Acoustics and a sound system of a university auditorium hall in Wyzsza Szkola Menedzerska in Warsaw – design and results

Michal Kaminski

Laboratorium Auditionis, Acoustic Consultant, ul. Mietowa 3B 7, Gdynia 81-589, Poland

ABSTRACT

Typically, the design of a modern auditorium hall starts with the architect's vision of the whole building. Architects rarely allow acousticians to interfere with the shape and interior design of their work as they are responsible for the whole project. Better or worse compromises are achieved during the design process, and sound system planning usually comes after, only to fit in the previously developed space. To satisfy the architect's intentions, the acoustician proposed an interesting solution of the shape and structure of the ceiling of the auditorium hall in Wyzsza Szkola Menedzerska in Warsaw bearing in mind the importance of its modern appearance. The GRG ceiling was intended to function as a "wavy sound transporter-projector" capable of directing a non-amplified human voice from the lecturer's platform and spreading it evenly over the audience. Moreover, it was to serve as a horn-like enclosure to accommodate custom-built loudspeakers. Two speaker clusters were designed as a multi-array construction working as a point source so that each listener would have the impression that the speaker addressed him/her directly. The economic aspect of the design, besides its assumed functionality, was also important. This paper describes the design and acoustic results achieved after the completion of the auditorium hall.

INTRODUCTION

In one case out of three, reputed architects bidding for spectacular projects hire acoustic advisers to secure contracts [6]. Unfortunately, even experienced architects often start their design without taking into account suggestions made by acoustic consultants, focusing in the main on their vision of a given building. Problems surface later at the interior design stage. Architects hope that acousticians will help solve their problems simply by suggesting adequate acoustic materials to be used. But even then there are many constraints and objectives on the architect's side which restrict the acoustician's freedom to perform his job well. The auditorium in Wyzsza Szkola Menedzerska in Warsaw was no exception to this rule.

The university authorities decided to redevelop the university buildings and connect them with the old ones. Apart from all administrative offices and classrooms, the complex was to include a recreation centre (with a swimming pool), and three halls joint with one another (the senate room, four small lecture halls for 200 students, and main auditorium for 650 seats). The architectural contest was organized and won by a team of young architects who specialize in designing modern structures (Figure 1).

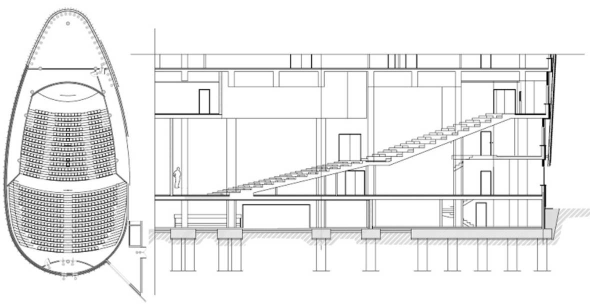


Figure 2. Plan and section of the main auditorium in Wyzsza Szkola Menedzerska in Warsaw – construction design

Other examples of proper procedures of blending architectural and acoustic factors in designing were described by Ando *et al.* [12].

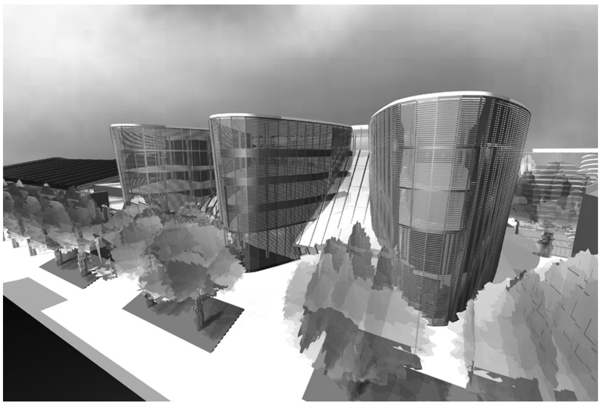


Figure 1. Visualization of the complex of new buildings of Wyzsza Szkola Menedzerska in Warsaw – architectural contest

BACKGROUND

The first consultancy meeting on acoustics was held in summer 2002 while calculating the budget for prospective general contractors. At that moment the construction design was ready, and no changes to the general shape of the auditorium were possible (Figure 2). The acoustician prepared a list of recommendations concerning general building acoustics, such as noise insulation and the selection of final acoustic materials in commonly accessible areas to provide acoustic comfort for users. Preliminary ideas concerning the interior of the auditorium were discussed, but at that stage there was no official commission for interior design at all. Given the lack of experience with project of such a scale, both sides, i.e. the client and the architect, were not ready to prepare the final design for all interiors. This was to be done later during construction work and after estimating the real costs of the undertaking, as the economic aspect was of importance.

