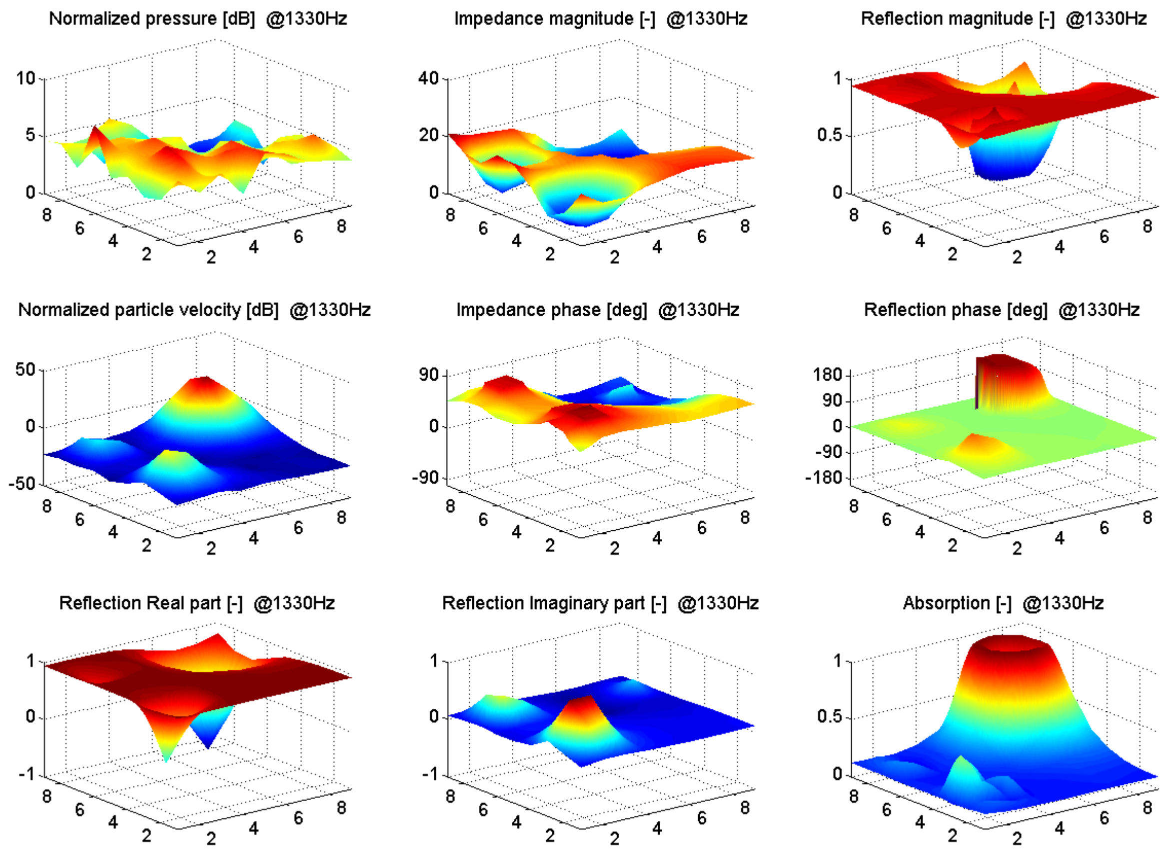


Figure 9. Sample with three tubes at 1330 Hz. The upper tube is most dominant (l = 62 mm), position [7,7]

