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Fast accurate non-destructive measurement of absorber impedance and absorption

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ABSTRACT

Cabin acoustic comfort is a major contributor to the potential sales success of new aircraft, cars, trucks, and trains. Recent design challenges have included the increased use of composites, and the switch to electrically powered vehicles, each of which change the interior noise spectral content and level. The role of acoustic absorption in cabins is key to the optimisation of cabin acoustic comfort for modern vehicles, with acoustic impedance data needed in order to assess and optimise the impact of each component of a given lay-up.

Measurements of absorbing interior trim are traditionally performed using either sample holder tests in a static impedance tube (impedance and absorption), or through tests in reverberation rooms (absorption only). Both of these procedures present challenges. In-tube absorption and impedance measurements are destructive, requiring highly accurate sample cutting and sealing. Reverberation room absorption measurements are subject to the effects of varying room diffusion, along with the impact of edge diffraction, sample geometry, and location. Finally, while non-destructive methods using hand-held probes also measure absorption, they are not able to measure impedance accurately.

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This paper describes fast non-destructive tests using a portable flanged impedance tube, and how they be used to quantify and optimise the absorption of interior trims. Measurements are made on non-locally reacting lay-ups, with the results corrected to equivalent in-tube results using a flanged-to-sample holder correction factor. The corrected flanged tube results are then compared with baseline in-tube measurements. Discussions address data quality and how the non-destructive measurements may be used to optimise lay-ups for increased absorption.

Keywords: Absorption, Measurement, Non-destructive
I-INCE Classification of Subject Number: 72

1. 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[7,8,9]. This paper follows on from reference 10 which described the use of an alternative non-destructive 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 non-destructively for in-situ measurements. This work has been prompted largely by an identified need for non-destructive in-situ measurements of materials in their final installed state. A flanged to sample holder correction is used to convert the in-situ measurements to quasi sample holder results. The corrected data may then be used to either measure the installed performance of lay-ups, or for production line quality control.

Reference 10 described the relative pros and cons of the traditional fixed Kundt tube method with a sample holder, the reverberation room method and the P-U probe. The traditional kundt tube method provides well-defined normal incidence impedance and absorption results provided there is good quality sample cutting and sealing. However, it is a destructive test, and it is time consuming. The reverberation room method measures absorption at random incidence, but results may be greater than unity, and are subject to edge diffraction, varying room diffusion, sample size, mounting, and location. Sample preparation and test set-up is time consuming. Also, measuring just absorption, it is not possible to separate out the resistive and reactive components of a sample lay-up, and thereby understand the physics behind the absorption process. The P-U probe method is non-destructive, like the proposed technique, but it also measures just absorption.

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.

The goal of this follow-on work is to demonstrate the correction of non-destructive flanged kundt tube measurements on non-locally reacting materials, so they generate quasi in-tube results. This is realized using a flanged-to-sample-holder impedance correction routine which is programmed into the Brüel and Kjær portable impedance tube. The routine measures a given material in a sample holder (locally reacting result) and with the flanged tube. The normal impedance shift is then used as a correction factor to convert further flanged tube measurements into quasi sample holder results.

The application of the flanged tube correction factor will be demonstrated initially using the measurements reported in Reference 10 (on a locally reacting perforate panel and a non-locally reacting ceiling panel). This will be followed by results on tests of two acoustic insulation mats (web plus scrim). These are more non-locally reacting than the ceiling panels. They are also compressible and therefore provide a sterner test of the efficacy of the impedance correction procedure.

The performance of the method will be assessed versus frequency and as a function of material resistance. The use of the method to measure compressible lay-ups in either their uncompressed or compressed states will also be discussed.

The body of this paper begins with a description of the sample holder and flanged measurement methods, 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.

2. METHODS

2.1 Traditional 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,

$$R = |R|e^{j\emptyset} = R_r + R_i = \left\{\frac{H - e^{-jks}}{e^{jks} - H}\right\} e^{2jkx_1} \tag{1}$$

where s is the distance between the wall microphones, and x_1 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,

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

$$Z = \frac{1+R}{1-R} \tag{3}$$

The normal incidence impedance ratio, Z, is the complex ratio between the acoustic pressure and particle velocity at the sample surface normalized the impedance of air. 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 impedance tube used here is shown in Figure 1. The tube diameter and microphone spacing allow the meter to be used between 500Hz and 6400Hz. It also has a sample holder (Figure 1) 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 the test samples.

