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Optimizing acoustic conditions for two lecture rooms in Faculty of Agriculture, Cairo University

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KEYWORDS

Field measurements;
Speech intelligibility;
Reverberation time;
Noise

Abstract This paper analyses the acoustic conditions inside two lecture rooms in faculty of agriculture, Cairo University, based on field measurements and simulation technique. Ambient noise and reverberation time were measured in the unoccupied rooms. The measurement results were utilized for validating the results of CATT software that was used to estimate occupied reverberation time, STI and C^{50}. These parameters were analysed in comparison with rooms' properties, optimal reverberation time and maximum acceptable noise for learning spaces. The results demonstrated that acoustic design of the first room is far from the recommended values, whereas the second room includes many defects. For optimizing the rooms' performance, acoustic treatments were proposed and explored. Results clarified that reducing the excessive reverberation to the optimal value, either by increasing room absorption or decreasing room volume, significantly optimizes speech intelligibility. The results also clarified that reforming the ceiling eliminated the shadow and increased the early reflections.

1. Introduction

Low energy of early arriving speech, high ambient noise (L) and excessive reverberation time (T) are common defects in speech rooms [1]. These defects impede the learning process as the spoken words become unclear and incomprehensible [2]. The satisfactory acoustic conditions in lecture rooms should achieve effective speech-to-noise ratio (SNR) that is the ratio between effective signals to the effective noise in decibel [3]. Speech intelligibility (SI) increases proportionally with increase of SNR; achievement of an optimal reverberation time (T_{Opt}) comes in the second importance after achieving suitable L [4]. Although reverberation time gives lesser indication about room suitability for speech than other relevant parameters such as clarity (C_{50}), sound strength and speech transmission Index (STI) [5,6], there is no useful alternate for controlling the reverberation [3], which determines early decay time, early to-late sound index, and total sound-pressure level with volume [7]. In other words, excessive T decreases SI either in noisy or in quiet conditions [2], whereas low T reduces the desirable energy of early reflections and speech intelligibility accordingly [2]. In addition to L and T, STI is the most important single indicator that combines between S/N and room acoustic [4]. Difficult speech communication is considered a common issue in many lecture rooms in

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Egyptian university. For example, numerous auditoria in Faculty of Engineering, Ain Shams University are suffering from poor speech intelligibility due to excessive T and L [11]. Hence, the purpose of this paper was to analyse the acoustic conditions in two lecture rooms in Faculty of agriculture at Cairo University based on field measurements and simulation technique; it also includes proposed treatments to optimize their acoustic defects. The selected proposals will be applied in the future maintenance plan of these rooms. The Faculty of agriculture was established in 1889. It contains eighteen departments and huge numbers of lecture rooms. The examined rooms are Room 108 and Seminars room, the smallest typical room and the most important room in the faculty respectively. Room 108 is located in the ground floor of a new building (El Saman building) that consists of three stories. Seminars room is located in the ground floor of the general library building. The two buildings directly overlook a crowded street, approximately 20 m away from shared taxi stop and 180 m away from Giza square.

2. Literature review

The benefit of the early-arriving reflections has attracted many researchers. Bradly et al. for example [5] carried out speech intelligibility tests on normal and impaired listeners inside an anechoic room, using eight channels electro-acoustic system to generate the sound fields. The tests were performed with various speech-to-noise ratios (S/N) and constant noise level. The results clarified that the improvement in speech intelligibility scores, due to the increase in direct speech energy, is similar to the improvement resulting from the increase in early reflections energy. The research also included measuring early reflection benefit (ERB) in five different unoccupied rooms. The results showed that effect of increasing ERB was very close to the effect of increasing the direct sound level about 9 dB. Moreover, the effect of room design on early reflection strengths was explored using ODEN simulation software. The result confirmed that the first priority of room acoustic design is to increase the total energy of direct speech and early reflections, and the second priority is to achieve optimal reverberation time by minimizing the late reflections. Ellison and Germain [8] confirmed the importance of early reflections on speech intelligibility as well. They explored the effect of an active acoustic system on speech intelligibility in a School. The results showed that the system was able to increase the ERB while keeping the reverberation time within optimal value.

The most applicable solution for optimizing speech intelligibility in lectures room is the suitable selection for the properties of internal surfaces [6]. For example, different arrangements of the same absorptive material can change the values of acoustic parameters up to 50% [9], whereas diffusive surfaces increase the quality of room acoustic due to its indirect effect on room absorption. Pavlović and Petrović [9] studied the effect of diffusivity in a specifically designed physical model on room acoustic parameters. Impulse response of the model at eighteen various combinations of flat and diffuse inner surfaces were measured at 1/3 octave band frequencies, and the surface diffusivity index of the model proposals varied from 0 to 1. The result showed that the measured T resulted from using diffuse surfaces was lesser than T resulted from Sabine equation, whereas C_{50} and D_{80} constantly increased as a function of surface diffusivity index. Currently, room acoustics softwares such as ODEON, CATT and EASE are considered feasible tools for exploring the room acoustic parameters; according to DiMarino et al. [10] "*The combination of such computer model studies and a limited number of validation measurements in real rooms is a cost effective approach for developing better information for designing better classrooms*". For instance, Elkhateeb [6] used ODEON software to verify the acoustic suitability for his proposed interior design of new lecture room in the Faculty of Law, Ain Shams University. The considered acoustic parameters were T, D_{80}, STI and L. After the room construction, the same parameters were measured using MILSA system and compared to the estimated parameters during design phase. The results clarified that room design successfully achieved a satisfactory level of SI though L was high for the usage of natural ventilation.

