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Use of a Portable Flanged Impedance Tube for Absorber Design and Measurement

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Abstract

Acoustic material testing is becoming increasingly relevant to engineers, designers and manufacturers from a broad range of industries. This paper presents comparisons between material absorption measurements made using the traditional approaches of the reverberation room method and the fixed impedance tube using a sample holder, with those obtained using a lightweight portable flanged impedance tube method.

The portable tube allows fast non-destructive in-situ material measurements. It may therefore be used to measure the impact of the installed lay-up (e.g. effects of facing sheets, curvature, material compression, bagging, etc.).

Results are presented for both non-locally reacting and locally reacting materials. The flanged tube results are compared directly with in-tube data. They are also corrected for random incidence to allow comparison with the diffuse field reverberation room data. It is concluded that the flanged portable impedance tube method provides an attractive alternative to existing methods.

Introduction

Acoustic material absorption may be measured using a number of approaches. These include the diffuse field reverberation room method [1,2], the Kundt tube with sample holder method [3,4,5], the Adrienne in-situ reflection method [6], and the Microflown p-u probe method [7]. This paper reports on the use of an alternative nondestructive method, which is currently used for impedance measurement of aero engine acoustic panels. The method involves adding a flange to a Kundt tube, allowing it to be used nondestructively for in-situ measurements.

This work has been prompted largely by an identified need for in-situ measurements of materials in their final installed state, which are not always representative of laboratory lay-ups. Reference [8] reports on two variants in the signal processing of the reflection method. These provide similar results for materials of high absorption coefficient, but are less accurate at low frequencies, with the uncertainty driven by the geometry of the measurement space. Reference [9] compared the reflection method with the reverberation room method and also with the Kundt tube sample holder method. The authors pointed out the errors introduced in the sample holder method when the samples are not perfectly cut to the inner diameter. However, they also reported on general agreement between the sample holder method and the reverberation room method. It was noted that the reflection method provided significantly lower absorption values at mid-range frequencies (~500Hz to 4KHz), and generally agreed with the other two methods at higher frequencies. The authors pointed to limitations of the reflection method for the small sample sizes used.

Reference [10] compared the reverberation room method and the sample holder Kundt tube method with three different manifestations of the P-U probe (mirror source method, plane wave surface impedance method, and intensity method). The P-U probe was used to measure samples in rooms with varying levels of reverberation and size, for the mirror-source and plane wave impedance methods. The results showed relatively little impact of the test room environment. Subsequent comparisons were made of all three P-U methods with the reverberation room and the Kundt tube sample holder methods. All methods showed fairly good agreement for high frequencies (above between 1KHz and 2.5KHz respectively, depending on the material type), while they began to diverge at lower frequencies. The Kundt tube sample holder method agreed best with the P-U measurements at lower frequencies. However, the reverberation room method measured consistently higher levels of absorption below either 1 or 2KHz, depending on the sample type. It was also noted that the plane wave impedance P-U method was performed with a sound source at normal incidence and with a diffuse field, showing this method to be independent of the field type.

The reflection method and the Microflown p-u methods have been proposed for in-situ measurement of absorption coefficient spectra. A significant benefit of the flanged Kundt tube in-situ method is that it also provides the acoustic impedance, in addition to the absorption coefficient. Flanged tube measurements are made using a well-defined source and source-to-sample distance. As opposed to the measurement of absorption only, which provides a peak level and a variation with frequency, the measurement also of impedance permits an assessment of the frequency-dependent resistive and reactive components of a given lay-up, which may then be re-tuned (if necessary) to provide improved absorption per unit area.

In addition to providing in situ capability, this paper also identifies the benefits of a portable flanged impedance tube as an alternative or complement to the reverberation room and Kundt tube with sample holder methods. Work from previous authors has highlighted the relatively high levels of uncertainty in reverberation room measurements [11,12,13,14,15] and the difficulties of dealing with the effect of edge diffraction, along with the difficulties in preparing samples for sample holder Kundt tube measurements.

The test materials reported in this study included a locally reacting single layer perforate panel with honeycomb core, and a non-locally reacting acoustic tile with a high density glass wool core. Tests were performed using the reverberation room method (absorption only), the Kundt tube sample holder method, and the flanged portable impedance (Kundt) tube method.

In order to compare the impedance tube results with the reverberation room data, the flanged impedance tube results were corrected for random incidence to simulate diffuse field conditions. This was done using Fahy's method16. Although the high density glass wool acoustic tile was not strictly locally reacting, both sets of impedance and absorption coefficient results were corrected using this approach.

