Understanding chair absorption characteristics using the perimeter-to-area method

John S. Bradley a, Young-Ji Choi b, *, Dae-Up Jeong b

a Institute for Research in Construction, National Research Council, 1200 Montreal Rd., Ottawa, Canada K1AS 0R6
b Department of Architectural Engineering, Chonbuk National University, 664-14 1Ga, Duckjin-Dong, Duckjin-Gu, Jeonju, Jeonbuk 561-156, Republic of Korea

Article info

Article history:
Received 31 January 2013
Received in revised form 14 March 2013
Accepted 22 March 2013

Keywords:
Perimeter-to-area
Theater chairs
Absorption coefficients

Abstract

Measurements of the sound absorption of several blocks of chairs with varied perimeter-to-area (P/A) ratios were used to examine how chair absorption coefficients are related to their physical characteristics. Because the P/A method combines the results of several samples of each type of chair, a more accurate understanding can be obtained of how the physical properties of the chairs are related to their sound absorption characteristics. Unoccupied chairs are shown to have a wide range of characteristics and it is necessary to test each type of chair to accurately predict their effect in an auditorium. However, the absorption characteristics of occupied chairs are strongly influenced by the absorption of the occupants and an approximate average sound absorption characteristic can be useful for predicting the effect of occupied chairs in an auditorium. Although the variations of sound absorption with row spacing are related to P/A, the variations are quite different than when simply changing the P/A for chair samples with constant row spacing. Both chair underpass height and chair back height affect the absorption characteristics of theater chairs, but the effects can be influenced by the presence of carpet under the chairs or by occupants in the chairs. Common sources of increased sound absorption in each octave band are identified and discussed.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

The sound absorption of chairs, either occupied or unoccupied, is usually a significant part of the total sound absorption in an auditorium. As a result, chair absorption has a very important influence on the overall acoustical properties of such spaces. It is therefore important to be able to predict the amount of sound absorption that will be added to a room by the chairs to ensure that the auditorium has the desired acoustical properties.

The sound absorption of materials to be included in buildings is usually measured in standard sound absorption tests in a reverberation chamber [1,2]. Unfortunately, the measured absorption coefficients vary with the dimensions of the sample and larger samples tend to have lower effective absorption coefficients. The variations with sample size have been shown to relate linearly with the sample perimeter-to-area ratio for both simple flat panels of porous absorbing material [3,4] and also for rectangular arrays of chairs [5].

It has been shown that by measuring the sound absorption coefficients of sample blocks of chairs with a range of perimeter-to-area (P/A) ratios, one can predict the expected absorption coefficients of the larger blocks of chairs (having smaller P/A ratios) found in auditoria [5–8]. This method of estimating the expected sound absorption of chairs in auditoria is referred to as the P/A method. It involves fitting linear regression lines to relate the measured absorption coefficients of samples of chairs to the P/A values of the samples of the form,

\[ \alpha = \beta(P/A) + \alpha_\infty \]  

(1)

Here \( \alpha \) is the absorption coefficient of the sample with a particular P/A ratio. \( \beta \) is the slope of the regression line and \( \alpha_\infty \) is the intercept of the regression line which corresponds to the absorption coefficient of an infinitely large sample of chairs. Because the regression coefficients are derived from the measurements of typically five samples of chairs, they can be expected to more accurately characterize particular types of chairs than one sound absorption test of a single sample of chairs.

The method has been shown to successfully predict the absorption coefficients of chairs measured in an auditorium both in full scale [5] and in model studies [7,8]. Recently, the accuracy of the method has been further explored [9].

In this paper, measurements of eight types of theater chairs are used, with the P/A method to determine how the physical properties of the chairs influenced the acoustical characteristics of the different chairs. Three of the eight types of chairs were also tested...
when occupied. The chairs varied from mostly non-absorptive to highly absorptive. Further tests were carried out on model chairs to explore the effects of the height of the chair backs and the height of the chair underpasses on the sound absorption of the chairs. These results give insight into the physical details that contribute to the sound absorption of theater chairs.

