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5aAAb3. Exploration of the differences between a pressure-velocity based in situ absorption measurement method and the standardized reverberant room method

Peter Cats, Emiel Tijs* and Dani F. Comesana

***Corresponding author's address: Microflown Technologies, P.O. Box 300, Zevenaar, 6900 AH, Gelderland, Netherlands, tijs@microflown.com**

Several measurement techniques are available for the determination of the sound absorbing properties of material packages. The Kundt's method and the reverberant room method are the most commonly used techniques and they are standardized. However, both methods cannot be used in situ. In the past it has been shown that the PU in situ method can be used in a broad frequency range (typically from 300 Hz up to 10 kHz), on small samples (typically 0.03 m2 to 0.38 m2 or larger), while hardly being affected by background noise and reflections. Several studies revealed that similar results can be obtained as with the Kundt's tube if the measurements are performed under certain circumstances. A thorough comparison with the reverberant room method has not been conducted yet. In this paper preliminary results are presented of a comparison of the reverberant room method, the PU in situ method, and measurements with PU probes in a reverberant room. Several factors that may cause discrepancies amongst the methods are discussed. In addition, edge effects, which are experienced with the reverberant room method due to the finite size of the sample, are visualized with 3D intensity measurements that are performed in a reverberant room.

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INTRODUCTION

The Kundt's tube (ISO 10534-2 and ASTM E1050-98) and reverberant room absorption measurement method (ISO 354 and ASTM C423) are well-known and commonly used to measure the absorption coefficient of sound absorbing material packages. However, because these methods cannot be used *in situ* their outcome may not properly reflect the properties of the sound absorbing packages after installation. There are several *in situ* absorption techniques, but most of them are limited in frequency range and cannot be used for certain sound absorbing sample types or for the way in which they are installed [1-3]. In [4] an *in situ* absorption method was introduced that utilizes combined sound pressure – particle velocity probes called PU probes [5]. A sound source is installed above a probe that is placed near the sample. The absorption is then obtained with a sound field model from the measured sound pressure and particle velocity. This method was further investigated and developed in e.g. [6-7]. It has been shown that measurements can be performed in a broad frequency range (typically from 300 Hz up to 10 kHz), on small samples (typically 0.03 m^2 to 0.38 m^2 or larger), while hardly being affected by background noise and reflections [8-13].

In [13-16] it was shown that the results from *in situ* absorption measurements with PU probes can be similar to those of the Kundt's tube method if the measurement conditions are preserved. Although the results of *in situ* measurements with PU probes and results of reverberant room measurements have been compared in some studies, see e.g. [7, 17], a thorough comparison has not been conducted. The preliminary results of a study in which both methods are evaluated are presented in this paper. With PU probes the absorption coefficient is acquired under several circumstances (anechoic and reverberant fields) and estimated with different methods (plane wave and two spherical wave methods). Firstly, the different techniques are briefly described. Next, the measurement results are presented.

Furthermore, a method to study one of the limitations of the reverberant room method is introduced here. The overestimation of the absorption coefficient with the reverberant room method is sometimes partly attributed to the edge diffraction effect. Here, the energy flow around the edge of a sample is measured with three a dimensional PU probe. Such measurements can be performed because PU probes can measure the acoustic intensity, even in environments with a high pressure – intensity index [18-19]. The Scan & Paint routine [20-22] is utilized to quickly acquire the intensity at multiple measurement positions. The measurement method will be presented along with examples of energy flow measurements around the edge of a sample in a reverberant room.

PU BASED ABSORPTION MEASUREMENT METHODS

In this section the *in situ* absorption methods that will be used are briefly introduced. A more detailed description of the methods can be found in the concerned references.

The mirror source method

Plane sound waves are not easily generated in the free field in a broad frequency range. The distance between the sample and the sound source should be large to avoid near field effects, especially at low frequencies. Arrays of loudspeakers could generate more planar wave fronts, but again at lower frequencies there are difficulties because the array would need to be large to avoid diffraction.

