ACOUSTIC EVALUATION OF TYPICAL ERRORS IN THE DESIGN OF MODERN LECTURE THEATRES

AG Sotiropoulou School of Architecture & School of Civil Eng., Tech. University Athens, Greece
G Poulakos School of Architecture & School of Civil Eng., Tech. University Athens, Greece
G Kabourakis School of Electrical Eng., Tech. University Athens, Greece

1. INTRODUCTION

The fast increasing population of students in universities of modern societies has resulted, since a few decades ego, in an ongoing massive explosion of lecture auditoria in size and number. Acoustic considerations are often overlooked at the design and construction stage, though they become important only after completion whenever poor acoustics calls for remedy.

Acoustic principles for the design of speech auditoria, have been available since the beginning of last century. However the identification of errors in the acoustic design which are consistently repeated in auditoria of modern universities, as well as the evaluation of such errors through measurements in situ, is an exercise that needs be done. This could tell us of the effects that unsuitable design features can have on the acoustic performance of lecture auditoria, and possibly cast some light on the understanding of room acoustic design.

With the above in mind, the aim of the present work is to investigate typical errors in the design of lecture auditoria and evaluate the effects of these on the acoustic performance of the auditorium. The present work consists of a series of physical acoustic measurements in lecture auditoria of university buildings.

2. REVIEW OF PAST WORK

Much work has been reported in modern scientific literature about the acoustics of speech auditoria[1,etc]. The acoustics of educational buildings has also been given attention in the relevant literature over the last few decades; some of these studies discuss acoustic principles and techniques for the design of good lecture auditoria[2]; other studies investigate subjective aspects of the acoustics of lecture auditoria[3,4], classroom acoustics and its effects on speech communication[5], optimum reverberation time in classrooms in relation to Greek language[6], etc. Nevertheless more studies are needed, in order to investigate the effects of typical design errors on the acoustic performance of lecture auditoria in universities.

3. EXPERIMENTAL DESIGN

The following room acoustic parameters were measured, which are considered by modern standards[3] as adequate descriptors of room acoustics for speech.

- A **speech intelligibility measure** (in this case the 50ms early energy fraction (EEF)).
- **Reverberation time** (RT)
- A **measure of the 'amplification' of speech sound level** by the auditorium (in this case, the attenuation of the steady state sound pressure level vs distance from source, for a standard source on stage).
- **Background noise level.**

Measurements were carried out in the octave bands from 125 Hz to 4000 Hz. Only mid frequency results (mean of 500 and 1000 Hz) are discussed in this paper.

The criterion value of acceptability in taken greater than 0,50 for the intelligibility measure[1]. Reverberation times in full audience lecture auditoria can be considered acceptable, by and large, below 0.9 s[7] with flat frequency response. The background noise level criterion for lecture auditoria is taken 35 NC[8]. The criterion of acceptability for the speech sound level is derived below.

Measured values of the attenuation of the steady state sound pressure level vs distance from source, refer (0 dB) to the measured average (direct) sound level at the foremost seat in the auditorium. This location for classrooms and lecture theatres is normally relatively close to the standard location of speaker; for instance, in the present lecture auditoria the distance from source of foremost seat, ranges from 1,2 m to 4,0 m and mean distance is 2,5 m. At this (reference) location the non-direct sound component is relatively low, therefore, virtually one measures there barely direct sound.

We need to know the minimum acceptable value for the speech sound level. The following calculations refer to mid frequencies (mean of 500 and 1000 Hz). Considering the mean speech sound power level for a lecturer, equal to an actor's voice level, this is 70 dB[1]. This corresponds to a mean direct sound level at 2,5 m of 51 dB. If S is the speech sound level, then the actual sound level at a seat is (51 + S) dB. The mean value of the acceptable background noise level at mid frequencies is 38 dB. Considering a reasonable signal-to-noise ratio equal to 10 dB for intelligible speech transmission we have,

$$51 + S \geq 38 + 10$$

or

$$S \geq -3 \text{ dB}.$$

Table 1: Basic details of measured lecture auditoria of the Tech. Univ. Athens. ** unoccupied auditoria*

