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공석 시 측정값을 활용한 만석 시 강의실의 음향상태 예측법

Proposing a simple procedure for predicting the acoustical conditions in occupied classrooms from the measured unoccupied values

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Abstract

This work proposes a simple method to use the added absorption per person values to predict the expected values of the acoustical conditions in occupied classrooms. This method is based on the effects of the values of added absorption per person on the unoccupied total absorption values of the classrooms and on other room acoustical parameters. The total sound absorption in an unoccupied classroom can be calculated from measured reverberation times in the classroom. The expected occupied absorption can be calculated using equation which was obtained in a previous study (Choi, 2017) by fitting a linear regression line to a plot of total occupied absorption versus the corresponding unoccupied total absorption values measured in 12 university classrooms. The ratios of occupied-to-unoccupied sound absorption are used to predict increments in the values of acoustical parameters that result when occupants are added to the rooms.

Keywords: Occupants, Total room sound absorption, Classrooms, Acoustical parameters

1. Introduction

The changes to the values of room acoustics parameters due to added occupants in classrooms are influenced by the percentage change of the total sound absorption[3] and also by the size of sample blocks of chairs[3]. The two university classroom acoustics studies[3, 7] showed a significant effect of the presence of occupants on the acoustical conditions in classrooms. That is, the addition of occupants to the more reflective classrooms led to larger fractional increases in the total sound absorption of the classrooms and to larger incremental changes to the values of the related room acoustics parameters. The changes to the values of acoustical parameters were: the *EDT* values (early decay time), the C_{50} values(early-to-late-energy ratios), the G_{late} values (strength of the late-arriving sounds), and the U_{50} values (useful-to-detrimental sound ratios)[4].

In the previous work[3], a simple method for estimating the added sound absorption per occupant to classrooms that are similar to the 12 university classrooms was proposed. Linear regression lines were fitted to a plot of the total measured sound absorption of the occupied classrooms versus that of the unoccupied classrooms at mid-frequencies (500 Hz and 1 kHz octave bands). One could estimate average octave band values (500 Hz and 1 kHz octave bands) of the sound absorption added per occupant in

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classrooms and apply these values to other classrooms.

This work is a follow-up to previous work[5] that introduced a simple procedure for estimating the expected effects of occupants on the acoustical conditions of 12 university classrooms. Values of room acoustics parameters such as *EDT*, C_{50}, G_{late}, and U_{50} are useful indicators of the quality of conditions for speech in rooms intended for speech communication. It is more difficult to measure these parameters in occupied spaces and hence being able to predict occupied values of these acoustical parameters from unoccupied measurements is a great asset to achieving acoustically successful classrooms. This process is based on the effects of the values of added absorption per person on the unoccupied total absorption values of the classrooms and on other room acoustics parameters. The goal of the present work is to propose a simple method to use the unoccupied values to predict the expected values of the acoustical parameters in occupied classrooms.

2. Measurement procedures

2.1 Measurements of acoustical parameters in classrooms

Table 1 presents the mean dimensions of the 20 university classrooms and the mean percentage of seats occupied during the measurements. The mean T_{30} values at mid-frequencies (500-1000 Hz) for both occupied and unoccupied classrooms are also included in Table 1. Here, the T_{30} values were averaged over the two octave bands between 500 and 1 kHz, which are important for speech. Of the 20 classrooms, the measured data for 12 classrooms (#1~#12 listed in Table 2) in previous paper[5] was used. New measured data for the other 8 classrooms (#13~#20 listed in Table 2) was included in Table 1. Of the 20 classrooms, 17 were used for lectures, and 3 were used for computers, teleconferences and conferences. Fifteen classrooms had rectangular shapes with windows on one side and 5 classrooms had non-rectangular shapes. The mean percentage of seats occupied during the measurements was 58%. The occupants were allowed to choose where they wished to sit. Most of the occupants were wearing heavy winter jackets during the measurements of the occupied classrooms. The measured mean mid-frequency (500-1000 Hz) T_{30} values for the 20 classrooms with and without occupants were 0.65 and 1.04 s respectively. Speech-reinforcement systems were installed in some larger sized classrooms, but they were not in operation during the measurements.

Room acoustical quantities were determined from the measured impulse responses in occupied classrooms. A logarithmic sine sweep signal was used as the source signal and was radiated into the classroom from a dodecahedron loudspeaker (Norsonic, Nor276). Measurements were made at four to nine receiver positions using 1/2"free-field microphones (G.R.A.S, Type 46AF) evenly distributed among the seated occupants in each classroom, at a height of 1.2 m. One centre source position at a height of 1.5 m was used.

