TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
CIVIL ENGINEERING | BUDOWNICTWO
2-B/2015

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AN ACOUSTIC STUDY OF THE AUDITORIUM HALL TO BE LOCATED IN THE PROPOSED BUILDING OF THE APPLIED ACOUSTICS LABORATORY OF CRACOW UNIVERSITY OF TECHNOLOGY

STUDIUM AKUSTYKI SALI AUDYTORYJNEJ ZNAJDUJĄCEJ SIĘ W PROJEKTOWANYM BUDYNKU LABORATORIUM AKUSTYKI STOSOWANEJ POLITECHNIKI KRAKOWSKIEJ

Abstract

This paper presents an acoustic study of the auditorium hall located in the proposed building of the Applied Acoustics Laboratory of Cracow University of Technology. The study shows a comparative analysis of two solutions to the acoustic adaptation of this room. The aim of this study was to demonstrate that with a given room shape and finishing materials, it is possible to optimize the sound quality of the interior through changes to some architectural details, for example, by the adequate formation and arrangement of finishing elements.

Keywords: building and architectural acoustics, room acoustic parameters

Streszczenie

W niniejszej pracy przedstawiono studium obejmujące adaptację akustyczną sali audytoryjnej znajdującej się w projektowanym budynku Laboratorium Akustyki Stosowanej Wydziału Inżynierii Lądowej Politechniki Krakowskiej. W opracowaniu zaprezentowano i dokonano analizy porównawczej dwóch wariantów adaptacji akustycznej analizowanego pomieszczenia. Celem pracy było wykazanie, że przy zadanej bryle pomieszczenia i zestawie materiałów wykończeniowych sposobem optymalizowania jakości akustycznej wnętrza są działania w zakresie detalu architektonicznego, np. odpowiednie rozmieszczenie i formowanie elementów wykończenia wnętrza.

Słowa kluczowe: akustyka budowlana i architektoniczna, parametry akustyczne wnętrz

DOI: 10.4467/2353737XCT.15.142.4179

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1. Introduction

Since ancient times, room acoustics have been an important consideration in the design of buildings. Initially, this was perceived subjectively, so some impressions connected with speech intelligibility, sound volume or sound clarity were particularly important. However, mathematical apparatus was not sufficient to describe such acoustic parameters until the twentieth century, hence their prediction and measurement. The progress of understanding some acoustic phenomena and the ability to describe them had a beneficial effect upon the development of room acoustics. Due to this, it has become possible to confirm the subjective feelings by objective values. The objective criteria has an advantage over the subjective criteria due to their replicability, their measurable outcome and the possibility of applying them during the design stage. In the literature, a number of objective parameters for determining the acoustic quality of a given room are defined. In the case of auditoria, the most important predictors describing the sound field are reverberation time T_{60}, speech transmission index *STI* defining the level of speech intelligibility and sound strength *G*.

Reverberation time T_{60} is a commonly used parameter and the earliest defined in room acoustics. This indicates the time required to reduce the sound pressure level of 60 dB [1]. The length of reverberation determines the suitability of the analysed room for specific purposes, however, it does not provide information regarding the sound quality. The speech transmission index *STI* is a particularly important parameter in auditoria. It provides values from 0 to 1, wherein a value of 1 means excellent speech intelligibility while a value of 0 defines the lowest quality. In order to determine the *STI* parameter, there are some techniques used based on the modulation of noise with a bandwidth similar to the human voice band by frequencies similar to those found in natural speech. Changes to the modulation depth of the output of the system are then analysed. The next mentioned parameter, sound strength *G*, is the difference of volume at which the source is heard in the room compared with the volume in free field at a distance of 10 m from the same source [2].

The values of the described acoustic parameters highly depend on the room's shape and facing materials used. The suitability (from an acoustic perspective) of the designed room's shape and the arrangement of sound absorbing and reflecting materials might be verified using one of the three basic methods: wave; geometric; statistical [3]. Each of these methods enables studying a different set of acoustic field parameters, therefore, the combined use of all methods allows the acoustic properties of the room to be determined to a high degree of precision. The analyses presented in this paper are mainly based on geometric and statistical methods due to the application of CATT-Acoustics software during numerical analysis.