A point source is typically used instead of plane- or diffuse sound source. Corrections have to be made to take into account near field effects and spherical wave fronts in order to obtain the plane wave impedance, reflection or absorption that most people are familiar with. There are many models describing the sound field above a sample due to a point source which allow extracting the plane wave absorption properties [23]. One of the mostly used and most robust model is the image source or mirror source model [6,14].

The mirror source model can be used to calculate the absorption from an impedance measurement with a sound source at normal incidence. The reflected sound wave from the surface is represented as a 'mirror source' below the impedance boundary. The impedance as measured close to the sample can be corrected for the difference in near field effects that occur between the incoming- and the reflected sound wave. It has been shown that this model can also be applied successfully for measurements in non-anechoic environments, such as a car [11] and a concert hall [12]. Here it will be applied for the first time for measurements in reverberant rooms. To acquire the signals a small hand-held set-up is used, which consists of a small spherical sound source (10.1cm diameter) and a PU probe (26cm probe – source separation), which both are suspended to dampen the structural vibrations from the sound source, see [11].

It must be mentioned that deviations can be found with the mirror source model, because, although it accounts for the propagation of spherical sound waves above the sample, it does not account for propagation of spherical waves inside the sample [24]. The degree and frequency of deviations depends upon the impedance and damping of the material. Such discrepancies are not found in case there are plane waves, when the sample is infinitely thin (then it is allowed to model the reflections as a single mirror source), or when the sample is infinitely thick (then the sound that penetrates through the sample is fully damped).

Plane wave surface impedance method

Although it is difficult to generate plane waves in the free field, it is sometimes possible to create a diffuse sound field were plane waves arrive from all directions. In [7] either ambient noise was used or a reverberant room where seven loudspeakers were installed. The absorption was calculated from the sound pressure and particle velocity that were measured by a PU probe, which were integrated across a surface. Because there are plane waves, an absorption model can be used that is less complex than most absorption models that incorporate spherical sound waves. Here the same principle is now used in a reverberant room.

Intensity extrapolation method

In [24] a method was presented that utilizes multiple measurements of the measured ratio of the active intensity near the sample to the active intensity without sample. A sound source is placed at normal incidence in a similar configuration as with the mirror source method, with the difference that multiple measurements with different distances between the probe and the sound source are performed. The measured ratio of intensities is different for each measurement because the near field effects are different for each measurement. These measurements are combined by extrapolating the results from the measurements at different distances to an infinite sound source distance; thus obtaining the plane wave absorption coefficient.

ABSORPTION MEASUREMENTS

Test description

The following samples were used in our tests:

- A 10 mm thick layer of recycled polyurethane foam with the brand name: Agglomer
- A 25 mm thick layer of melamine foam with the brand name: Flamex 25N
- A 50 mm thick layer of melamine foam with the brand name: Flamex 50N

These samples were tested with the following absorption measurement methods:

(1) The ISO 354 reverberant room method
(2) The Kundt's tube method (only data of Flamex 25N was available for this method).
(3) The *in situ* PU probe based Mirror Source method (abbreviation MS method)
(4) The Plane Wave PU probe based surface impedance method (abbreviation PW method)
(5) The *in situ* PU probe based Intensity method (abbreviation I method)

The Kundt's tube that was used had a square inner cross-section of 45 x 45 mm. For method (3), (4), and (5) the sample size was in between 0.72 m^2 and 1.2 m^2, which can be considered sufficiently large as in e.g. [13] it was mentioned that the samples of at least 0.1 m^2 are required.

The mirror source method was applied in several environments. The first environment is a room with sound insulation materials on the walls, which approximates the condition of a semi-anechoic room. Next, measurements were also performed in more reverberant environments to study if there is a deviation. In [11] and [12] it was shown already that this method can be used in non-anechoic environments by measurements that were performed in respectively a car and a concert hall. Here, measurements were performed in three reverberant environments; i.e. a small reverberant room (a toilet), and two large reverberant rooms. In these three reverberant rooms measurements were also performed with the plane wave surface impedance method.

Measurements with the mirror source method and the Plane wave method

Before comparing the results of the different absorption measurement methods it is studied to which extend the results of the mirror source method and the plane wave method vary if different rooms are used. Figure 1 up to 3 show the measured absorption coefficients for the three samples in third octave bands. In reverberant room 2 the signal to noise ratio was poor above 6 kHz, so these results are omitted.