3. Methodology

To attain the purpose of this research, architectural features of the rooms were surveyed. Room shape analysis based on geometric acoustic was investigated as well; as shown in Table 1, the pattern of sound rays' distribution was classified into four zones [11]. The acoustic conditions in the rooms under consideration were explored through four acoustic parameters: T, L, C_{50} and STI. Ambient noise level and Reverberation time in unoccupied rooms were first measured at octave band centre frequencies; the measurements followed ISO1996-2 [12] and ISO3382-2 [13]. Brüel&Kjer Sound analyser type 2260 in combination with Omni-directional sound type 4296 was the measuring device. Air temperature and relative humidity were recorded during the measurements by thermo-hygrometer device. Otherwise, reverberation time in occupied room (T_{Ocatt}), C_{50} and STI were estimated using CATT acoustic software. The 3D-model of each room was drawn using AutoCAD software. The absorption coefficients of materials surfaces were defined in the Geometry file as in reality; seating area of the listeners was simulated as wooden rectangular block in the unoccupied case and as audience on wooden chairs block in the occupied case. The measured parameters in the unoccupied rooms were utilized to validate CATT model outputs. The unoccupied reverberation time obtained from field measurements (T_M) and that obtained using CATT (T_{Catt}) were compared as shown in Fig. 1. The difference

Table 1 Zones categories based on acoustic quality [11].

Zones categories	Indication	Zone description
Good	(blue)	Areas that receive direct and first Order early reflections only
Medium	(red)	Areas that receive direct, early and late reflections from rear walls
Hard	(green)	Areas that receive direct and late reflections from rear walls
Shadow	(black)	Areas that do not receive reflections due to unstudied arrangement of walls and/ or ceiling

between them is less than 10%, the acceptable deviation due to the differences resulting from daily conditions [5].

Logarithmic average (L_{ave}) of the measured L in each room was calculated using Eq. (1) [14].

$$L_{ave} = 10log\frac{1}{r\left(10^{\frac{l1}{10}} + 10^{\frac{l2}{10}} + \cdots + 10^{Lr/10}\right)}dB \quad (1)$$

where r is the number of ambient noise measurements.

The optimal reverberation time (T_{OPT}) at Octave band frequencies was calculated using Eqs. (2)-(4) [11,15]. Eq. (2) was used to calculate T_{Opt} at 500 Hz and above, whereas Eq. (3) was used to calculate $T_{optOBCF}$ at frequencies less than 500 Hz.

$$T_{opt} = 0.3\ \log\frac{V}{10}(s) \quad (2)$$

V is room volume.

$$T_{optOBCF} = nT_{opt}(s) \quad (3)$$

where n is a ratio and can be estimated from Eq. (4):

$$n = \frac{5.6716}{F^{0.2856}} \quad (4)$$

F is centre frequency of the band.

The results of L_{ave} were compared with the maximum acceptable noise level for learning spaces (NC-35) [2], and the results of simulation were compared to their optimal values. In the light of the comparison results, the acoustic defects of each room were determined. Then, proposals to optimize the acoustic conditions in the rooms were suggested and explored using CATT software.

4. Architectural features of the two rooms

Room 108 is a small lecture room of simple rectangle-shape in which the wooden benches have been arranged parallel to the room width, as shown in Fig. 2. Slope of the audience area is 5°, which is less than the minimum required slope for sight lines [16] and negatively affects speech perception. Room volume per person (v/p) fulfilled the recommended values (3:6 m^3/person) [7]. Other than floor finishing, all surfaces are of reflective materials as indicated in Fig. 3(a). The architectural features of the two rooms are summarized in Table 2. Due to usage of air condition system in both rooms, the windows are maintained closed that fortunately isolate the rooms from the surrounding noise.