Finally, in January 2005 the architect and the client approached Laboratorium Auditionis requesting assistance in the design of the main auditorium designated not only for lectures but also for music events with sound reinforcement, congresses, and conferences. This was to become the biggest auditorium located at Praga, Warsaw's eastern district. It was agreed that the interior design would be completed within tree months.

The building complex was commissioned for use on 1 January 2006; however, the acoustic wall treatment of the auditorium came later, and then it was possible to proceed with all final sound system tunings. The auditorium was completed during summer 2006 (Figure 3).

Figure 3. Complex of new buildings of Wyzsza Szkola Menedzerska in Warsaw after completion – on the left: recreation centre; in the middle: two office buildings, classrooms, two small lecture halls; on the right: building with the main auditorium, senate room, and two small lecture halls

DESIGN CONCEPT

Architectural idea

The general architectural concept was to maintain a sense of modernity of the structure that resembled a big ship standing in a dry dock. From the plan view the structure resembled an egg (Figure 2). Another consideration from the architect's point of view was to maintain a sense of roundness inside the auditorium. While in the plan view the auditorium seems symmetrical, its left side was to be glazed with outside jalousies, and the opposite sides were to be made of brick and mortar. The original concept was in the shape of an elongated horseshoe with the house placed on the rising slope. Floors were to be covered with a carpet. The auditorium measurements were as follow: length: 30 m; width: max. 20 m, min. 17 m; average height: 7 m, especially at the platform: 6.50 m, in the first rows: 10.50 m, in the middle: 7 m, at the back: 2.70 m; total floor area: approx. 500 m^2, cubature: approx. 3500 m^3.

Acoustical objectives

The proposed acoustical layout of the auditorium was to meet objective acoustical requirements which are highly correlated with the subjective perception of a speaker and the audience (to achieve excellent speech clarity with reduced level of reverberance due to the primary function of the auditorium) [1]. Further acoustical requirements were described by commonly known criteria based on impulse responses and current standards to provide adequate diffusion in accordance with the desired program [9][10]. Target parameter values were as follows: reverberation time (T30) of 0.8 ÷ 1.2 s for mid frequencies (0.5, 1, 2 kHz); Early Delay Time (EDT) of 0.7 ÷ 1.0 s; Clarity C50 and C80 of > +1 dB and Lateral Fraction (LF) of > 0.15 [13]. Another goal of this project was to solve acoustic problems caused by the concave "egg" shape of the auditorium walls prompted by the original vision of the complex.

Project solutions

Due to the constrains of the acoustical treatment on the left glass wall side (neither curtains nor other wooden interior jalousies or fabric vertical blinds would be a good solution because of rising stairs around the house and lack of a horizontal line of the windows), and keeping in mind similar acoustic conditions on the opposite wall, the logical solution was to focus on the ceiling design in order to provide both adequate diffusion and efficient uniform coverage over the house.

Rooms for speech require short reverberation time, but creating the so called "dead acoustics" is not a good solution, especially when the audience constitutes a highly absorbing element [5]. If the ceiling were also absorptive, the effect of a strong echo would appear, especially flutter echo between reflecting side walls [8]. There was hardly any room left to determine the type of seats in the auditorium. The investor had already ordered inexpensive wooden chairs on a metal frame with upholstered seat and back. For some areas (mostly in the back of the house), higher wooden backs were proposed to provide additional back-reflection. Unfortunately, due to economic aspects, the client ignored that detail, and removed them from the project. It is understandable, as the cost of a single seat was about US$ 175 including installation. The client required a mobile stage (the problem was solved by extending the platform by installing 3 removable rows of chairs at the front), and a big screen (6 m wide and 4 m high). An overhead concrete shelf parallel to the platform only added to that. These factors were considerable constraints in the proper modelling of sound reflectors above the platform.