2. Measurement procedures

2.1. Full-scale reverberation chamber measurements

Tests were performed in a 254 m\(^3\) 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 [10], 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 9 independent microphone positions in the room. A 20 dB interval of each decay was used according to the procedures described in ASTM C423 [1]. Four independent noise sources were used to create the interrupted noise decays. The facility requirements exceed those of ASTM C423 [1] which are said to provide the best diffusion that is practically achievable. 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 row-to-row spacings of between 0.76 and 1.10 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 construction details of the chairs are summarized in Table 1. More details are included in Refs. [5,9,11] as indicated in Table 1.

2.2. Model reverberation chamber measurements

The volume of the 1/10 scale model reverberation chamber was 300 m\(^3\) (full scale) and it was built using 20 mm thick acrylic panels. In the measurements, a 1.37-s logarithmic sine sweep from 1 kHz to 100 kHz was used, which corresponds to full-scale frequencies from 100 Hz to 10 kHz. The correction for air absorption in the model reverberation chamber was dealt with by substituting nitrogen for the air. The reverberation chamber was kept at a constant temperature of 25 °C and a relative humidity of 4%. Six combinations of two source positions and three receiver positions were selected for measuring the absorption coefficients of the unoccupied chairs. Twenty dB of each decay, from −5 dB to −25 dB, was used to calculate reverberation times according to the procedures described in ISO 354 [2]. Prior to the measurements, the diffusivity of the sound field in the reverberation room was also examined according to ISO 354 [2]. There was no evidence of non-linear decays over this range when the absorption of the chairs was measured. 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 measurements for the absorption coefficients of the chairs was carried out to check whether the results were consistent for each measurement. The measurements were repeated three times, and the results were presented as the mean absorption coefficients.

Model chairs having a width of 0.6 m (full scale) were constructed as bench type seats with an underpass. A 1.0 mm single layer of felt was added on the seat and back of the model chairs and the model chairs are referred to as Felt chairs. The absorption of a sample of 3 rows of 5 model chairs (R3C5) with a row-to-row spacing of 0.9 m was measured. The measurements were carried out with the chair edges exposed and the absorption coefficients were calculated using floor areas that included the row-to-row space in front of the first row of each block of model chairs.

3. Variation of absorption characteristics of unoccupied chairs

3.1. P/A method slopes and intercepts

Linear regression lines were fitted to plots of absorption coefficient, \(z\), versus P/A for blocks of chairs measured in a reverberation chamber. These analyses were performed using the origin plotting and analysis software [11] to perform standard least squares linear regression fits to the data, and in addition to the slopes and intercepts of the regression lines, determined the coefficients of determination (\(R^2\)), and the statistical significance of the results (p-value) to establish the statistical significance of the results. Where the relationships were not significant and (p < 0.2), it was assumed that there was no P/A effect and the slope was assumed to be 0. For these cases the intercept was calculated as the average of the measured absorption coefficients from all representative blocks of chairs. Non-significant results were often found for chairs with lower absorption coefficients and with very low regression slope values and occurred most often at 125 Hz [9,12]. The slopes and intercepts of the regression lines varied with the type of chairs [9].

Fig. 1a plots the values of the slopes of the regression lines versus octave-band frequency for sample blocks of the eight types of unoccupied chairs. Fig. 1b plots the intercepts of the same regression lines for the same eight types of unoccupied chairs. The data show a range of characteristics.