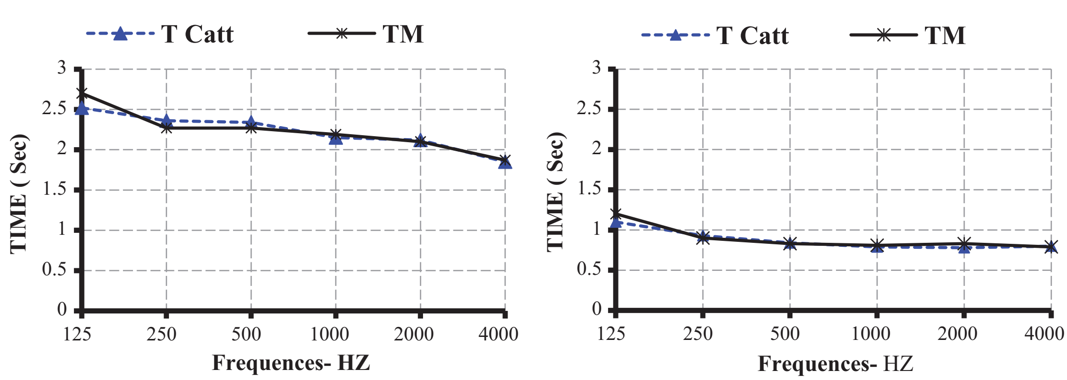
Seminars room is a rectangle room, as shown in Fig. 4, and consists of two audience levels, hall and balcony. The slope of hall level is 6° that is less than the minimum required slope for sight lines (7°), while the slope of the balcony level is 22°, which provides satisfactory sight lines [18] and allows a direct sound path for listeners. Although the capacity of seminars room is almost twice the room 108, v/p in this room is higher than v/p in Room 108 by a factor of 1.75. Except the ceiling and back wall, all surfaces were treated with absorptive materials as indicated in Fig. 3(b); the seats are also of absorptive upholstered.

5. Acoustic performance of the rooms

Suitability of the two rooms for speech function is analysed as the follows.

5.1. Room 108

Shape analysis of room 108 based on geometric acoustic, as shown in Fig. 5, clarified that the forms of walls and ceiling caused even distribution of early and late reflections, and no probable echo. Based on Table 1, the room is in the hard zone, which receives early reflections from ceiling in addition to excessive early and late reflections from the reflective walls. The analysis of the measured spectrum of L_{ave}, as indicated in Fig. 6(a), clarified that L_{ave} (NC-40) is slightly higher than the maximum acceptable value of ambient noise (NC-35) [2]. The highest difference occurs at mid and high frequencies, the important frequencies for speech intelligibility. Although the room is adjacent to the crowded Giza square, L_{ave} is not too high. This result is expected due to closing the windows as a result of utilizing air condition system. The comparison between T_{Ocatt} and T_{OPT}, as shown in Fig. 6(b), clarified that T_{Ocatt} highly exceeds T_{OPT} by more than a factor of 2.5 at mid and high frequencies, and 3 at low frequencies. Average values of C_{50}, as shown in Fig. 7(a), are lesser than 0 dB at all frequencies, where the maximum value of C_{50} is at the nearest listener to sound source (listener No. 7). Although L_{ave} is not too high, STI values of all listeners lay in the fair zone, as shown in Fig. 7(b). This result can be justified due to the



(a) Room108 (b) Seminars room

Figure 1 Comparison between T_M and T_{catt} in unoccupied condition.

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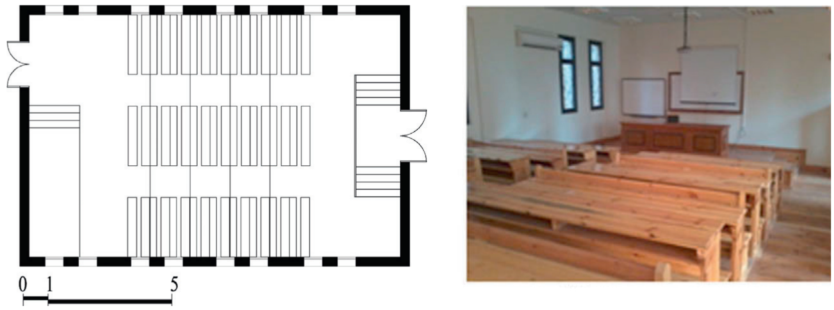
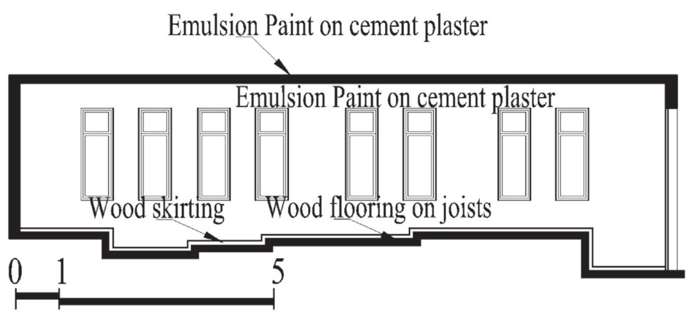
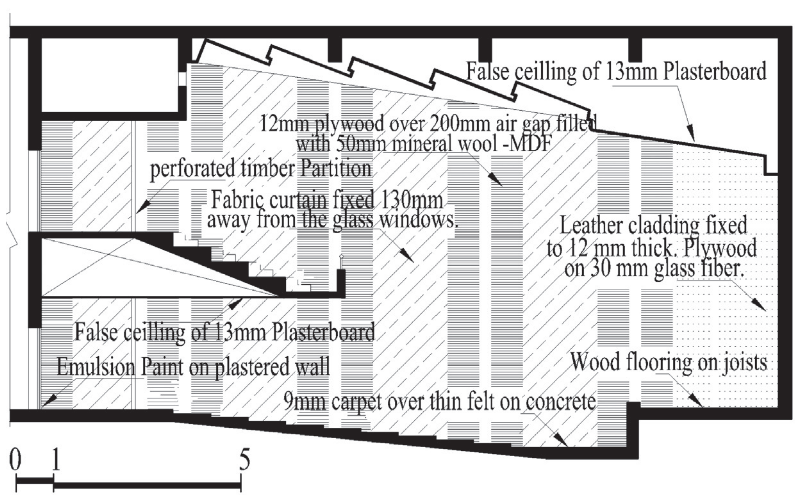


(a) Plan (b) Over View

Figure 2 Room No. 108.



