The sound absorption of occupied auditorium seating

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Measurements of the sound absorption coefficients of blocks of occupied theatre chairs varied approximately linearly with the ratio of sample perimeter-to-area ratio. Extrapolations of such measurements were used to predict the absorption coefficients of occupied chairs in auditoria. Analyses of these and other published data show that the absorption coefficients of occupied chairs also vary with the absorbing properties of the chairs. A more general method for predicting the sound absorption of occupied chairs as a function of sample perimeter-to-area ratio is proposed based on classifying chairs as having low, average, or high absorption characteristics. The new method is simple to apply and is thought to be more accurate than currently accepted methods.

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INTRODUCTION

Estimating the sound absorption of occupied auditorium chairs has long been a problem in architectural acoustics. This paper proposes two new approaches for estimating the sound absorbing properties of occupied theatre chairs. One approach allows quite precise predictions from measurements of various groups of the same type of occupied chairs in a reverberation chamber. The other approach predicts the absorption of occupied chairs from the average properties of measured occupied chairs, but includes the effects of the perimeter-to-area ratio of each block of chairs in the auditorium. Both procedures are improvements on existing techniques.

In early work chair and audience absorption was predicted in terms of the effective amount of sound absorption per person. Beranek[1,2] proposed an improved approach that estimates the effects of chairs and audience in terms of absorption coefficients for the floor area occupied by the chairs and the audience. Beranek's method adds a 0.5-m-wide strip to the floor area occupied by the chairs where there are aisles and other spaces. This extra area is intended to approximate the effects of edge absorption and diffraction for the block of chairs. Beranek derived average absorption coefficients for both occupied and unoccupied chairs.

More recently, Bradley[3] measured absorption coefficients of various sized blocks of chairs in a reverberation chamber. He showed that the absorption coefficients of theatre chairs were linearly related to the sample perimeter-to-area ratio, P/A, as is true for simple planar absorbing materials. That is, the effective absorption coefficient α for a particular sample of chairs is related to P/A as follows:

$$\alpha = \beta(\mathrm{P/A}) + \alpha_\infty, \qquad (1)$$

where α_∞ is the absorption coefficient of an infinite area of chairs and β is a regression constant.

Further, it was possible to estimate the effective absorption coefficients of the larger blocks of chairs found in auditoria. This was done by using Eq. (1) to extrapolate to the smaller P/A values corresponding to the larger blocks of chairs found in auditoria. This approach was thought to more accurately account for sample size and edge effects. However, this procedure would require several sound absorption tests for each type of unoccupied chairs. Such estimates could be made for an average chair, but significant differences in the absorbing properties of unoccupied chairs were found and these were usually related to construction details of each type of chair.

While it is important to be able to predict the absorbing properties of unoccupied chairs, it is perhaps more important to know the properties of occupied chairs. In this paper the measured sound absorbing properties of occupied chairs are also shown to be linearly related to P/A ratios as in Eq. (1). The properties of occupied chairs were measured in reverberation chamber tests. Extrapolations of these measurements were used to successfully predict the expected absorption of occupied chairs in auditoria having the same type of chairs. These results were then used to develop more general procedures for estimating the sound absorbing properties of occupied theatre chairs.

I. REVERBERATION CHAMBER MEASUREMENTS

Samples of a type of theatre chair that were installed in several high school auditoria were obtained for reverberation chamber sound absorption tests. A total of 18 chairs were available and these were arranged in various groups with a row-to-row spacing of 0.76 m. That is, the back of one chair was 0.76 m behind the same point on the corresponding chair in the next row. This corresponded to the row-to-row spacing found in the school auditoria. The various samples gave a range of P/A values between 1.5 and 3.3 m^{-1} for unoccupied chairs and 1.7 to 3.3 m^{-1} for occupied chairs. The chairs included no porous absorbing material. As illustrated in Fig. 1 they had plywood backs, vinyl covered upholstered seats, and solid metal seat pans. Unoccupied, the chairs were not very absorptive. Occupied measurements were made with 13- to 19-year-old high school students in the chairs. They were essentially adult in size and were wearing normal indoor clothing.