Figure 1 Brüel and Kjær Portable impedance tube

When used in the traditional kundt tube mode, samples are cut to fit within the 29mm diameter sample holder (Figure 1), which is then screwed directly onto the impedance tube. This ensures continuity of the area of the tube and the sample, and zero leakage from the top of the sample.

2.2 Flanged Impedance Tube Method

The portable meter may be used non-destructively by screwing a flange onto the end of the tube. The flange used for the test materials was flat, though it may be machined to fit any given surface contour. The acoustic centre task was performed before either the sample holder or flange was used, to ensure the distance to the sample surface was updated accordingly, thereby ensuring the accuracy of the impedance measurements.

3. TEST MATERIALS

The test materials were as follows,

- Locally reacting – 1.4m^2 Diehl Aircabin single layer, 10mm deep perforate panels, with 3.2mm wide honeycomb core.
- Non-locally reacting –Ecophon ceiling panels, with a 200mm overall depth of system (O.D.S.).
- Non-locally reacting –3M acoustic insulation mat – 21mm thick TAI-3027 (scrim backing)
- Non-locally reacting –3M acoustic insulation mat – 21mm thick TAI-3027 (scrim facing)
- Non-locally reacting –3M acoustic insulation mat – 26mm thick AU 4020-6 (scrim backing)

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

4. RESULTS

4.1 Sample Holder Impedance Tube Results

Figure 3 to Figure 7 show the sample holder impedance and absorption measurements for samples cut from the test materials to fit inside the 29mm inner diameter sample holder. Measurements were performed at a surface OASPL of 120dB.

The non-locally reacting ECOPHON ceiling panel was relatively straightforward to cut to size and seal at the tube inner walls. While the 3M insulation mats were easy to cut, they were oversized (to 32mm) in order to improve their sealing in the sample holder (Figure 2).

Figure 2 Sample holder testing of insulation mat

The locally reacting single layer perforate panel, with a facing sheet plus honeycomb core construction, was the most difficult to cut to size. As a result, tests on this material were repeated with plasticine used to seal around the edges of the facing sheet. Figure 3 provides the impedance and absorption results for tests on this material. This panel has a relatively narrow bandwidth, given the fast moving reactance characteristic, driven by the air filled cavity and relatively high inertance facing sheet.

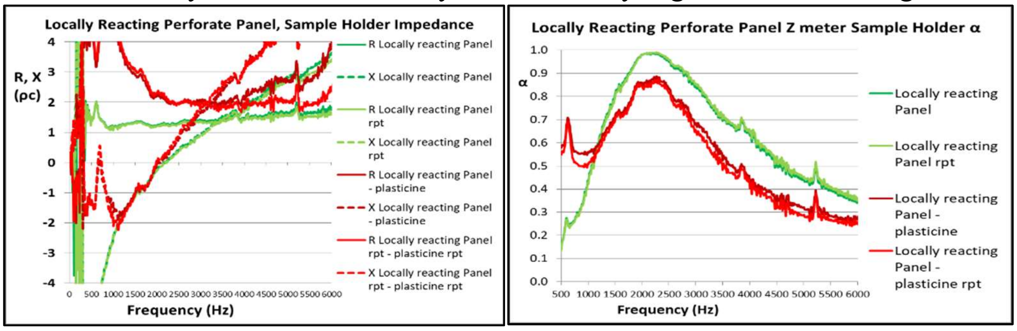

Figure 3 Locally reacting perforate panel. Sample holder normal incidence impedance (left) and sound absorption coefficient, α (right)

The combination of poor sealing and the plasticine absorption lead to very different results for the locally reacting perforate panel tests inside the sample holder. The difficulty in cutting the facing sheet leads to unacceptable repeatability. However, the mean of these results was found to lie quite close to the flanged tube results (Figure 8).

Figure 4 provides the sample holder results for the ceiling panel. The ceiling panel was much more amenable to cutting to size and sealing in the impedance tube. The impedance results show a lot of character. This is driven by the 200mm sample overall depth (panel plus air gap), which leads to multiple air cavity anti-resonances within the test frequency range. These anti-resonances are heavily damped by the 40mm deep ceiling panel.