(a) Longitudinal section of Room 108



(b) Longitudinal section of Seminars room

Figure 3 The existing finishing materials of the studied rooms.

long reverberation time and the excessive delayed reflections, which reduce S/N. The results are compatible with the analysis of the room shape, where STI values of all listeners are very close. The distant listeners, Nos. 2, 3, 6 & 9, receive the weakest first Order early reflections from the ceiling and side walls, in addition to the strongest first and second Order late reflections from the rear walls, while the other listeners receive relatively abundant first Order early reflections from the side walls and ceiling, in addition to first and second Order late reflections from the rear walls.

5.2. Seminars room

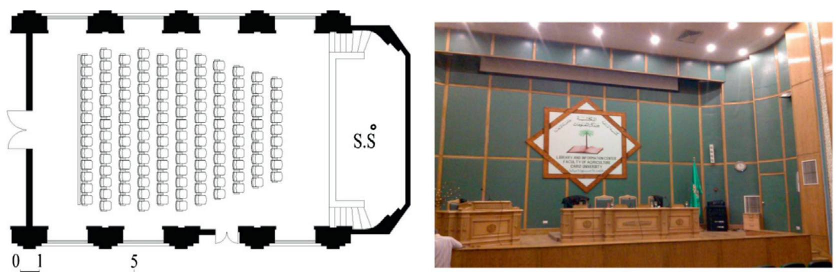
The shape of seminars room, as shown in Fig. 8, mainly is divided into three acoustic zones, good, medium and hard zones. The good zone represents approximately 23% of hall area, which receives direct sound and weak early reflections from the ceiling and from the walls due to the ceiling height (more than 9 m) and absorptive walls surfaces. The medium zone, which occupies approximately 8.5% of hall area, resulted from the weak early reflections from the walls and ceiling. The

Table 2 Description of room 108 and seminars room.

	Hall			Balcony			Area m^2		Volume m^3	D Max. m[a]
	L	W	H	L	W	H	Hall	Balcony		
Dimensions										
Room 108	15	9.75	3.6	–	–	–	146.3	–	530.80	12.00
Seminars room	19	11	6.3	7.85	11	4.1	209.45	86.55	1741.7	15.20

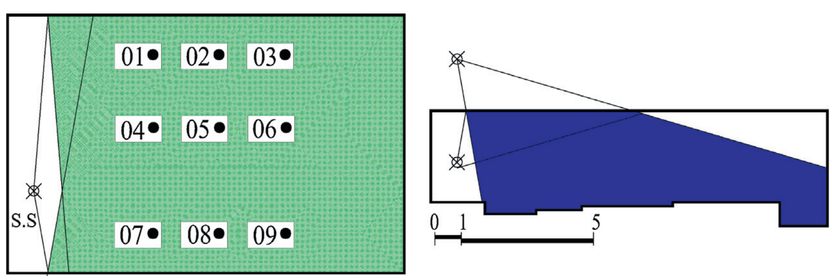
	Audience no.	v/p m^3	Area/person m^2	Environmental conditions	
				RH%	Temperature
Statistical data					
Room 108	105	4.92	1.35	42%	25 °C
Seminars room	205	8.5	1.44	40%	24 °C

[a] The maximum distance between the sound source and the farthest listener.



(a) Plan of Hall level (b) Front View

Figure 4 Seminars room.



(a) Plan (b) Longitudinal Section

Figure 5 Ray diagram analysis of room 108.

hard zone includes the audience area under and on the balcony, which receive shadows from the ceiling and uneven first Order weak reflections and shadows from the walls.

Similar to room 108, the spectrum of L_{ave} (NC-40) is slightly higher than the maximum acceptable level (NC-35) at all frequencies as indicated in Fig. 9(a); the highest difference is at the important frequencies for SI. The comparison between T_{Ocatt} and T_{opt}, as shown in Fig. 9(b), clarified that T_{Ocatt} slightly exceeds T_{OPT} a factor of 1.3 at all frequencies. Average values of C_{50}, as shown in Fig. 10(a), are higher than 0 dB at all frequencies, and the minimum value for C_{50} is at the area located under the balcony. Although T_{Ocatt} and L_{ave} is not too high, STI values showed that all listeners lay in fair zone, as shown in Fig. 10(b). This result is justified due to the huge volume of the room and the low beneficial reflections.