2. The subject of study

The analysed auditorium is one of the rooms of a proposed building that has been designed for the Applied Acoustics Laboratory of the Faculty of Civil Engineering at Tadeusz Kościuszko Cracow University of Technology [4]. This building would be located on the campus on the Avenue of John Paul II on Czyżyny (Fig. 1). It is simple in form, on the plan of a regular rectangle with dimensions of 35.75 m x 22.70 m (Fig. 2). It has two ground floors where there are located laboratory rooms, offices, sanitary facilities, as well as the designed auditorium and an underground floor with exhibition rooms, storage rooms and technical rooms.

The discussed auditorium (Figs. 3, 4) was designed for an audience of 220 people. The room dimensions in plan are 20.9 m × 9.8 m and its volume is approximately 1025 m^3. The lectern is located at -1.2 m, while the audience rises upward at an angle of 9° (the front portion of the audience) and 10° (the rear portion of the audience). In the auditorium there are three doors – two at a level of -1.2 m and one at 0.0 m. Six windows on one side-wall extend from the floor up to the false ceiling. Additionally, there are some technical rooms located behind the back wall of the auditorium.

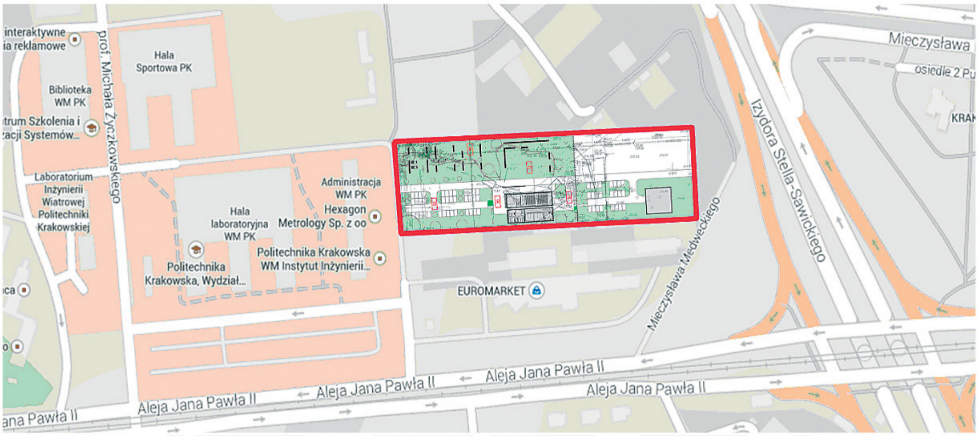

Fig. 1. The location of the Applied Acoustics Laboratory on the campus at the Avenue of John Paul II on Czyżyny [5]

Fig. 2. The visualization of the building of the Applied Acoustics Laboratory [4]

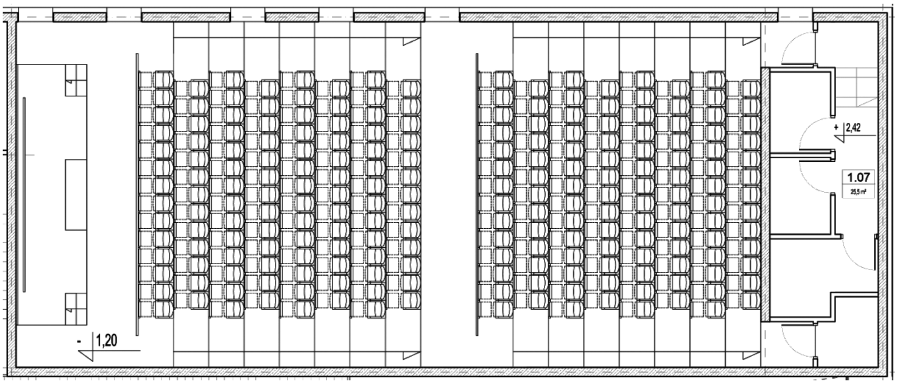

Fig. 3. The plan of the first floor in the designed auditorium located in Applied Acoustics Laboratory [4]

