ACOUSTICS OF SUSPENDED CEILINGS AND SPEECH PRIVACY

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ABSTRACT

Acoustics is an integral factor of indoor environmental quality, and it's essential that suspended ceilings systems of modern office building provide adequate acoustical separation. This paper evaluates the acoustic performance for different suspended ceilings systems installed in rooms with dividing partitions as to their speech privacy characteristics. The relation between speech privacy index and ceiling attenuation class (CAC), articulation class (AC), and subjective speech privacy rating has also been presented in this paper.

RÉSUMÉ

L'acoustique est un facteur intégrante de la qualité de l'environnement intérieur, et il est essentiel que les systèmes de suspension des plafonds de immeuble de bureaux moderne de fournir suffisamment de séparation acoustique. Cet article évalue la performance acoustique pour différents systèmes de plafonds suspendus installés sur les chambres de séparation des partitions à des fins de confidentialité de la parole. En outre la relation entre l'indice de la confidentialité des conversations et le plafond d'atténuation de classe CAC, classe d'articulation, AC et subjective Note confidentialité de la parole a été présenté dans le présent document.

1. INTRODUCTION

Modern office buildings are usually designed with large office areas where all services (including electricity, plumbing, and air supply ducts) are installed above a suspended ceiling. The plenum space above the suspended ceiling permits offices to be constructed with demountable walls and provides a flexible space to suit the occupants' needs. The partition wall extends up to the underside of the suspended ceiling to provide enough acoustical isolation between the rooms (offices). The sound propagates through the suspended ceiling, across the plenum space and back down through the ceiling of the other room [1]. Offices and meeting rooms are often intended for confidential discussions. Speech originating inside such a room being difficult to hear or understand in the adjoining spaces implies that the room provides good speech privacy. In cases where the degree of privacy is sufficiently high, one can speak of architectural speech "security". Improved security would be provided, for instance, by a room constructed with boundaries having higher sound transmission loss [2]. The typical private office provides far less than the minimum required level of confidential speech privacy. Most offices allow occupants located outside these private offices to easily overhear and understand sensitive conversations that occur inside [3]. This paper evaluated acoustically different ceiling systems installed over spaces that have partition wall of high sound insulation extending up to the underside of these systems for their speech privacy characteristics between closed rooms.

2. ACOUSTIC METRICS

The following acoustic descriptors have been used for different suspended ceilings systems to evaluate its speech privacy performance of closed rooms.

2.1 Speech privacy

The degree of privacy offered by a closed room is an indication of how audible or intelligible conversations occurring within are in the adjoining spaces [4]. ASTM Standard, E 1130, describes a means of measuring speech privacy objectively between locations in open offices. The standard uses acoustical measurements, published information on speech levels, and provides a method for assessing speech communication. The standard could also be adapted for measuring the speech privacy between fully enclosed spaces [6]. While both the articulation index and the ASTM E1130 standard can be expected to reliably predict average speech privacy, neither predicts the specific degree of speech privacy afforded to closed office occupants. The useful scale for speech privacy is called Privacy Index, (PI). It is expressed in percent and can be calculated from the Articulation Index, (AI) as follows [5]:

$$PI = (1 - AI) \text{X} 100\% \qquad (1)$$

2.2 Articulation Class (AC)

Articulation class is a single number rating that can be used for comparing building systems and subsystems for speech privacy purposes. The rating is designed to correlate with transmitted speech intelligence between office spaces. In particular, the AC considers that the effect of signal attenuation articulation class is the result of the attenuation provided by a single component. AC is calculated according to ASTM E 1110 [6]. AC is used as a tool to classify and compare ceiling systems. Articulation class shows the performance of individual components and fittings that affect speech privacy.

AC is a weighted single value using scaled ANSI S3.5 [7] weighting factors defined for Articulation Index. For each source-receiver location, the weighted attenuations for all involved frequencies are added together and rounded off to the nearest multiple of 10, giving the AC value for a given location. The lowest AC figure shall be presented and expressed as minimum AC value [6, 8].

2.3 Ceiling Attenuation Class (CAC)

With the current light construction, walls often do not extend to the structure. The path for sound through the ceiling plenum is the weakest path between offices. The sound path is related with a ceiling attenuation class (CAC) that is analogous to a sound transmission class rating. The CAC value is measured in accordance with ASTM Standard E1414 [9] and measures the sound transfer from one room to another room through ceiling, plenum and then back to the adjacent room through the ceiling tiles.