5.3. Discussion

The rooms' analysis clarified that their acoustic conditions are not suitable for speech function due to poor speech intelligibility. Room 108 is much worse than seminars room that has less acoustic defects. Ambient noise is not considered the main reason for low SI in the rooms, where it slightly exceeds the maximum acceptable value of ambient noise (NC-35) [2]. Though, it may be needed to improve windows insulation in order to

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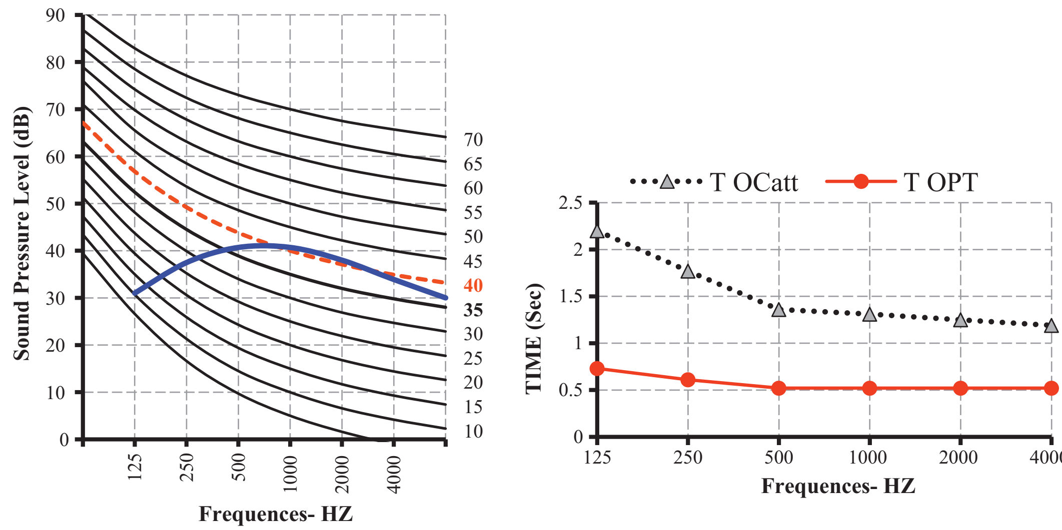
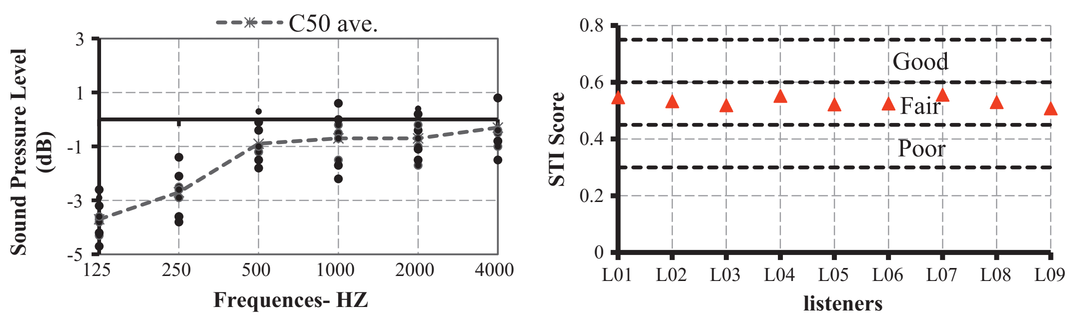


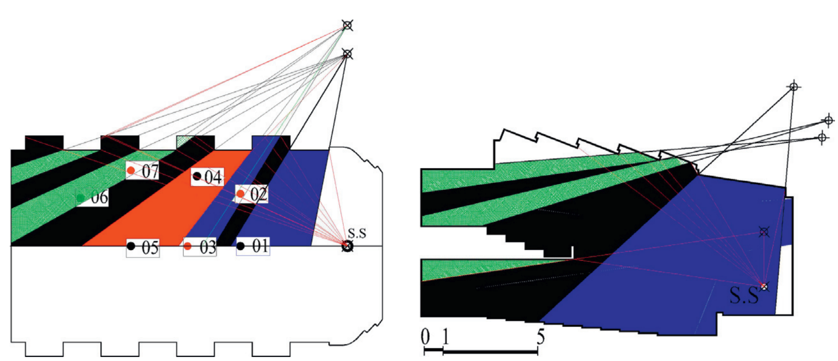
(a) L_{ave} indicated on NC (b) Comparison between T_{Ocatt} and T_{Opt}

Figure 6 Noise level and reverberation time in Room 108.



(a) Average C_{50} (b) STI

Figure 7 Clarity and STI in room 108.



(a) Plan (b) Longitudinal Section

Figure 8 Ray diagram analysis of Seminars room.

increase the sound transmission class (STC) by about 10 dB. The excessive T_{Ocatt} at all frequencies in room 108 go back to the presence of the excessive reflective surfaces where volume per person (v/p) is compatible the recommended values [7]. This defect caused negative values of C_{50} and fair STI level. Hence, late reflections and excessive reverberation time in this room need to be minimized by increasing the total power of room absorption. For the Seminars room, the difference between T_{Ocatt} and T_{OPT} is not very large, and it results from the huge volume of the room. The room volume per person, (8.5 m^3), highly exceeds the recommended values (3:6 m^3/seat) [7], which also negatively affects the beneficial early reflections.