The reverberation times (T_{30}), the early decay time (*EDT*), the early-to-late-energy ratios (C_{50}), and the strength (*G*) were measured in accordance with ISO 3382 (2003) using the Dirac software V.6.0 (BRÜEL & KJÆR, 2014)[8, 9]. The strength of the late-arriving sounds (G_{late}) was calculated from the measured *G* values and C_{50} values. The G_{late} values are the strength of the later arriving reflections arriving after the first 50 ms of the impulse response. The actual ambient noise levels were measured at each receiver position in each classroom. Useful-to-detrimental sound ratios (U_{50}) values were determined from both signal-to-noise ratios (SNR) and C_{50} values. In this work, U_{50} values[4] were calculated by averaging octave band values from 125 to 4000 Hz and using the frequency weightings from the STI measure (IEC 60268-16, 2011) following the procedure used in BRADLEY's work (2011)[1, 8].

Table 1 Mean dimensions of the 20 classrooms and the mean percentage of seats occupied during the measurements including mean mid-frequency (500-1000 Hz) T_{30} values for both occupied and unoccupied cases.

	Volume, m^3	Percentage of seats occupied, %	Number of occupants	Unoccupied 500-1000 Hz T_{30} values, s	Occupied 500-1000 Hz T_{30} values, s
Mean	519	58	47	1.04	0.65
s.d.	584	26	23	0.47	0.20
Max	2535	100	84	1.81	0.89
Min	188	20	11	0.31	0.26

Table 2 Mean 1000 Hz total sound absorption for occupied and unoccupied classrooms and the ratios of occupied-to-unoccupied total room sound absorption for 20 classrooms.

Classrooms	Mean 1000 Hz total sound absorption, m^2		The ratio of occupied-to-unoccupied total room sound absorption
	Occupied	Unoccupied	
#1	35.5	23.1	1.54
#2	42.1	35.5	1.19
#3	59.9	40.5	1.48
#4	48.4	33.8	1.43
#5	72.0	31.2	2.30
#6	53.0	22.9	2.31
#7	381.8	377.0	1.01
#8	313.6	245.1	1.28
#9	415.0	388.7	1.07
#10	184.5	153.2	1.20
#11	454.7	428.8	1.06
#12	258.3	242.9	1.06
#13	84.7	65.2	1.30
#14	68.3	34.4	1.98
#15	48.0	23.2	2.06
#16	75.4	31.6	2.39
#17	67.4	30.8	2.18
#18	48.3	25.0	1.94
#19	121.7	73.4	1.66
#20	81.6	54.0	1.51

2.2 Calculation of ratios of occupied-to-unoccupied total room sound absorption

Table 2 presents an example of the mean 1000 Hz total sound absorption values for occupied and unoccupied classrooms determined from the measured occupied and unoccupied reverberation times using Sabine equation (1).

$$A = 0.16\ V/T_{30}$$

where, A is total sound absorption in m^2, V is the room volume in m^3, and T_{30} is the reverberation time in s.

The ratios of occupied-to-unoccupied total room sound absorption at 1000 Hz for each classroom are also included in Table 2. The ratios of occupied-to-unoccupied total room sound absorption varied from about 1.01 to 2.39 for the 20 classrooms.

3. A simple procedure of estimating acoustical parameter values in occupied classrooms

Previous studies[5, 7] clearly showed that the addition of occupants to the more reflective classrooms led to larger fractional increases in the total sound absorption of the classrooms and to larger incremental changes to the values of the related room acoustical parameters. These acoustical parameters were *EDT*, C_{50}, G_{late}, and U_{50} values.

This section compares incremental changes to the values of the acoustical parameters, *EDT*, C_{50}, G_{late}, U_{50} values due to the added absorption of occupants. Linear regression analyses were performed to each plot of incremental changes on acoustical parameter values versus fractional increase in the total sound absorption of rooms with added occupants. The regression results calculated from the measurements of 20 classrooms are included in Table 3. Significant regression results ($p<0.01$) are found for the incremental changes to *EDT*, C_{50}, G_{late} and U_{50} values (see Table 3). The new regression results show better correlation coefficients compared to the regression results calculated from the measurements of 10 classrooms reported in a previous study[5]. This is probably due to the more varied ratios of occupied-to-unoccupied total room sound absorption values for the 20 classrooms in Table 2.