The measurement of a normalized ceiling attenuation requires that the value of a normalization term dependent upon the amount of sound absorption present in the receiving room be known. The ceiling attenuation (Dc) between the source and receiving rooms where flanking transmission by all paths are at least 10 decibels lower than the path through the ceiling and plenum is determined as follows [9]:

$$D_c = \overline{L_S} - \overline{L_R} \quad (2)$$

where $\overline{L_S}$ is the average one-third octave band sound pressure level in the source room,

$\overline{L_R}$ is the average one-third octave band sound pressure level in the receiving room

Normalized ceiling attenuation ($D_{n,c}$) is the ceiling attenuation adjusted to account for receiving room absorption as follows:

$$D_{n,c} = D_C + N_f \quad (3)$$

where N_f is the normalization term for receiving room absorption. The normalization term is given by the formula [9]:

$$N_f = 10 \log \frac{A_0}{A} \quad (4)$$

where, A_0 = 12 metric sabins, and A is the sound absorption of the receiving room in metric sabins measured by the decay method

The ceiling attenuation class (CAC) is a single figure rating derived from the normalized ceiling attenuation values in accordance with ASTM Standard E413 [10].

3. THE EXPERIMENT

Acoustic measurements for different ceiling systems have been carried out in Housing and Building National Research Center, HBRC. The acoustic measurements included:

- Ceiling attenuation class (CAC)
- Articulation class, (AC)
- Privacy Index, (PI)
- Subjective speech privacy rating

The laboratory test facility consists of an outer shell divided into two rooms by a partition and a suspended ceiling (the test specimen). The rooms are built so that the only significant sound transmission path between them is that provided by the test specimen and the ceiling plenum. One continuous 10m × 5m ceiling with 1 m deep plenum was constructed with a STC 65 partition, resulting in two rooms, 4m × 5m source room and 6m × 5m receiving room as shown in Figure 1.

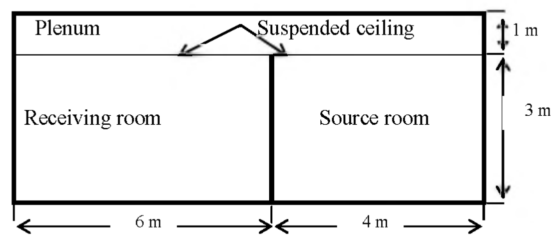

Figure 1. Details of the Two Rooms

The ceiling attenuation is determined in each of the test frequency bands, by placing a sound source in one room and then calculating the difference of the average sound pressure levels in both rooms. All internal surfaces of the two rooms were covered with ordinary cementatious material and the floor of the two rooms was ceramic tiles. Different ceiling systems were installed over the partition with the same plenum depth. The codes and specifications of these ceiling are summarized in Table 1.

Table 1. Description of the tested ceiling systems

ID	Ceiling description
SA1	Metal tiles 0.5 cm thick without perforation and thin PVC black layer, weight 5.8 kg/m^2
SA2	Metal tiles 0.5 cm thick of perforation 20% with thin PVC black layer, weight 4.5 kg/m^2
SA3	Metal tiles 0.5 cm thick of perforation 20% with thin PVC black layer, weight 4.5 kg/m^2 and 1.25 cm rock wool of density 50 kg/m^3
SA4	Metal tiles 0.5 cm thick of perforation 20% with thin PVC black layer, weight 4.5 kg/m^2 and 2.5 cm rock wool of density 50 kg/m^3
SA5	Metal tiles 0.5 cm thick of perforation 20% with thin PVC black layer, weight 4.5 kg/m^2 and 3.8 cm rock wool of density 50 kg/m^3
SA6	Metal tiles 0.5 cm thick without perforation and thin PVC black , weight 5.8 kg/m^2 and of 5 cm rock wool of density 50 kg/m^3
SA7	2.44m × 0.3 m × 20 mm perforated panel MDF with matte veneer and 5 cm rock wool of density 50 kg/m^3, Perforation: diameter of hole 12 mm of percentage open area 15%, weight 7.5 kg/m^2

The partition that divided the two rooms has the following construction layers as shown in Figure 2.

1. single layer of 13 mm type X gypsum board
2. single layer of 13 mm type X gypsum board
3. 40 mm steel studs at 610 mm on centre
4. 40 mm of mineral fibre insulation in cavity 50kg/m^3
5. 90 mm air gap
6. 40 mm steel studs at 610 mm on centre
7. 40 mm of mineral fibre insulation in cavity 50kg/m^3
8. single layer of 13 mm type X gypsum board
9. single layer of 13 mm type X gypsum board

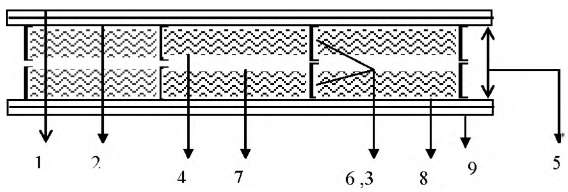

Figure 2. Construction of Partition Wall between Source and Receiving Room

The sound transmission of this partition was measured according to ASTM E90 [12] the transmission results are shown in Figure 3.