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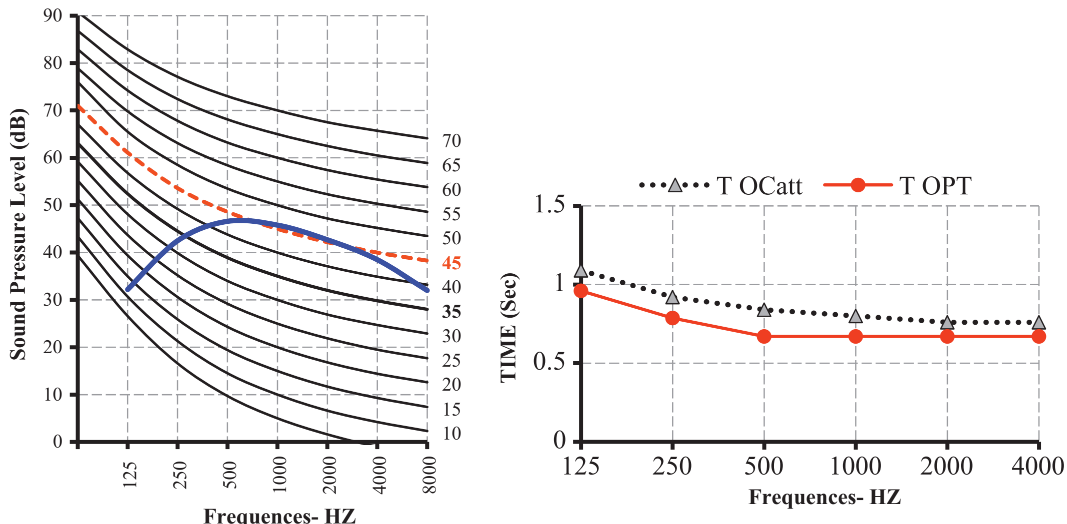
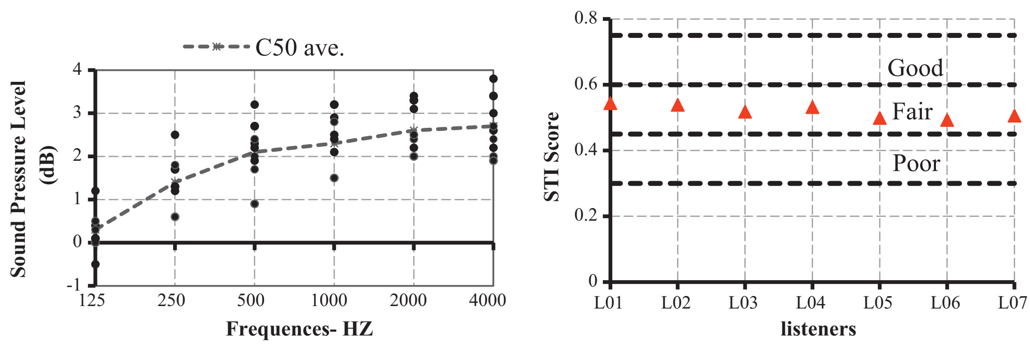


(a) L_{ave} indicated on NC (b) Comparison between T_{Ocatt} and T_{Opt}

Figure 9 Noise level and reverberation time in Seminars room.



(a) Average C_{50} (b) STI

Figure 10 Clarity and STI in seminars room.

Moreover, approx. 50% of audience area in this room does not receive any desirable early reflections from the ceiling due to its inefficient form. This explanation justifies the low values of C_{50} and STI. For optimizing the reverberation time and maximizing the benefits of early reflection energy in this room, the huge height of the ceiling needs to be reduced, whereas the ceiling form needs to be modified to eliminate the shadow zones. Consequently, different treatments for each room are proposed from which the best proposal will be selected.

The proposals of room 108 are as follows:-

- First proposal includes adding micro-porous plaster [17] to the one-third distant part of the ceiling, in addition to covering the back and side walls with 4 mm hard fibreboard (with 13% perforation, on 0.5 m cavity with 100 mm mineral wool at front of cavity) [6]. The proposal includes adding soundproof windows to increase STC from 26–28 to 38–44 to reduce the ambient noise by 10 dB [18].
- Second proposal is similar to the first proposal but without any treatments to windows.
- Third proposal is similar to the first proposal but without treatments to the distant part of the ceiling.