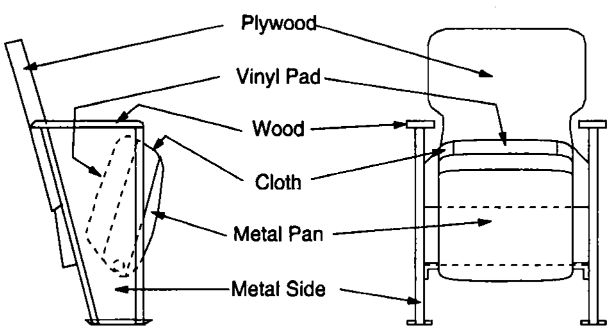

FIG. 1. Construction details of the low absorption auditorium chairs.

Tests were performed in a 250-cubic-meter reverberation chamber having fixed diffuser panels as well as a large rotating vane. The chamber is kept at a constant temperature of 20 °C and a relative humidity of 55%. Measurements were made using least-squares fits to the decays from the ensemble average of 20 sound decays at each of nine independent microphone positions in the room. Measurements were made in $\frac{1}{3}$-oct bands, but the three individual $\frac{1}{3}$-oct sound absorption coefficients in each octave band have been arithmetically averaged to produce a single value representative of the octave for subsequent comparison with octave-band measurements in halls. Absorption coefficients were calculated using the Sabine reverberation time equation and the floor area occupied by the chairs as the sample area. For these results no attempt has been made to physically eliminate the absorption of the edges of the blocks of chairs, because this is accounted for by the extrapolation to smaller P/A values.

The measured absorption coefficients were then plotted versus the ratio of the sample perimeter-to-area, P/A. Figure

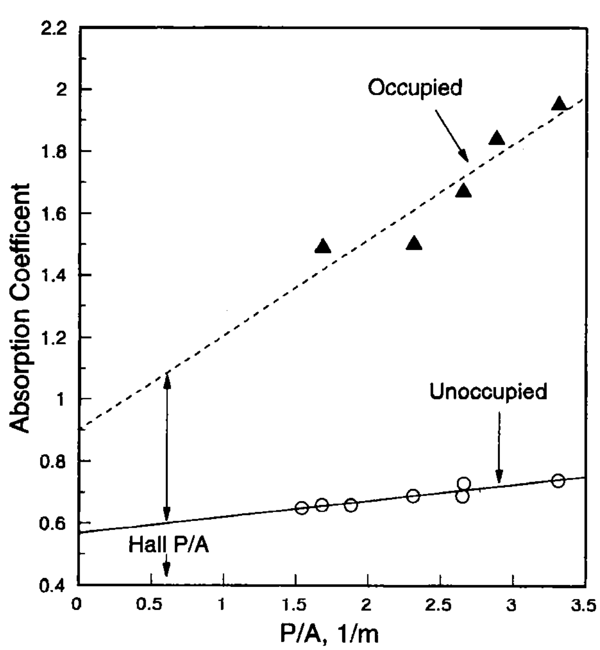

FIG. 2. Measured 1000-Hz absorption coefficients versus sample P/A for occupied and unoccupied low absorption chairs.

TABLE I. Regression coefficients and their standard errors, SE, relating octave band absorption coefficients to sample P/A values for the lowabsorption school auditorium chairs

		Occupied		
frequency	β	SE	α_∞	SE
125	0.092	0.028	0.522	0.075
250	0.131	0.029	0.745	0.076
500	0.212	0.038	0.923	0.100
1000	0.308	0.072	0.900	0.189
2000	0.309	0.081	0.931	0.212
4000	0.276	0.093	1.051	0.243
		Unoccupied		
frequency	β	SE	α_∞	SE
125	−0.014	0.018	0.529	0.043
250	0.045	0.011	0.582	0.027
500	0.049	0.021	0.580	0.049
1000	0.052	0.008	0.569	0.020
2000	0.035	0.011	0.463	0.026
4000	−0.026	0.029	0.516	0.068

2 shows as an example the 1000-Hz results for both occupied and unoccupied chairs. Linear regression lines were fitted to each set of data and these were extrapolated to a P/A value of 0 m^{-1} corresponding to a sample of infinite area. The difference between the regression lines for occupied and unoccupied chairs can be used to estimate the incremental effect of an audience for a specific P/A value. That is, for a particular sized block of chairs one can estimate the incremental effect of adding an audience. Of course, this is only possible if the properties of both the occupied and unoccupied chairs are known.