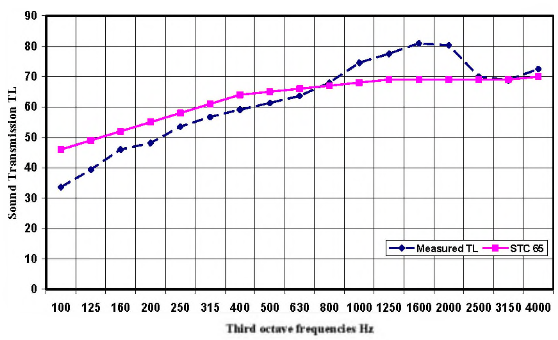

Figure 3 Measured Transmission Loss and STC

3.1 Ceiling Attenuation Class

The sound signals used for these tests were random noise having a continuous spectrum within each test frequency band from 100 to 4000 Hz generated by Bruel & Kajer sound source type 4292. The sound source was far enough away from the test partition and pointing in to the test specimens. The sound source radiated enough sound above the back ground noise (more than 10 dB). The sound level meter type 2270 connected to microphone type 4189 (B&K) that was calibrated by using calibrator type 4231 (B&K) to measure the sound pressure levels in the source room and receiving room. Fixed microphone is used in 5 positions which were 1.5 from the sound source at least in source room and 5 positions in the receiving room which were 1 m at least from any surface in the rooms. The sound decay rates in the receiving room have been measured 3 time for two positions of sound source. The average decay and reverberation time determined to calculate the sound absorption in receiving room according ASTM E 2235 [11].

The CAC values were then determined by applying Equations 2, 3 and 4.

3.2 Speech Privacy Index

The speech privacy in the receiving room was evaluated as follows. At the listener location, the ambient sound pressure levels were measured in each one-third octave-band from 200 to 5000 Hz as well as the overall A-weighted sound level, dBA. The Bruel & Kajer sound source type 4224was located at two positions in the source room and oriented towards the receiving room location. The source was driven with pink noise at a level sufficient to increase the one-third octave-band sound pressure levels at the measurement location. The sound pressure levels at different distances, at least 1m from the source were measured. The sound pressure levels, in the receiving room, in one-third octave bands, were also measured at 5 positions with the source on with the microphone, located 1.2 m above the floor. The level reduction in each one-third octave band has been calculated, that is, the difference in average sound pressure levels produced by the sound source at the source room and receiving room. The one-third octave-band sound pressure levels for the speech spectrum at the receiving room were evaluated by subtracting the measured level reductions from the speech spectrum male speech peaks from as shown Table 2 [5].

Table 2. Speech peaks for males

Third octave band center frequency, Hz	Sound pressure levels of speech peaks for normal voice effort , dB
200	60
250	64
315	63
400	65
500	66
630	64
800	58
1000	58
1250	59
1600	56
2000	52
2500	53
3150	53
4000	50
5000	46

With the test signal off, the average background sound pressure level was measured in each one-third octave band over a time period of 1 min at the five selected positions in the receiving room. The average one-third octave-signal to noise ratio was thus established. The Articulation Index was determined as follows [5]:

$$AI = \sum_{i=1}^{i=15} W_i R_i \quad (5)$$

where:
AI = Articulation Index,

Wi = weighting factor (table 2) for band i, and
Ri = signal-to-noise ratio for band i.

Privacy Index, (PI) was expressed in percent and calculated from the Articulation Index, (AI) from Eq. (1). The required weighting factors are shown in Table 3.

3.3 Articulation Class

The Articulation Class (AC) is determined by a similar procedure. The attenuation that is, the difference in average sound pressure levels produced by the sound source at the source room and receiving room is determined. Articulation class (AC) is the sum of the weighted sound attenuations in a series of 15 test bands from 200 to 5000 Hz. It is calculated as follows:

$$AC = \sum_{f_i} A(f_i) W_i(f_i) \qquad (6)$$

where,

f_i = the center frequency of the bands from 200 to 5000 Hz,
$A(f_i)$ = the measured attenuation in decibels in the one third octave band with center frequency fi, that is the difference in average sound pressure levels measured at the source room and receiving room and
$W(fi)$ = the weighting for that band, from Table 3.