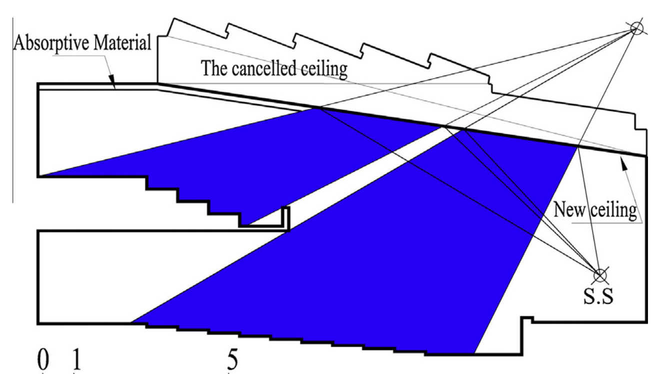
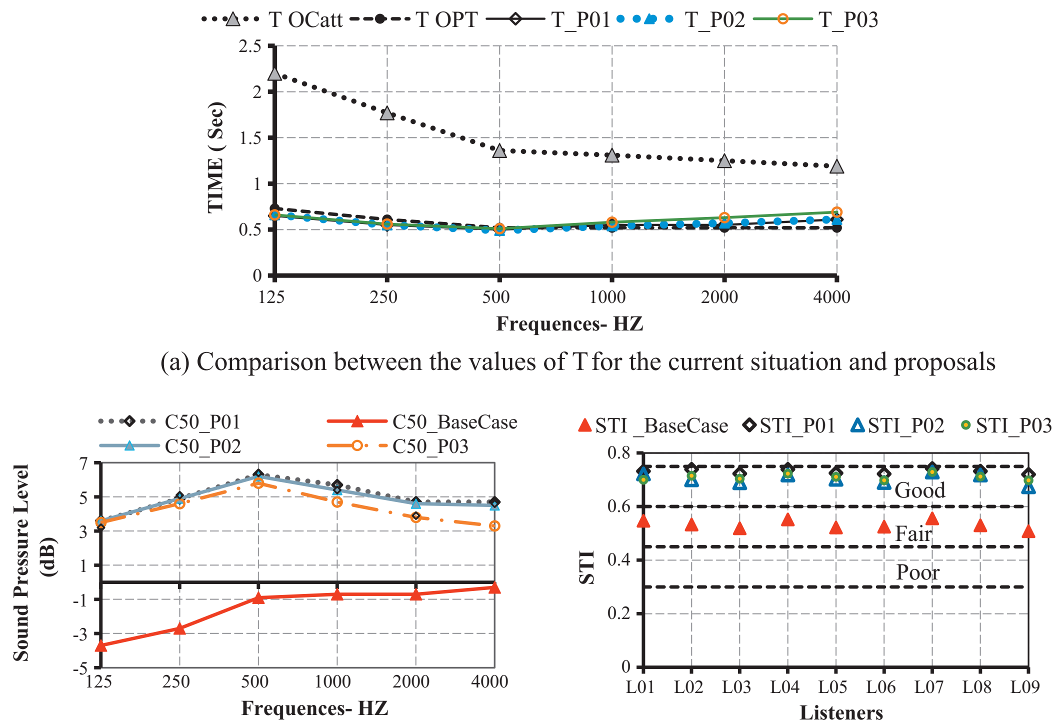


Figure 11 Longitudinal section of the proposed treatment for seminars room.

The proposals of seminars room are as the followings:-

- First proposal includes replacing the existing false ceiling with flat ceiling inclined upward from 8° as shown in Fig. 11. The front half area of the new ceiling is a reflective material (metal tiles), and the other area is an absorptive



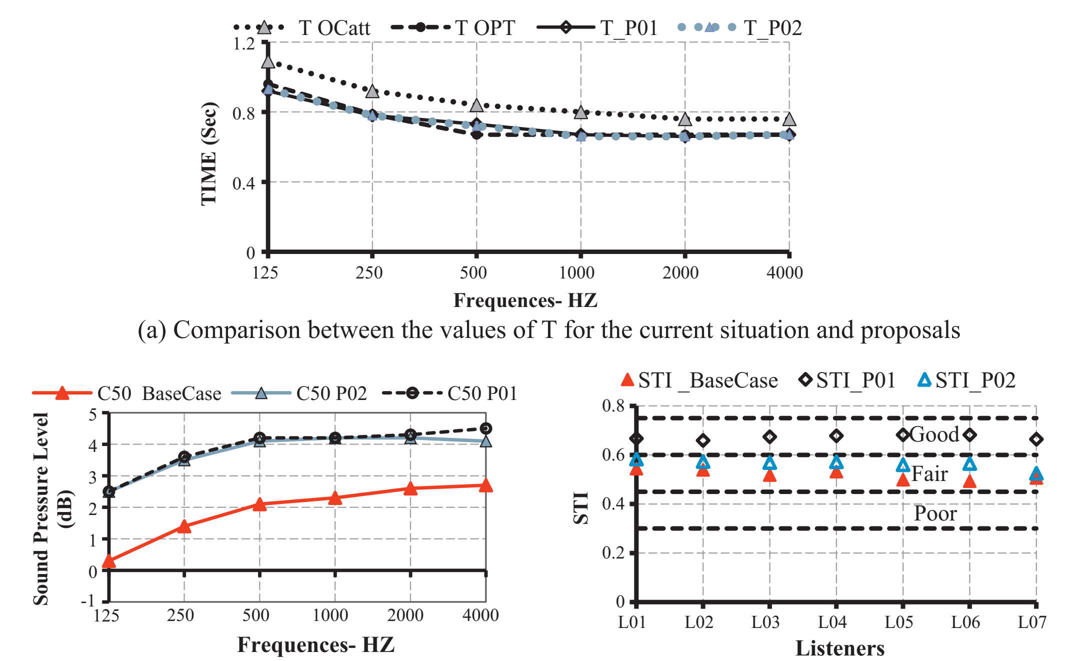
(a) Comparison between the values of T for the current situation and proposals

(b) Comparison between the values of C_{50} for current situation and proposals

(c) Comparison between the values of STI for current situation and proposals

P01,P02 & P03 is the results of the three proposals

Figure 12 Effect of different proposals on T, C_{50} and STI in room 108.



