Acoustic absorption of textiles: comparison of theory, measurement and practice

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ABSTRACT

Fabrics and textiles are commonly used as decorative facings, for light control or as interior design elements. However, apart from fabrics designed for acoustic purposes, reliable acoustic data for textiles is often not available. This places acoustic designers in a position of not understanding the acoustic properties of the textile, or restricting selections to textiles with known performance, which may rule out textiles that are aesthetically desirable but do not have acoustic data. This paper compares predicted and measured absorption coefficients for fabrics using transfer matrix theory, commercially available software packages, full laboratory tests and measurements of absorption using a small reverberation chamber to evaluate the accuracy of engineering methods for predicting or measuring textile sound absorption.

1 INTRODUCTION

Textiles for acoustic purposes should generally be either acoustically transparent with low flow resistance (allowing sound to pass through the fabric with minimal loss, so that an acoustic finish concealed behind the fabric behind can be visually screened while remaining acoustically effective) or have moderate-to-high flow resistance (so that the fabric acts as an absorber in its own right). In some circumstances, a fabric with very high flow resistance might be desirable so that it becomes largely acoustically reflective and minimises incidental absorption in a room (e.g. a blackout curtain that is permanently in a room).

While there are some subjective tests for acoustic properties of a fabric (e.g. the "breath test" for resistance to breathing air through it, or the "light test" based on visual light transfer through the fabric) these tests do not allow an objective measurement of acoustic properties. Objective tests range from measurements of flow resistivity (ISO 9053), from which acoustic performance can be predicted; impedance tube measurements of normal-incidence sound absorption coefficients of the fabric sample (ISO 10534-2); small chamber random incidence measurements (SCRAM method) (Carlisle and Hooker 2004) which does not meet the full laboratory requirements for test chamber size (< 200 m³) or full scale (>200 m³) laboratory tests of random incidence absorption (ISO 354).

The time and expense of full laboratory testing can be prohibitive on projects, particularly during earlier design stages where multiple products may be in consideration. Impedance tube testing is relatively fast and requires only small sample sizes (~10cm×10cm) but is limited to normal incidence only. Testing under the SCRAM method is commonly adopted in the automotive industry and offers similar reproducibility and repeatability to full scale test chambers (Veen et al 2005) but is limited to mid/high-frequency measurements only (> 400Hz) due to the difficulties of achieving a diffuse sound field at lower frequencies in the small chamber (Chappuis 1993).

This paper looks at comparing various methods of estimating and predicting the acoustic performance of textiles with measured data from full-scale laboratory tests (where available) and random-incidence absorption tests conducted within an *AlphaCabin* small reverberation chamber. Due to time constraints, normal-incidence measurements with an impedance tube or evaluating textiles behind slotted/perforated facings could not be conducted.

2 THEORETICAL BACKGROUND

The acoustic performance of porous absorbers such as textiles, foams and bulk insulation has been extensively studied, with many models for predicting the acoustic properties of the material based on some combination of physical properties. The simplest and most practical (but not necessarily the most accurate) models are one parameter models such as the well-known Delany and Bazley 1970 model which predict acoustic properties such as acoustic impedance and propagation constant / complex wave number using material flow resistivity. More complicated models such as Johnston-Champoux-Allard model (Allard & Champoux 1992) offer potential improvements in accuracy (Oliva and Hongisto 2013) but require additional information regarding the fine-scale structure of the porous material such as characteristic lengths, porosity and tortuosity, which may not always be reliably known for a given textile and may not be practicable to measure in the office. Recent research (e.g. Cai et al 2020) has explored the use of micro-CT scans or regressions based on fibre diameter to allow some of these physical properties of textiles to be measured or predicted for input into the JCA acoustic impedance model.

2.1 Layered Absorbers

There are several methods for predicting the surface impedance of a layered absorber system, including modelling as an equivalent electrical circuit (Pieren & Heutschi 2015) and transfer matrix (e.g. Brouard et al 1995). These approaches produce identical expressions for the surface impedance (Pieren & Heutschi 2015). For multiple layers of absorbent, the angle-dependent surface impedance of each layer $Z_{s,i}$ of thickness d_i can be calculated based on the characteristic impedance of the layer Z_i, wavenumber in the layer k_i and the surface impedance of the previous layer $Z_{s,i-1}$.

$$Z_{s,i}(\theta) = \frac{Z_c}{\cos\theta} \cdot \frac{{Z_i}/{\cos\theta} - jZ_{s,i-1}\cot(k_i \cos\theta d_i)}{Z_{s,i-1} - j{Z_i}/{\cos\theta}\cot(k_i \cos\theta d_i)} \tag{1}$$

The lowest layer in the stack is typically modelled as either being on a rigid termination (infinite impedance) or being an air-backed absorber; however, a termination with finite impedance (e.g. a lightweight wall) could be included if needed. Each layer can either be air (where Z_i, $k_i$are replaced by Z_0, k_0 values for air) or a porous absorbent as appropriate. The surface impedance of each layer can also be modified by directly adding the lumped impedance of a thin facing such as a textile or perforated sheet.