The type F chairs had the lowest intercept values at almost all frequencies, because only the vinyl covered seat pad would absorb sound at most frequencies. The plywood backs and metal seat pans

<table>
<thead>
<tr>
<th>Chairs</th>
<th>Back pad</th>
<th>Rear of back</th>
<th>Seat pad</th>
<th>Seat sides</th>
<th>Seat underside</th>
<th>Arm rests</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>CCP</td>
<td>Metal</td>
<td>CCP</td>
<td>CCP</td>
<td>Metal</td>
<td>Wood</td>
</tr>
<tr>
<td>B</td>
<td>CCP</td>
<td>CCM</td>
<td>CCP</td>
<td>CCP</td>
<td>Metal</td>
<td>Wood</td>
</tr>
<tr>
<td>C</td>
<td>Thin CCP</td>
<td>Rigid plastic</td>
<td>CCP</td>
<td>CCP</td>
<td>Metal</td>
<td>CCW</td>
</tr>
<tr>
<td>D</td>
<td>CCP</td>
<td>Metal</td>
<td>CCP</td>
<td>CCP</td>
<td>Metal</td>
<td>CCP</td>
</tr>
<tr>
<td>E</td>
<td>CCP</td>
<td>CCP</td>
<td>CCP</td>
<td>CCP</td>
<td>Met. perf. metal</td>
<td>CCW</td>
</tr>
<tr>
<td>F</td>
<td>Wood</td>
<td>Wood</td>
<td>CCP</td>
<td>CCP</td>
<td>Metal</td>
<td>Wood</td>
</tr>
<tr>
<td>G</td>
<td>CCP</td>
<td>CCM</td>
<td>CCP</td>
<td>CCP</td>
<td>Metal</td>
<td>CCP</td>
</tr>
<tr>
<td>H</td>
<td>CCP</td>
<td>Wood</td>
<td>CCP</td>
<td>CCP</td>
<td>Plastic</td>
<td>Wood</td>
</tr>
</tbody>
</table>

CCP = cloth covered pad, CCM = cloth covered metal, CCW = cloth cover wood, and VCP = vinyl covered pad.
may have added a little low frequency absorption. The intercept values correspond to the expected absorption coefficients for a very large sample of the chairs and the values for the eight types of chairs were most similar at 125 Hz. Chair types G and E have the highest intercept values at mid and high frequencies. Chair types A, B, C, D and H tended to have more intermediate intercept values at mid and high frequencies.

The values of the slopes of the regression lines shown in Fig. 1a vary quite differently as a function of frequency for the eight types of chairs. Chair types A, E and G tend to have the higher slope values that would lead to higher variations of absorption coefficients with \( P/A \) value. This is illustrated in Fig. 2a–c, which show plots of calculated absorption coefficients versus frequency for a range of \( P/A \) values from 0.0 to 3.0 in steps of 0.5. These correspond to the variations expected in absorption coefficients from the largest block of seats in a large hall to the smallest sample in a reverberation chamber test. Fig. 2c shows the calculated absorption coefficients for the type F chairs. These were very low absorption chairs with plywood backs and vinyl covered seat pads. Fig. 2c shows only small variations in absorption coefficient over both frequency and \( P/A \) values.

Fig. 2b for the type H chairs shows relatively low absorption in the 125 Hz octave and some small variations with \( P/A \) that are largest at mid-frequencies. These chairs had absorbing seat pads and back pads but other surfaces were hard non-porous materials that would absorb little sound.

The type E chair results in Fig. 2a show quite different characteristics with larger variations in absorption coefficient with frequency and \( P/A \) values. These are due to the higher slopes of the original regression lines for these chairs that increased with frequency as shown in Fig. 1a. These more varied results are probably caused by the presence of absorbing material on almost all surfaces of the type E chairs. In addition to the seat and back pads, the seat sides, undersides, arm rests, and the rears of the seat backs were all quite absorbing.

The results in Fig. 2 clearly show that variations of absorption coefficients with \( P/A \) ratios can be quite different for various types of chairs. One cannot assume a common relationship for all types of unoccupied chairs, between the results of tests in reverberation chambers and the properties of the chairs as installed in an auditorium. Precise predictions of the effects of chairs in auditoria require reverberation chamber tests of samples of the particular chairs with a wide range of \( P/A \) values.