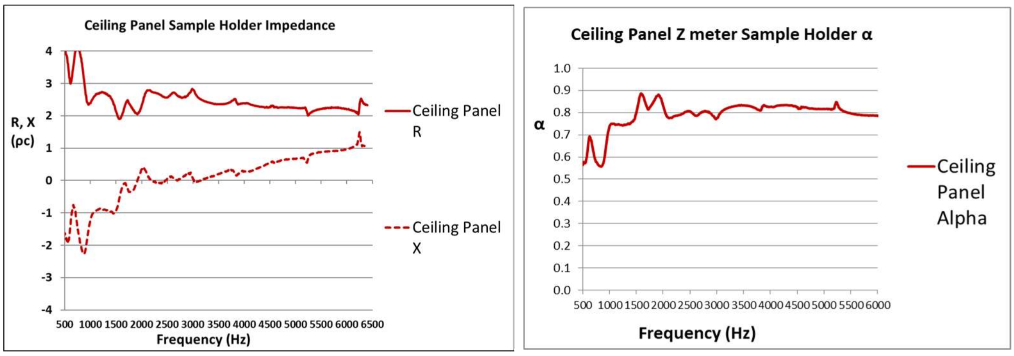

Figure 4 Non-locally reacting ceiling panel. Sample holder normal incidence impedance (left) and sound absorption coefficient, α (right)

Figure 5 to Figure 7 show the sample holder measurements for the insulation mats. The impedance and absorption spectra are smooth for all cases, exhibiting good broadband absorption.

The impedance and hence the peak absorption frequency varies in accordance with the material thickness and resistivity. Each of the sample types exhibit good repeatability between test samples with the material impedance and absorption lying within a relatively small tolerance band. The impedance and absorption spectra vary in line with the sample resistivity, thickness, and whether the scrim is a facing or a backing layer.

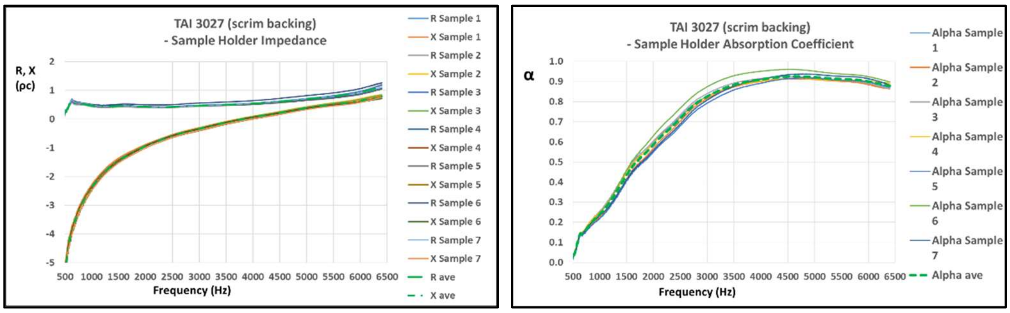

Figure 5 Non-locally reacting insulation mat, TAI 3027 – scrim backing. Sample holder normal incidence impedance (left) and sound absorption coefficient, α (right)

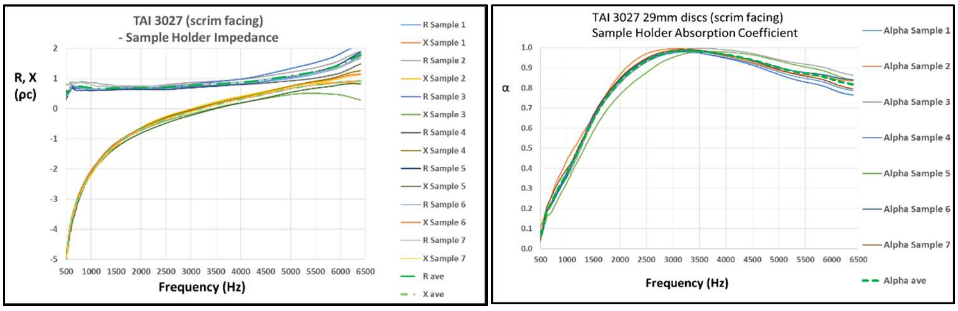

Figure 6 Non-locally reacting insulation mat, TAI 3027 – scrim facing. Sample holder normal incidence impedance (left) and sound absorption coefficient, α (right)