2.2 Impedance of Textiles

A textile is commonly modelled as a limp sheet, assuming that the textile is freely supported (free to vibrate) and is thin relative to the wavelength of sound over the frequency range of interest. For high flow resistivity textiles, non-viscous effects in the fabric can be neglected and the fabric acoustic impedance can be assumed to be the static flow resistance R_S (Pieren & Heutschi 2015) however for very open fabrics including nominally “acoustically transparent” fabrics, inertial and flow distortion effects may need to be included. Tang and Xhu 2023 reported better agreement between predictions taking into account tortuosity than predictions considering only the flow resistance. However, adding these non-viscous effects to the prediction requires knowledge of additional parameters including the degree of openness of the fabric (porosity), the effective hole size for the pores between yarns of the fabric and the effective tortuosity to be included, which is generally not available from the manufacturer.

The impedance of the fabric is the equivalent impedance in parallel of the acoustic impedance of the fabric itself (R_S) and the mechanical impedance of the stretched fabric acting as a thin elastic plate ($j\omega m''$) with surface mass m'', however for higher frequencies ($f > \frac{R_S}{\pi m''}$) the effect of the fabric mass is small (Pieren & Heutschi 2015). The full mechanical impedance of the fabric consists of the mass term ($j\omega m''$) and a flexural rigidity term however the flexural rigidity is typically negligible for limp materials and to be calculated requires knowing the mechanical properties of the fabric including Young’s Modulus that may not be readily available for fabrics. This results in the following expression for the characteristic impedance of a thin fabric:

$$Z_f = \frac{j\omega m'' R_S}{j\omega m'' + R_S} \tag{2}$$

2.3 Prediction of Random Incidence Absorption Coefficients

The angular incidence absorption coefficient α and random incidence absorption coefficient α_s can be calculated from the angle-dependent normalised surface impedance of the layered absorber taking into account the average radiation impedance (for either an infinite or finite-size sample) and averaging for a diffuse sound field using an angular weighting function $\mathrm{w}(\theta)$ (Pieren et al 2016), using the formula from Pieren & Heutschi 2015. NB in this equation σ denotes the radiation impedance, not flow resistivity.

$$\alpha_s = 2\int_0^{\pi/2} \left(\mathrm{w}(\theta) \frac{4\Re e[z_S(\theta)]}{|z_S(\theta) + \langle\sigma\rangle|^2} \right) \sin(\theta) d\theta \tag{3}$$

2.4 Absorption of Non-Flat Fabrics

For a fabric that is installed with "fullness" as a curtain, Pieren et al 2016 proposed a theoretical correction that applies above a cut-on frequency based on the pleat geometry, where ξ is an energy ratio (0 below and 0.5 above the cut-on frequency) accounting for how many times sound passes through the fabric pleats:

$$\alpha_{s,fullness} = \alpha_s + \xi(1 - \alpha_s) \cdot \alpha_s \quad (4)$$

3 FABRICS EXAMINED

Five fabrics were evaluated as part of this study, which cover a range of typical textile applications. The flow resistance (R_s) of all five fabrics was tested using the procedure of ISO 9053. Flow resistance is rounded to the nearest 50 rayls. Subjective breath and light tests of each fabric were also conducted:

- Fabric A is an engineered textile designed for controlled flow resistance to act as a sound absorptive element, which comes in two different variants, A1 (R_s 600 rayls) and A2 (R_s 200 rayls); light sources were visible and locatable through the fabric; minor (noticeable) breath resistance. Lab data is available for Fabric A tested on 50mm airgap; 100mm airgap; and as a facing for a 50 mm acoustic foam (~2300 rayls/m).
- Fabric B is a decorative upholstery/curtain textile (cotton/polyester), R_s 2300 rayls; light sources were not directly visible through the fabric, but a diffuse light was visible through the fabric; the fabric offered high resistance to breathing through the fabric. No lab data is available.
- Fabric C is a blackout lining textile (polyester); the flow resistivity was too high to be tested with the test rig (flow could not be achieved even at the highest-pressure setting). Light was not visible through the fabric; the fabric offered very high resistance to breathing through the fabric. The best fit between predicted and measured data was for R_s 30,000 rayls. No lab data is available.
- Fabric D is a woven decorative textile used as an acoustically transparent facing, R_s <50 rayls; light sources were visible and locatable through the fabric; the fabric offered minimal resistance to breathing through the fabric. Note that Fabric D has such low flow resistivity that it could not be measured on the test rig. The best fit between predicted and measured data was for R_s 30 rayls.
- Fabric E is an acoustic upholstery/curtain textile (wool felt), R_s 650 rayls; light sources were just visible through the fabric through individual pores of the fabric ; the fabric offered minor (noticeable) breath resistance. Lab data is available for Fabric E tested as a curtain with 250% fullness on a 170 mm airgap

4 SOFTWARE SIMULATIONS

Simulations of the acoustic absorption of the fabrics were conducted using three commercially available software packages for predicting absorption coefficients, using the flow resistivity of the five fabrics.