### 3.2. Effects of chair construction details

One can more accurately compare the absorption characteristics of the eight types of unoccupied chairs by calculating the...
absorption coefficients versus frequency from the regression parameters obtained from the reverberation chamber tests of the chairs for one common P/A value. This was done for a P/A value of 0.5 m$^{-1}$, which is representative of the larger blocks of chairs in an auditorium. Fig. 3 compares the calculated absorption coefficients for the eight types of unoccupied chairs for a P/A value of 0.5 m$^{-1}$. By comparing these calculated values one is averaging over the mean trend of 5 or 6 measurement samples for each chair type, which is more likely to show trends more clearly. The details of Fig. 3 can be used to explain the factors influencing the absorption characteristics of the chairs.

The type F chairs are seen to be generally the least absorptive and have lower absorption coefficients at almost all frequencies. This is not surprising given the details of their construction (plywood seat backs and vinyl covered seat cushions with heavy metal seat pans). The types E and G chairs are seen to be generally the more absorptive at mid frequencies. Chair types A, B, C, D, and H are seen to be moderately absorptive at most frequencies. All chairs tend to have similar absorption coefficient values at 125 Hz of about 0.5. This indicates that the details of the chair do not have much effect on the absorption of the chairs at 125 Hz.

In addition to these more general trends a number of particular details can be explained. The type B chairs, although moderately absorptive at most frequencies, are quite highly absorptive at 4000 Hz. This can be explained by the cloth covered metal (CCM) rears of the seat backs, which would add some high frequency absorption to the type B chairs.

Chair types A, B, D, and G all had thin metal seat pans and all had higher absorption coefficients at 250 Hz. This is most likely due to the resonant sound absorption of the thin metal seat pans. The type E chairs had a perforated metal seat pan over loose glass fiber material, and the type H chairs had a plastic seat pan. They both have a little less absorption at 250 Hz than most chairs with non-perforated metal seat pans. The exception was the type F chairs, which had metal seat pans but were less absorptive at 250 Hz. This is thought to be related to the much older type F chairs having heavier metal seat pans and also less absorption at this frequency from other parts of the chairs.

Among the moderately absorptive group of chairs, the type C chairs were a little less absorptive at 500 Hz. This is likely due to the relatively thin cloth covered pad (CCP) of the seat back.

From these results one can conclude that to make an unoccupied chair less absorptive, one should: (a) avoid thin non-perforated metal seat pans, (b) keep cushions on seat backs as thin as possible to reduce unoccupied absorption, and (c) not put fabric or any other porous absorbing material on any surface that is not covered by the seated people (i.e. not on: rears of chair backs, sides and arms of chairs, nor undersides of seats).

### 4. Occupied chairs

The types E, F and G chairs were also measured occupied for chair samples of varied P/A ratio. The types E and G chairs were among the most highly absorbing chairs but the type F chairs were the least absorbing of the eight types of unoccupied chairs. Fig. 4a plots the slopes of the regression lines versus frequency for the occupied chairs. The intercepts of the regression lines are plotted versus octave band frequency in Fig. 4b. Although the results include the least and most absorbing of the eight types of occupied chairs, these plots show smaller differences among the results for the three types of occupied chairs than found for the unoccupied chairs in Fig. 1a and b. The intercepts of the regression lines for the types F and G chairs in Fig. 4b are very similar at most frequencies in spite of the large differences between these chairs when unoccupied. However, the type E chairs have somewhat higher absorption coefficient values. On average the intercept values increase up to 500 Hz and then vary little with further increases in frequency.

The slopes of the regression lines for occupied chairs in Fig. 4a also indicate quite similar characteristics. The slopes for all three types of occupied chairs increase with frequency up to 1000 Hz and then tend to level off and have similar values at higher frequencies. There are not as large differences in slope values among the three types of occupied chairs, as were found for unoccupied chairs.