The occupied and unoccupied chair absorption coefficients were approximately linearly related to the P/A values of the blocks of chairs in each octave band. The coefficients of the equations for all the regression lines similar to those in Fig. 2 are given in Table I along with the associated standard errors. These are statistical relationships and the standard deviations give an indication of the scatter about the mean trend of the regression lines.

II. AUDITORIUM MEASUREMENTS

Reverberation time measurements were made in three geometrically quite different school auditoria containing the same type of chairs as shown in Fig. 1. The volume and number of seats in each auditorium are given in Table II. along with the slope of the floor. Lisgar and Glebe were older auditoria with relatively high ceilings and a balcony. The Ridgemont auditorium is a more modern design that is somewhat fan shaped and with a relatively low ceiling. Dur-

TABLE II. Details of the three school auditoria.

Name	Volume (m^3)	No. of seats	No. of people present	Floor slope (deg) main	Floor slope (deg) balcony
Lisgar	3800	878	910	4.0	25.0
Ridgemont	3000	783	780	7.5	···
Glebe	5000	1200	750	3.5	26.0

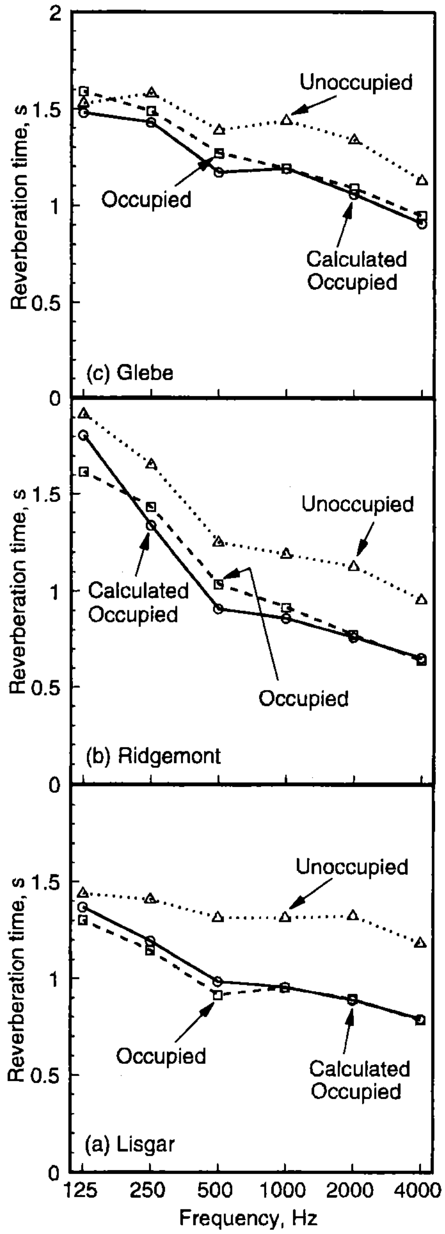

FIG. 3. Comparison of measured reverberation times for occupied and unoccupied cases with calculated occupied reverberation times. (a) Lisgar, (b) Ridgemont, and (c) Glebe auditoriums.

ing the measurements in the Lisgar and Ridgemont auditoria, they were fully occupied and had additional people onstage. The Glebe auditorium was not fully occupied but the audience was concentrated in the front portions of the seating.

Reverberation times were measured using our room acoustics measurement software, RAMSoft-II. This uses a maximum length sequence signal and a fast Hadamard transform procedure to obtain impulse responses. Using a reduced signal level and averages of ten 2.5-s-long sequences, good decays were obtained. The test signals were lower in level than the normal activities in the auditoria.

Measurements were made at six locations in each hall for both occupied and unoccupied conditions. Exactly the same positions were used for the occupied and unoccupied

TABLE III. Regression coefficients and their standard errors, SE, relating octave-band absorption coefficients to sample P/A values for occupied highly absorptive type E chairs from Ref. 3.

Frequency	β	SE	α_∞	SE
125	−0.057	0.061	0.792	0.118
250	0.045	0.101	1.136	0.197
500	0.181	0.059	1.254	0.114
1000	0.337	0.098	1.115	0.189
2000	0.399	0.076	1.073	0.148
4000	0.431	0.074	1.018	0.144

tests. Average octave-band reverberation times, RT, were determined for both conditions of occupancy in all three halls.