Lecture autitoria	*Date*	*Seats*	*Volume per seat [m³]*	*Size*			*RT*mid [s]*
				Width [m]	*Depth [m]*	*Height [m]*	
1. Echotechnia's theatre	1966	77	2,2	5.0	11,9	3,2 ~ 2,0	0,70
2. Theatre in Theocharis' bldg.	1960	135	2,7	6.8	15,8	3,9 ~ 2,0	2,00
3. Theatre 015 in Lambadarios' bldg.	1970	252	3,7	14.0	17,0	5,5 ~ 2,8	1,95
4. Theatre 01 in Vays' bldg.	2001	108	4,7	10,0	15,0	3,8 ~ 2,0	0,85
5. Twin theatres of Civil Eng. School	2002						
i) together		269	6,0	14.0 ~ 20.5	14,1	5,4 ~ 4,0	1,32
ii) right hand theatre only		135	6,0	7.2 ~ 10.9	13,2	5,4 ~ 4,0	1,20
6. Grand theatre in Tossitsa bldg.	1955	417	7,2	13.0 ~ 17.5	25,1	8,2 ~ 5,0	2,20
7. Theatre Γ18 in Ginis' bldg. *(refurbished in 1980)*	1920	208	4,7	11.7	15,3	6.0 ~ 4.0	1,55
8. Theatre 01 in Tossitsas' bldg.							
i) before treatment	1955	64	3,1	6.10	8,9	3,7 ~ 2,3	1,50
ii) refurbished	2007	64	3,1	6.10	8,9	3,7 ~ 2,3	0,41
9. Classroom 05 in new Premises of Civil Eng. School	2002	111	4,8	9.45	17,2	3,3	1,25
10. Classroom 020 in Lambadarios' bldg.	2001	53	8,0	9.45	11,8	3,9	2,40
11. Classroom 31 of Chem. Eng. School	1980	102	4,3	8.40	15,2	3,5	1,80
12. Classroom Γ105 in Ginis' bldg. *(refurbished in 1980)*	1920	294	2,5	11.6	19,4	3.6	1,51

4. ACOUSTIC MEASUREMENTS; PROCEDURE AND RESULTS

Acoustic measurements were carried out in twelve lecture auditoria of the Tech. Univ. Ahtens, in the unoccupied rooms. Six of these have raked floor and will be referred to as lecture theatres; the remaining have flat floor and will be referred to as classrooms. Basic details are given in Table 1 and Fig. 1.

The early energy fraction and reverberation time were derived from monophonic recordings of the impulse response, using directional loudspeaker source on stage. For measurements of energy fractions in speech auditoria it is realistic to employ speech directional sound source. The loudspeaker used in the present measurements has its maximum output ahead, in the mid and high frequency region. The source was located on stage in the standard speaker's position, facing the audience. The 50 ms early energy fraction was derived by analysing the recorded impulse response, using computer programme (DIRAC) by B & K.

The steady state sound pressure levels were measured with octave filtered white noise emitted via a standard source on stage, using a calibrated portable sound level meter. The sound source HP 1001 and the sound power source 4205, both by B & K were employed. The portable sound level meter was of type 2203 with associated filter set of type 1613, by B & K. The latter was also used for measurements of the background noise. The test positions for each lecture auditorium are shown in Fig. 1.

Results are shown in Figures 2, 3 and 4, as well as in Table 1.

5. DISCUSSION

• **Echotechnia's lecture theatre** (Table 1, Fig. 1). This is a tiny theatre which demonstrates the virtues of the small auditorium The reverberation time is appropriately short, thanks to necessary absorptive treatment. Objective measures of intelligibility do show high (right) values owing to the short paths of direct sound as well as to reflective room boundaries closely surrounding the audience area. Speech sound level is maintained satisfactorily loud, throughout, thanks also to the remarkably low ambient noise in this location of the Tech. Univ. Campus (Figures 2,3,4).

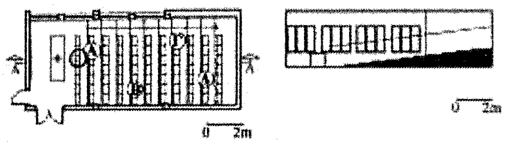
• **Lecture theatre in Theocharis' buinding** (Table 1, Fig. 1). This is a small lecture theatre, though, deep structural beams across the ceiling as well as entire absence of any absorptive treatment, ruin the acoustics; not surprisingly, the reverberation time is excessive. Furthermore, objective measures of speech intelligibility are well below the criterion value (Fig. 2), apparently owing to the deep ceiling beams hindering the propagation of early reflections. The latter also influences speech sound level which becomes too faint further away from the source (Fig.3); this, combined with the unpredictable intrusive road traffic noise calls for immediate attention to the design.