![Fig. 3. Calculated absorption coefficients versus frequency from the slopes and intercepts of regression line fits to absorption coefficients versus P/A values, for P/A = 0.5 m$^{-1}$.](image)

![Fig. 4. (a) Slopes and (b) intercepts of regression lines of absorption coefficients versus P/A for occupied theater chairs and the average of the three sets of values.](image)
The smaller differences among the results for occupied chairs suggest that the occupants are the most important factor in determining their absorption characteristics, but the materials of highly absorbing chairs (e.g. type E) can still further influence the occupied absorption values. In many situations one could estimate the absorption of occupied chairs from the averages of the slopes and intercepts of the measurements from the three types of occupied chairs shown by the solid lines in Fig. 4a and b.

The absorption coefficients of the types E, F and G occupied chairs were compared by calculating absorption coefficients versus frequency for samples with a P/A ratio of 0.5 m⁻¹ shown in Fig. 5. This gives more reliable comparisons by using the mean trend over several measurements of blocks of chairs. Also shown in Fig. 5 are average occupied chair absorption coefficients from the average regression coefficients shown in Fig. 4a and b. Considering how different the unoccupied types E, F and G chairs were, it is remarkable how similar the occupied absorption coefficients are.

The differences among the three types of occupied chairs can be explained by the surfaces that differ among the chairs and which are not covered by the occupants. These would include the CCP (cloth covered pad) on the rears of the seat backs of the type E chairs, that would contribute to the higher absorption coefficients at all frequencies for these occupied chairs. The CCM (cloth covered metal) rears of the seat backs of the type G chairs may lead to the generally higher absorption coefficients than for the type F chairs. Although the unoccupied type F chairs were much less absorptive than the unoccupied types E and G chairs, when occupied they were each a little more similar to the other two types of chairs. However, at 4000 Hz the type F chairs were more absorptive than the type G chairs in Fig. 5. This may be because the relatively low backs of the type F chairs exposed more of the occupants to the sound field.

Where measured data for the particular chairs that are to be used are not available, the average sound absorption coefficients shown for occupied chairs with P/A = 0.5 m⁻¹, can be used as approximate estimates of the absorption coefficients of all occupied theater chairs. When the P/A values of individual seating blocks are known, then the average slopes and intercept values can be used to enable better predictions. Of course it would always be most accurate to predict the expected absorption coefficient of the chairs using the P/A method and measurements of the same chairs in a reverberation chamber.

Beranek and Hidaka estimated the absorption coefficients versus frequency for occupied chairs [13] by subtracting estimates of the residual absorption, due to all surfaces in 21 concert halls, from the measured total absorption. They derived average absorption coefficients versus frequency for three types of occupied chairs referred to as Group 1, Group 2 and Group 3 occupied chairs. Group 1 occupied chairs were the most absorptive and Group 3 the least absorptive. These are included on Fig. 6 for comparison with the average measured values from Fig. 5. The range of absorption coefficients between the three groups of chairs is not large, which is in agreement with the measured results in this paper. However, Beranek and Hidaka’s estimates of the average absorption coefficients of the most absorptive group of chairs (Group 1 data) were less absorptive than the values calculated from the measured average of a wide range of types of occupied chairs from the current results. It is not clear why the two studies give such different results. Beranek and Hidaka’s results depend on estimates of the sound absorbing properties of many materials in 21 different concert halls. This would be difficult to do very precisely. Of course, there could also be inaccuracies in the P/A method and the average P/A of blocks of chairs in concert halls may be a little different than the 0.5 m⁻¹ assumed here. However, the P/A method has been shown to successfully predict measured chair absorptions in full scale [5] and model halls [8].

To reduce the sound absorption of occupied chairs, it is most important to eliminate any absorbing surface that is not covered by the occupants of the chairs. This would include layers of fabric as well as fabric covered sound absorbing pads. However, when the chair back is not particularly absorbing, such as the plywood seat backs of the type F chairs, a higher back may also reduce the high frequency sound absorption by blocking sound from being absorbed by the occupants.