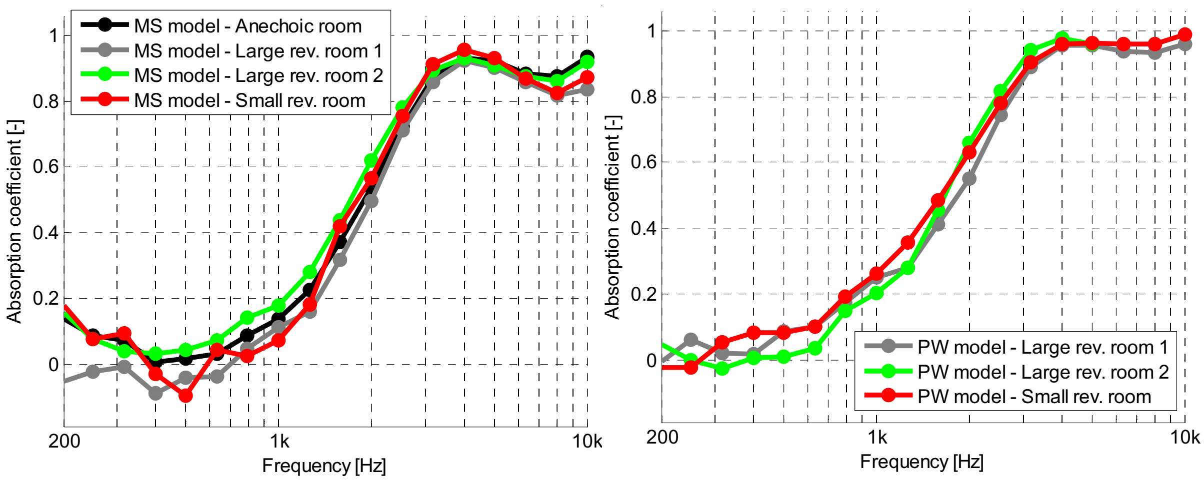

FIGURE 1. Absorption coefficients of Agglomer measured in different rooms. Left: Mirror source method. Right: plane wave method.

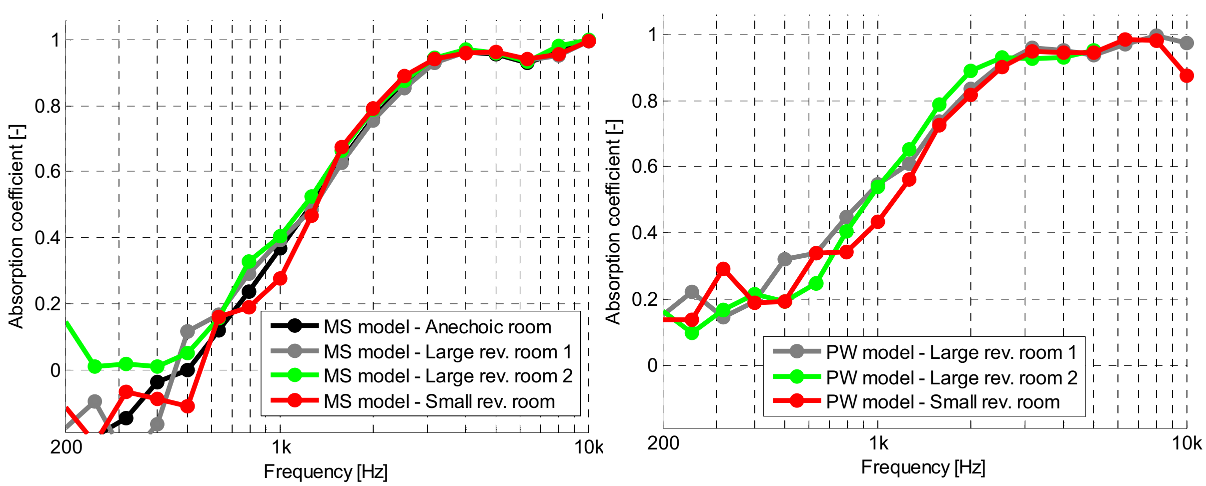

FIGURE 2. Absorption coefficients of Flamex 25N measured in different rooms. Left: Mirror source method. Right: plane wave method.