4.1 Software A

Software A includes a choice of several impedance models with the default being the JCA model and assumes locally reacting absorbent. An air cavity or finite size effects cannot be included. Software A is not capable of predicting free-suspended textiles but has been included for textiles as a covering for another absorber.

4.2 Software B

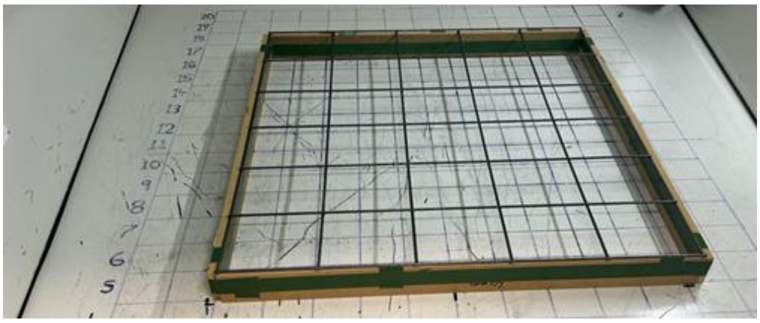
This software implements a transfer matrix using a single parameter model. Several impedance models are available with the default model being the Bies single parameter (flow resistivity) model (Bies 1981). Finite size panel effects can be considered although the method for calculating finite size radiation impedance is not stated.

4.3 Software C

This software implements a transfer matrix approach using a single parameter impedance model using the Miki 1990 model. Finite-size panel effects are taken into account via Davy et al 2014 model for radiation impedance.

5 ALPHA CABIN TESTS

A series of absorption tests were conducted in an AlphaCabin test rig (Autoneum nd), which is a 1:3 scale reverberation chamber (6.4 m³), with the tests attempting to replicate the construction of the samples tested in the full-scale laboratory tests as closely as practicable. A test frame was conducted within the AlphaCabin consisting of a 1.1×1.1m (~1.2 m²) square of 100 mm thick timber battens. An open thin wire grid was stretched over the top of the test frame to support the fabric samples. An image of the AlphaCabin with the test rig is shown in Figure 1.



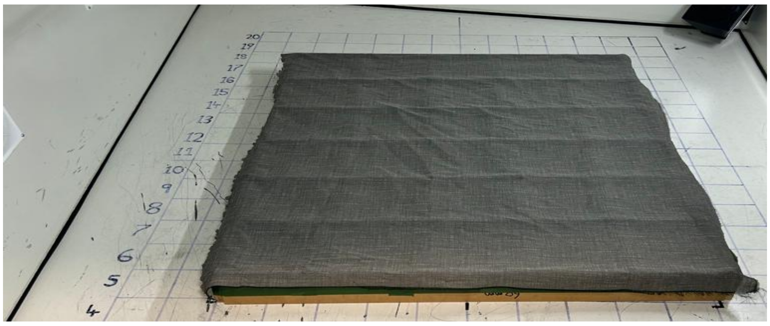


Figure 1: Image of AlphaCabin with test frame in place and with fabric over frame

The support by the wire grid may change the vibrational properties of the fabric compared to a full-scale lab test where the fabric is hung under gravity and only fixed by the top edge. All fabric samples were tested both with the fabric stretched tightly over the test frame and with the fabric resting on top of the mesh. This was to determine the influence of the fabric tension on the acoustic properties. In addition, Fabric B was tested with the fabric bunched up in pleats to simulate a curtain made from the fabric. A frame extension was added for some tests to allow for a larger airgap or for two layers of fabric to be tested. This consisted of a 25 mm timber frame with metal mesh that could be laid over the top of the main test frame and allow for a 125 mm airspace behind the top layer. Table 1 summarises the tested samples in the AlphaCabin.

Table 1: Summary of AlphaCabin absorption tests

Test	Fabric Layer 1	Extension Frame Used?	Fabric Layer 2
1	Fabric D	No	None
2	Fabric A1	No	None
3	Fabric B	No	None
4	Fabric C	No	None
5	None	Yes	Fabric B
6	Fabric A2	Yes	Fabric A1
7	Fabric C	Yes	Fabric B

6 RESULTS

Theoretical predictions using the transfer matrix method, predicted results from the software packages, lab test and AlphaCabin test results for the different textiles are compared in the following sections.

6.1 Fabric A

6.1.1 Facing for Acoustic Foam

Figures 2 and 3 present an overview of the absorption coefficients for Fabric A when used as a facing on 50 mm acoustic foam and 25 mm acoustic foam, respectively.