• **Theatre 015 in Lambadarios' building** (Table 1, Fig. 1). This is a large lecture theatre entirely deficient in any absorptive treatment; this situation is depicted in the too long reverberation time of the auditorium. Nevertheless, the speech sound level is well maintained throughout (Fig. 3), which is apparently the effect of the reflective enclosure; this works synergistically with the exceptionally low background noise in the auditorium (Fig. 4), to allow audible speech sound levels. However, the speech intelligibility measure here is well below the criterion value (Fig. 2). This can possibly be the combined effect of relatively high late sound portions and, of the widely apart side walls which project weak early sound to the central audience area.

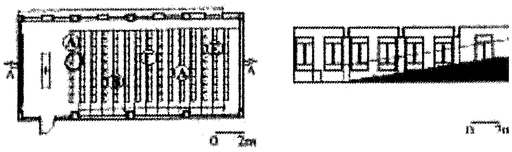
• **Theatre 1 in Vays' building** (Table 1, Fig. 1). The Vays' auditorium is packed in absorption throughout; this, results in relatively short reverberation time. Surprisingly enough the objective measure of speech intelligibility is well above the criterion value (Fig. 2); this can be the effect of relatively reduced late sound.

• **Twin theatres of Civil Eng. School** (Table 1, Fig. 1). These lecture theatres can also operate together as a single space. In either mode of operation there is excessive room volume, which entails inappropriately long reverberation times. The rear wall and rear part of ceiling is treated with moderate absorption in either case. In the case of the twin theatres operating as a single space, the average speech sound level was found to be within acceptable limits (Fig. 3). The background noise in the auditorium(-a) is at the borderline i.e. NC = 37 dB owing to noisy A/C system (Fig. 4). The above two results combined suggest that no further absorption can be introduced in the auditorium, or the average speech level could become hardly audible. So, for instance, the excessive reverberation time could be amended through modifications only in the room volume. The intelligibility criterion is marginally satisfied (Fig. 2) obviously owing to inadequate early reflections from the enormous ceiling height and the widely apart, splayed side walls.

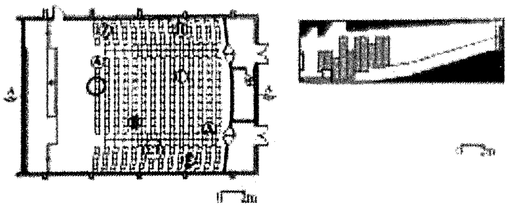
1. Echotechnias theatre



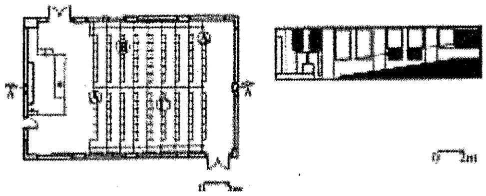
2. Theatre in Theocharis' building



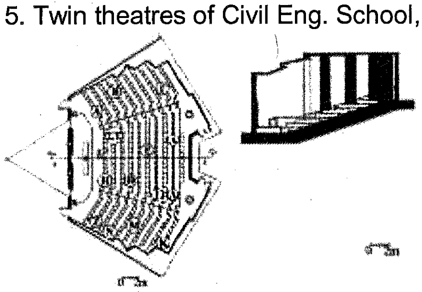
3. Theatre 015 in Lambadarios' building



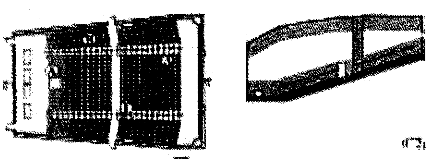
4. Theatre 01 in Vays' building



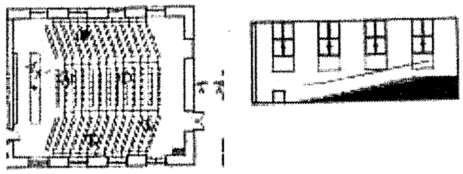
5. Twin theatres of Civil Eng. School, together



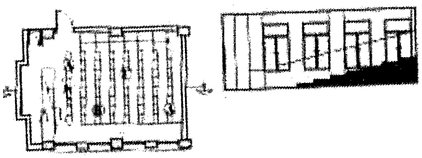
6. Grand theatre in Tossitsas' building.



