Effects of edge screens on the absorption of blocks of theatre chairs

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1. Introduction

Two methods have been proposed for predicting the absorption of chairs in auditoria from measurements of the absorption coefficients of the same type of chairs in a reverberation chamber. Kath and Kuhl [1,2] proposed using screens around the exposed edges of blocks of chairs to eliminate the edge absorption effects. They suggested placing the sample blocks of chairs in the corner of a reverberation chamber, with screens around the exposed edges of the chairs, so that the chair array is mirrored in the adjacent walls of the chamber to effectively increase its size [1–3]. Although the edge absorption may be reduced by using screens around the seating blocks, diffraction effects are not eliminated by this method [4–6].

The linear relationship between absorption coefficients and sample perimeter-to-area (P/A) ratios is the basis of the second method for predicting theatre chair absorption. The absorption coefficients of samples of porous absorbing materials have been shown to be linearly related to the P/A ratios of the samples [7,8]. Hegvold [4] showed that this also occurred for blocks of model chairs. Bradley demonstrated that absorption coefficients of both unoccupied and occupied theatre chairs were linearly related to the P/A ratios of the blocks of chairs [5,9]. Although the edge effect is due to both edge absorption and diffraction effects [4–6,10], it is difficult to separate the edge absorption and diffraction effects for theatre chairs. However, Bradley [5] found that even with screens around the edges, the absorption coefficients of the seating blocks still varied with the sample P/A ratio. This suggests that diffraction effects for samples of chairs are also linearly related to the sample P/A ratios.

Fitting regression lines to measurements of blocks of chairs with a range of P/A values results in regression equations of the form,

\[ \alpha = \beta \left( \frac{P}{A} \right) + \alpha_\infty \]  

where \( \alpha \) is the sound absorption coefficient of a finite sample, \( \beta \) is the slope of the regression line, and \( \alpha_\infty \) is the intercept corresponding to the absorption coefficient of an infinite sample area. P/A is the perimeter/area ratio of the sample. If \( \alpha \) is measured for various-sized samples having different P/A values, a linear regression line, fitted to the data, can be extrapolated to the P/A values of the larger seating blocks of chairs found in halls or to a P/A of 0 m⁻¹ corresponding to a sample of infinite area. Bradley proposed that measurements of several different sized blocks of chairs in a reverberation chamber could be used in this way to predict the absorption of the larger blocks of chairs in auditoria using Eq. (1) and referred to this as the P/A method [5].

Validations of the P/A method for measuring absorption coefficients of unoccupied and occupied chairs have been carried out in both full scale and scale-model measurements [5,9,11–14]. Bradley...
measured absorption coefficients of various-sized blocks of unoccupied and occupied chairs in a reverberation chamber and compared predictions from these measurements with measurements in real halls. He confirmed that the larger blocks of chairs in real auditoria could be more accurately predicted by extrapolating from measurements of various-sized blocks of chairs, in a reverberation chamber, with the chair edges exposed. In an earlier study, Bradley [5] also examined the use of screens to minimize the effects of edge absorption and found that the absorption coefficients of blocks of chairs with screens still varied with the P/A values of the samples of chairs. He concluded that the reverberation chamber tests of chair absorption should be performed with the edges of the chairs exposed, to avoid the low-frequency problems found for the samples of chairs with screens, and because the screens did not eliminate the variation of absorption coefficients with P/A. In a later publication, Bradley [6] showed, that for a simple porous absorber, samples of absorbing material, measured in the corner of a reverberation chamber, did not give results similar to the absorbing properties of a sample having four times as large an area as the actual sample area. New results in this paper examine the success of the Kath and Kuhl method for theatre chairs to determine whether the corner placement of the chairs increases the effective size of the sample of chairs.

Barron and Coleman [11] examined the perimeter/area method by measuring the absorption coefficients of seating blocks with a wide range of the sample P/A values (0.4–2.4 m⁻¹) and using scale model seating in a 1/25 scale-model reverberation chamber. They found that the P/A method was useful for measuring the seating absorption in a reverberation chamber and results could be extrapolated to the P/A values found in auditoria. Martellota and Cirillo [12] and Martellota et al. [13] measured the sound absorption of church pews and they too confirmed that the P/A method provided accurate predictions.

One of the advantages of measuring the sound absorption of chairs in a scale-model is that the properties of chairs and sample configurations are more easily varied in a scale model than in full scale. It is also much easier to compare the predicted chair absorption coefficients from a scale model reverberation chamber with those measured in scale-model halls. In recent work, Choi et al. [14] compared predictions of absorption coefficients from reverberation chamber measurements with those in a model recital hall using the P/A method. Their results using 1/16 scale model chairs showed good agreement between values measured in the model recital hall and those predicted from model reverberation chamber tests.