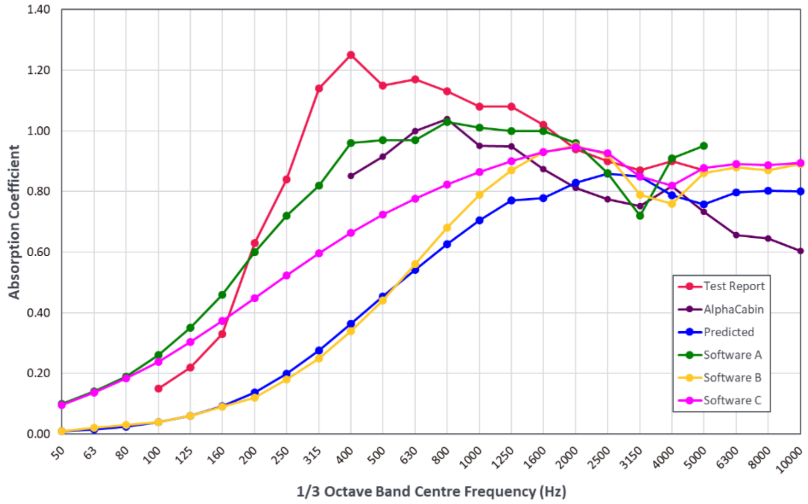


Figure 2: Comparison of predicted and measured absorption – Fabric A facing 50mm acoustic foam

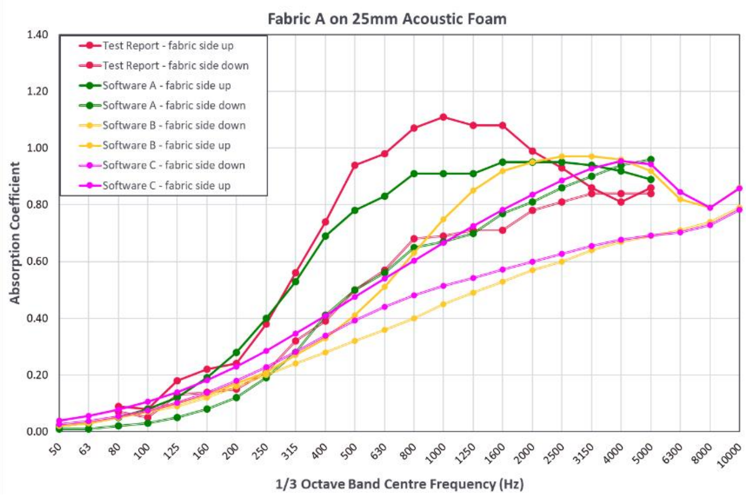


Figure 3: Comparison of predicted and measured absorption – Fabric A facing 25mm acoustic foam

6.1.2 Airspace Behind

Figure 4 presents an overview of the predicted vs measured absorption coefficients for Fabric A when mounted with an airgap behind.

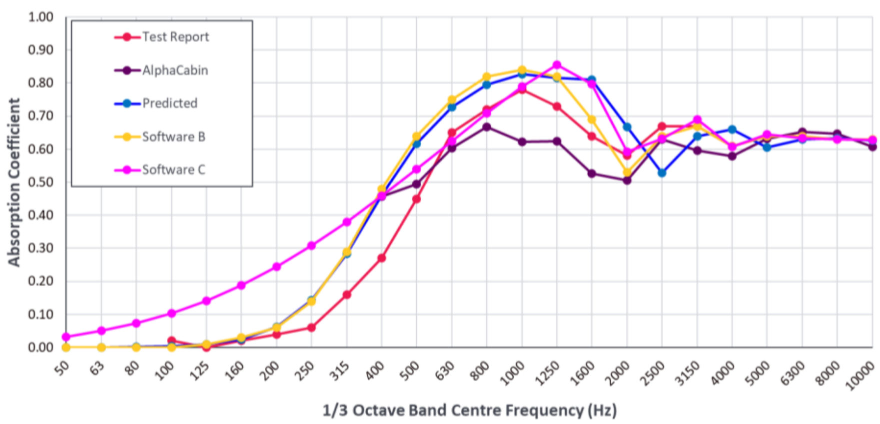


Figure 4: Comparison of predicted and measured absorption – Fabric A on airgap

Figure 5 presents an overview of the predicted vs measured absorption coefficients for a double layer of Fabric A1 and Fabric A2 with a 25mm airgap between the fabric when mounted with a 100mm airgap behind.