The body of this paper begins with a description of the three measurement methods used in the reported testing, and a description of the test samples. This is followed with presentation and analysis of the results. Conclusions are then drawn from the study, with recommendations made for future investigations. Finally, the contributors to this work are acknowledged.

Methods

Reverberation Decay Time Method

The procedure for measurement of panel absorption using the reverberation room method is outlined in ASTM c423-9a [1] and ISO354 [2]. The ISO specifies target conditions for the test room in terms of volume, shape, absorption, diffusivity, and the sample size and installation. The number of recommended source and microphone locations is also specified, along with limits on the ambient test conditions (temperature, humidity).Two source procedures are defined; interrupted noise and impulse response methods.

The interrupted source method is used for the tests reported here, averaged over 12 measurements (3 omni-directional source locations and 4 microphone locations). The reverberation time, T20, was calculated for each test configuration using that part of the decay curves between 5dB and 25dB below the source level, with 10 averages made per source/ microphone location. Measurements were made at 1/3rd-octave frequencies between 100Hz and 5KHz.

The average reverberation time was measured with and without the test panel installed in the room. From these reverberation times, the equivalent sound absorption area of the test specimen, A_T, and the sound absorption coefficient, α_s, for the sample materials was calculated for each 1/3rd-octave frequency using Sabine's equation,

$$\alpha_s = A_T/S = (A_2 - A_1)/S = \frac{55.3V}{S}\left\{\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right\} - 4V\{m_2 - m_1\} \quad (1)$$

where V is the room volume (m^3), S is the total panel area (m^2), c is the speed of sound (m/s), T_1 is the hard wall, and T_2 is the lined, reverberation time (s), and m is the power attenuation coefficient, defined as m=Atten/10log(e) where Atten (dB/m) is the atmospheric attenuation coefficient for the ambient room conditions. The room temperature and humidity varied negligibly for the tests performed.

The Brüel and Kjær test room (Figure 1), in Naerum, Denmark, was used for the tests. It has non-parallel walls, with one vertical wall and the ceiling serrated. The room volume was 209.6m^3. As the ceiling is a little low, the maximum diagonal length of 12.4m exceeds the ISO target of 11.3m (1.9V$^{1/3}$). This points to potentially non-ideal diffuse field conditions. The measured standard deviations were in good agreement with those specified in Reference [1] above 400Hz.

Figure 1. Brüel and Kjær reverberation room, Naerum, Denmark

Impedance Tube Method

The impedance tube, or Kundt tube, method is specified in ASTM E1050-12[3] and ISO10534-2[4]. A sound source is applied at one end of a cylindrical, thick-walled, tube. When the opposite end of the tube is placed on a test sample, a standing wave is created. Two flush-mounted and phase-matched wall microphones are located on the tube wall. When a broadband source is used, the transfer function, H, between the microphones is used to extract the sample reflection coefficient spectrum and subsequently also the absorption and the impedance spectra. The inner diameter of the tube is chosen to ensure only a plane wave propagates in the frequency range of interest, while the microphone spacing is chosen for maximum accuracy in the desired frequency range.

The normal incidence complex reflection factor, R, is given by,

$$R = |R|e^{j\emptyset} = R_r + R_i = \left\{\frac{H - e^{-jks}}{e^{jks} - H}\right\} e^{2jkx_1} \tag{2}$$

where s is the distance between the wall microphones, and x1 is the distance from the sample surface to the furthest microphone.

The normal incidence absorption coefficient, α, and normal incidence specific acoustic impedance ratio, Z, are given respectively by,

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

$$Z = \frac{1+R}{1-R} \tag{4}$$

The normal incidence impedance ratio, Z, is the complex ratio between the acoustic pressure and particle velocity at the sample surface. It therefore generally has a real (r) and imaginary component (x), Z = r +jx, where r is the acoustic resistance and x is the acoustic reactance.

It is noted that the absorption coefficient is determined from |R|, which is a function only of the transfer function, H, and the distance between the two microphones, s. It is independent of the distance from the sample surface to the microphones, x_1. If the impedance is to be extracted accurately, the distance to the sample surface must also be known to a high degree of accuracy (within 0.2mm). A hard wall calibration routine is performed to calculate this distance.

The 29mm inner diameter Brüel and Kjær portable flanged impedance tube (type WA-1599-W-005) used here is shown in Figure 2, along with the rest of the type 9737 system. The tube diameter and microphone spacing allow the meter to be used between 500Hz and 6400Hz. It also has a sample holder (Figure 2) which accommodates materials up to a depth of approximately 200mm. The speaker permits testing at levels exceeding 150dB, which may be used to measure the non-linear response of a material. The tests in this report were performed at 120dB OASPL, in the linear regime, for compatibility with the reverberation room tests.