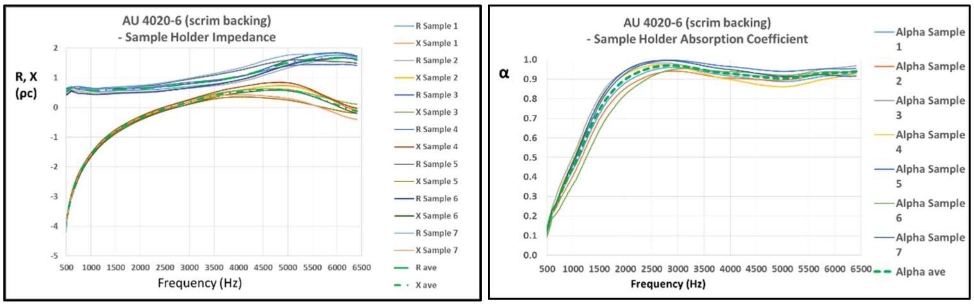

Figure 7 Non-locally reacting insulation mat, AU 4020-6 – scrim backing. Sample holder normal incidence impedance (left) and sound absorption coefficient, α (right)

It is clear that the range of sample lay-ups provides a group of widely varying material characteristics which will provide a good evaluation of the sample holder correction procedure.

4.2 Flanged Impedance Tube Results

The flanged impedance meter provides a fast non-destructive measurement of material acoustic performance. These measurements were also 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).

Reference 10 demonstrated that locally reacting materials (e.g. the perforate panel with honeycomb cells to ensure plane wave normal propagation), and high resistance non-locally reacting materials (e.g. the ceiling panel), provide flanged results close to sample holder results. This is particularly true at higher frequencies (> 2KHz) where beaming ensures that the majority of the incident sound from an impedance tube is reflected back up the tube by the sample. As the sample resistance reduces, more of the incident sound "escapes" laterally. As a result, the sample holder and flanged data diverge to a greater extent, with the divergence increasing as frequency reduces. This effect may be combatted by applying the flanged to sample holder impedance correction procedure.

Figure 8 and Figure 9 show the flanged impedance measurements on the locally reacting perforate and ceiling panels. Comparing these results with the sample holder equivalents (Figure 3, Figure 4), it can be seen that the non-destructive flanged impedance data is much more repeatable for the perforate panel. It is also very repeatable for the flanged tests on the ceiling panel.

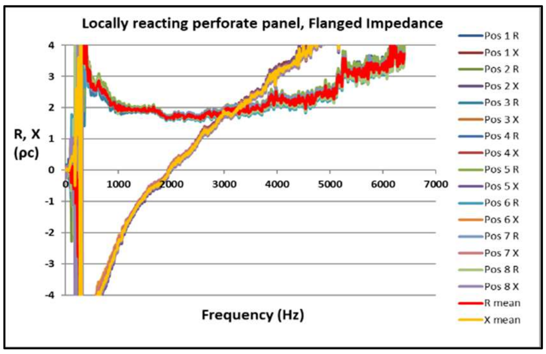

Figure 8 Locally reacting perforate panel. Flanged normal incidence impedance

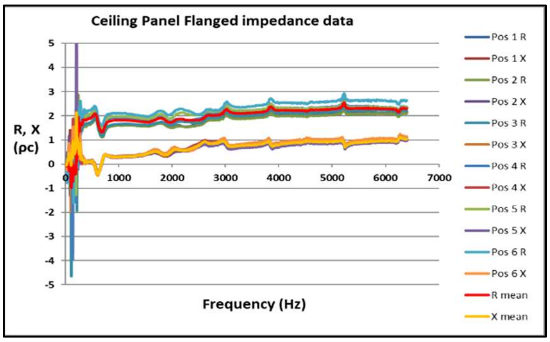

Figure 9 Non-locally reacting ceiling panel. Flanged normal incidence impedance

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 of Figure 8 and Figure 9 allows a designer to evaluate the panel resistive and reactive components. For example, the normal incidence absorption at the peak frequency may be increased through a reduction in facing sheet resistance for the perforate panel or via a reduction in resistivity (resistance per unit thickness) or material thickness for the non-locally reacting panels.