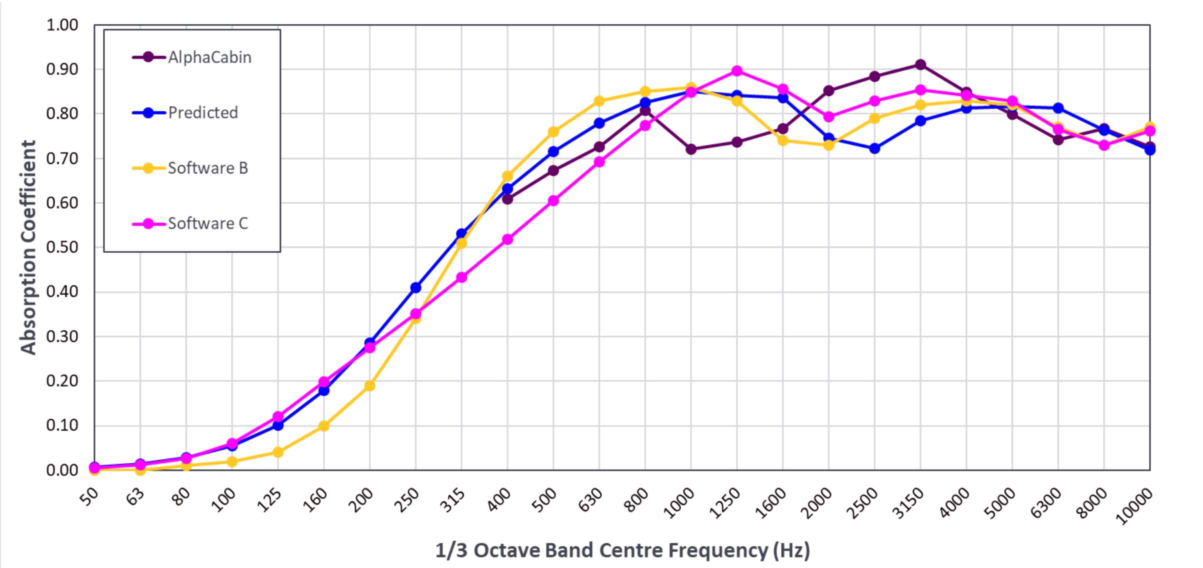


Figure 5: Comparison of predicted and measured absorption – Fabric A1 | 25 mm gap | Fabric A2 | 100mm gap

6.2 Fabric B

Figure 6 presents an overview of the predicted vs measured absorption coefficients for Fabric B when mounted with an airgap behind. Data for flat fabric in 100 mm airgap (solid line), flat fabric on 125mm airgap (dotted line) and fabric bunched as a curtain (dashed line) are shown. For the theoretical and software predictions, the average of the predicted flat fabric at 100 mm and 125 mm data has been used to estimate the bunched curtain performance using the Pieren et al 2016 correction.

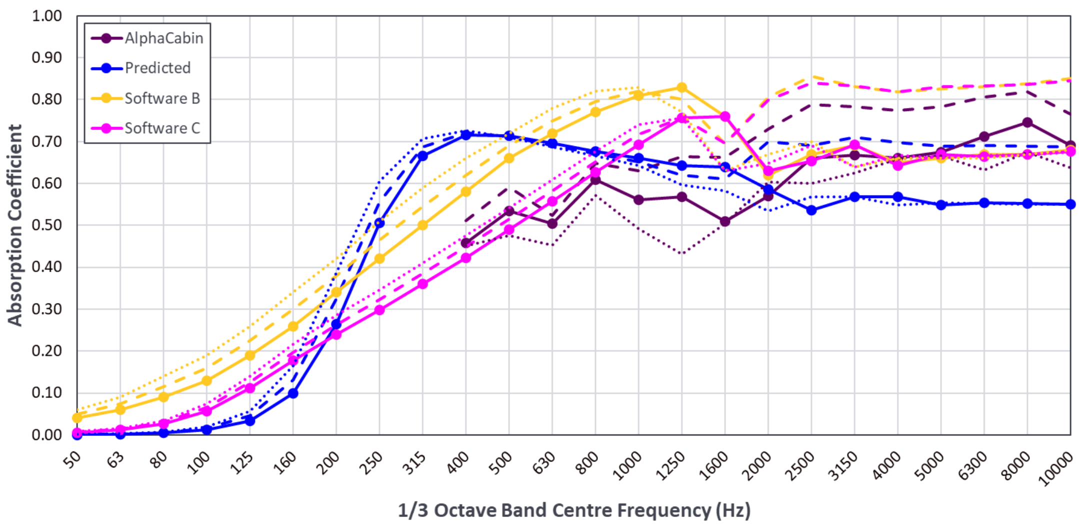


Figure 6: Comparison of predicted and measured absorption – Fabric B on airgap

Figure 7 presents an overview of the predicted vs measured absorption coefficients for a double layer of Fabric B and Fabric C with a 25mm airgap between the fabric when mounted with a 100mm airgap behind.