Figure 2. Brüel and Kjær Type 9737 Portable Impedance System

The portable meter was used both with a sample holder, and non-destructively, by screwing the sample holder or the flange onto the end of the tube. The flange used for the test panels was flat, though it may be curved to fit any given surface contour. The acoustic centre task was performed before the sample holder or flange was used, to ensure the distance to the sample surface was updated accordingly.

Test Materials

A locally reacting material is one where the acoustic impedance at a point on the surface is independent of the angle of the incident sound. Typical examples are resistive sheets backed by relatively narrow cavities made from honeycomb cells, such as those used for aircraft engine nacelle ducts. In these materials only plane waves may propagate inside the panel at the design frequencies, up and down the individual honeycomb cells. Typical non-locally reacting materials include porous materials, mufflers with large acoustic cavities, and aircraft engine acoustic panels whose honeycomb cells are slotted for fluid drainage. Tests were performed here on both types of materials in order to compare the normal incidence flanged meter performance with that of the sample holder method, and with the random incidence reverberation room method.

The test panels were as follows,

- Non-locally reacting - 11.3m^2 Ecophon ceiling panels, with a 200mm overall depth of system.
- Locally reacting - 1.4m^2 Diehl Aircabin single layer, 10mm deep perforate panels, with 3.2mm wide honeycomb core.

Figure 3. Non-locally reacting (above), and locally reacting (below), test panels

In order to utilise the full eight square Ecophon panels in a uniform (rectangular) layout, they had an aspect ratio of approximately 0.5:1, slightly below the ISO1 target of 0.7:1. Also, the available single layer perforate panel area fell well below the ISO1 target of 10m^2 to 12 m^2. However, the locally reacting panels were efficient enough to provide an equivalent absorption area change of more than 1m^2 between 1000Hz and 3150Hz.

Each of the panels were tested in the reverberation room, with the flanged impedance tube, and with samples cut to fit the 29mm impedance tube sample holder.

Results

Reverberation Room Results

A fixed combination of microphone/source locations was used for the hard wall measurement and for the two lined measurements. The ambient conditions showed negligibly variations for the three measurements, and the same hard wall measurement was used for the calculation of absorption coefficient for each panel type.

Figure 4 presents the measured reverberations times at 1/3rd-octave frequencies between 100Hz and 5000Hz. While the large area (11.3m^2) non-locally reacting panel significantly reduces reverberation time at most frequencies, the relatively small area (1.4m^2) locally reacting panel provides a smaller impact, peaking at around 1KHz to 1.6KHz.

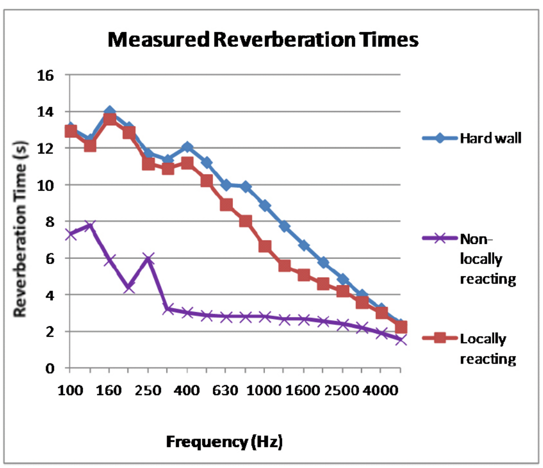

Figure 4. Measured Reverberation times

Figure 5 shows the corresponding percentage standard deviation (standard deviation of 12 measurements from combinations of 3 source and 4 microphone locations, and with 10 averages per combination). These are compared with a nominal limit standard deviation of 10% [17]. The plot shows that the standard deviation of the measured reverberation times is good for the locally reacting panel. The standard deviation for the non-locally reacting panel is generally only good for frequencies above 315Hz. This is likely due to the existence of 2D modes which are not well attenuated for this panel [17]. The existence of these poorly attenuated modes is evidenced by some double slope decay curves at low frequencies, with a shorter decay time for 3D modes and a longer decay time for some 2D modes, for microphone and source locations most distant from the test panel.