Figures 1-4 plot the measured changes at 1000 Hz of *EDT*, C_{50}, G_{late} and U_{50} values due to adding occupants to 20 classrooms versus the ratios of occupied-to-unoccupied total sound absorption at 1000 Hz for 20 classrooms. Data for the 12 classrooms[5] is marked in open circles (○) and the new data for the other 8 classrooms is marked in closed circles (●). Because the regression results in Table 3 show that these relationships are likely to be linear, the incremental changes in other classrooms due to adding occupants can be estimated from the resulting regression equations. These plots could be used to predict expected changes to acoustical parameter values in other classrooms based on the total sound absorption of unoccupied rooms and estimates of the added absorption due to the occupants. In Figure 4, the G_{late} results for some rooms deviate the most above or below from the regression line indicating varied occupied absorption than the mean trend.

Table 3 Summary of: the correlation coefficients (R^2), the statistical significance (p-value) of the correlation coefficients (* $p<0.05$, ** $p<0.01$), the values of slopes (β), and intercepts (α) for incremental changes in rooms.

		Incremental changes to acoustical parameter values			
N		ΔEDT	ΔC_{50}	ΔG_{late}	ΔU_{50}
20	R^2	0.925	0.839	0.711	0.873
	p	**	**	**	**
	b	-0.772	4.594	-4.267	0.729
	a	0.828	-4.557	3.177	-0.779

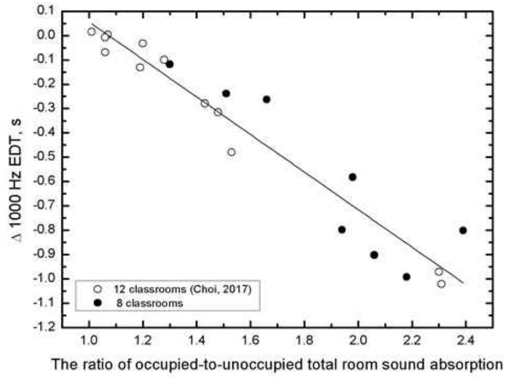

Fig. 1 Measured incremental changes to *EDT* values at 1000 Hz due to adding occupants to 20 classrooms versus the ratios of occupied-to-unoccupied total room sound absorption at 1000 Hz for 20 classrooms.

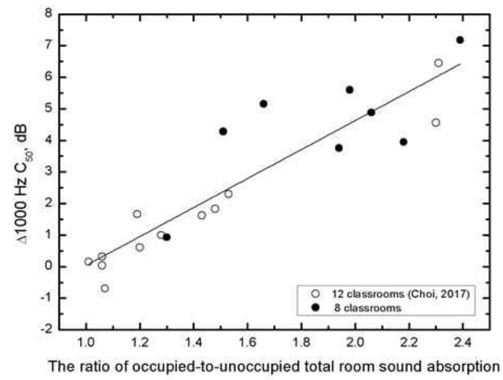

Fig. 2 Measured incremental changes to C_{50} values at 1000 Hz due to adding occupants to 20 classrooms versus the ratios of occupied-to-unoccupied total room sound absorption at 1000 Hz for 20 classrooms.

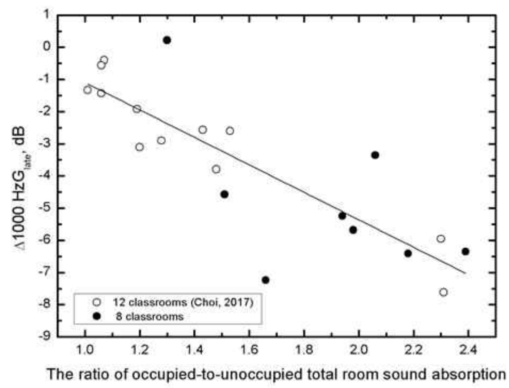

Fig. 3 Measured incremental changes to G_{late} values at 1000 Hz due to adding occupants to 20 classrooms versus the ratios of occupied-to-unoccupied total room sound absorption at 1000 Hz for 20 classrooms.