The present study further investigates the effects of edge screens on the absorption of blocks of theatre chairs. Four points concerning the measurements of the absorption coefficients of sample blocks of chairs using screens around the edges of chairs in a reverberation chamber are examined and the uncertainties of using the Kath and Kuhl method are considered. These four points are: (1) to investigate whether placing samples of chairs in the corner with screens around the edges of the chairs provides results representative of larger blocks of chairs, (2) to determine preferred screen heights for obtaining accurate predictions of results in large halls, (3) to consider whether more accurate predicted absorption coefficients for an infinite sample of chairs result from measurements with edges screened or without screens, and (4) to examine the accuracy of both the P/A and screen methods by comparing the predicted absorption coefficients from model reverberation chamber measurements with those measured in a model recital hall. The measurements were carried out both in full scale and in a scale model of a reverberation chamber. The first three discussion points are examined using results from a full-scale reverberation chamber. Parts of the third and fourth points are investigated using results from a model reverberation chamber and a model recital hall because model tests were found to be a more practical approach to examining these issues.

2. Measurement procedures

2.1. Full-scale reverberation chamber measurements

Tests were performed in a 254 m³ reverberation chamber, having fixed diffuser panels as well as a large rotating vane, located at the National Research Council in Ottawa. The chamber was kept at a temperature of 20 °C and a relative humidity of 50% and absorption coefficients were corrected to be representative of these conditions using ANSI S1.26 [15], when there were small deviations from these values. Reverberation time measurements were made using least-squares fits to the decays from the ensemble average of 20 pink noise decays at each of nine independent microphone positions in the room. A twenty decibel range of decay was used according to the procedures described in ASTM C423 [16]. Four independent noise sources were used to create the interrupted noise decays. The facility requirements exceed those of ASTM C423 [16] which are said to provide the best diffusion that is practically achievable. When the measured samples included screens, the empty room measurement did not include the screens. Although measurements were made in 1/3 octave bands, the three individual 1/3 octave sound absorption coefficients in each octave band were arithmetically averaged to produce octave band values for subsequent comparison with octave band measurements in rooms.

Groups of up to 18 chairs were measured in various configurations with a row-to-row spacing of 0.90 m. The calculated sample areas included the spaces between rows and included the same space in front of the first row of the sample of chairs. The various samples had a range of P/A values between 1.35 and 2.94 m⁻¹ for the chairs without screens and P/A values between 1.33 and 2.85 m⁻¹ for the chairs with screens around the edges of the blocks.

![Fig. 1. Sketch of type G theatre chair. CCP: cloth covered pad, CCM: cloth covered metal, Metal: metal seat pan.](image-url)
of chairs. The chairs were highly absorptive theatre chairs; they are referred to as type G chairs and are illustrated in Fig. 1. They had cloth covered seat and back pads, a metal seat pan, cloth covered metal seat backs, and cloth covered padded arm rests.

2.2. Model reverberation chamber measurements

A scale model reverberation chamber was used to measure the absorption of blocks of 1/16 scale model chairs. The model reverberation chamber had inside dimensions 1.2 by 1.5 by 1.1 m and was built using 20 mm thick acrylic panels. Prior to the measurements, the diffusivity of the sound field in the reverberation room was examined according to ISO 354 [17]. In the measurements, a 1.37-s logarithmic sweep from 1.6 kHz to 100 kHz was used, which corresponds to full-scale frequencies from 100 Hz to 6.3 kHz. The compensation for the air absorption in the reverberation chamber was achieved by replacing the air with nitrogen during measurements. The reverberation chamber was kept at a constant temperature of 23 °C and a relative humidity of 4%. Six combinations of two source positions and three receiver positions were used for measuring the absorption coefficients of the model chairs. A twenty decibel range of each decay from –5 dB to –25 dB, was used to calculate reverberation times according to the procedures described in ISO 354 [17]. There was no evidence of non-linear decays over this range when the absorption of the chairs was measured. When the measured samples included screens, the empty room measurement did include the screens. The measurements were made in 1/3 octave bands, but the absorption coefficients were presented as octave band values derived by averaging the three individual 1/3 octave sound absorption coefficients in each octave band. A repeatability test of the absorption coefficient measurements of the chairs was carried out to check consistency of the results. The measurements were repeated three times, and the results were presented as the mean absorption coefficients and the associated standard deviations.