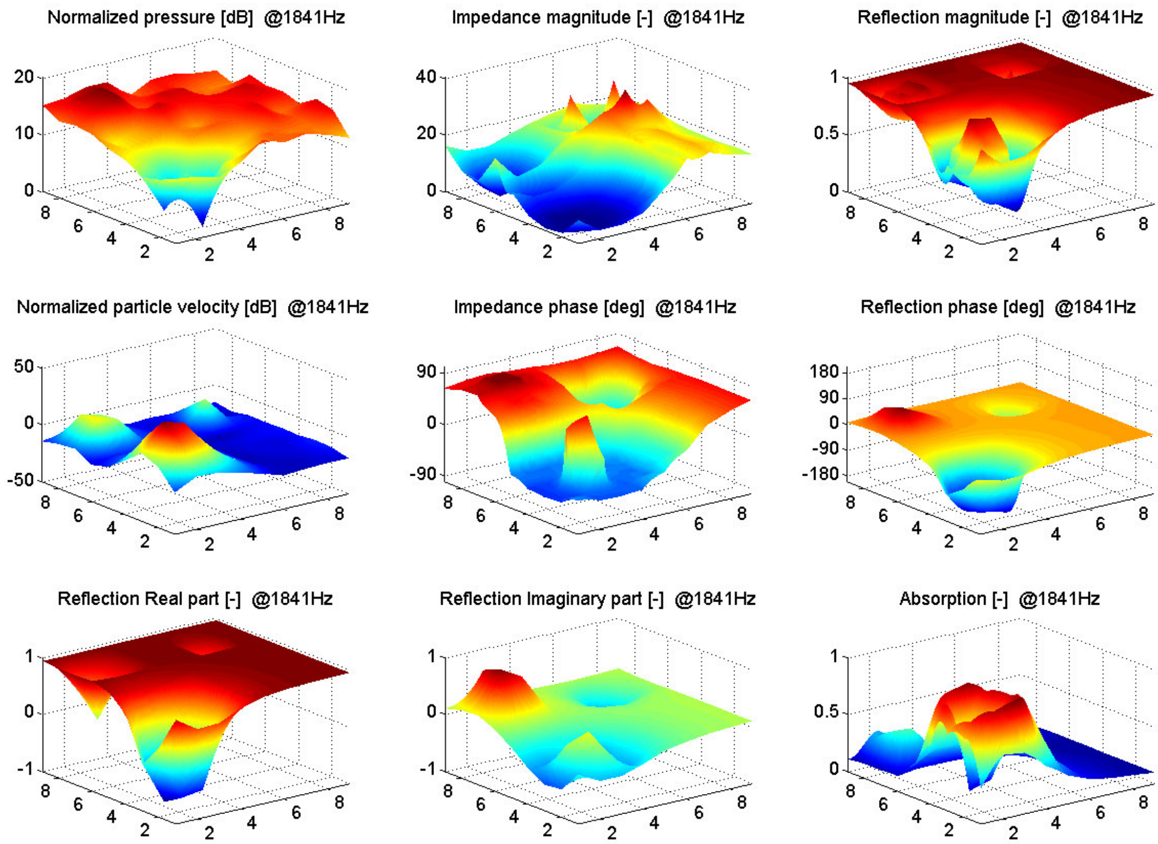


Figure 10. Sample with three tubes at 1841 Hz. The lower tube is most dominant (l = 45 mm), position [3,3]