The tests on the insulation mats were performed on 300mm square samples. As the mats are compressible, they were placed under a frame supporting a highly open (low impedance) perforate (Figure 10).

Figure 10 Flanged meter testing on perforate + insulation mat

The flanged tube impedance measurements on the insulation mats are shown in Figure 11 to Figure 13. It is immediately clear that the flanged impedance is very different from the sample holder impedance (Figure 5 to Figure 7) at low frequencies. However, it is also seen that the flanged impedance approaches the sample holder value at high frequencies (beaming effect).

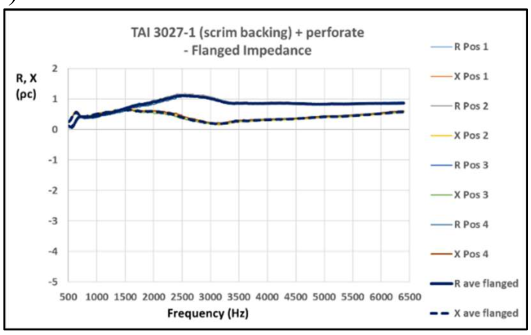

Figure 11 Non-locally reacting insulation mat, TAI 3027 – scrim backing. Flanged normal incidence impedance

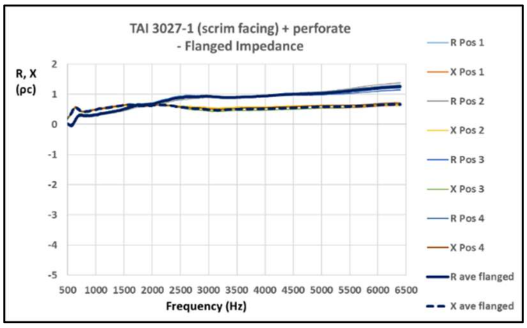

Figure 12 Non-locally reacting insulation mat, TAI 3027 – scrim facing. Flanged normal incidence impedance

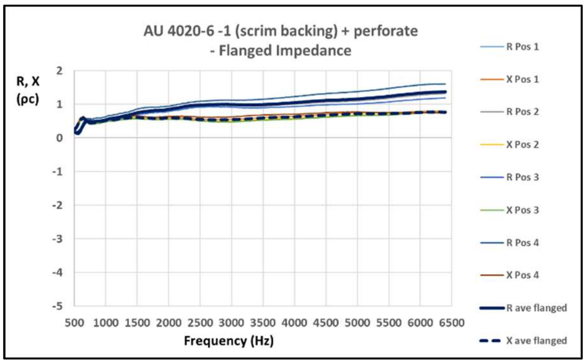

Figure 13 Non-locally reacting insulation mat, AU 4020-6 – scrim backing. Flanged normal incidence impedance

4.3 Flanged to Sample Holder Impedance Correction

This section presents the averaged flanged and sample holder impedance for each sample type, along with the flanged-to-sample-holder impedance correction.

Figure 14 shows the impedance correction for the locally reacting perforate panel. It was difficult to cut and seal this configuration inside the sample holder, leading to a large variation in the measured impedance between samples (Figure 3). Hence, the average impedance has a larger standard deviation than desired. Nevertheless, as expected, the impedance correction is relatively low for frequencies above ~1KHz. The high frequency correction would be improved (reduced) with an improved sample preparation and sealing inside the sample holder. Below 1KHz the impedance differences arise as a result of the area-induced impedance correction between the flanged tube and the visible (honeycomb) area within the sample.

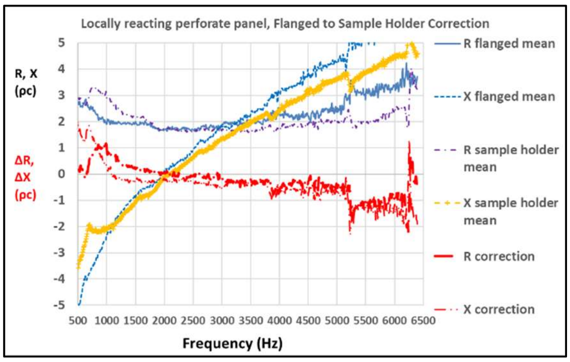

Figure 14 Flanged impedance correction - locally reacting perforate panel

Figure 15 shows the equivalent information for the non-locally reacting ceiling panel. While the impedance correction is generally greater than that seen for the locally reacting panel, it is still relatively small for frequencies above ~1.5KHz. As expected, the correction reduces dramatically at high frequencies. This is as a result of the relatively high panel resistance (> 2 ρc).