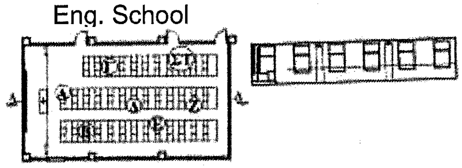
7. Theatre Γ18 in Ginis' building



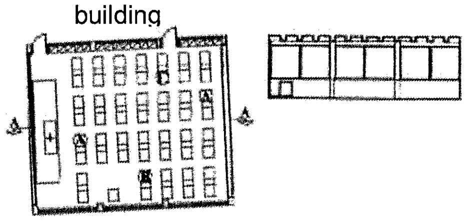
8. Theatre 01 in Tossitsas' building



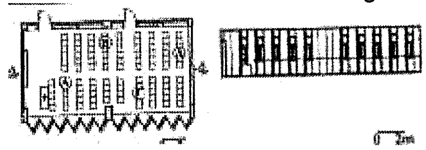
9. Classroom 05 in New Premises of Civil Eng. School



10. Classroom 020 in Lambadarios' building



11. Classroom 31 of Chem. Eng. School



12. Classroom Γ105 in Ginis' building

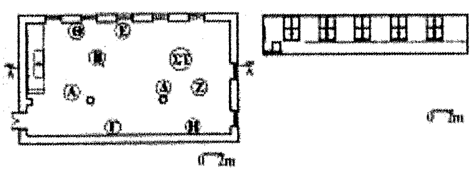


Fig. 1. Architectural plans and long sections of measured lecture auditoria of the Tech. Univ. Athens. Test positions are shown on plans .