The model chairs were constructed as 175 mm long benches (2.8 m full-scale) with no under pass. This is equivalent to the width of four chairs. A 1.0 mm single layer of felt was added as the seat pad of the model chairs. The chairs are referred to as type A model chairs and are described in more detail in Ref. [14]. Samples of 6–63 model chairs were arranged in various-sized blocks with a row-to-row spacing of 1.30 m (full-scale). A total of nine seating configurations were used to give a wide range of P/A values from 0.6 to 1.22 m⁻¹. The measurements were carried out both with the model chair edges exposed and screened. The absorption coefficients of the sample blocks of chairs were calculated using the floor area occupied by the model chairs. The floor area included the same space between the rows in front of the first row because this was found to give more accurate regression results.

2.3. Model recital hall measurements

A 1/16 scale-model of a recital hall was used for measuring the absorption coefficients of larger blocks of chairs with lower P/A values as found in auditoria. Fig. 2 shows the model recital hall and placement of chairs. The model recital hall had a (full-scale) volume of 5810 m³ and was a simple rectangular shape with a flat floor under the seating area. The model recital hall was constructed using 15 mm thick varnished MDF panels. Various-sized diffuser panels, made using 1.5 mm thick acryl panels, were installed on the walls to prevent flutter echoes. Porous absorbing material (5 mm thick polyester fibre) was added on the ceiling. In the model hall measurements, a single block of 10 rows, each five benches wide (equivalent to 160 chairs) with a row-to-row spacing of 1.30 m (full-scale) was used. This seating block had a P/A value of 0.34 m⁻¹. Reverberation times were measured both with and without the chairs in place using one source position and nine microphone positions. The measurements were repeated three times. The hall was kept at a temperature of 23 °C and a relative humidity of 40% during the measurements. The correction for increased air absorption at model frequencies in the recital hall was numerically determined [18].

3. Results and discussion

3.1. The concept of placing the sample in the corner with screens (the Kath and Kuhl method)

Kath and Kuhl recommended measuring the absorption of theatre chairs by using blocks of chairs located in the corner of a reverberation chamber with screens around the two exposed sides of the sample of chairs. The screens were intended to minimize the absorption of the edges of the block of chairs and placing them in a corner eliminated the need for screens on two sides of the block of chairs. This approach was thought to eliminate the effect of edge absorption with minimal influence of the added screens. The mirroring of the sample in the corner of the room was said to lead to results representative of a much larger sample [1,3].

In earlier work, Bradley [6] showed that for a simple 5 cm thick layer of porous absorbing material, the procedure of measuring samples placed in the corner of a reverberation chamber did not give similar absorption coefficients to those of a sample having four times as large an area as the actual sample area. This test was repeated in the current work for blocks of chairs with screened edges placed, in the corner, and in the middle of the reverberation chamber (i.e. away from the walls). A large block of three rows of six chairs (R3C6) with an area of 9.1 m² was placed in the centre of the reverberation chamber and a small block of two rows of two chairs (R2C2) with an area of 2.1 m² was tested both in the corner and in the centre of the room. All blocks of chairs had their edges screened using 0.6 m high screens made of 10 mm thick plywood. Fig. 3 shows the absorption coefficients of sample blocks of chairs placed in the corner and in the centre of the reverberation chamber.

Moving the small block of chairs from the centre of the room to the corner of the reverberation chamber decreased the absorption coefficients of the block of chairs, but the absorption coefficients of the small sample of chairs were not the same as the approximately four times larger block of chairs. The absorption coefficients of the larger sample of chairs at mid- and high-frequencies were closer in value to those of the small sample of chairs placed in the centre of the reverberation chamber than to those for the small sample of chairs placed in the corner of the room.
Davies et al. [3] mentioned in their paper that the corner placement of chairs was advantageous because it increased the effective size of the sample of chairs, but with the disadvantage of increased sound pressure levels near the boundaries of the reverberation chamber that they said would lead to increased absorption coefficients relative to those found using a centre placement of the chairs in the reverberation chamber. This argument was adopted directly from Kath and Kuhl’s earlier paper [1]. They suggested corrections to the effective test areas to account for increased sound levels close to the room boundaries. The method to correct for obtaining the effective test area is described in Ref. [1,3].