Expected occupied RT values were calculated from the unoccupied measurements using Eq. (1) and the regression coefficients in Table I. That is, for each block of seats the P/A ratio was determined and the effective incremental absorption coefficients were calculated. From these, the total sound absorption added by the audience was calculated and added to the total measured absorption of the unoccupied hall. The resulting calculated RT values for occupied conditions are compared with average measured values in Fig. 3 for the three halls. The addition of the audience changed RT values most in the Lisgar auditorium and the calculated RT values are in excellent agreement with the measured values in Fig. 3(a). The RT values in the other two auditoria changed less with the addition of the audience, but calculated RT values were again in good agreement with measured occupied values. Of the 18 octave-band RT calculations for the three halls, 16 were within 0.1 s of the measured occupied values.

The comparisons in Fig. 3 demonstrate the success of the procedure. The absorbing properties of one type of occupied theatre seating were accurately predicted from reverberation chamber tests of the same type of chairs by using Eq. (1) and the appropriate regression coefficients. The extension of this approach to other types of occupied chairs is considered in the following section.

III. DEVELOPING A GENERAL PREDICTION SCHEME

Two possible approaches for predicting the absorbing properties of occupied theatre chairs are proposed. The most accurate would be to measure the sound absorbing properties of various sized blocks of each type of occupied chairs in a reverberation chamber and extrapolate to the smaller P/A values expected in a particular hall. This is the approach used to predict the effect of the occupied chairs in the three auditoria above. The regression equations formed by using Eq. (1) and the regression coefficients in Table I could be used to predict the effect of these same chairs in any other auditorium where the dimensions of the seating blocks are known. This is thought to be the most accurate approach but would require several reverberation chamber sound absorption tests for each type of occupied chairs. A more convenient approach would be to base predictions on the average absorbing properties of several types of occupied theatre chairs.

Because the occupants tend to cover most of the sound absorbing parts of theatre chairs, one might suppose that dif-

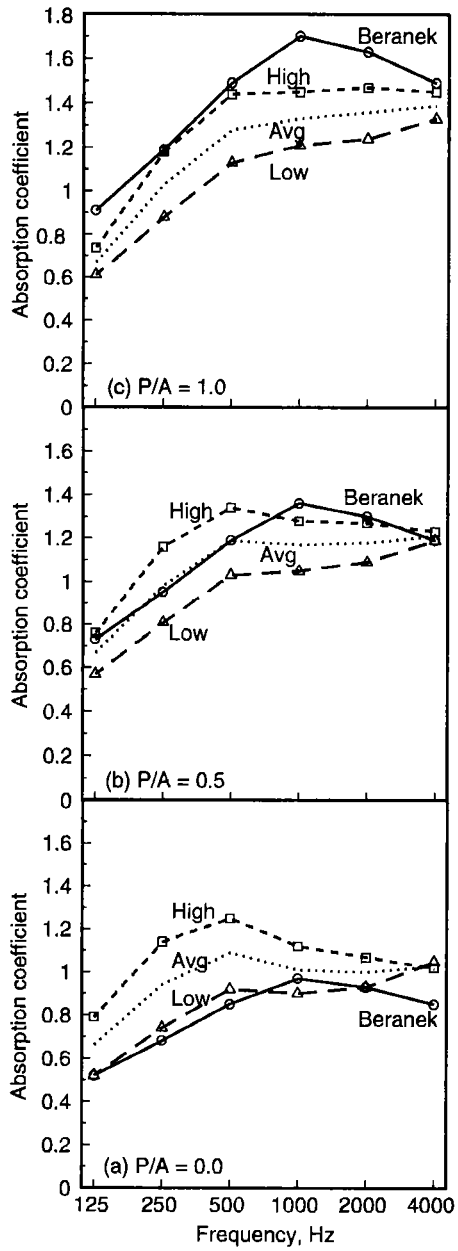

FIG. 4. Comparison of calculated absorption coefficients for occupied chairs with low, average, and high absorption, with results using Beranek's method, (a) P/A=1.0, (b) P/A=0.5, and (c) P/A=0.0.

ferent occupied theatre chairs would have similar absorbing properties. (This has previously been suggested by Davies *et al.*[4] and Barron.[5]) To ideally test this idea, sound absorption data as a function of P/A ratio would be required for a range of types of theatre chairs. Such occupied absorption data are not available, but data for the extremes of this range are known. The chairs described in Fig. 1 are representative of theatre chairs with about the least possible sound absorption and will be referred to as low absorption chairs. The measurements of the occupied type E chairs of Ref. 3 are representative of the most sound absorptive chairs and will be referred to as high absorption chairs. These data include sound absorption coefficients of the occupied type E chairs as a function of sample P/A ratio obtained from reverberation chamber measurements. Almost all surfaces of the type E

TABLE IV. Regression coefficients relating octave-band absorption coefficients to sample P/A values for the average of the school chairs and the type E chairs from Ref. 3.