5. Effect of row spacing on sample absorption

Varying the spacing of rows of chairs can also influence their absorbing properties similar to changing the internal properties of other absorbing materials. Davies et al. [14] showed chair absorption coefficients increasing with decreasing row spacings of from 1000 to 820 mm. They stated that for measurements of the same chairs, the total absorption of the sample of chairs increased with row spacing without showing the measurement results. They explained that although the total absorption increased...
with increasing row spacing, the effect of sample areas increased more rapidly causing the absorption coefficients to decrease with increasing row spacing.

Barron and Coleman’s model chair data [6] also showed chair absorption decreasing with decreasing row spacings of from 1.0 to 0.8 m. Their chairs, with a 0.8 m row spacing, were less absorptive than the other spacings but the 0.90 m and 1.0 m spacings led to very similar total absorption values. From an examination of these results they claimed that chair absorption behaved differently in reverberation chambers than in auditoria. However, this was because they were comparing two different effects. They compared the effect of differences in row spacing in a model reverberation chamber with variations in sample size in auditoria with constant row spacing. The new results in this paper show that these are quite different effects that are differently related to the \( P/A \) ratios of the samples of chairs.

Measurements were made of samples of 3 rows of 6 chairs (R3C6) of type G and type H chairs for varied row spacing. Fig. 7a plots measured absorption coefficients of the type H chairs for row spacings of 0.8, 1.0, 1.1, and 1.2 m to represent the widest likely range of row spacings. Fig. 7b plots the corresponding total sound absorption values of the samples of the type H chairs versus frequency. Absorption coefficients decrease significantly with increasing row spacing and the total absorption increases a small amount with increasing row spacing. That is, the absorbing properties of the sample of chairs vary with the actual row spacing. As Davies et al. explained, (a) the total absorption increases a little because some parts of the chairs are more exposed to the sound field as the row spacing increased, and (b) in spite of the increase in total absorption, the increasing sample area causes the absorption coefficients to decrease quite significantly with increased row spacing.

One can obtain samples of varied \( P/A \) by varying the spacing of the rows of chairs for a fixed number of rows and chairs, or alternatively by varying the numbers of rows or chairs for samples with the same row spacing. However, the two approaches to varying \( P/A \) lead to quite different effects and the rates of variation of absorption coefficients with \( P/A \) values are quite different. Fig. 8 compares plots of absorption coefficients versus \( P/A \) values for both, changing row spacing, and changing sample \( P/A \) with a fixed row-spacing for the type G and type H chairs at 1000 Hz. This figure shows that when the row spacing is increased, the absorption coefficient increased much more rapidly with \( P/A \), than when the constant row space sample \( P/A \) values are changed. These are two quite different effects. When the constant row space sample \( P/A \) is varied by changing the numbers of rows and/or chairs, one can extrapolate these results to values representative of other sizes of samples of chairs such as the larger samples of chairs found in large halls having the same row spacing as the samples tested. When the row spacing is varied, one is also changing the basic characteristics of the sample being tested, much the same as if one were to stretch a porous absorbing sample to a larger area. Different row spacings should be considered to be different samples of chairs with different absorption characteristics. It is possible that one could measure the two types of variations with \( P/A \) values in reverberation chamber absorption tests and use the combined results to extrapolate to different sample sizes and row spacings.

Some insight into the possibility of predicting the absorption coefficients for other row spacings is given by the results in Fig. 9. This figure shows measured absorption coefficients versus \( P/A \) for varied row spacing for three types of chairs. The chairs are the types G and H chairs described in Table 1 and heavy wooden church pews with thin absorbing seat cushions [15]. The slope of the type G chair data is most rapid. The type G chairs were seen to be generally more absorptive and the more rapid variation of the absorption coefficients of the type G chairs with \( P/A \) is probably influenced by the cloth covered rears of the chair backs, which were not present on the type H chairs. As the row spacing increased, this material becomes more exposed to the sound field and the sample of chairs would absorb more sound. The pews were much less absorptive than the other two types of chairs and their absorption coefficients varied least rapidly with changing row spacing. Although the trend of the variations in the slopes of the data in Fig. 9 seems understandable, it is not possible to accurately
estimate the expected slope for other types of chairs. A different row spacing can lead to differences in absorption coefficients as large as occurs for differences between different types of chairs. It is therefore better to carry out reverberation chamber tests of chairs using the same row spacing as will be used in the hall where they will be installed.