Table 3: Articulation Index Weighting Factors [5], [6]

Third octave center frequency, Hz	Weighting factors	
	Articulation index	Articulation class
200	0.0004	0.12
250	0.0010	0.3
315	0.0010	0.3
400	0.0014	0.42
500	0.0014	0.42
630	0.0020	0.6
800	0.0020	0.6
1000	0.0024	0.72
1250	0.0030	0.9
1600	0.0037	1.11
2000	0.0038	1.14
2500	0.0034	1.02
3150	0.0034	1.02
4000	0.0024	0.72
5000	0.0020	0.6

3.4 Subjective Test

Subjective listening tests were conducted with subjects in the receiving room. The phonetically-balanced Arabic sentences as speech material were played in the source room. 50 Arabic speech sentences were played over loudspeaker at three locations in the source room. Five listeners at five locations in the receiving room identify the speech material. The subjects record their response of the sentence lists. The Arabic speech sentences were recorded using computerized speech lab. model 4300. The recorded speech material was played back at different levels over a range of 58 to 65 dBA at 1m from the source. The average of speech privacy score is then calculated by determining the number of incorrect answer and expressing this as percentage [13].

4. RESULTS AND DISCUSSION

Results of subjective rating of speech privacy scores, SPS, were classified to 4 classes as follows:

- Confidential Privacy (Excellent Privacy) when normal speech can not be heard and can not be understand for SPS greater than 95%
- Good Speech Privacy when normal speech can be heard with great difficulty for SPS greater than 80% and less than 95%
- Poor Speech Privacy when normal speech can be heard and can understand with difficulty for SPS greater than 65% and less than 80%
- Bad Speech Privacy when normal speech can be heard and can understand for SPS greater less than 65%

The subjective rating of speech privacy scores, SPS, and their classifications are summarized in Table 4. All the acoustic measurements results for the tested ceiling systems are summarized in Table 5

. Table 4: Speech Privacy Scores

Classification	Speech privacy Scores, SPS	Speech Hearing and understanding
Excellent	$100>SP\geq 95$	Normal speech can not be heard and/or understood
Good	$95>SP\geq 80$	Normal speech can be heard with difficulty and cannot be understood
Poor	$80>SP\geq 65$	Normal speech can be heard and can be understood with difficulty.
bad	$SP<65$	Normal speech can be heard and can be understoodd.

Table 5. Results for Different Ceiling Systems

ID	CAC	AC	PI	SPS
SA1	25	250	93%	Good
SA2	12	120	52%	bad
SA3	20	200	77%	Poor
SA4	27	300	94%	Good
SA5	25	250	93%	Good
SA6	32	300	95%	Good
SA7	40	400	98%	Excellent

The results reflect connection between the ceiling type and the acoustic measurements SPS, PI, AC, CAC and can be summarized as follows:

- the results of ceiling system SA2 is lower than the results of ceiling system SA1 because the perforation added to ceiling system SA2 increases the sound transmission between the two room;s
- the results for ceiling systems SA3, SA4, SA5, SA6 were compared to ceiling system SA2 because adding layer of sound absorptive material increases the reduction in sound transmission between the two rooms
- the ceiling systems SA4, SA5, SA6 were better than the ceiling system SA3 because increasing the thickness of sound absorptive material increases the reduction in sound transmission between the two adjacent rooms
- ceiling type SA7 achieved higher acoustic results due to increase of mass.

Generally the sound attenuation (reduction in sound transmission) via ceiling system path between the two adjacent rooms can be increased with added mass of the ceiling system and adding sound absorptive materials inside these systems. The increase of the sound transmission loss via ceiling system path between the two rooms improves the acoustic measurements (acoustic performance) SPS, PI, AC, CAC.

5. CONCLUSIONS

This paper evaluated the acoustic performance of suspended ceilings systems installed over rooms with dividing partitions from a speech privacy perspective. The objective acoustic metrics were ceiling attenuation class (CAC), articulation class, (AC) and privacy Index, (PI) were evaluated for seven ceiling systems. In addition, the subjective speech privacy test was carried out to establish the relationship between the subjective and objective acoustic measurements.

The results showed that sound attenuation via the ceiling system path between the two adjacent rooms can be increased with the increase of weight of the ceiling system. Also adding sound absorptive materials inside the ceiling system was found to increase the sound reduction. The increase of sound transmission loss via the common ceiling system path between the rooms was shown to improve the values for the performance metrics, SPS, PI, AC, CAC for the closed spaces under these ceiling systems

The results also showed that the closed spaces with common ceiling system of CAC values equal to or greater than 35 and AC values equal or greater than 350 are desirable for speech privacy. On the other hand ceiling system of CAC values less than 20 and AC less than 200 are not adequate for speech privacy. Ceiling system with PI value greater than 97% can achieve confidential privacy (Excellent Privacy) but PI less than 77% may not be adequate for speech privacy.

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