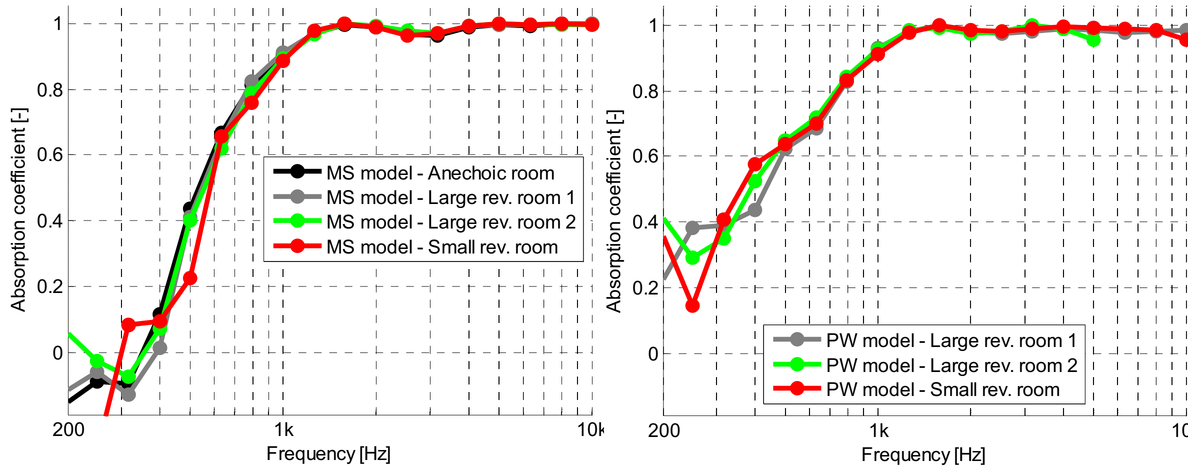

FIGURE 3. Absorption coefficients of Flamex 50N measured in different rooms. Left: Mirror source method. Right: plane wave method.

For the Agglomer sample and to some degree also for the Flamex 25N sample there are slight variations of the obtained absorption coefficients. By comparing results from different measurements it was found that the difference in position of the probe is one cause for these variations (these results are not shown here). The absorption coefficients obtained are similar under all conditions for the Flamex 50N sample. These measurements show that the mirror source method is hardly affected by the reverberant conditions, and that the results found with the plane wave method follows the same trend for these three reverberant rooms. Because the same trends are measured with both methods under all conditions, only one curve is used in the following subsection, i.e.: the curve obtained in the semi-anechoic room in case of the mirror source model, and the curve obtained in large reverberant room 1 in case of the plane wave method.

Comparison of the measurement methods

Next, the results of the different methods are compared. Figure 4 and 5 illustrate the results obtained for the three samples.