6. Effects of chair back height and seat underpass height

6.1. Seat underpass height

The height of the seat underpass is the height of the open space underneath the chairs. Barron and Coleman [6] found that decreasing the seat underpass from 400 mm to 150 mm (full scale) led to increased absorption at mid and higher frequencies. They used model chairs with absorption characteristics approximating those of full scale chairs. Their chairs were not occupied and there was no carpet under the chairs. Although they pointed out that the effect of underpass height was a potentially important effect, they did not explain how reductions to the height of the seat underpass led to increased mid- and high-frequency absorption.

In the current work, scale model chairs were used to further evaluate the effect of the height of the seat underpass. The absorption of a sample of 3 rows of 5 model chairs (R3C5) was measured in a model reverberation chamber for three different seat underpass heights. The measurements were repeated for the same samples of chairs with and without carpet under the chairs. Fig. 10 plots the measured absorption coefficients versus frequency for the R3C5 block of model chairs with and without carpet under the chairs, for three seat underpass heights of 0, 150 and 280 mm (full scale).

For the chairs with carpet results, two different effects are seen. First, when the gap under the chairs is completely filled (underpass height 0 mm), the 125 Hz absorption is more than doubled in value when the seat underpass was completely closed. There was also a modest increase in 125 Hz absorption coefficient, when the seat underpass height is increased from 150 mm to 280 mm. There is a small decrease in sound absorption coefficients when the seat underpass height is increased from 150 mm to 280 mm.

With a carpet under the chairs, opening up the seat underpass allows more incident sound to interact with the carpet and be absorbed, explaining the increase in mid- and high-frequency absorption with increased underpass height. However, at lower frequencies, the resonant absorption effects seem to be more important and the more the seat underpass height is reduced, the stronger the low frequency absorption.

When the same measurements were made without carpet under the model chairs, the results were a little different. There was again a large increase in 125 Hz absorption coefficient, when the seat underpass was completely closed. There was also a modest change in mid- and high-frequency absorption coefficients. The increased mid- and high-frequency absorption coefficients with decreasing underpass height, for the no-carpet case, were qualitatively similar to the results of Barron and Coleman [6], but different than the with-carpet results in Fig. 10.

6.2. Chair back height

Another possibly important parameter of theater chairs is the height of the seat back. The absorption of a block of model chairs (R3C5) was measured for two different chair back heights: 0.55 and 0.85 m (full scale). These measurements were also repeated with the chairs both occupied and unoccupied with model listeners. The measured absorption coefficients of the unoccupied chairs in Fig. 11 are seen to have increased absorption coefficients at all frequencies when the seat back height was increased. As the seat backs were covered with porous absorbing material, the increased absorption is probably due to the increase in the total area of this material. Since the material was quite thin, the effect of increased seat back height increased with increasing frequency as shown in Fig. 11.

Fig. 11 also shows the measured absorption coefficients for the occupied blocks of model chairs (R3C5). Again the increased seat back height led to increased sound absorption at all frequencies. However, for the occupied chairs, the increase in sound absorption coefficient is least at 4000 Hz rather than largest as found for the unoccupied model chairs in Fig. 11. This may be because, although the increased seat back height increased the amount of seat back absorption, it also covers more of the occupant, reducing the effective sound absorption of the occupants in the chairs.
7. Discussion and conclusions

The variation of chair absorption coefficients between measurements in a reverberation chamber and the effective absorption coefficients of the chairs in a large auditorium can be related to the $P/A$ ratio of the blocks of chairs in each space. However, these relationships vary with the details of the particular chairs. That is, the same relationship cannot be used for all types of unoccupied chairs. The current results indicate that one should test each type of chair in a series of reverberation chamber absorption tests including a range of sample sizes and apply the $P/A$ method for predicting the expected absorption in an auditorium.