Ceiling

The maximum height of the auditorium above the front rows created considerable cubature, so the only possibility to reduce it was to develop a suspended ceiling. The acoustician proposed a tent-like shape which gradually flattened at the back of the auditorium. At the same time came an idea of a central speaker cluster combined with the waveguide construction of the ceiling, which would act as one unit (point source enveloped with big horn-like ceiling elements) to provide controlled sound guiding over the house. This effect was desirable as it was possible to create authentic reproduction of voice generated in one point to all listeners, and for the production of live music during various cultural events (Figure 4).

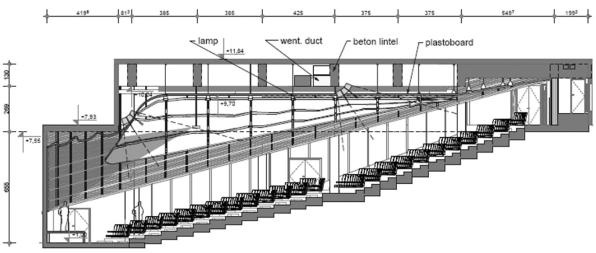


Figure 4. Section of the auditorium in an early design concept for overhead stage reflectors, suspended ceiling, and speaker clusters

The architect's intention was to keep the shape of the ceiling with flat surfaces of each element. Meantime, a geometrical model (aided by CATT-Acoustic) was developed in order to obtain the parameters desired and to determine the general layout of delimiting surfaces (Figure 5).

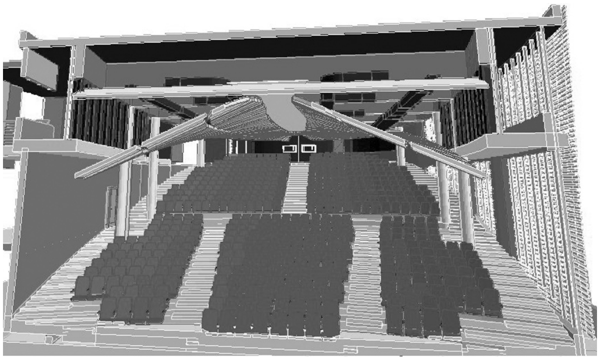


Figure 5. Sample section of the auditorium geometrical model

To avoid undesirable focalizing effects caused by large flat surfaces of the tent fragments, the acoustician proposed to modulate the surfaces in a convex way. Similar solutions were proved successful in Orlowski's experiments with curve-shape optimization (from Arup Acoustics) [11].

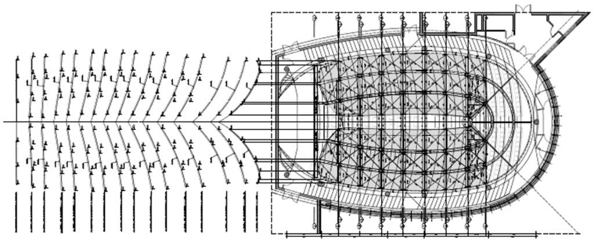


Figure 6. Plan and sections of the primary ceiling panel design

A set of 48 detailed panel drawings was prepared and sent to Acoustic GRG Products Ltd. in Kent, UK, a reputed specialist in GRG products (glass reinforced gypsum), and BIS (Bespoke Interiorer Solutions Ltd., Essex, UK) contractor, as they were the proper companies for this kind of project (Figure 6). It occurred that the elements were too big to fit the existing mould, and new moulds had to be pre-manufactured, which could result in delays and have financial implications (Figure 7).