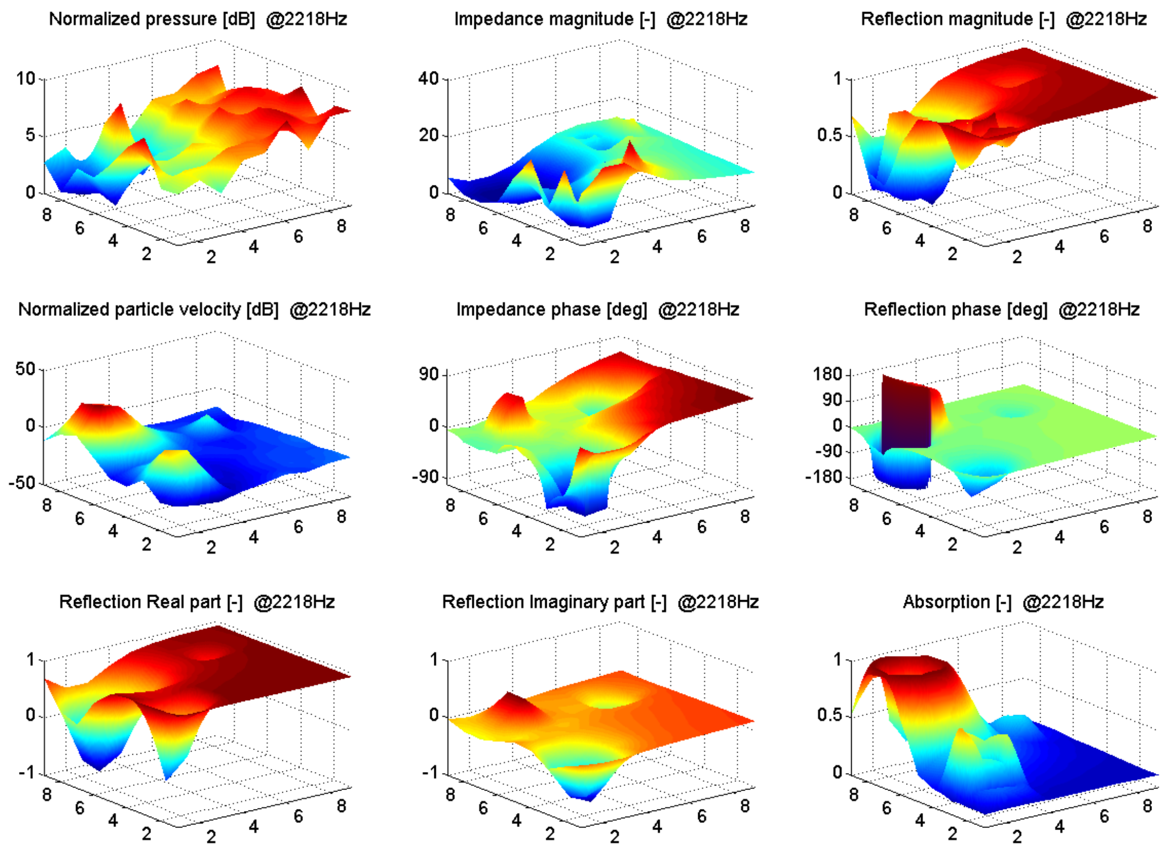


Figure 11. Sample with three tubes at 2218 Hz. The left tube is most dominant (l = 37 mm) , position [7,3]

3.2 Kundt's tube comparison

With the averaged sound pressure and particle velocity value close to the plate the effective impedance of the covered surface can be calculated:

$$Z = \frac{\sum |p| e^{i\varphi_p}}{\sum |u| e^{i\varphi_u}} \tag{4}$$

With the effective impedance the reflection and absorption of the entire sample can be obtained, formula (2) and (3). Figure 12 shows the Kundt's tube and the effective absorption of the local impedance measurements give a comparable result.

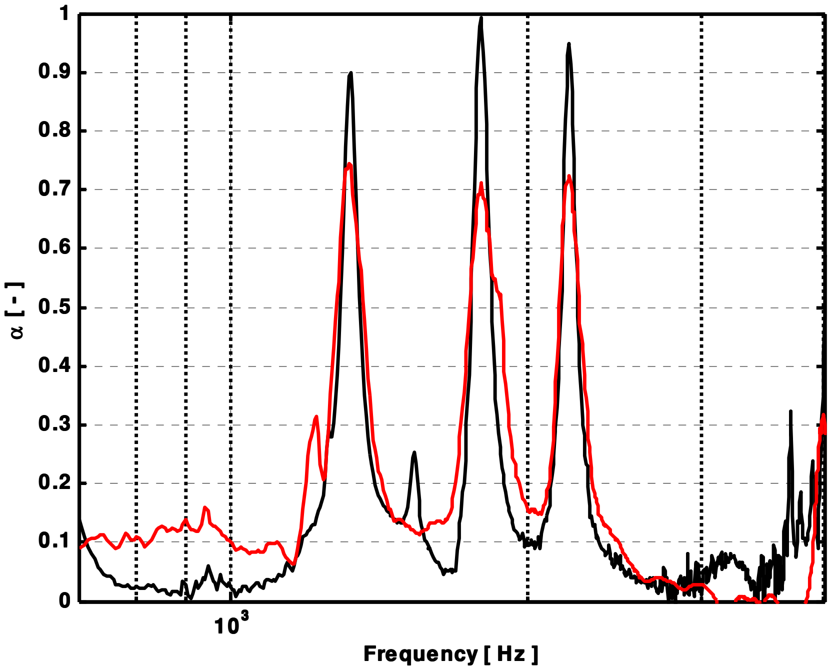


Figure 12. Kundt's tube response of the 3 tubes sample (black line) and effective absorption of the local impedance measurements (red line)

To avoid deviation due to sample positioning, the plate is directly placed at the end of the Kundt's tube. Nevertheless the sample properties change because the sample area is affected in the Kundt's tube. As mentioned earlier the absorption value of a quarter lambda resonator in a wall is determined by the relation between tube diameter and the area around the tube. The unwanted modification of the sample area because of the Kundt's tube dimensions might explain the different results of the two methods.