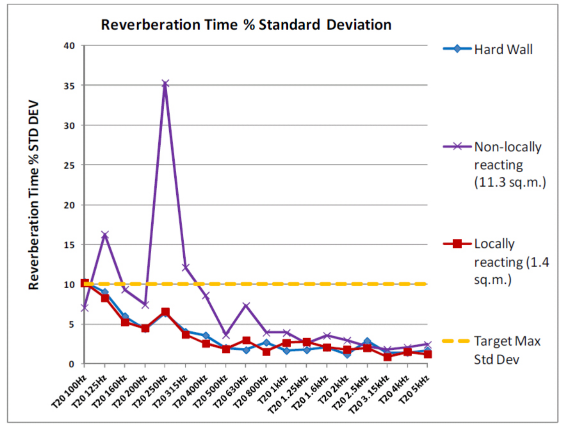

Figure 5. Reverberation time percentage standard deviation

Figure 6 and Figure 7 show the measured absorption coefficient for the two panels, along with the uncertainty due to the variation in reverberation time measurements. As expected, the non-locally reacting panel absorption coefficient spectrum is more broadband, while the single layer locally reacting panel is more narrowband. The single layer data shows absorption coefficients greater than 1. This is most likely due to edge diffraction, where the apparent panel area is greater than the physical area, particularly for panels with a relatively high perimeter to area ratio [13, 14]. It is noted that this is a phenomenon which cannot occur for a normal incidence impedance tube measurement, where the absorption coefficient must be between 0 and 1.

Equation (1) was differentiated with respect to the measured reverberation times T1 and T2 in order to assess the influence of the standard deviation in the measured decay time on the calculated absorption coefficient, α_s. Assuming constant speeds of sound and constant atmospheric absorption for the hard wall and lined measurements, the uncertainty in α_s due to the reverberation time uncertainty, and the subsequent root sum square uncertainty, is given by,

$$\delta\alpha_s(HW) = \left|\frac{-55.3V}{cS}\right|\left(\frac{\delta T_2}{{T_2}^2}\right) \tag{5}$$

$$\delta\alpha_s(Lined) = \left|\frac{55.3V}{cS}\right|\left(\frac{\delta T_1}{{T_1}^2}\right) \tag{6}$$

$$\delta\alpha_s(Root\ Sum\ Square) = \left|\frac{55.3V}{cS}\right|\left\{\left(\frac{\delta T_2}{{T_2}^2}\right)^2 + \left(\frac{\delta T_1}{{T_1}^2}\right)^2\right\}^{0.5} \tag{7}$$

Figure 6 shows an approximate uncertainty in α_s of +/−0.1 at low frequency, reducing to around +/−0.04 at high frequency, for the 11.3m^2 non-locally reacting panel. The minimum root sum square uncertainty for the 1.4m^2 locally reacting panel is +/− 0.05 and generally between +/−0.10 and +/−0.20. The uncertainty in α_s arising from the hard wall measurements is higher for the smaller area of the locally reacting panel, than for the non-locally reacting panel, due to the 1/S term in equation 5.

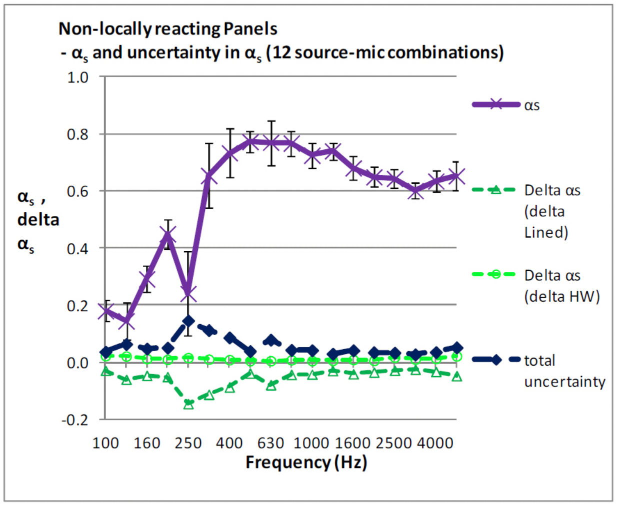

Figure 6. Non-locally reacting panel Sound Absorption coefficient, α_s, and uncertainty due to reverberation time standard deviation (12 source/ mic combinations)