Frequency	β	α_∞
125	0.018	0.657
250	0.089	0.939
500	0.196	1.088
1000	0.322	1.008
2000	0.354	1.002
4000	0.355	1.032

chairs had cloth covered sound absorbing material and the seat pans were perforated metal over sound absorbing material. Thus these two types of chairs are very good approximations to the possible extremes for the sound absorbing properties of theatre chairs.

It is thought that the most critical differences between various types of occupied chairs are the surfaces of the chairs that are not covered by the occupants. That is, the most important differences will relate to the sound absorbing characteristics of the underside of the seat and the rear of the seat back. Where these two surfaces are essentially nonabsorbing the absorbing properties of the occupied chairs should approximate the low absorption chair case. Where these surfaces are highly absorptive, the occupied chairs should approximate the properties of the high absorption case. Intermediate absorbing characteristics should approximate the average of the low and high absorption examples.

The sound absorption characteristics of the low, average, and high absorption occupied chairs were first compared for several P/A values. Equation (1) and the regression coefficients in Table I were used to predict effective sound absorption coefficients of blocks of the occupied low absorption chairs as a function of the P/A value of the blocks. Similar regression coefficients were published for the type E chairs[3] and are repeated here in Table III. The predicted effective sound absorption coefficients for the two types of occupied chairs are compared in Fig. 4. Comparisons are given for P/A values of 0, 0.5, and 1.0 m^{-1}. A P/A value of 0 m^{-1} corresponds to an infinite area sample. Most blocks of chairs in halls have P/A values in the range of 0.5–1.0 m^{-1}. Thus these P/A values represent the range of most interest.

There are systematic, but not very large, differences between the sound absorbing properties of the low and high absorption chairs. Thus all occupied chairs do not have the same effective sound absorption coefficients. However, both of these two extreme types of occupied theatre chairs do vary approximately linearly with sample P/A ratio.

Also shown in Fig. 4 are the absorption coefficients of an average occupied chair intermediate to the low and high absorption chairs. The properties of an average occupied theatre chair were calculated from the average of the two extreme types of chairs. Again equations of the form of Eq. (1) were fitted to the average data and the resulting regression coefficients are given in Table IV. These are the average of the two sets of regression coefficients and so standard errors are not included.

These average chair absorption coefficients should be a reasonable approximation to the properties of occupied theatre chairs with absorbing properties intermediate to the low and high absorption examples, that is, chairs with a small amount of absorption on the rear of the seat back and/or the underside of the seat. The differences between the absorption coefficients of the two extreme chair types and the average chair are typically ±0.1 or a little greater. The largest difference is 0.17. Thus by determining which of the three characteristics (low, average, or high absorption) a particular type of occupied chair resembles, it should be possible to accurately predict the absorption coefficients as a function of the size of the block of chairs.

Figure 4 also includes sound absorption coefficients calculated using Beranek's procedure which will be discussed later, in Sec. IV.

Using this new approach, occupied chair absorption coefficients are not just a simple function of frequency, they depend on both frequency and P/A value. Figure 5 illustrates the resulting surface of absorption coefficients for the average chair case. The low and high absorption case results lead to similar surfaces. P/A values of 0.5–1.0 m^{-1} are typical of blocks of seats in actual auditoria. P/A values of 2.0–4.0 m^{-1} are representative of the much smaller blocks of chairs normally tested in reverberation chamber sound absorption tests. This figure illustrates how the shapes of the absorption coefficient versus frequency curves change with P/A value and that reverberation chamber test results do not correctly characterize the absorbing properties of theatre chairs in auditoria. It is essential to also consider the sample P/A value to more completely describe the absorbing properties of occupied chairs.