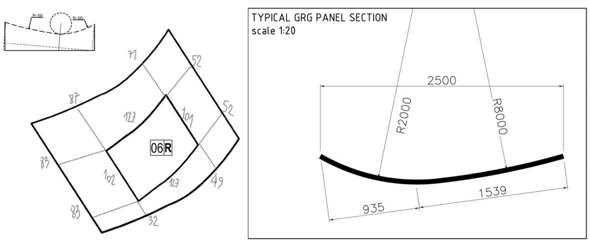


Figure 7. Existing panel mould owned by Acoustic GRG

A slight compromise was reached, and the new revised ceiling element sizes and configurations were prepared just to match the existing mould. The solution resulted in a bigger number (92) of smaller and more manageable elements; some of them could be joint on-site by a plaster specialist (Figure 8). The installation of these elements and some of the acoustic materials described later (QRD diffusors and perforated back ceiling) were performed by BIS. The cost of the specialized acoustic works, including materials and delivery totalled US$ 200 000.

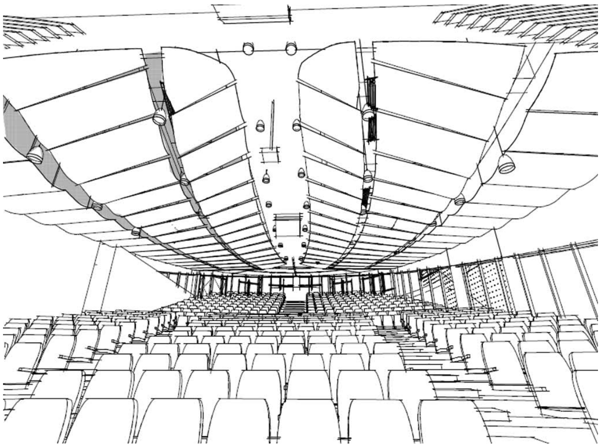


Figure 8. Modelled view from the stage over the house with revised smaller panel elements

The commonly accepted procedure to avoid long sound path reflections from the back in rooms for speech is to provide absorption in these areas [5]. Spread fan-shaped perforated flat panels were designed to close the tent ceiling, which provides smooth banding of its two nearly flat sides (at the end of the auditorium) (Figure 9). The optimized perforation scheme was designed, and the AUTO-CAD drawings were sent directly to the wood-specialists in the UK who had programmed the CNC machines in accordance with the architectural detailed drawings. Drilled fire rated MDF boards were later RAL-colour matt painted. After fitting and fixing the MDF boards on site, they were covered with health-approved mineral glass wool.

Figure 9. Spread fan-shaped perforated panels at the rear of the auditorium

Diffusion and absorption

Meanwhile, the solution to build a suspended partition ring surrounding the house was introduced to optically detach the audience from the outside walls and create a separate space over the outside aisles. Such a solution satisfied the architect's idea of being inside the 'egg' as well as the acoustician's specific requirements (Figure 10).

In general, the sound reflected from the ceiling was to be further diffused on some of the elements of the inner surface of the ring and directed towards the house providing listeners with lateral diffused reflections. The unwanted spillage of the sound that would be directed to reflecting side walls (glass and plain wall) was to be reduced in the event of a possible flutter echo by the absorbing aisles space (especially in the case of sound transmitted by the centre sound system clusters).

Figure 10. Arrangement of acoustic materials in side aisle area: view on perforated plasterboards on the ceiling and the outside of suspended partition ring

In this part the partition was to be covered with perforated plaster boards, and resonating cavity was produced for providing wider working absorption also on lower frequencies. And from the inside, a full plywood-plaster board sandwich base was to be covered with QRD 734 diffusors and the band of FlutterFree made by RPG Diffusor Systems [2]. From the overall number of 306 QRD panels, about half was tailor-made due to different sizes, to match exactly the motif on the concave base wall of the ring (Figure 11).