The results in Fig. 3 do not support the argument that there will be increased absorption coefficients for chairs located near the room boundaries. When the larger block of chairs (R3C6) was tested with screens both in the centre of the room and in the corner of the room, the absorption coefficients were lower for the corner location and not higher (see Fig. 4). The same result was found for the smaller block of chairs in Fig. 3, which also indicated higher absorption coefficients when the sample is placed near the centre of the room.

Fig. 5 shows the measured absorption coefficients of various-sized blocks of chairs with screens around the chair edges and located in the corner of the reverberation chamber. The measured absorption coefficients vary with sample size and these variations are larger at lower frequencies. Although the different screened samples have similar absorption coefficients at and above 400 Hz, there were significant differences below 400 Hz. For example, the smaller sample block of chairs (R2C2) has significantly larger absorption coefficients at low-frequencies. When these results were examined in terms of octave band absorption coefficients, as shown in Fig. 6, they were all considerably lower than the infinite area estimates for these chairs at medium and higher frequencies (obtained from Fig. 9 and Table 1). These results suggest that the Kath and Kuhl method of measuring screened samples of chairs in the corner of the reverberation chamber, does not properly take account of the variations of the edge absorption and diffraction effects with changing sample size.

3.2. The effect of the screen height on the chair absorption

There is no guideline for selecting an optimum screen height for screens around samples of chairs. Screen heights of from 0.6 m to 1.2 m have been used in earlier studies [1,3–5,11]. Davies et al.
tested screen heights varying from 0.3 m to 1.5 m in 0.3 m steps. The results did not show systematic variations of chair absorption with increasing screen height over all frequencies and the results varied depending on which parts of the chairs were covered by the screens. Fig. 7 shows new results of measurements of the absorption coefficients for a block of three rows of four type G chairs (R3C4) with screen heights increasing from 0.6 m to 1.0 m. The lowest screen height (0.6 m) tends to lead to larger absorption coefficients in the 250 and 500 Hz octaves but the highest screen height (1.0 m) led to larger absorption coefficients at high-frequencies. There are variations in absorption coefficients with varied screen height, but no systemic effect over all frequencies was found. The results with screens in Fig. 7 are compared with the absorption coefficients for an infinite sample of chairs obtained by extrapolating the reverberation chamber measurements with varying P/A values for blocks of chairs without screens. The infinite area results are in general quite different than all three measurement results with screens. No screen height led to absorption coefficients for the chairs similar to those for an infinite area of chairs.

3.3. Absorption coefficients for an infinite area of chairs predicted for both with and without screens measurements versus P/A

Fig. 8 shows the absorption coefficients of blocks of three rows of six type G chairs (R3C6) both with and without 0.6 m high screens around the chair edges. The screens decreased the absorption coefficients above 160 Hz, but increased the absorption coefficients at lower frequencies. The measured absorption coefficients of the screen itself were 0.12, 0.09, 0.07, 0.08, 0.14 and 0.20 in 1/1 octave bands from 125 to 4 kHz. The plywood screen has higher absorption at low frequencies and may add some low frequency absorption to the results for chairs.

Fig. 9 plots the absorption coefficients versus sample P/A for type G chairs with the chair edges both exposed (upper graph) and with 0.6 m high screens (lower graph).
coefficients of the unoccupied chairs vary with the P/A values of the blocks of chairs both with and without the screens around the edges of chairs. This indicates that the screens do not completely eliminate the edge absorption and diffraction effects. The absorption coefficients for an infinite sample of the chairs both with and without screens, obtained from the regression results in Table 1 are shown in Fig. 10. The chairs with screens around the edges underestimate the absorption coefficients of an infinite area of chairs compared to those predicted from the chairs without screens.

Fig. 9 showed that the absorption coefficients of blocks of chairs increase with increasing P/A value even when there are screens around the edges of the chairs. This was verified in the model reverberation chamber with various-sized sample blocks of model chairs. In the model, the screens were constructed from 2 mm acrylic panels with a height (full scale) of 0.9 m. To eliminate the sound absorption of the screens, the absorption of the screens was determined from measured reverberation times with the screens present but without the chairs. These absorptions of only the screens were subtracted from those of the chairs and the screens to give a better estimate of the absorption coefficients of only the chairs. No low frequency increase in the absorption coefficient of chairs with screens around the edges was then found. Fig. 11 shows the absorption coefficients versus sample P/A for blocks of type A model chairs [14] both with the edges exposed (upper) and screened (lower).