However, when occupied, the differences in the acoustical characteristics between various types of chairs are smaller because the occupants have a dominant effect on the effective absorption of occupied chairs. The absorption coefficients of occupied chairs do vary significantly with the $P/A$ ratio of the sample of the chairs, but the differences among various types of occupied chairs are relatively small. One can therefore approximately estimate the effects of occupied chairs in an auditorium from the average characteristics determined in this paper. Of course, it would normally be more accurate to measure the particular occupied chairs and apply the $P/A$ method to predicting the expected absorption in the auditorium. There is some need for caution because, although the $P/A$ method has been shown to predict the absorption coefficients in auditorium spaces reasonably accurately, the average characteristics of occupied chairs, determined in this paper, do not agree closely with those estimated from absorption analyses in a number of concert halls [16].

The current analyses show that specific details influence the absorption coefficients of unoccupied theater chairs at particular frequencies.

- At the lowest frequency (125 Hz octave band) measured absorption coefficients were quite similar among all eight types of unoccupied chairs and tended to vary less with $P/A$ values. However, when the chair underpass was completely closed there was a considerable increase in the measured 125 Hz absorption coefficients.
- In the 250 Hz octave band, chairs with thin metal seat pans had higher absorption coefficients than other chairs. This was assumed to be due to resonant absorption of the thin metal seat pans. Chairs with perforated metal seat pans over loose glass fiber material were less absorptive than the chairs with non-perforated metal seat pans in the 250 Hz octave band.
- At mid-frequencies (500–2000 Hz) the sound absorption coefficients were increased for chairs with absorptive material on the rear of the seat backs, or on arm rests and the sides of chairs. Chairs with plain plywood backs had decreased mid-frequency absorption.
- At the highest frequencies (4000 Hz), the rear of the seat backs had obvious effects including those with cloth covered pads (CCPs), or even just cloth covered metal backs (CCMs), which had higher absorption coefficient values at 4000 Hz.

For occupied chairs, other than the effects of the occupants, the surfaces not covered by the occupants, had the most effect on the measured absorption coefficients. Chairs with cloth covered pads on the rear of the seat backs had increased absorption at all frequencies. Chairs with cloth covered metal on the rears of chairs had increased absorption in the 4000 Hz octave band. Although higher chair backs led to increased absorption for unoccupied chairs, when non-absorptive chair backs were lower, they exposed more of each occupant to the sound field and led to increased sound absorption coefficients in the 4000 Hz octave band.

Several results indicate that one should not measure the effects of individual components in isolation. In many cases the combination of factors determines the effective absorption coefficients of the chairs. For example, the effect of the seat underpass depends on whether there is carpet present and might also vary with the type of carpet. Similarly the rank ordering of the effective absorption coefficients of chairs can vary depending whether they are occupied or not.

The interactive effects of some important materials have not been thoroughly evaluated. This would include the influence of $P/A$ on the addition of carpet under blocks of chairs of various sizes. It is not known how the individual variations of chair and carpet absorption combine and vary with $P/A$. Further research is also required to investigate the gaps between various estimates of occupied theater chair absorption coefficients.

Acknowledgements

The travel grant to support collaboration for this research was provided by the Korean Advanced Institute of Women in Science, Engineering and Technology Support Programs for R&D Activities, 2011. This work was partly supported by a National Research Foundation of Korea Grant funded by the Korean Government (1101-000381). The authors thank the National Arts Centre of Canada for their helpful cooperation with the testing of several of the types of chairs.

References