4. ACTUAL SAMPLE

4.1 Local impedance measurements

Aluminum foam plates filled with hollow spheres can be used as a strong ultra lightweight aircraft material. As example the highly uneven surface of a sample of such a material (trade name Alulight®) is tested for its acoustical uniformity, see Figure 13 and Figure 14. Again the 46 x 46 mm sample is positioned between plates so that it can be directly mounted at the end of the 46 x 46 mm square Kundt's tube to avoid deviation due to mounting. The same measurement grid is used as in the previous measurements.

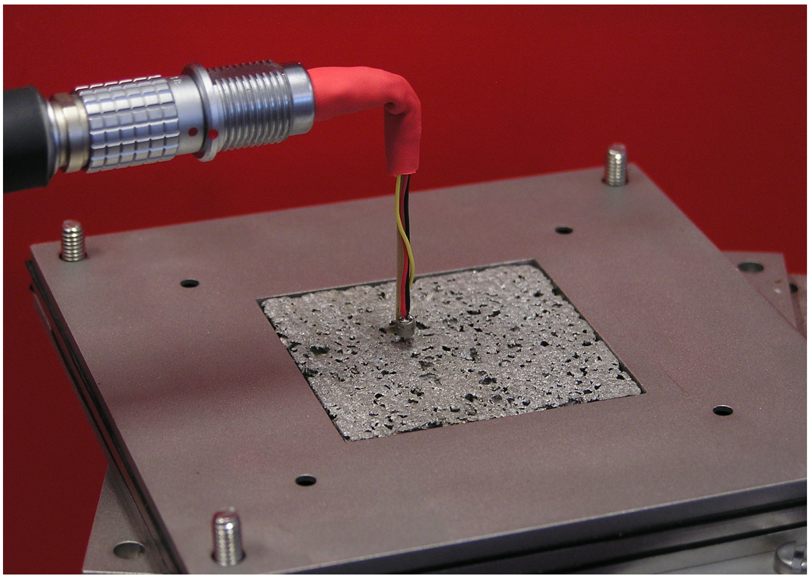


Figure 13. Ultra lightweight sample with hollow spheres

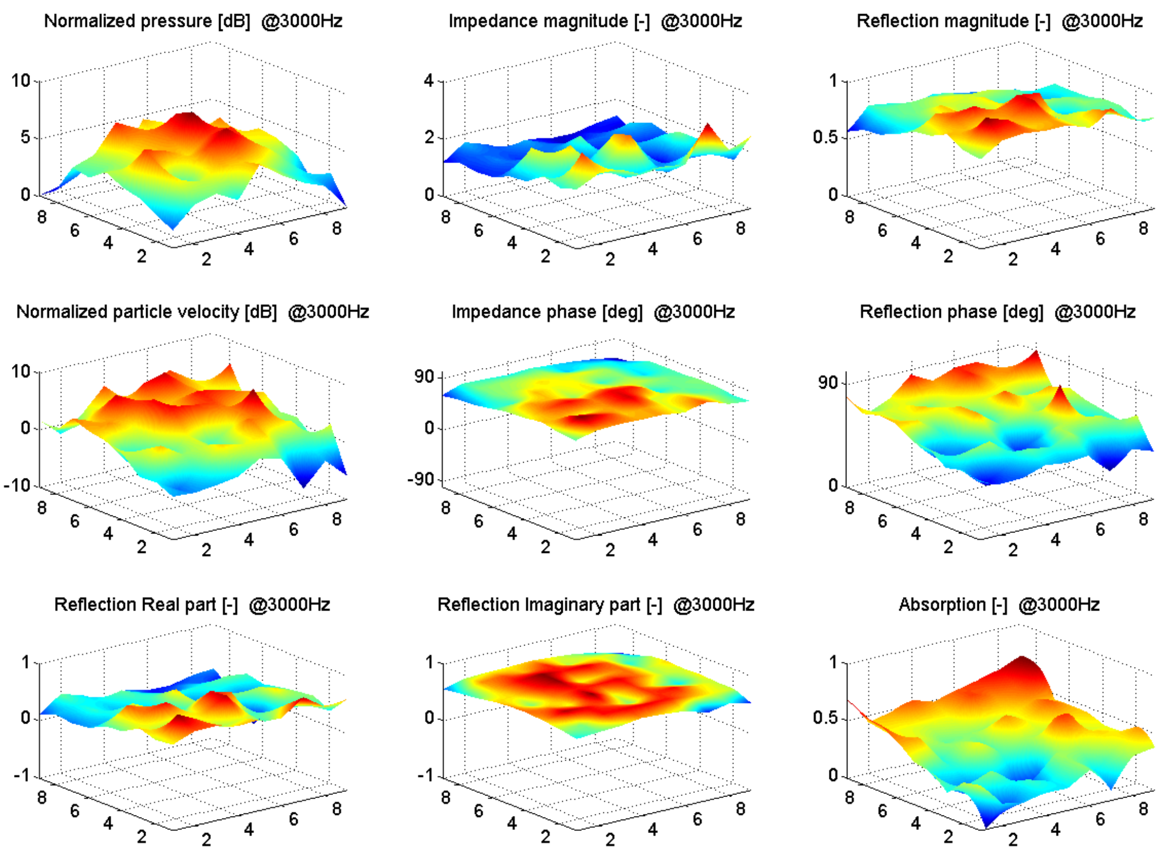


Figure 14. Reflection and absorption of the sample with hollow spheres at 3000 Hz

4.2 Kundt's tube comparison

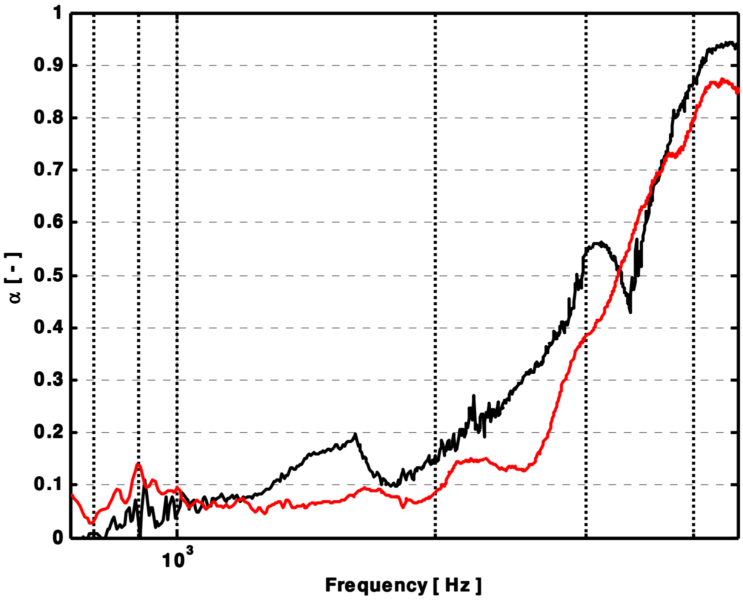


Figure 15. Hollow sphere sample. Kundt's tube (black line) and effective absorption of the local impedance measurements (red line)

In Figure 15 a similar trend between the Kundt's tube and the local impedance measurements can be observed.

5. CONCLUSION

A method has been presented to determine the impedance, reflection and absorption very locally. The measurements are performed in a normal room with a simple sound card for data acquisition. The spatial resolution is in the order of millimeters. This is a vast contrast to existing methods like the reverberant room and the Tamura method. And without the disadvantage of cutting samples which brings sample restrictions and measurement deviation as in the Kundt's tube.

The measurements on a quarter lambda resonator make it clear that there is enough dynamic range to estimate impedance with a pressure microphone only inside a tube. Outside the tube only particle velocity shows a large variation.

The measured frequency of the resonance peaks corresponds to the Kundt's tube method. And it is even possible to reconstruct the effective impedance and absorption value from the local measurements. These values show to be comparable with the Kundt's tube results.

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