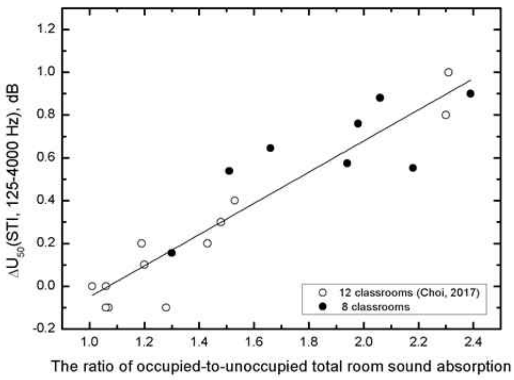

Fig. 4 Measured incremental changes to U_{50} values averaged of the octave bands 125 Hz to 4000 Hz due to adding occupants to 20 classrooms versus the ratios of occupied-to-unoccupied total room sound absorption at 1000 Hz for 20 classrooms.

Sample classroom A having a volume of 245 m^3 and a seating capacity of 80 seats is used for estimating the acoustical parameter values of occupied conditions from unoccupied data. The predicted changes at 1000 Hz of *EDT*, C_{50}, and G_{late} values for the sample classroom A were estimated from the resulting regression equations in Table 3. By predicting these values for this sample classroom, it will be demonstrating the usefulness of this simple method that uses the added absorption per person values to predict the expected values of the acoustical parameters in classrooms.

Table 4 presents the measured mean 1000 Hz T_{30}, *EDT*, C_{50}, and G_{late} values averaged over all receiver positions for the unoccupied classroom A. U_{50} values were not included in Table 4 because the SNR values were not measured in this classroom. The mean T_{30} value at mid-frequencies (500 Hz and 1000 Hz octave bands) for unoccupied sample classroom A was 0.69 s.

Table 4 Measured mean 1000 Hz T_{30}, *EDT*, C_{50}, and G_{late} values averaged over all receiver positions for the classroom A without occupants.

Acoustical parameter values			
T_{30}, s	*EDT*, s	C_{50}, dB	G_{late}, dB
0.59	0.56	4.1	12.4

The total sound absorption in an unoccupied classroom can be determined from measured reverberation times in the room using the Sabine equation (1). The expected occupied absorption can be estimated using equation (2) which was adopted from a previous study[3] by fitting a linear regression line to a plot of total occupied absorption versus the corresponding unoccupied total absorption values at 500 Hz and 1 kHz octave bands measured in 20 different university classrooms.

$$A_{occ}=1.04\bullet A_{unocc}+23.5,\ m^2\ (R^2=0.987,\ \sigma=0.028\ m^2) \quad (2)$$

Where A_{occ}=occupied absorption in m^2, and A_{unocc}=unoccupied absorption in m^2.

This relationship is quite accurate suggesting that for similar rooms with similar acoustical characteristics, one should be able to use it to predict expected occupied total sound absorption values from measured unoccupied absorption values. The measured unoccupied total sound absorption value, A_{unocc}, for the sample classroom A was 57.9 m^2. The expected occupied absorption value, A_{occ}, for the same classroom is 83.7 m^2. From the measured unoccupied total sound absorption values and the estimated occupied total sound absorption values one can calculate the ratios of occupied-to-unoccupied sound absorption. The ratio value would be 1.45. This ratio value is used to estimate increments in the values of acoustical parameters that result when occupants are added to the rooms using the regression equation in Table 3.

To illustrate this procedure Table 5 shows the predicted mean 1000 Hz *EDT*, C_{50}, and G_{late} values with their standard deviations for the occupied sample classroom A.

Table 5 Predicted mean 1000 Hz *EDT*, C_{50}, and G_{late} values with their standard deviations for the occupied sample classroom A.

	Acoustical parameter values		
	EDT, s	C_{50}, dB	G_{late}, dB
Predicted	0.27	6.2	9.4
s.d.	0.106	0.975	1.316

4. Conclusions

This work has proposed a simple procedure for estimating the acoustical characteristics of occupied classrooms from unoccupied values. It has shown that the incremental changes to acoustical parameters, *EDT*, C_{50}, G_{late}, and U_{50}, due to adding occupants to the classrooms can be predicted based on the ratio of occupied-to-unoccupied total sound absorption values for the rooms using the regression equations in Table 3.

Using this simple procedure, example predictions of mean 1000 Hz values of room acoustical parameters with their standard deviations for the occupied classroom A are presented in Table 5. If one knows the total absorption of an unoccupied room, the total absorption when occupied can be predicted from equation (2). Then, the added total sound absorption of occupants can be obtained from the differences between the occupied total absorption values and unoccupied total absorption values. The expected changes in acoustical parameters due to adding occupants can be predicted using the regression coefficients given in Table 4. Because the resulting regression equations are based on the ratios of occupied-to-unoccupied room absorption values, one can also apply them to predict the acoustical conditions of classrooms with varied occupancy.

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