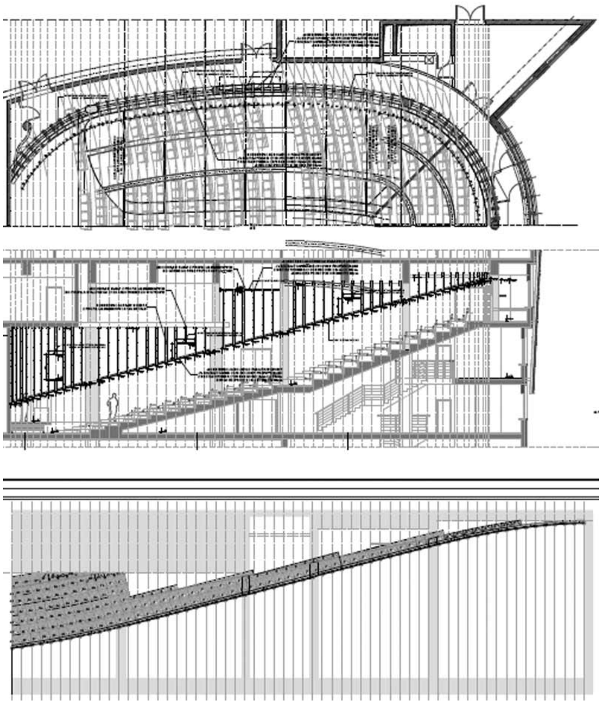


Figure 11. Plan, construction section, and QRD diffusors layout of the suspended partition ring

Due to fire security regulations and not to limit the width of the aisles, it was impossible to cover the right side concrete wall with any soft or thick acoustic material. This is why the semi-perforated gypsum panels were introduced (producer: Iberplaco - Spanish division of BPB, model: Decogips Gama Silencio, price per square meter: US$ 20) (Figure 12). The solution was acclaimed by the architect because their layout matched the arrangement of window frames on the opposite side. From the acoustical point of view, these panels were useful to enhance lateral diffusion, providing effective energy distribution to reduce the risk of strong reflection.

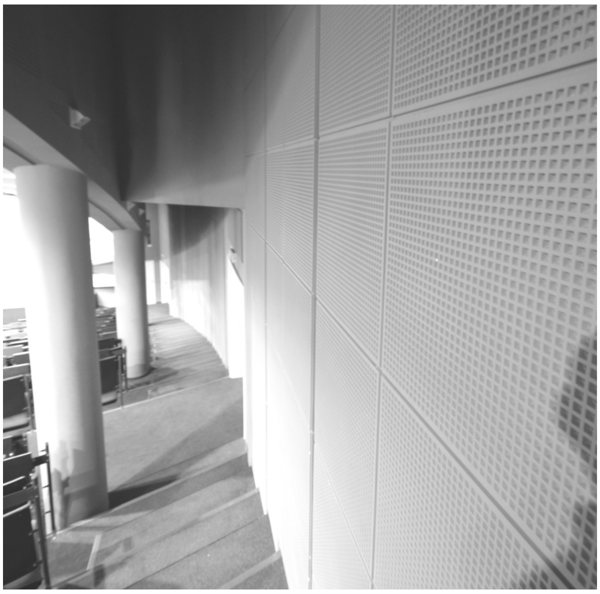


Figure 12. Arrangement of acoustic materials in side aisle area: view on semi-perforated Decogips modules covering concrete wall

At the back of the auditorium, there is a booth for interpreters and audio-video operators which is separated by a modelled convex wall with glass elements. The rest of the wall was covered with the same material to avoid undesirable echo effects that could return to the front platform (Figure 13).

Figure 13. Operation booth convex wall at the back of the auditorium covered with semi-perforated Decogips modules; left: sectional detail through Decogips module and sound diffusion

LOUDSPEAKER DESIGN AND SOUND SYSTEM SET-UP

In order to meet the requirements of equal loudness throughout the auditorium, direct and time-coherent amplified sound, a high degree of speech and music resolution and its clarity and articulation, a tailor-made loudspeaker system was developed and manufactured by a German specialist in cooperation with Laboratorium Auditionis. It was planned as a centrally mounted multiple point source which was to deliver a constant sound response over the audience in a calculated range of vertical and horizontal patterns. This configuration was to be enhanced by the unique shape of the ceiling to provide undistorted authentic speech without any sound timber changes and undesirable delay effects to each seat. The set-up was separated in two speaker clusters, each consisting of three modules. The first cluster was hanged in front of the auditorium, and the second was producing the sound with the delay, set up in accordance with the distance from the front cluster. The complete system was controlled by a digital (24bit/96kHz) loudspeaker management system processor, and thus each of the six loudspeaker modules had its own programmed acoustic parameters for different functions as well as level control in accordance with its directivity.