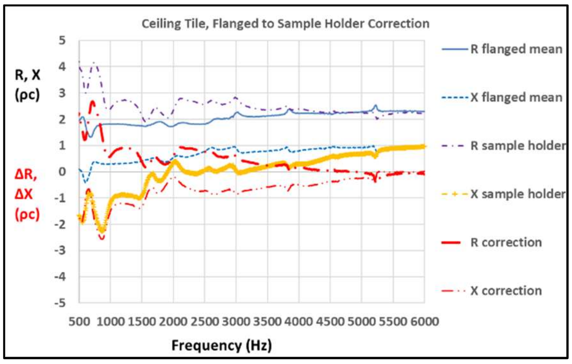

Figure 15 Flanged impedance correction – non-locally reacting ceiling panel

Figure 16 to Figure 18 show the equivalent impedance correction information plots for the insulation mats. The flanged tests were performed in the presence of a highly open (low impedance) perforate facing sheet. However, as the delta impedance is calculated, the (constant) impedance of the perforate does not alter the quality of the correction.
The sample holder correction is greater for these samples given their larger non-locally reacting nature (generally low resistance). This is particularly evident at low frequencies.

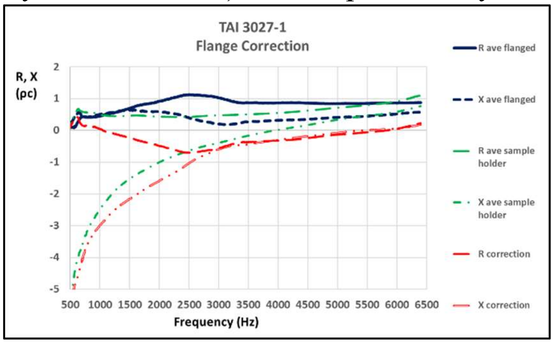

Figure 16 Flanged impedance correction – TAI 3027-1 (scrim backing)

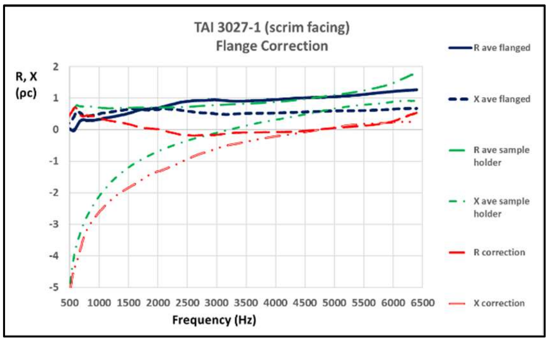

Figure 17 Flanged impedance correction – TAI 3027-1 (scrim facing)

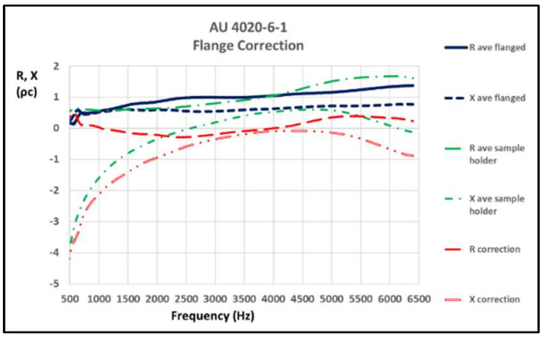

Figure 18 Flanged impedance correction – AU 4020-6 (scrim backing)

The next paragraph will look at the application of the sample holder correction to flanged impedance tube tests.

4.4 Corrected Flanged Impedance Measurements

Figure 19 to Figure 23 show the outcome of taking flanged impedance data and applying the associated correction for each of the sample types.