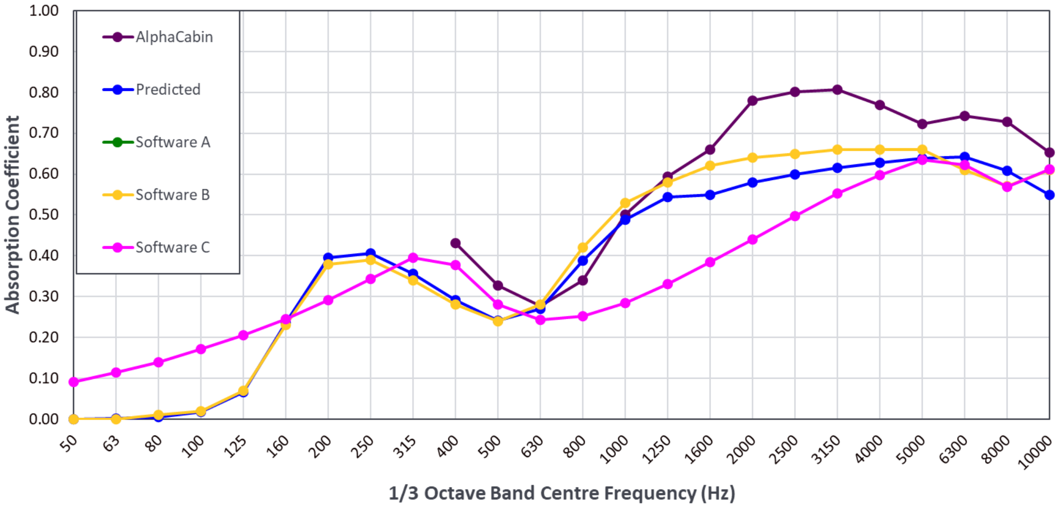


Figure 7: Comparison of predicted and measured absorption – Fabric B | 25 mm gap | Fabric C | 100mm airgap

6.3 Fabric C

Figure 8 presents an overview of the predicted vs measured absorption coefficients for Fabric C when mounted with an airgap behind.

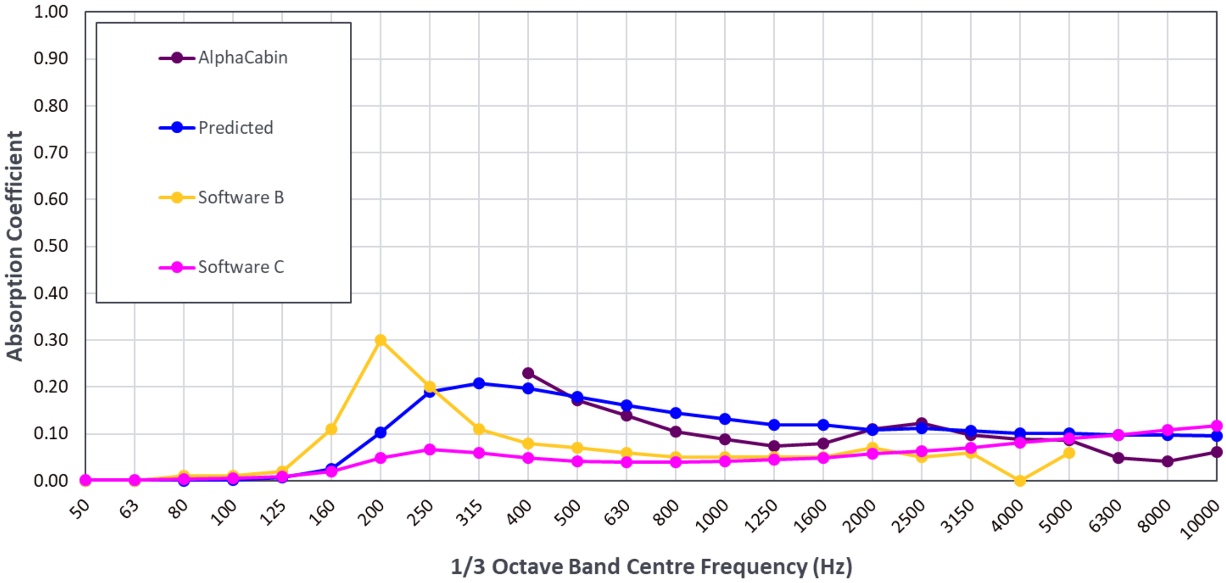


Figure 8: Comparison of predicted and measured absorption – Fabric C on airgap

6.4 Fabric D

Figure 9 presents an overview of the predicted vs measured absorption coefficients for Fabric D when mounted with an airgap behind.