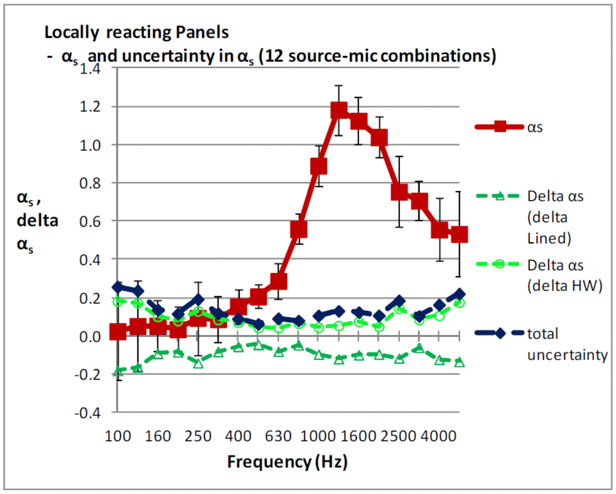

Figure 7. Locally reacting panel Sound Absorption coefficient, α_s, and uncertainty due to reverberation time standard deviation (12 source/ mic combinations)

The reverberation room has the benefit of providing absorption coefficient results at random incidence. Uncertainties result from reverberation time differences for varying source/microphone locations, and from variations in edge diffraction for panels with differing perimeter to area ratio. It is noted that the measured uncertainty in sound absorption coefficient due to reverberation time uncertainty is increased in these test cases relative to that for ideal test conditions due to the non-perfectly diffuse room conditions, and the small locally reacting panel size.

It is also relatively time consuming. The portable impedance tube provides rapid measurements of absorption coefficient and impedance, in much reduced time. One drawback of the impedance tube is that it can only measure normal incidence results. However, results for locally reacting panels may be corrected for random incidence using Fahy's method. The next section reports on the corresponding flanged impedance tube measurements.

Flanged Impedance Tube Results

The impedance meter provides a more direct means of measurement of absorption coefficient. The meter is portable, and measurements are very fast (<1 minute typically per test location). Figure 8, Figure 9, Figure 10, Figure 11 show the flanged impedance tube normal incidence absorption coefficient and impedance for the test panels. Measurements were performed at a surface OASPL of 120dB. The 29mm inner diameter tube measurements were made over a number of locations for each panel type. As the method is non-destructive, the repeatability at a fixed location is excellent (not shown). Hence, the repeatability and reproducibility is much better that for the Kundt tube with a sample holder (see Table 2, Reference 3).

As stated earlier, one of the advantages of the impedance meter is that it measures impedance in addition to absorption. Looking at the impedance curves allows a designer to evaluate the panel resistive and reactive components. For example, the normal incidence absorption at the peak frequency may be increased via a reduction in resistivity (resistance per unit thickness) or material thickness for the non-locally reacting panels, or through a reduction in facing sheet resistance for the perforate panel. Also, sample holder tests on samples with reduced thicknesses of resistive material (not shown) demonstrated that "blips" in the spectra are due to quite heavily damped reactance oscillations for the 200mm O.D.S. (Overall Depth of System) installation. These oscillations are less damped for shallower thicknesses of the absorptive material.

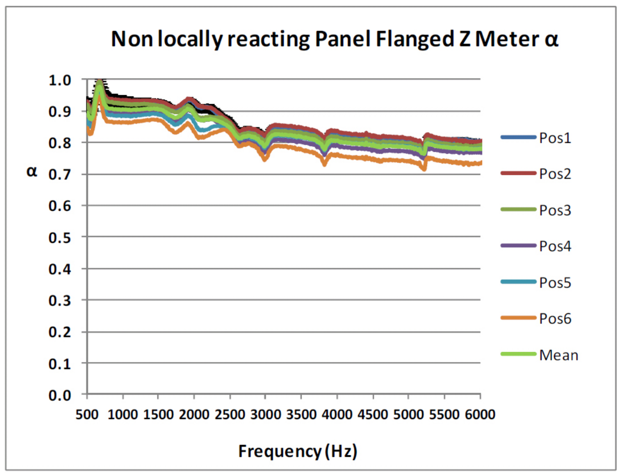

Figure 8. Non-locally reacting panel. Fanged impedance tube normal incidence sound absorption coefficient, α

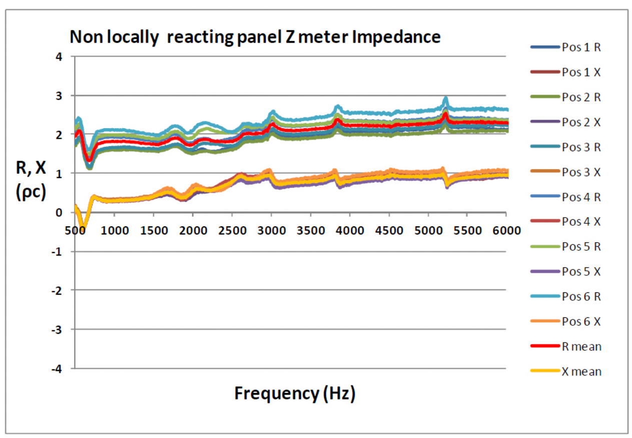

Figure 9. Non-locally reacting panel. Flanged impedance tube normal incidence impedance