Figure 19 shows the corrected flanged normal incidence impedance, and the associated corrected normal incidence absorption coefficient for the locally reacting perforate panel.

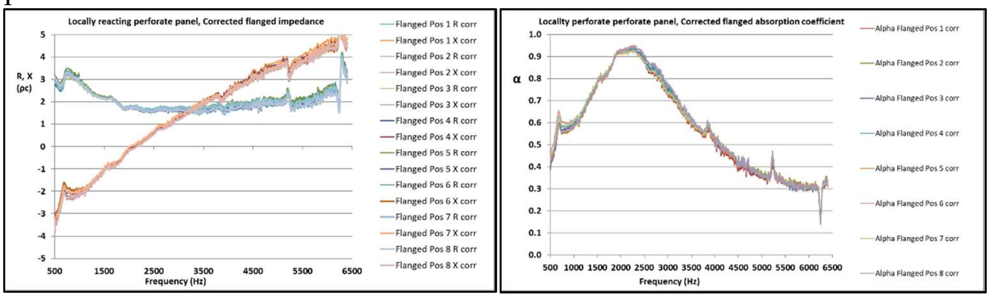

Figure 19 Corrected flanged impedance (left) and absorption coefficient (right)-locally reacting perforate panel

Given the difficulty faced with the cutting and sealing of the perforate panel, and the relatively small correction required for "ideally prepared" sample holder samples, it may be argued that the best results are realized by using the flanged impedance measurements directly.

Figure 20 shows the corrected flanged data for the non-locally reacting ceiling panel.

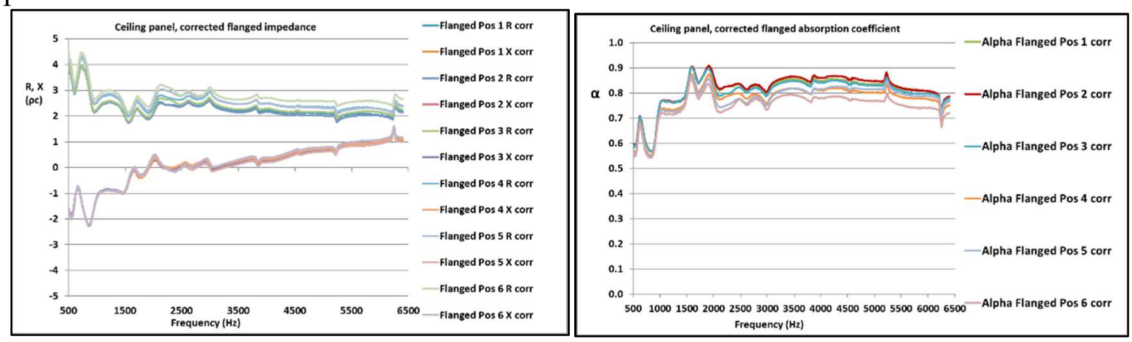

Figure 20 Corrected flanged impedance (left) and absorption coefficient (right) – non-locally reacting ceiling panel

Figure 21 to Figure 23 shows the corrected flanged impedance and absorption coefficient for one of four 300mm x 300mm samples for each of the insulation mat lay-ups. The results for the other insulation mat samples are not shown, but they show similar trends.

The insulation mats were tested with a frame and a perforate facing sheet at their design depths (21mm for TAI 3017 and 26mm for AU 4020-6). However, should the installed depths differ from this, the flanged test set-up could be adjusted accordingly.

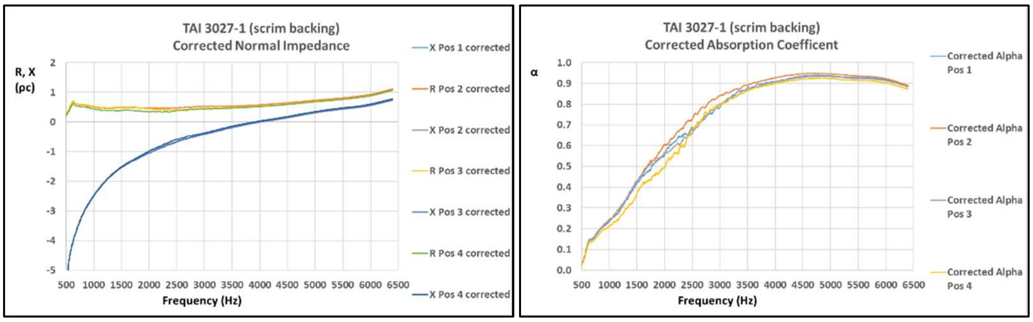

Figure 21 Corrected flanged impedance (left) and absorption coefficient (right) – TAI 3027-1 (scrim backing)