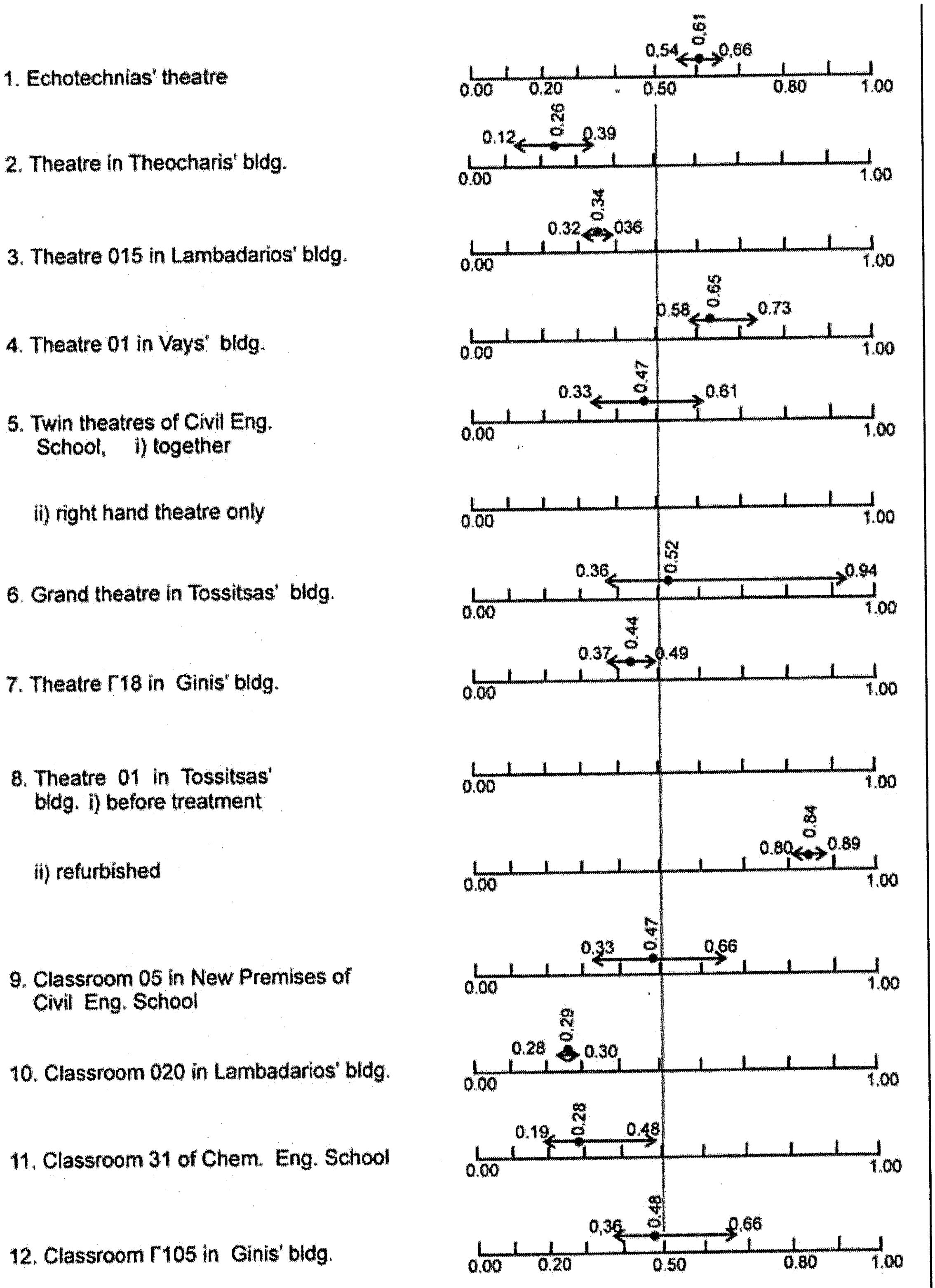


Fig. 2. Measured values of the mid frequensy 50 ms early energy fraction for a directional sound source, in lecture auditoria of the Tech. Univ. Athens. The range and mean of values is given. The criterion value is ⩾ *0.50*