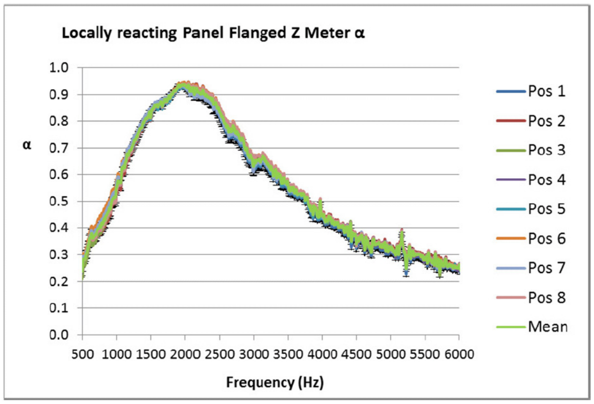

Figure 10. Locally reacting panel. Flanged impedance tube normal incidence sound absorption coefficient, α

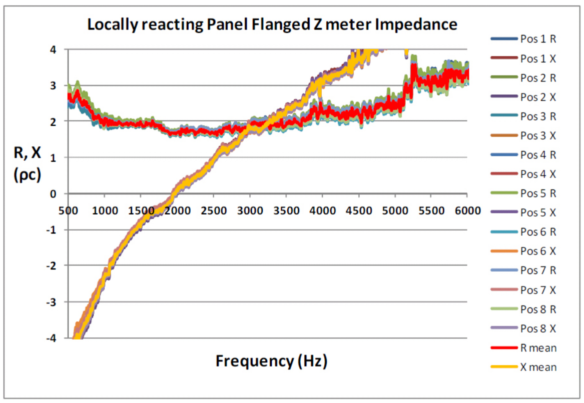

Figure 11. Locally reacting panel. Flanged impedance tube normal incidence impedance

Sample Holder Impedance Tube Results

Figure 12, Figure 13, Figure 14, Figure 15 show the equivalent measurements for samples cut from the large test panels, to fit inside the 29mm inner diameter sample holder. While the non-locally reacting panel material was relatively straightforward to cut to size and seal at the tube inner walls, the single layer perforate panel, with a facing sheet plus honeycomb core construction, was more difficult to cut to size. As a result, tests were repeated with plasticine used to seal around the edges of the facing sheet.

The results for the non-locally reacting panel are consistent between the sample holder (Figure 12, Figure 13) and the flanged tube (Figure 8, Figure 9) for frequencies above 2000Hz. The results diverge slightly at lower frequencies. This is due to a combination of the flange effect (mismatch between tube area and "visible" area of the sample [18]) and the non-locally reacting nature of the material; both effects are greatest at low frequency.

The combination of poor sealing and the plasticine absorption lead to very different results for the locally reacting panel tests inside the sample holder. The difficulty in cutting the facing sheet leads to unacceptable repeatability (see targets in Table 2 of Reference 3). The mean of these results lie quite close to the flanged tube results. It is noted that Reference [19] provides guidance for obtaining the best possible sample mounting in an impedance tube sample holder.

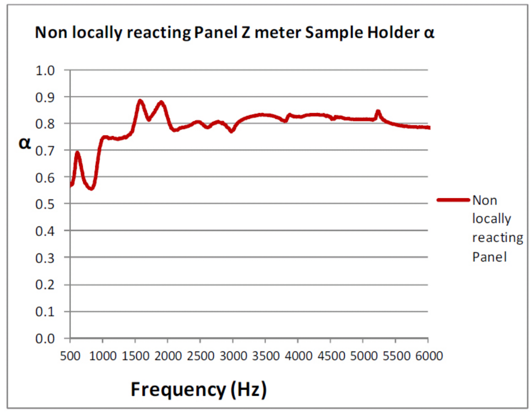

Figure 12. Non-locally reacting panel. Impedance tube sample holder normal incidence sound absorption coefficient, α