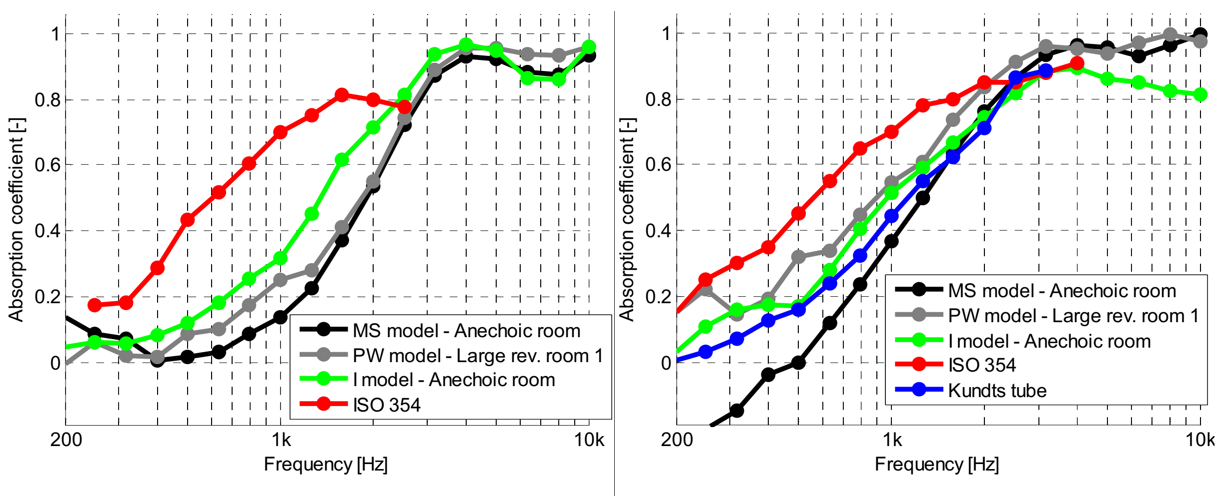

FIGURE 4. Absorption coefficients of Agglomer (left) and Flamex 25N measured with different methods.

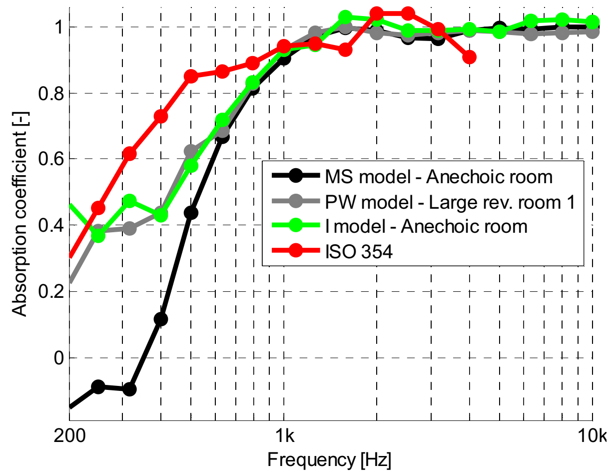

FIGURE 5. Absorption coefficients of Flamex 50N measured with different methods.

Some conclusions can be drawn from these measurement results, i.e.:

- The results of the mirror source model seem to be underestimated at low frequencies, especially for both Flamex samples. In [24] it was found that these deviations occur because only spherical waves above the sample are considered, and not those inside the sample.
- The results of the Plane Wave method, the Intensity method, and the Kundt's tube are similar, which is remarkable because the fundamentals of these methods and the measurement conditions are different (the methods respectively utilize a diffuse sound field, a sound field with spherical waves, and a plane wave sound field).
- The values of the ISO 354 reverberant room method are higher than the other methods at low frequencies that the values of the higher methods. This behavior has been discussed in many studies and has e.g. been attributed to finite sample size and to edge diffraction. However, up to date, the impact of these effects has not been well characterized. In the next section the phenomenon of edge diffraction is studied further.
- Sometimes the difference in values between the ISO 354 method and those of the Kundt's method and these PU based methods are also attributed to the fact that the first method utilizes a reverberant field where plane sound waves arrive from all directions, ant that the other methods utilize a sound source at normal incidence. However, measurements have also been performed in diffuse conditions with the plane wave method, and because these results are similar to the Kundt's tube and the intensity method it is demonstrated that this explanation does not hold.

It is worth mentioning that erroneous estimates of the absorption coefficients are acquired with the Kundt's tube method for some sample types because the sample size is limited and, as a result, the estimated absorption values differ for different sample sizes, see e.g. [13]. Such behavior occurs mostly for materials that have a high flow resistivity and a low Young's modulus [25].

VISUALIZATION OF EDGE DIFFRACTION EFFECT WITH ENERGY FLOW MEASUREMENTS

In this section a method is presented that can be used to measure energy flow. The aim here is to capture diffraction around the edge of a sample in a reverberant room; an effect which is often attributed to errors of the reverberant room method. The method utilizes 3D acoustic intensity data obtained with a three dimensional PU probe and a quick scanning measurement technique called Scan & Paint. Firstly, the measurement principle and the measurement routine are described. Thereafter, some measurement results are shown.