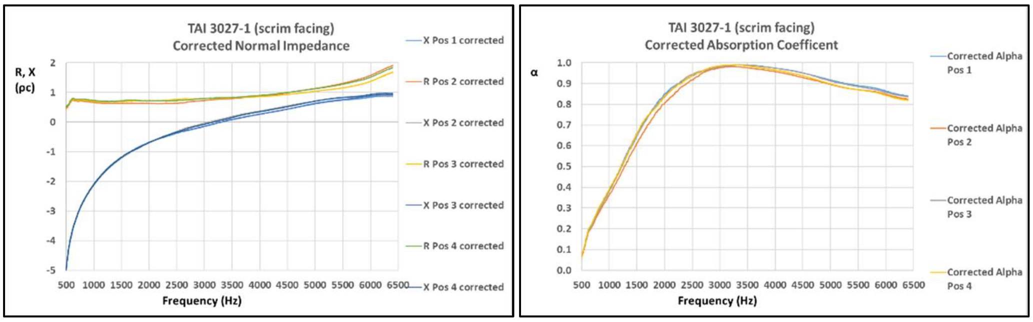

Figure 22 Corrected flanged impedance (left) and absorption coefficient (right)– TAI 3027-1 (scrim facing)

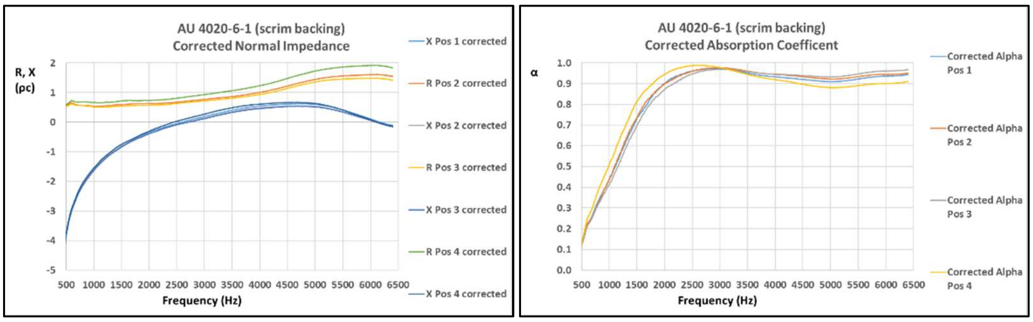

Figure 23 Corrected flanged impedance (left) and absorption coefficient (right) – AU 4020-6-1 (scrim backing)

The corrected impedance and absorption spectra show behavior consistent with the expected locally reacting absorptive performance of these lay-ups (Figure 5 to Figure 7). While the absorption spectra occasionally show slightly less smooth trends at low frequencies, it may be concluded that the impedance correction procedure provides good quality data which may be used to measure equivalent (destructive) sample holder data from non-destructive flanged measurements. It is also believed that repeating these tests with a stiffer perforate facing sheet will improve the results further.

5. CONCLUSIONS AND RECOMMENDATIONS

This paper has described a method of obtaining equivalent sample holder impedance and absorption measurements from non-destructive flanged impedance tube measurements.

Absorption coefficient and impedance measurements were made on locally reacting and on non-locally reacting materials with varying levels of resistivity.

Sample holder tests highlighted the advantages and disadvantages of this method. 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.

Portable flanged impedance tube tests were shown to be considerably quicker, simpler, and much more repeatable than sample holder impedance tube tests. 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 absorption. Impedance also provides a two-parameter check on manufacturing quality.

The impedance (and hence also absorption coefficient) correction procedure has been demonstrated to provide a fast, reliable, means of obtaining equivalent sample holder data using non-destructive measurements. It is recommended that future testing should look at refining the flanged test set-up to improve the flange correction procedure further.

6. ACKNOWLEDGEMENTS

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