Prototype tests

The single loudspeaker module design was based on a wide-angle coverage construction. To achieve this goal the pre-test dummy model was developed and tested in a workshop to simulate similar working conditions. The construction of a single module consisted of four compression drivers with equivalent mini horns in coaxial configuration with four 12” diameter low-mid frequency paper cone loudspeakers (enclosure size: width 135, depth 85, height 35 cm). The angles of each driver and their mutual position were precisely checked (Figure 14). The passive crossover was tuned using latest sound system measurement instrumentation and software with real-time analyser, and also by subjective evaluation. The durability was later tested with a long term test for high power handling within full frequency response.

Figure 14. Prototype tests of the single speaker module

Later on the 6 modules were manufactured and hanged one by one in a proper angle to ensure complete audience coverage (Figure 15).

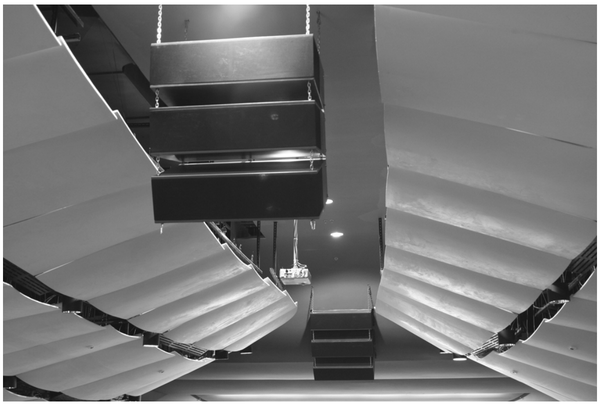


Figure 15. Arrangement of speaker clusters

Final sound system fine tuning was performed in accordance with the ultimate acoustic conditions achieved in the room. It occurred that a much wider frequency response and dynamics (especially in low frequencies) were achieved due to the coupling effect and the ceiling, which would obviously be hard to predict in any design software. Enough headroom with no feedback problems was created, allowing sound reproduction with very good resolution and dynamics starting from 50 Hz, and detailed high frequency range well above 10 kHz. Each loudspeaker module was driven by a single power amplifier channel. The total amplifiers power available was 4800 watts @ 4 Ohm r.m.s.

OBJECTIVE RESULTS

Shortly after the completion of the auditorium, its acoustic measurements were checked without the audience present, by computing the objective acoustical parameters based on the ISO 3382-1997 standard [7] (Figure 16).

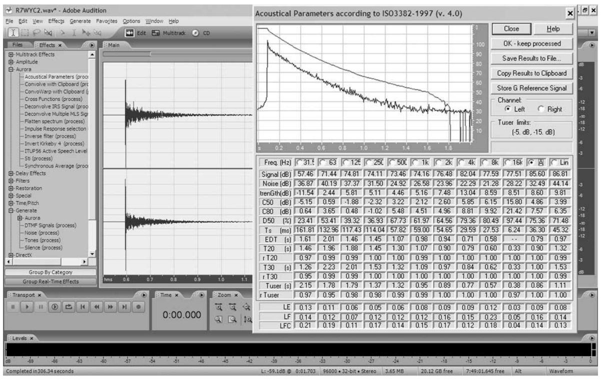


Figure 16. Typical screen shot of Acoustical Parameters window of Farina’s AURORA v. 4.0 plug-in for ADOBE Audition v. 2.0 software

Methodology of analysis

The results were obtained with two kinds of sound sources. An omnidirectional loudspeaker with a subwoofer placed in the central area of the platform and an installed sound reinforcement system were used. It served for checking different sources and offered an opportunity for deeper verification and understanding of the implemented design. A pressure-velocity SOUNDFIELD microphone probe captured four signals, known as B-format, which were utilized during the calculation of monaural and 3-dimmensional parameters. A log sine sweep method was employed for the measurement of the impulse responses, the algorithms implemented by Farina [3][4] in AURORA v. 4.0, the up-to-date excitation-deconvolution technique software plug-in for ADOBE Audition v. 2.0. Three 15 seconds long exponential sweep repetitions, followed by 10 seconds silence, were generated in the frequency range from 22 Hz to 22 kHz. The W, Y, X, Z signals coming from microphone processor were directly stored as .wav files on a notebook hard-disc by means of high-end quality 24bit/96kHz 8 channel RME MultiFace II sound interface (Figure 17).