Measurement method

While PP probes cannot be used in environments with high levels of background noise or reflections, the error of PU probes is unaffected by the height of the pressure-intensity index (the ratio of sound pressure squared to active intensity) [18,19]. On the other hand, its error mainly depends upon the reactivity of the sound field (the ratio of reactive- to active intensity in logarithmic form). If the reactivity is high, as for example in the near field of a source, even a small phase mismatch between the two transducers may lead to a considerable error in the intensity estimate. In [26] it was mentioned that in practical situations the reactive intensity should not exceed the active intensity with more than 5 dB, which correspond to a ±72 degrees phase difference between sound pressure and particle velocity. Although the active intensity values may be incorrect in reactive fields, it is possible to detect when this occurs because the phase can be measured properly. The three dimensional version of a PU probe (called the USP probe) that is used for our intensity measurements, comprises one sound pressure sensor and three orthogonally oriented particle velocity sensors. With this probe the sound pressure and the three particle velocity components are measured. Hence, quantities such as impedance, energy and intensity can be obtained in 3D.

A method called ‘Scan & Paint’ is used to quickly visualize a slice of a sound field with a very high spatial resolution. A detailed description of the method can be found in [20-22]. The method involves a PU probe that is swept across the slice of interest. While the signals of the sensors are recorded, a video is captured simultaneously with a webcam that is placed at a certain distance. The position of the probe is determined from the video using an automatic tracking algorithm that detects a marking on the probe. The sound properties are then calculated for each position. In this paper, the Scan & Paint method is used for the first time to acquire 3D intensity measurements. The results of these measurements are visualized with normalized intensity vectors and color maps of the intensity level, in a similar way as was done in [27]. In this publication, complicated patterns of the active intensity were encountered even around simple structures. Even vortices, similar to those regularly visualized with smoke around aircraft wings in a wind tunnel, were measured.

Test description

A 11.5 m^2 large slab of Flamex 25N was installed on the floor of a reverberant room. Around the perimeter edge of the sample steel borders were placed that were flush with its surface. 3D intensity measurements were performed by a test engineer that manually scanned with the USP probe through the measurement planes, while the sound source of the room was excited. Three measurements were performed; i.e. one in a horizontal plane 5 cm above the sample surface and two vertical planes at 40 cm from the edges of the sample. Each of the planes were measured in approximately 5 minutes. As mentioned previously an intensity measurement is only valid if the reactivity is not too high. Therefore the results from positions where the measured phase exceeds ±72 degrees are omitted.

Measurement results

Figure 6 and 7 show some results from the intensity measurements for the horizontal plane and, because the results from both vertical planes are similar, only one vertical plane. The intensity vectors in these figures are normalized so they all have the same length. The level of the 3D intensity is displayed as a color map, where 0 dB is the maximum of the intensity values each particular figure.

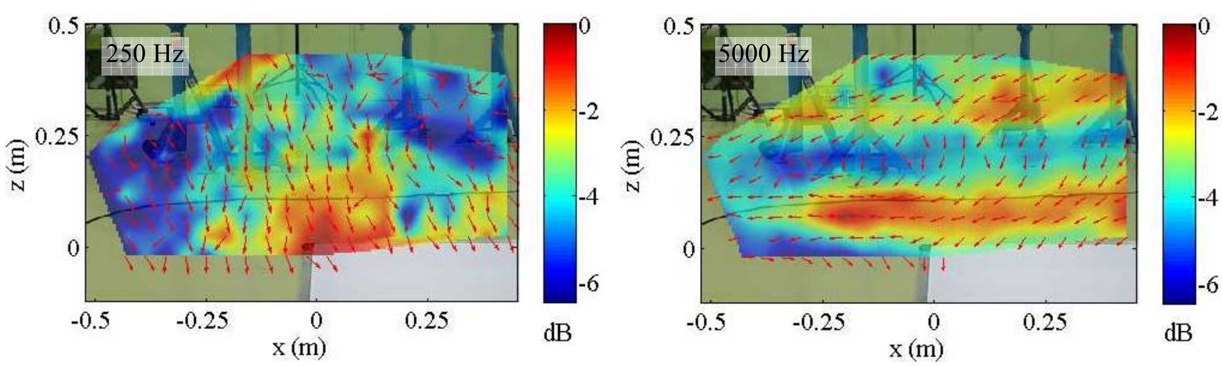

FIGURE 6. Normalized intensity vector field with a color map of the intensity level at two third octave bands (front view).