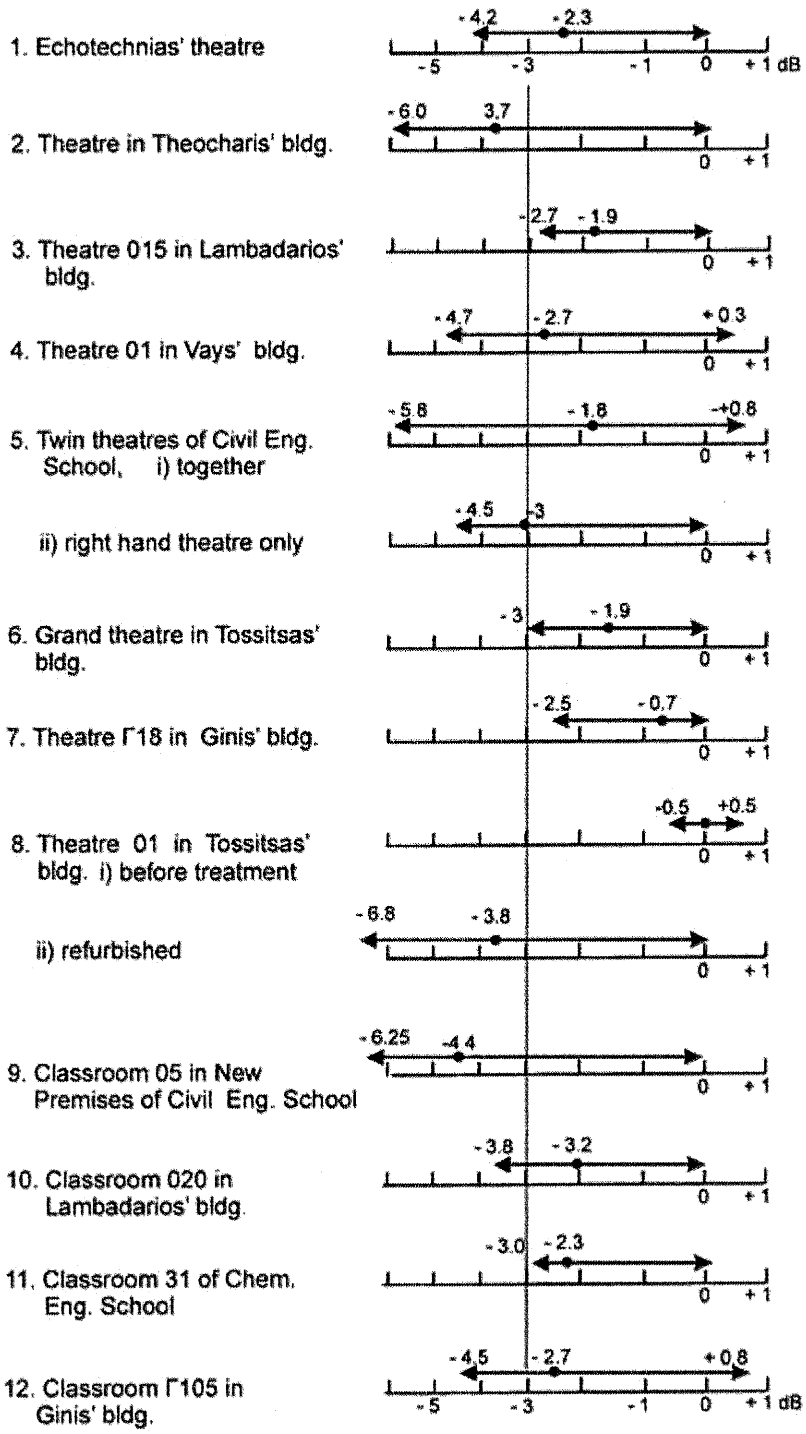


Fig. 3. Measured values of mid frequency speech sound level (in dB), in lecture auditoria of the Tech. Univ. Athens. The range and mean of values is given. 0 dB is the sound level at the foremost seat. The criterion value is ≥ -3 dB

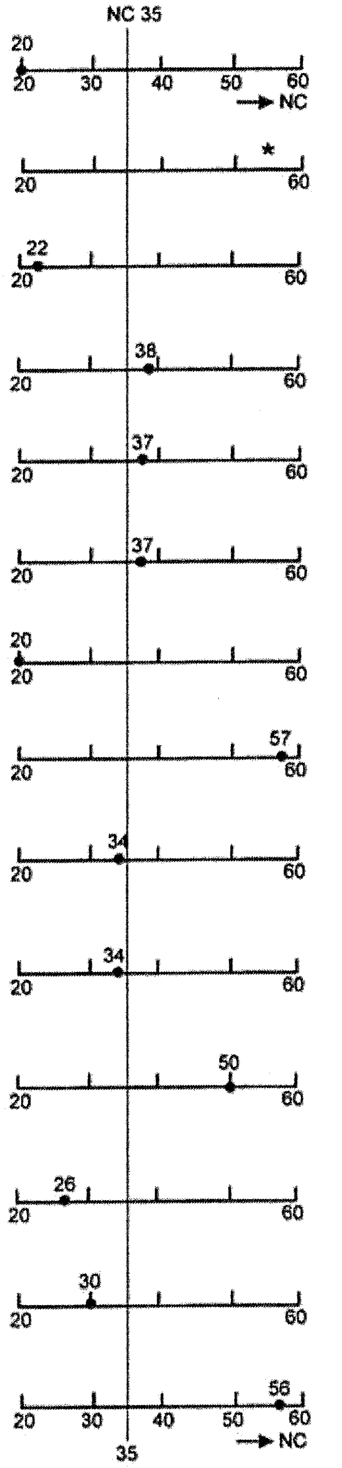


Fig. 4. Background noise levels (in NC), in lecture auditoria of the Tech.Univ. Athens. The criterion value is ≤ NC 35 dB.

** Not easy to measure due to large fluctuations in intruding road traffic noise*

• **Grand theatre in Tossitsas' building** (Table 1, Fig. 1). This is an enormous auditorium, with hugh volume per seat, inadequate reflective surfaces and scanty absorptive treatment. This situation engenders excessive reverberation time, non satisfactory intelligibility criterion (Fig. 2), but adequate average speech sound level (Fig. 3) due to ample reverberant sound in the auditorium. The background noise criterion is satisfactorily low (Fig. 4).

• **Lecture theatre Γ18 in Ginis' building** (Table 1, Fig. 1). This is a large auditorium in a neoclassical building of early 20th century; the ceiling was much later treated with absorption of reduced performance though, due to inappropriate attempts to maintain this painted. This ceiling is relatively high, and the side walls stand wide apart. As would be expected, this auditorium has relatively long reverberation time, non satisfactory intelligibility criterion owing to scanty early sound (Fig. 2), but adequate average speech level (Fig. 3). Apparently the average speech sound level in the auditorium is dominated by late sound. Unfortunately, the excessive ambient noise due to intrusive road traffic noise (Fig. 4) can make the average speech level hardly audible.