The recommended procedure for estimating the sound absorption coefficients of occupied theatre chairs can be summarized as follows:

(a) Categorize the chairs in questions as similar to the low, average, or high absorption chair examples. (This should be based on the absorbing properties of the rear of the seat backs and the underside of the seats.)

(b) Use the regression coefficients from either Tables I, III, or IV (corresponding to the chair category) and Eq. (1) to predict the effective sound absorption coefficients for each block of chairs (i.e., based on the P/A value of each block of chairs).

(c) Calculate the sound absorption of each block and sum these with the absorption of other surfaces of the hall to calculate the expected occupied reverberation time.

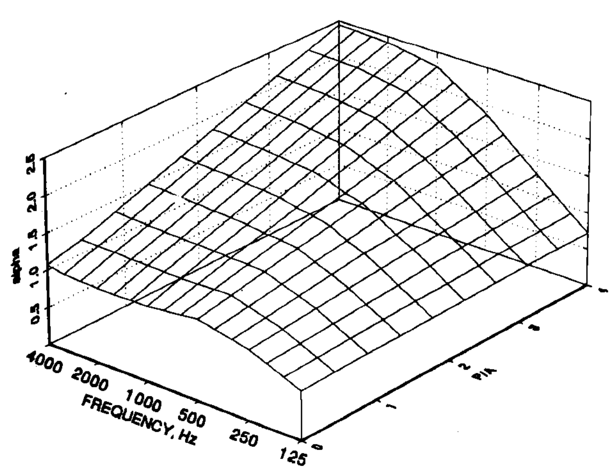

FIG. 5. Average absorption coefficients for occupied chairs as a function of octave-band frequency and sample P/A ratio. Calculated using Eq. (1) and regression coefficients in Table IV.

Using this approach, it is estimated that one can expect to predict most absorption coefficients for occupied theatre chairs within about ±0.1. To further improve the method, one could also create intermediate categories of absorption coefficients for chairs with properties between the average chairs and the two extreme types of chairs. In this way one could more closely approximate the absorbing properties of a particular type of chair.

IV. COMPARISONS WITH OTHER PUBLISHED RESULTS

In this paper the absorption coefficients of samples of occupied chairs are shown to vary with the sample size and can be predicted from the sample P/A ratio. Beranek[1,2] has proposed a different method for predicting the absorption coefficients of various sized blocks of audience seating. In a previous publication[6] Beranek's method was shown to be mathematically equivalent to making predictions based on Eq. (1). While the two methods are mathematically equivalent their implementations are different. Beranek's method is based on adding an edge strip 0.5 m wide at all frequencies. The β values reported in this paper would suggest that the width of the added edge strip should vary with frequency as previously reported for unoccupied chairs.[4]

Beranek's procedure for occupied theatre chairs is compared with the present results in Fig. 4. Beranek's absorption coefficients for occupied chairs[2] are compared directly with our infinite area results (P/A=0 m^{-1}) in Fig. 4(a). This comparison shows Beranek's data to agree most closely with the low absorption occupied theatre chairs. Beranek's method was also compared for blocks of chairs having P/A values of 0.5 and 1.0 m^{-1} in Fig. 4. In performing these calculations, each block of seats was assumed to have an aisle on either side and at the front of the block. The plotted results are the average of several different seating blocks having the same P/A ratio. For a P/A 0.5 m^{-1} the Beranek method again agrees most closely with the low absorption case, but for smaller blocks of chairs (P/A=1.0 m^{-1}), Beranek's method tends to be intermediate to the low and average absorption cases.

The results obtained using Beranek's method are in remarkable agreement with the new predictions for low absorption chairs. Perhaps most of the chair types included in his derivations were similar to the low absorption case in this paper. That is, they may have tended to have relatively nonabsorptive surfaces on the rear of the seat backs and the underside of the seats. The new results corroborate Beranek's