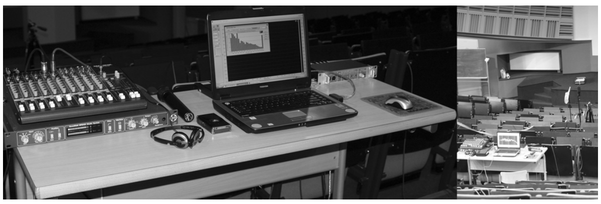


Figure 17. Acoustic measurements instrumentation in the middle of the auditorium

22 different receiver positions were chosen, allowing the representative auditorium test. 11 were located in the front part of the house (3 on the auditorium axis, 4 by the left and 4 by the right side symmetrically), 8 in the rear (2 on the axis and 3 by the left and 3 by the right side), and 3 in the wide

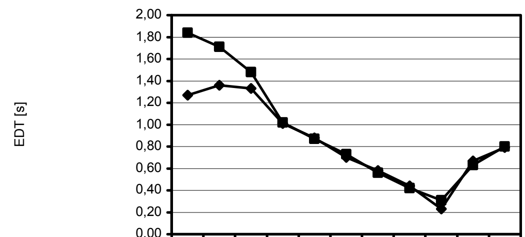
middle aisle, perpendicularly separating the front and the rear of the auditorium.

Figures interpretation

It was interesting to estimate the acoustic symmetry of the auditorium. There were no significant differences between the left and the right side as well as in the rows: symmetrically located paired points shoved only slight variations from the values of those on the auditorium axis.

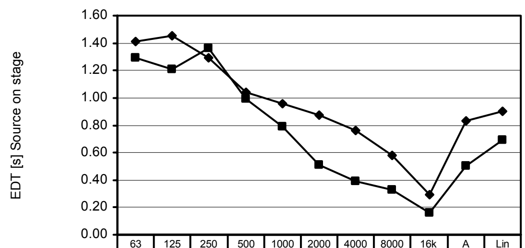
Similarly, the uniformity of the spatial description showed equality throughout the house. Obviously, the difference was shown between sound source origination. During on stage excitation, LF (Lateral Fraction) values tended to 0.10, while using the installed sound system - to 0.20, thus proving a good sense of spaciousness and envelopment even while listening to the variety of sounds reproduced from monophonic point source speaker clusters.

Furthermore, closer analyses were shown on diagrams. Starting for EDT, satisfying results, yet not equal, were achieved for mid-range (0.5, 1, 2 kHz) (Figure 19). Higher values are measured in the lower range, due to the coupling and horn shaped environment of installed loudspeakers. The lower values were obtained in the higher range, but while comparing front and rear parts of the auditorium they became even lower, mostly for rear parts when the sound originated form the stage (Figure 19).



	63	125	250	500	1000	2000	4000	8000	16k	A	Lin
Stage source	1,27	1,36	1,33	1,01	0,88	0,70	0,58	0,44	0,23	0,67	0,79
Installed system	1,84	1,71	1,48	1,02	0,87	0,73	0,56	0,42	0,31	0,63	0,80

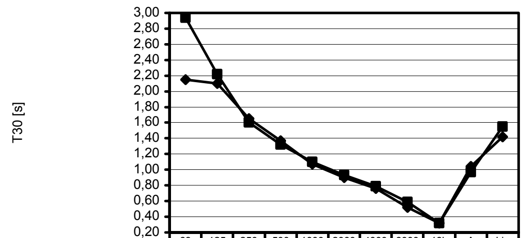
Figure 18. Early Decay Time curves for sound source on the stage and for the installed sound system



	63	125	250	500	1000	2000	4000	8000	16k	A	Lin
Front	1.41	1.45	1.29	1.04	0.96	0.87	0.76	0.58	0.29	0.83	0.90
Rear	1.29	1.21	1.36	0.99	0.79	0.51	0.39	0.33	0.16	0.50	0.69