• **Theatre 01 in Tossitsas' building** (Table 1, Fig. 1). This tiny theatre of the mid 20th century was recently refurbished to amend also its poor acoustics.
- BEFORE TREATMENT. Although the volume per seat of the theatre is appropriate, entire absence of any absorptive treatment results in excessive reverberation time. The speech level criterion is satisfied in this case (Fig. 3), owing to short paths of direct sound as well as to the reflective room boundaries closely surrounding the audience area. The background noise criterion is marginally satisfied (Fig. 4).
- AFTER TREATMENT. In order to amend the excessive reverberation time in the auditorium, the side walls and rear part of ceiling were treated with absorptive perforated wood panels. The reverberation time has been dramatically improved, the speech intelligibility criterion is amply satisfied (Fig. 2), but the speech sound level has been reduced well below the criterion value (Fig. 3). The room now operates fine with electronically assisted sound.

• **Classroom 05 in New Premises of Civil Eng. School** (Table 1, Fig. 1). This classroom, has relatively high volume per seat, ceiling lavishly treated with absorptive tiles and side walls wide apart. The reverberation time is relatively long. The speech intelligibility criterion falls well below the criterion value with distance increasing from the source (Fig. 2) apparently owing to inadequate early reflections. For the same reason the average speech sound level is also well below the criterion value (Fig. 3). It is interesting to observe, though, that despite the generous absorptive treatment throughout the ceiling, the reverberation time criterion still fails to be met; apparently no deliberate acoustic predictions have been involved.

• **Classroom 020 in Lambadarios' building** (Table 1, Fig. 1). This classroom is characterised by an excessive volume per seat, shallow beams across the ceiling which contribute diffuse sound portions, and reflective walls which stand wide apart. These features result in excessive reverberation time. The speech intelligibility criterion falls well below the criterion value (Fig. 2) possibly owing to relatively high late sound portions. By contrast, the average speech sound level is nearly satisfactory apparently owing to the highly reflective enclosure (Fig. 3). The background noise level criterion is well satisfied (Fig. 4) and contributes to audibility of the average speech sound level.

• **Classroom 31 of Chem. Eng. School** (Table 1, Fig. 1). This classroom is characterised by entire absence of absorptive treatment, and highly diffusive side walls. As would by expected the room has excessive reverberation time, and the speech intelligibility criterion decreases with distance below acceptable limits (Fig. 2). However, the average speech sound level and background noise level are satisfactory (Figures 3 and 4); the former is apparently the effect of the highly reflective enclosure.

• **Classroom Γ105 in Ginis' building** (Table 1, Fig. 1). This classroom belongs to a neoclassical building of early 20th century; the classroom ceiling was much later treated with absorption of reduced performance though, due to inappropriate attempts to maintain this painted. The remaining of the room is reflective and diffusive with an extensive series of windows facing a busy rood. It follows that the room has relatively increased reverberation time, and the speech intelligibility criterion decreases with distance, below acceptable limits (Fig. 2); The average speech sound level is marginally satisfactory (Fig. 3) but the background noise level is well above the criterion value (Fig. 4).

6. CONCLUSIONS

The above discussion clearly indicates a number of distinct typical errors in the design and construction of the lecture auditoria measured in the present study. Namely :

• **Misuse of absorptive treatment.** This, on the one hand, is **misplaced throughout the ceiling of the auditorium;** Identified deleterious effects on the acoustic performance of the auditoria, are: - Undue occupation of a potentially useful reflecting surface, which results in poor early sound portions to the audience, therefore the speech intelligibility criterion fails to be met. - Modification of the reverberation time in an erratic way, since no deliberate acoustic predictions are involved. - Moderation of the speech sound level, depending on the amount of absorption unduely introduced. On the other hand, the **absorptive treatment is employed to make up for excessive room volumes**. Even when this is made according to deliberate acoustic predictions, the present measurements confirm that this unavoidably plagues the 'amplification' potency of the auditorium. In such cases electronically assisted sound may be called for.