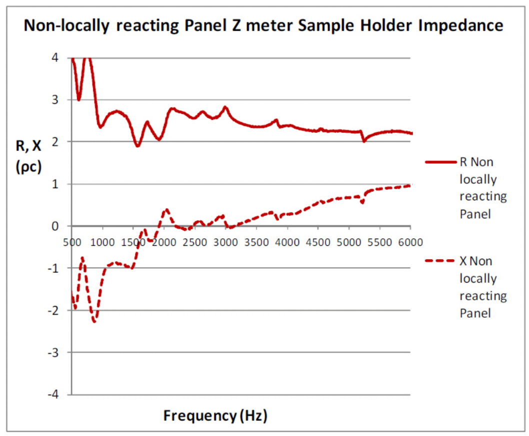

Figure 13. Non-locally reacting panel. Impedance tube sample holder normal incidence impedance

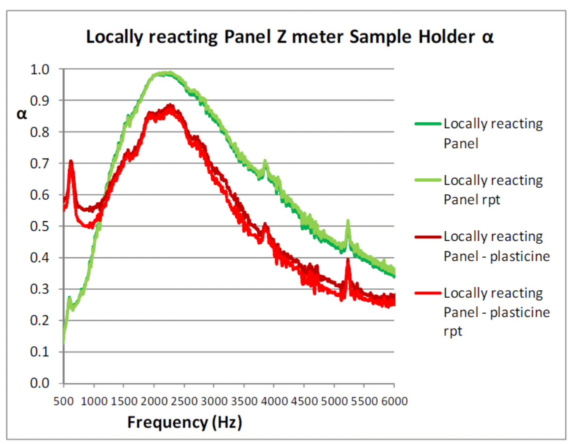

Figure 14. Locally reacting panel. Impedance tube sample holder normal incidence sound absorption coefficient, α

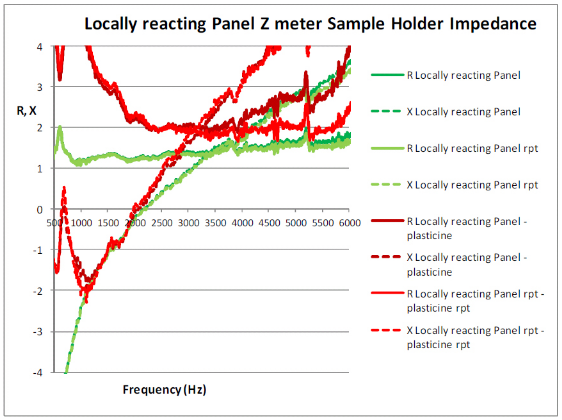

Figure 15. Locally reacting panel. Impedance tube sample holder normal incidence impedance

Comparison of Flanged Impedance Tube and Reverberation Room Measurements

The sample holder tests highlighted the advantages and disadvantages of the sample holder. The advantages include the tube area equalling the sample area, and the sample being forced to be locally reacting, giving more controlled conditions at low frequencies. The disadvantages are that some samples are difficult to cut and seal inside the holder, and that the tests are destructive.

In order to compare the flanged impedance tube results with the reverberation room measurements more directly, the flanged tube results were corrected for random incidence using Fahy's equation [16]. Fahy derived a relationship between the normal incidence impedance and the random incidence absorption coefficient ($\alpha_{Diffuse}$) for a locally reacting material, where $\alpha_{Diffuse}$ is given by,

$$\alpha_{Diffuse} = 8\Gamma\left\{1-\Gamma ln\left[\frac{r}{\Gamma}+2r+1\right]+\frac{x}{r}\Gamma\left[\left(\frac{r}{x}\right)^2-1\right]tan^{-1}\left[\frac{x}{r+1}\right]\right\} \tag{8}$$

R and X are real imaginary components of normal incidence impedance Z, and $\Gamma = (R^2+X^2)^{1/2}$.

Figure 16 and Figure 17 show absorption coefficient comparisons between the reverberation room measurements and the flanged impedance tube measurements, for the locally reacting and the non-locally reacting materials.

The flanged impedance tube normal incidence absorption coefficient is shown, along with the diffuse field value. In both cases, the diffuse field value is higher than the normal incidence value.

The diffuse field absorption coefficient and the reverberation room absorption coefficient results for the locally reacting panel (Figure 16) show excellent agreement for frequencies above 2KHz. Below this frequency, the reverberation room results exceed unity. This is likely due to edge diffraction. The diffuse field impedance tube results are expected to be good for this panel at low frequency, as the relatively narrow panel core width of 3.2mm minimises the ratio of the tube area to "visible" sample area.