The regression coefficients from linear fits to these data and the standard errors are presented in Table 2. Again, the absorption coefficients of model chairs vary with the P/A values of the blocks of model chairs both with and without screens around the edges of the chairs. The slopes, $b$, of the regression lines seem to be more rapid for model chairs with screens around the chair edges. There is a slightly negative intercept value, $\alpha_{\infty}$, at 125 Hz (absorption coefficient for an infinite area sample), which may be due to the increased scatter in the 125 Hz data. Fig. 12 compares the absorption coefficients of infinite samples of model chairs both with and without 0.9 m high screens measured in the model reverberation chamber. The chairs with screens around the edges underestimate the absorption coefficients of an infinite sample relative to those of the chairs without screens. This is generally in agreement with the full-scale reverberation chamber measurements in Fig. 10.

3.4. Comparisons with model recital hall measurements

Measured absorption coefficients for a large block of chairs in the model recital hall were compared with predictions from measurements of blocks of the chairs in the model reverberation chamber using the P/A method. The comparisons were made for chairs both with and without screens to determine if the use of screens for eliminating the edge effects of chairs led to more accurate predictions. Fig. 13 compares the predicted absorption coefficients of the model chairs from both exposed edges and screened sample tests, with the measured values in the model recital hall. The predictions from the chairs with screens around the edges underestimate the measured absorption coefficients of the large seating block in the model recital hall. However, the predicted absorption coefficients from the measurements of the
absorption coefficients were found when the edges were screened, sample area as has been previously suggested [1,3]. Lower conventional sample locations, the corner location did not lead to sound absorption near the room boundaries[1,3] because such area corrections that have been proposed to account for higher boundaries. Hence there was no evidence to validate the sample measured at more conventional locations away from the room absorption coefficients than when the same blocks of chairs were exposed edges of the blocks of chairs generally gave lower the corner of a reverberation chamber with screens around the

4. Conclusions

Measuring the sound absorption of blocks of chairs placed in the corner of a reverberation chamber with screens around the exposed edges of the blocks of chairs generally gave lower absorption coefficients than when the same blocks of chairs were measured at more conventional locations away from the room boundaries. Hence there was no evidence to validate the sample area corrections that have been proposed to account for higher sound absorption near the room boundaries [1,3] because such higher absorption did not occur. The lower observed absorption coefficients for samples close to the walls may be due to the lower particle velocities expected close to the rigid boundaries of the reverberation chamber [19].

Although these results were different than those at more conventional sample locations, the corner location did not lead to absorption coefficients similar to those for a four times larger sample area as has been previously suggested [1,3]. Lower absorption coefficients were found when the edges were screened, and this was found to occur at all sample locations. Although the corner location results for screened samples were different, it is not clear how to relate them to other estimates of the absorption coefficients of the chairs.

For theatre chairs with screens around them, the measured absorption coefficients vary with changes to the height of the screens, and the details of the changes vary with frequency. However, the variations were relatively small for the range of screen heights tested, and no systematic pattern of changes in sound absorption coefficients was identified with increasing screen height. The absorption coefficients of chairs with any screen height from 0.6 to 1.0 m gave absorption coefficients lower than those predicted for an infinite block of chairs in all octave bands except the 125 Hz band. These results indicate that it is not possible to identify an optimum screen height and for the range of screen heights considered, the absorption coefficients obtained were lower than expected for an infinity area sample. Hence they are not thought to be useful estimates of the properties of larger samples of chairs.

The addition of screens reduced the measured absorption coefficients at all frequencies above a frequency of 160 Hz and below this frequency the absorption can be increased by the presence of the screens. This is partly due to the low frequency sound absorption provided by the screens that were used. It may also be influenced by the acoustical properties of the enclosure formed by the screens.

The addition of screens around samples of chairs did not eliminate the variation of absorption coefficients with P/A. This was true for both full scale and model chair results. However, the results of extrapolations from measurements of blocks of screened chairs to infinite samples gave lower absorption coefficients than found for blocks of unscreened chairs. It is not clear how to interpret the extrapolations from tests of screened chairs, as the higher absorption coefficients from extrapolations of measurements of unscreened blocks of chairs have been shown to correctly predict the values measured for large blocks of chairs in performance halls (see Fig. 13 and [9]).

When the P/A method was used to predict the measured sound absorption of chairs in a model recital hall, the predictions from blocks of chairs without screens agreed closely with the measured values in the recital hall. However, this was not true for the extrapolations from measurements of blocks of screened model chairs. It is concluded that the absorption of chairs in large performance halls can best be predicted using the P/A method to extrapolate from reverberation chamber measurements of smaller unscreened samples of chairs to the larger samples and lower P/A ratios of blocks of chairs typical of performance spaces.

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