• **Entire absence of absorptive treatment;** the present measurements confirm that this results in excessive reverberation time, as well as in relatively low speech intelligibility criterion possibly owing to domination of late sound portions. Albeit the speech sound level criterion tends to be satisfied according to present results, this alone does not ensure good listening conditions.

• **Use of excessive room volume.** A common practice to make up for this defect is undue introduction of extra absorptive treatment in the auditorium. Although this, can be an effective antidote to long reverberation times, unfortunately it undermines the 'amplification' potency of the auditorium as discussed above.

• **Use of deep beams across the ceiling.** The present measurements, have identified unsatisfactory speech intelligibility criterion, and deterioration in the 'amplification' potency of the auditorium. It is interesting to observe here dominance of relatively weak speech sound levels even within entirely reflective enclosure (see lecture theatre in Theocharis' building, in section 5. above).

This exercise casts some light on the understanding of design needs, for acoustically effective lecture auditoria in universities of modern societies.

7. REFERENCES

1. M. Barron. Auditorium acoustics and architectural design, E & FN SPON, London (1993).
2. HMSO. Acoustics in Educational Buildings, Dept. of Education and Science, Building Bulletin 51 (1975).
3. S.M. Kennedy, M. Hodgson, L.D. Edgett, N. Lamd and R. Rempel, 'Subjective assessment of listening environments in university classrooms: Perceptions of students', J. Acoust. Soc. Am. 119(1) 299-309 (2006).
4. L. Mari. Η αντίληψη της ακουστικής αιθουσών διδασκαλίας· 'παραγοντική' περιγραφή της αντίληψης *(Subjective evaluation of the acoustics of lecture auditoria; multidimensional description of evaluations)*, Diploma thesis supervised by assist. prof. A. Sotiropoulou, School of Civil Eng., Tech. Univ. Athens (2007).
5. G. Kabourakis. Η ακουστική των αιθουσών διδασκαλίας και οι επιπτώσεις της στην επικοινωνία. (*Classroom acoustics and its effects an speech communication*). Proceedings of the Hellenic Institute of Acoustics (2006).
6. G. Poulakos. Μελέτη της ποιότητας της προφορικής επικοινωνίας σε συνάρτηση με το χρόνο αντήχησης για την Ελληνική γλώσσα (*Speech communication in rooms in relation to reverberation time, for Greek language)*, Doctorate thesis, School of Arch., Tech. Univ. Athens (1989).
7. L. Cremer and H.A. Müller. Principles and Applications of Room Acoustics, Vol. 1, Applied Science Publishers, London and N. York (1982).
8. SRL. Practical Building Acoustics, E & F.N. SPON, London (1976).

Acknowledgements

Thanks go to Prof. K. Moutzouris ex Rector of the Tech. Univ. Athens for support, to graduate student T. Karatzas and the technical group of Tech. Univ. Athens for technical assistance. Part of the present results have been produced in the context of diploma thesis of students G. Chryssanthakopoulou, N. Lebessis and J. Tamvakos.

ACOUSTIC EVALUATION OF TYPICAL ERRORS IN THE DESIGN OF MODERN LECTURE THEATRES

AG Sotiropoulou School of Architecture & School of Civil Eng., Tech. University Athens, Greece
G Poulakos School of Architecture & School of Civil Eng., Tech. University Athens, Greece
G Kabourakis School of Electrical Eng., Tech. University Athens, Greece

Typical errors in recently built lecture auditoria and in refurbishments of relatively old educational buildings, are massively identified in universities of modern societies. Acoustic measurements in twelve lecture auditoria of the Tech. Univ. Athens have been made to evaluate some of the deleterious effects of such design errors on the acoustic performance of the auditoria. Identified prevalent design errors and some associated effects, are: i) Misuse of absorptive treatment, either throughout the ceiling of the auditorium or employed to make up for excessive room volume; The former, results in poor speech intelligibility criterion and relatively low speech sound level, whilst the latter also entails relatively low speech sound level, ii) Entire absence of absorptive treatment, which results in excessive reverberation time and low speech intelligibility criterion, iii) Excessive room volume, which entails relatively long reverberation time the amendment of which may lead to risky remedies described in i) above, and iv) Deep beams across the ceiling, which result in poor speech intelligibility criterion and relatively low speech sound level. This exercise casts some light on the understanding of design needs for acoustically effective lecture auditoria in modern universities.