(a) Comparison between the values of T for the current situation and proposals

(b) Comparison between the values of C_{50} for current situation and proposals

(c) Comparison between the values of STI for current situation and proposals

Figure 13 Effect of different proposals on T, C_{50} and STI in seminar room.

material (Fissured mineral tiles) [15]. The new ceiling reduces the room volume by 17.6%. Like room 108, the proposal also includes adding soundproof windows to reduce the ambient noise by 10 dB.

- Second proposal is similar to the first proposal but without treating the windows.

6. Results of optimizing proposals

The proposed treatments for each room were explored using CATT software. The results were compared with each other and with current situation of the room as the following.

6.1. Room No. 108

The comparison between the proposals and the current situation, as shown in Fig. 12(a), demonstrates that T_{Ocatt} of the three proposals are very close to T_{opt}. Although the first and second proposals include additional absorptive area on the distant part of the ceiling, 52 m^2, T_{Ocatt} resulted from these proposals are less than T_{Ocatt} of the third proposal by only 0.1 s at high frequencies. Moreover, Average values of C_{50} for the first proposal are approx. 20% higher than the average values of C_{50} for the third proposal at mid and high frequencies, as shown in Fig. 12(b), while STI values of the first proposal are also higher than STI values of third proposal by approx. 3%, as shown in Fig. 12(c). Although L of first proposal is 10 dB lower than L of the second proposal, values of C_{50} and STI resulted from these two proposals are very close. On other words, 10 dB decreases in L that is already not too high, has insignificant effect on SI, whereas decreasing the excessive T by more than a factor of 2.5 at all frequencies, has significantly improved SI.

6.2. Seminars room

The comparison between the two proposals and the current situation, as shown in Fig. 13(a), clarified that T_{Ocatt} of the two proposals are identical and are very close to T_{opt}. Average values of C_{50} resulted from the proposals are also very close as shown in Fig. 13(b). Though STI values of the first proposal are 17% higher than STI values of the second proposal due to the reduced L in the first proposal, as shown in Fig. 13(c). The optimization in the speech intelligibility was accomplished at all listeners that are located in the good zone.

In summary, changing the inefficient form of the ceiling optimizes the acoustic conditions within the room by eliminating the shadows and increasing the desirable early reflections energy. The decrease in the room volume by 17.6% due to reshaping the ceiling reduces the excessive reverberation time to the optimal value. Moreover, reducing the ambient noise by 10 dB in the first proposal significantly optimizes STI from fair zone to good zone as shown in Fig. 13(c).

7. Conclusion

This work analyses and optimizes the acoustic conditions in two rooms in the Faculty of Agriculture, Cairo University, based on field measurements and simulation technique. Four acoustic parameters were studied: T, L, C_{50} and STI. The architectural survey clarified that the most surfaces in Room 108 are reflective, which can severely increase the reverberation time. v/p in Seminars room highly exceeds the acceptable range, which indeed increases the acoustic defects in this room. Furthermore, Shape analysis of Seminars room clarified that there are several shadow zones covering about 50% of the audience area due to the ceiling shape. In addition to these shadows, the uneven distributions of early and late reflections categorize the audience area in Seminars room into medium and hard acoustic zones, while the audience area in room 108 within hard acoustic zone due to the excessive late reflections from side and back walls. The measured L_{ave} (NC-40) in the both rooms are slightly exceeding the maximum acceptable noise level (NC-35) by about 5 dB at mid and high frequency ranges. This result returns mainly to noise generated from the rooms' air conditions. The results demonstrate that T_{Ocatt} highly exceeds T_{opt} at all frequencies; T_{Ocatt} is higher than T_{opt} by more than a factor of 2.5 in Room No. 108 and 1.3 in Seminars room. In other words, room 108 is highly reverberant room, whereas Seminars room is slightly reverberant. Consequently, values of STI are low, fair zone, whereas average spectrum of C_{50} is less than 0 dB in Room 108 and within 2 dB in Seminars room. To optimize the acoustic conditions in the rooms, many proposals have been explored. The main concept is to increase the amount of absorptive materials in Room 108 and decrease v/p of the other room to reduce the excessive reverberation. The proposed treatments of Seminars room include reforming the ceiling shape to remove the shadows. The proposal analysis using CATT software clarifies that T_{Ocatt} become very closer to T_{opt} when the back and side walls in Room 108 are covered with highly absorptive materials, and when the volume of Seminars room is decreased by 17.6% by reshaping the ceiling; the new shape of the ceiling was also designed to remove the shadow zones and increase the early reflections. Optimizing T_{Ocatt} significantly improved the speech intelligibility at all listeners as noted from the new values of C_{50} (about 4 dB) and STI (good).

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