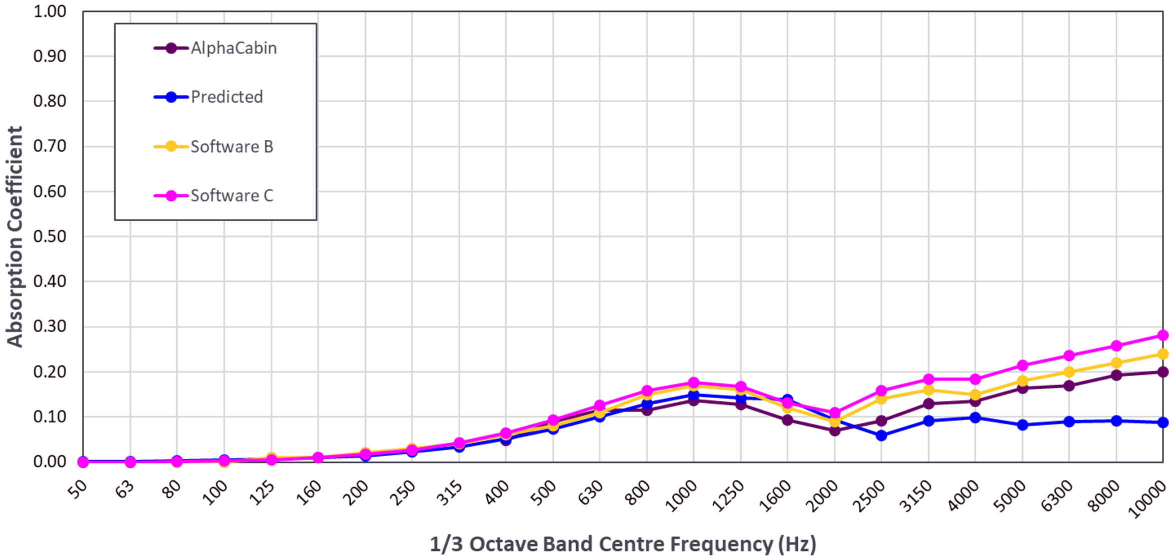


Figure 9: Comparison of predicted and measured absorption – Fabric D on airgap

6.5 Fabric E

Figure 10 presents an overview of the predicted (using the Pieren et al 2016 method using predicted flat fabric absorption) vs measured absorption coefficients for Fabric E when mounted as a curtain with an airgap behind.

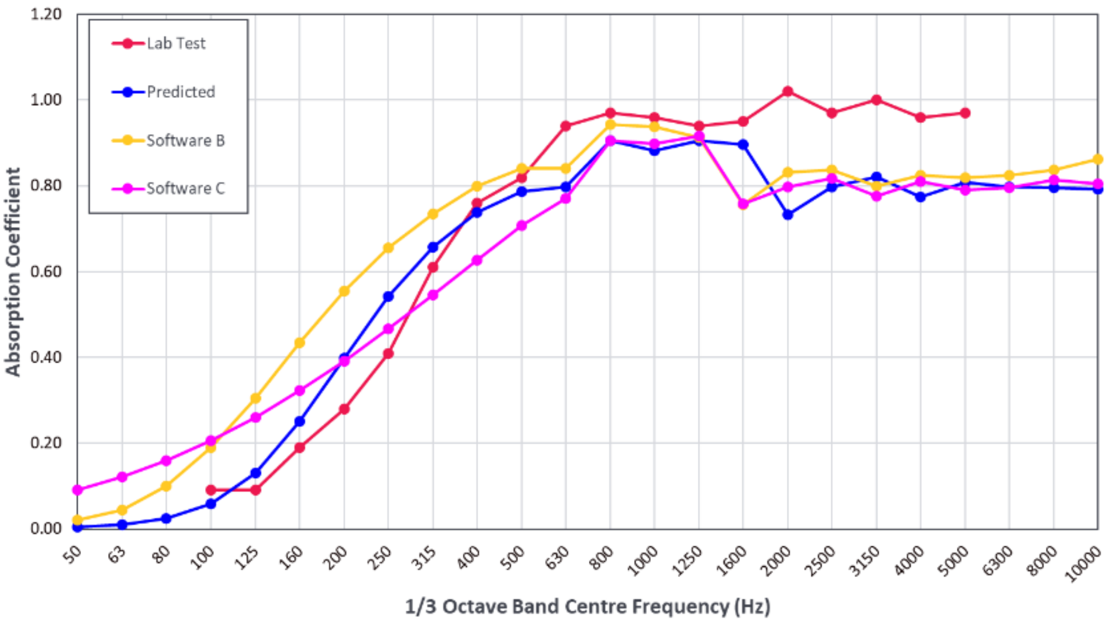


Figure 10: Comparison of predicted and measured absorption – Fabric E on airgap (as curtain)

6.6 Effect of Fabric Tension

Figure 11 presents a comparison of the test data for the four fabrics tested in the Alpha Cabin showing the effect of the fabric tension on absorption. Loose fabric is shown as solid lines with stretched fabrics dashed.