Figure 19. Front and rear EDT comparison for sound source on the stage

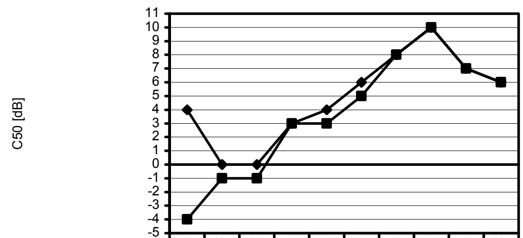
Even if not constant, the general character of T30 curve fits the target, and the richer reverberation time is observed with subjective impression warmth (Figure 20). However, this effect is mostly perceived while listening to the full range of music reproductions via the installed sound system. A typical lecture speech contains less energy in low frequencies, which does not disturb the speech intelligibility. No difference between the front and the back was measured. Those values are good for multipurpose function of the auditorium, especially when the installed sound system is on.



	63	125	250	500	1000	2000	4000	8000	16k	A	Lin
Stage source	2,15	2,10	1,65	1,37	1,07	0,90	0,76	0,52	0,32	1,04	1,42
Installed system	2,94	2,22	1,60	1,32	1,10	0,93	0,79	0,59	0,32	0,97	1,55

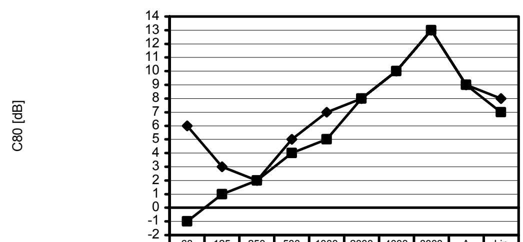
Figure 20. Reverberation Time curves for sound source on the stage and for the installed sound system

The values throughout the wide frequency range over 0 were achieved for clarity C50 with its A-averaged of +7 (Figure 21), and for C80 +9 (Figure 22). It follows that the original goal seems to have been reached, and these measures confirm the subjective impression of exceptional clarity and the observation that a quiet voice on the platform can be clearly understood even in the back of the auditorium.



	63	125	250	500	1000	2000	4000	8000	A	Lin
Stage source	4	0	0	3	4	6	8	10	7	6
Installed system	-4	-1	-1	3	3	5	8	10	7	6

Figure 21. Clarity C50 curves for sound source on the stage and for the installed sound system



	63	125	250	500	1000	2000	4000	8000	A	Lin
Stage source	6	3	2	5	7	8	10	13	9	8
Installed system	-1	1	2	4	5	8	10	13	9	7

Figure 22. Clarity C80 curves for sound source on the stage and for the installed sound system

CONCLUSION

The objective and subjective results obtained indicate that the geometry of the ceiling and the proper use and placement of diffusing and absorbing elements is the key (Figure 23, 24).

Figure 23. Ceiling of the main auditorium in Wyzsza Szkola Menedzerska in Warsaw

Figure 24. Arrangement of the front of the auditorium in Wyzsza Szkola Menedzerska in Warsaw

Acoustic problems can be solved without destroying the architectural concept even under such poor acoustic conditions as was the case at the initial project stage.

Even at low levels of the amplified sound, the general clarity and brilliance over good bass perception was achieved, although the monophonic point source sound system, optimised for speech reproduction, was used.

It seems that slightly better conditions could have been achieved in the back part of the auditorium, if the proposed back-reflecting wooden elements of the seats had been adopted. Also the second stage of the sound system upgrade to 5.2 channels sound reproduction was proposed, and additional spaces for customized loudspeakers were prepared in the inner parts of the suspended partition ring, simply by removing selected QRD diffusors modules. Two additional subwoofers were planned to be located symmetrically in the front corners of the auditorium, which turned out to be a good idea. In that configuration the centre clusters would be digitally high-passed over e.g. 150 Hz and the complete sound system tuning would be upgraded, which surely improves EDT and clarity at low frequencies throughout the audience.

ACKNOWLEDGEMENTS

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