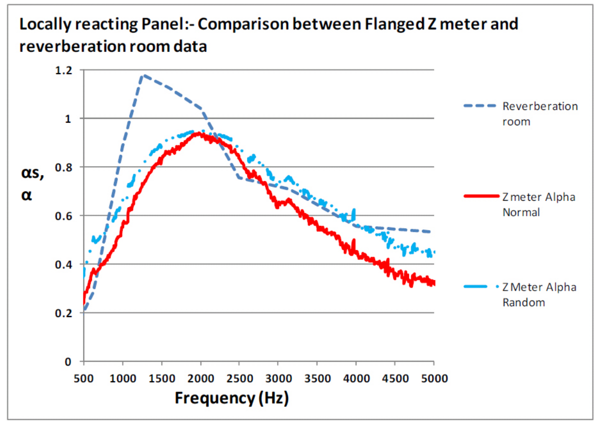

Figure 16. Locally reacting panel comparison of reverberation room and flanged impedance tube absorption coefficient measurements

The comparison for the non-locally reacting panel (Figure 17) show larger differences between the diffuse field impedance tube results and the large panel reverberation room results. The maximum delta of approximately 0.2 exceeds the test reverberation room uncertainty due to reverberation time uncertainty. The reverberation room absorption coefficient lies below that from the impedance meter, though the shape of the curves are similar.

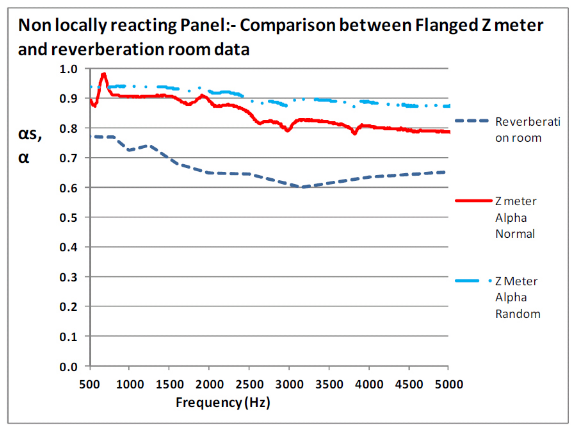

Figure 17. Non-locally reacting panel comparison of reverberation room and flanged impedance tube absorption coefficient measurements

Some cross-checks were made on the Brüel and Kjær reverberation room results. Results measured at a different reverberation room for the locally reacting panel, showed excellent agreement with the Brüel and Kjær data. The reason for the larger discrepancy for the non-locally reacting panel may be due to non-perfectly diffuse field conditions and/or sensitivity to the panel location.

Further work is recommended to investigate the sensitivity of the reverberation room measurements to the level of diffusivity of the Brüel and Kjær test room (as this has not been investigated), panel installation (e.g. grouped versus individual panels), panel orientation and panel location. Reference [15] points to the "remarkable" increase in measured absorption coefficient when additional diffusers were added to the reverberation test room. The same reference also highlights the impact of panel orientation, with high absorption coefficients being measured for panel orientations non-parallel to the reverberation room walls.

Conclusions and Recommendations

This paper has described a method of performing in-situ testing of panel absorption and impedance characteristics, using a flanged Kundt tube arrangement. Absorption coefficient and impedance measurements were made on non-locally reacting and locally reacting materials. Results were compared with absorption measurements made using the reverberation room method, and the impedance tube sample holder method.

The portable flanged impedance tube was shown to be quicker, simpler, and more repeatable than both reverberation room and sample holder impedance tube tests. This non-destructive procedure may be used in-situ to measure panels in the installed condition. Furthermore, the measurement of impedance, in addition to absorption coefficient, provides key additional information which may be used to help designers re-tune a given panel lay-up for improved performance.

Each of the methods compared have their pros and cons. The reverberation room method measures the absorption coefficient at random incidence. The uncertainty in absorption is a strong function of the standard deviation of the measured reverberation times, while differences in panel perimeter-to-area ratio lead to differing levels of edge diffraction. Impedance tube tests performed using a sample holder suffer for materials which are difficult to cut and seal in the tube.

Flanged tube absorption coefficient measurements for high resistivity, non-locally reacting panels, or for locally reacting panels, may be corrected for random incidence performance using Fahy's method. Measurements for highly non-locally reacting materials are most reliable at higher frequencies, as for lower frequencies, some of the incident sound not absorbed locally, and not reflected back up the tube, propagates laterally through the test material. It is noted that the Brüel and Kjær tube software can apply a factor to convert flanged tube results to the equivalent sample holder result. This may be derived by making flanged measurements, and comparing them with sample holder measurements made using well prepared samples.

It is recommended that additional flanged impedance tube measurements are made for non-locally reacting materials of both lower and higher resistivity than that tested, and for absorbers with air gaps behind them. Furthermore, comparisons with the p-u probe would help identify the strengths and weaknesses of both of these in-situ methods.

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