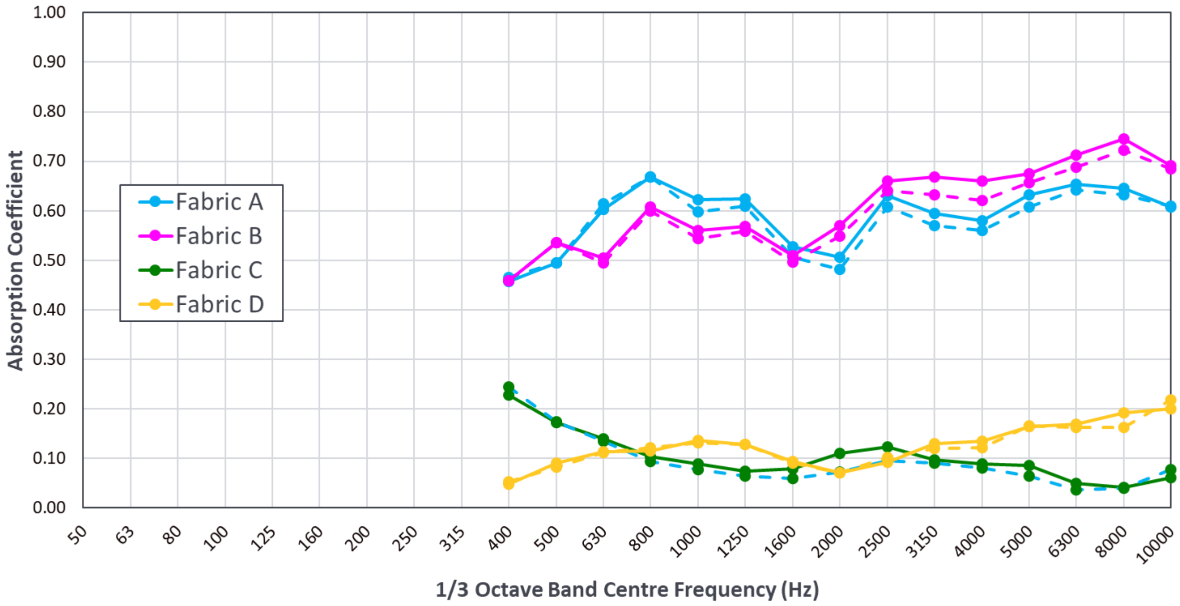


Figure 11: Comparison of measured fabric absorption with fabric loose (solid) or stretched over frame (dashed)

7 DISCUSSION

In general, there is quite good agreement between the various prediction methods, the measured AlphaCabin results and the laboratory tests (where available). The AlphaCabin results are consistently lower than the full-scale laboratory test results (8% lower on average across the frequency range where both methods produced data, averaged across the two situations for which lab test and AlphaCabin data are both available), but exhibit a similar shape of the overall absorption curve. For absorptive samples, the AlphaCabin results for several samples showed almost identical values in the 8 kHz octave band which may indicate a systematic factor affecting the AlphaCabin measurements at very high frequency. This is a different outcome to some previous comparisons e.g. Veen et al 2005 where the small room method tended to match the full-scale chamber at high frequency (>2 kHz) but tended to overpredict at mid frequency. However, Carlisle and Hooker 2004 (albeit using a different methodology where the small room was heavily treated with absorptive material) observed a similar outcome where the small room underpredicted (at least for glasswool) compared to full-scale lab tests.

The agreement between the theoretical Pieren and Heutshi 2015 method and the two software packages capable of predicting textile absorption with an airspace behind (B and C) and lab data and/or AlphaCabin tests is good for the low flow resistivity fabrics (A, D and E) and for the high flow resistivity Fabric C, but shows less good agreement for the moderate flow resistivity fabric B. The Pieren et al 2016 method for predicting curtain absorption matches the measured (lab or AlphaCabin) data reasonably well below 2 kHz but underpredicts above 2 kHz.

This may indicate that further fine-tuning of the ξ energy ratio parameter proposed by Pieren et al 2016 is necessary to predict the acoustic behaviour of the fabric at high frequency, where the pleat geometry of the fabric is significant relative to the wavelength of sound. Potentially some frequency-dependent factor for ξ beyond the current “binary” value (zero below a cutoff and constant above the cutoff) may be necessary. Additional geometric factors such as scattering of the reflected sound at high frequency that would increase the number of “hits” or “pass-throughs” of the fabric at high frequency may need to be included to improve the accuracy at high frequency.

8 CONCLUSIONS

The data available suggests that engineering methods for the prediction of fabric acoustic performance based on mass and flow resistance give acceptable accuracy when compared to small scale and full-scale absorption measurements. The effect of the fabric edge support (draped over a frame, freely suspended or stretched over a frame) appears to have minimal effect on the absorption properties – i.e. in each case the fabric can be acceptably modelled as a limp mass.

Theoretical transfer matrix calculation of absorption (either implemented directly or via software packages) provides acceptable accuracy. This provides some useful guidance for designers in predicting fabric performance using flow resistance data. Investment from fabric manufacturers in greater flow-resistance testing of fabric samples as an industry standard would be welcome to allow the acoustic properties of fabrics to be more reliably known without lab testing.

The acoustic performance of fabrics pleated as a curtain appears to be able to be predicted with good accuracy using the Pieren et al 2016 method at low and mid frequency; however, the method appears to under-predict the high frequency absorption of curtains. An extension to the method, potentially “tuning” the ξ energy ratio at high frequency would be useful to investigate whether increased accuracy can be obtained.

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