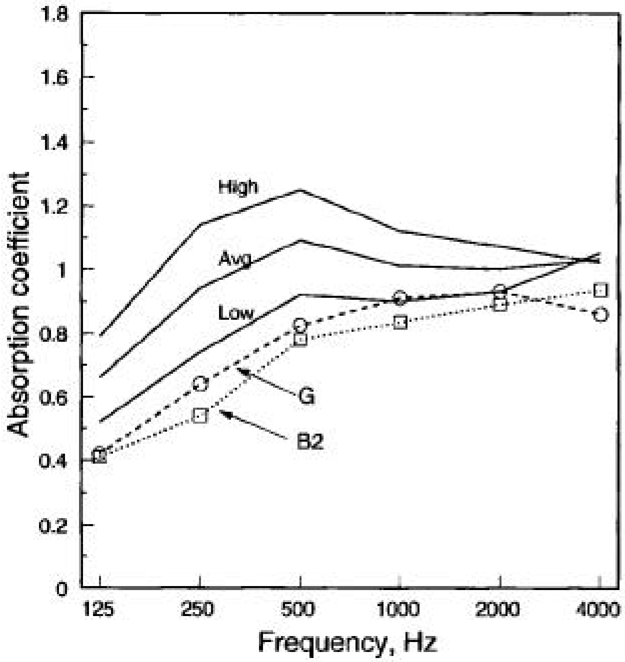

FIG. 6. Comparison of calculated absorption coefficients for occupied chairs having low, average, and high absorption with results from Davies *et al.*[4] types G and B2 occupied chairs (P/A=0).

earlier calculations and further explain the success of his method.

Very recently Davies *et al.*[4] published measured sound absorption coefficients for two types of occupied theatre chairs. They were measured in a reverberation chamber with 1.2-m-high screens around them to minimize edge effects. Thus these results are expected to represent those of an infinite sample (P/A=0 m^{-1}). The description of the chairs indicates that the rear of the seat back and the underside of the seats were essentially nonabsorbing and hence they would be expected to have similar absorbing properties as the low absorption case.

The occupied chair sound absorption coefficients for the "G" and "B2" chairs of Davies *et al.* are compared with the low, average, and high absorption data for P/A=0 in Fig. 6. These two sets of data are quite similar to the low absorption case results in Fig. 5, but tend to have slightly lower values in the lower octave bands. Several factors may combine to explain the differences between the Davies *et al.* data and the low absorption case results. There are possible errors associated with the measurement procedure used by Davies *et al.* In particular, it is not clear how precisely the use of screens leads to results that approximate those from an infinite sample. Such screens can lead to anomalous results at low frequencies[3] and the 1.2-m-high screens my also block some sound energy that would normally be incident on the top surface of the occupied chairs. There is also error associated with the extrapolations of the low absorption chair data to a P/A value of 0. The standard error values associated with the regression coefficients in Table I indicate that in some cases these errors could be quite substantial.

Overall, the comparisons with Beranek's results and the measurements of Davies *et al.* suggest that the new method is a quite useful approach for predicting the sound absorption of occupied theatre chairs. Of course, there is now a clear need to validate, and perhaps further fine tune, the procedure in terms of a larger set of measurements.

V. CONCLUSIONS

This paper provides a better understanding of, and two methods for predicting, the sound absorbing properties of occupied theatre chairs.

The measured effective absorption coefficients of low absorption theatre chairs and the high absorption type E chairs showed that all occupied chairs do not have the same absorbing properties. Even when occupied, measured sound absorption coefficients vary with the properties of the chairs.

The direct results of reverberation chamber tests of small samples of occupied chairs are not representative of the sound absorption of the larger blocks of chairs found in typical auditoria. The smaller blocks of chairs used in reverberation chamber tests will have much larger sound absorption coefficients. These differences are most pronounced at mid- and high frequencies.

The effective sound absorption coefficients of occupied theatre chairs are approximately linearly related to sample P/A ratio. Thus one can accurately predict the effective sound absorption coefficients of larger blocks of chairs by extrapolating from measurements of various sized blocks of chairs in reverberation chamber sound absorption tests.

Where detailed reverberation chamber absorption measurements of chairs are not available, this paper also proposes a new method for predicting the absorption of occupied chairs based on expected absorbing properties of low, average, and high absorption chairs. The sound absorption coefficients are predicted from the P/A ratio of each block of chairs in the auditorium. Regression coefficients for low, average, or high absorption occupied chairs can be used. The method is estimated to typically predict most absorption coefficients within an accuracy of about ±0.1.

Beranek's method is seen to be mathematically equivalent to the new method and produces absorption coefficients that are very similar to the low absorption chairs of this study.

There remains a need to further validate the new method for a wider range of auditoria and chair types with a larger series of measurements of the sound absorbing properties of occupied chairs both in a reverberation chamber and in auditoria.

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