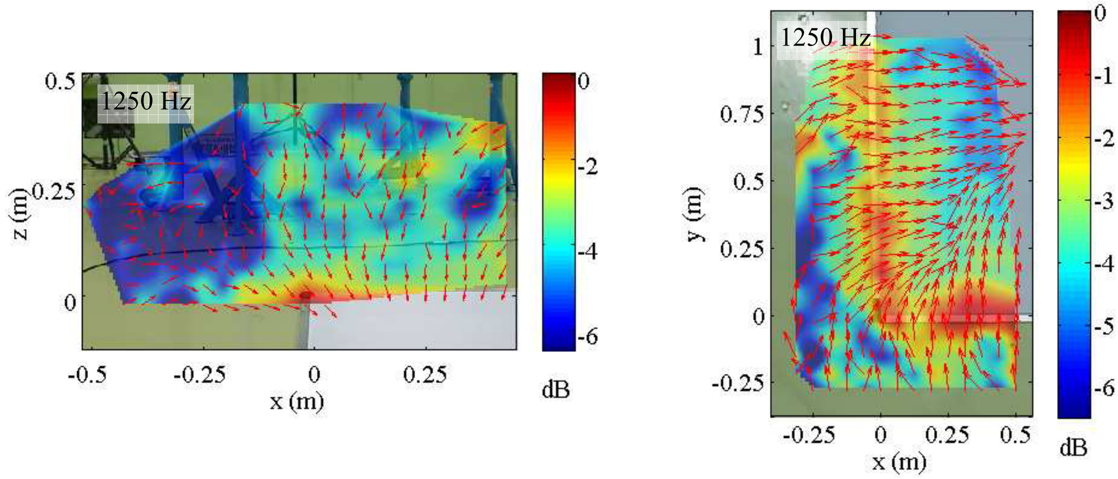

FIGURE 7. Normalized intensity vector field with a color map of the intensity level at the 1250 Hz third octave band. Left: front view. Right: top view.

The results from measurements of the same planes that were performed at different positions of the test engineer were similar, thus it is assumed that the presence of the test engineer who held the probe did not influence the sound field significantly. These figures show that there are no noticeable complex diffractions around the edge of this sample. At most frequencies the intensity vectors clearly point towards the sound absorbing sample. At high frequencies the interferes of the incoming- and reflected sound waves are clearly visible and in some cases the intensity vectors point away from the sample, see e.g. figure 6 right.

CONCLUSION AND DISCUSSION

In this paper the results have been presented of a preliminary comparison study of PU probe based (in situ) absorption methods, the reverberant room method, and the Kundt's tube method. Three methods have been applied to estimate the absorption coefficient from measurements with PU probes; i.e. the mirror source method and the intensity method, which utilize a spherical sound field and a plane wave surface impedance method, which utilizes a diffuse sound field. It was shown that the effects of reflections in a reverberant room are negligible for the mirror source method. Also, the results of the plane wave surface impedance method are similar for the three reverberant rooms that were utilized. Furthermore, it was found that it is possible to obtain similar results for the samples that were investigated from measurements with PU probes under normal incidence excitation, from measurements with PU probes random incidence excitation, and with the Kundt's tube. However, the values that were obtained with the ISO 354 reverberant room method were significantly higher at low frequencies.

In addition, it was investigated if diffractions around the edge of the sample, which are often attributed as a main source of error of the reverberant room method, are present. For this purpose, a method was introduced with which the three dimensional intensity can be measured quickly at multiple positions. A PU probe that is able to measure the intensity even if the pressure-intensity index is high is scanned through a measurement plane of interest. The Scan & Paint principle is then applied to acquire the intensity at each position. With measurements it was demonstrated that a) it is possible to perform such three dimensional intensity measurements in reverberant rooms, and b) that no significant complex edge diffraction effects are present when assessing the active acoustic intensity around the sample investigated.

These preliminary tests will be continued in the further. E.g. it is especially interesting to compare the obtained results with those from other absorption measurement methods and to use more sample types. Furthermore, it may be investigated if there are complicated diffraction effects around the edges of other sample types.

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