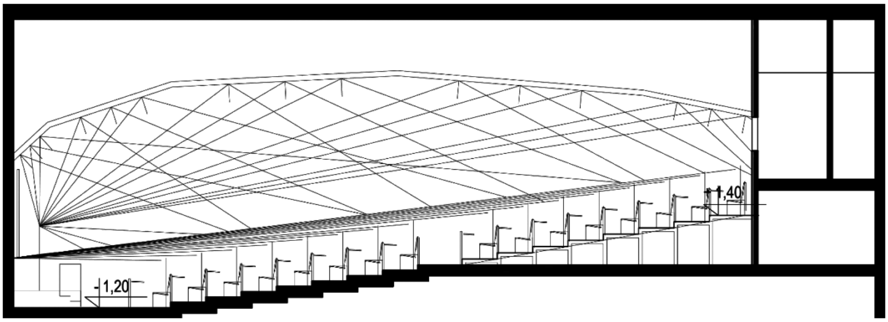

Fig. 4. The cross-section of the designed auditorium located in Applied Acoustics Laboratory [4]

3. Guidelines for acoustic adaptation

The model of the designed auditorium was made in CATT-Acoustics v9.0c software which allows the determination of the acoustic field in a room. The aim of the simulation was to obtain and assess the values of the following parameters, i.e. the reverberation time T_{60}, the speech transmission index *STI*, and the sound strength *G*.

In the literature, there are several formulas for determining the recommended reverberation time for auditoria depending on their volumes. The presented study was based on two empirical formulas:

$$T_{60}(V) = 0.20 \log V + 0.21 \quad [6] \tag{1}$$

$$T_{60}(V) = 0.30 \log V - 0.20 \quad [1] \tag{2}$$

where V is the volume of the room [m^3]. According to the above formulas, the recommended reverberation time for the octave band with a center frequency of 1000 Hz is equal to 0.81 s by equation (1) or 0.70 s by equation (2). Due to the fact that the room will be also equipped with an additional electroacoustic sound system, the required reverberation time is assumed to be 0.70 s. The guidelines for reverberation time include its frequency range, which is from 125 to 4000 Hz. This parameter should be approximately equal over the entire range, however, a higher value is allowed for low sound frequencies due to the wave nature of the acoustic field in this frequency range and a lower value for higher frequencies due to the medium damping. The recommended reverberation time dependence for the designed auditorium hall as a function of frequency is given in Fig. 5 with a tolerance range of ±20% [7].

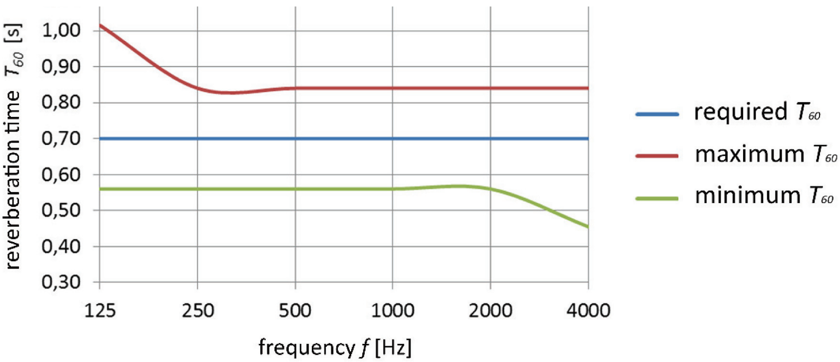

Fig. 5. The recommended reverberation time dependence for the designed auditorium as a function of frequency with a tolerance range of ±20% [7, 8]

Furthermore, it is assumed that the parameter *STI* should exceed the limit value of 0.6 at each point in the audience [8]. The sound strength *G* should not decrease more than 5 dB in the last row of seats in relation to the seats at the front of the room, which are close to the sound source [9].

4. The acoustic adaptation of the auditorium in two variants

The paper presents an analysis of two variants of an acoustic adaptation designed for the discussed auditorium. The first variant assumes that the shapes of the inner surfaces of the room are the same as are shown in the conceptual project. The required values of acoustic parameters were obtained by selecting appropriate finishing materials for walls, ceiling and floor. Sound absorbing and reflective materials were placed in accordance with the principle that reflective materials are situated close to the sound source, while sound absorbing materials are located in the back of the room, in particular, on the rear wall. Moreover, it was significant to choose seats with an appropriate absorption coefficient. Figs 6 and 7 show the model of the auditorium in the first variant.

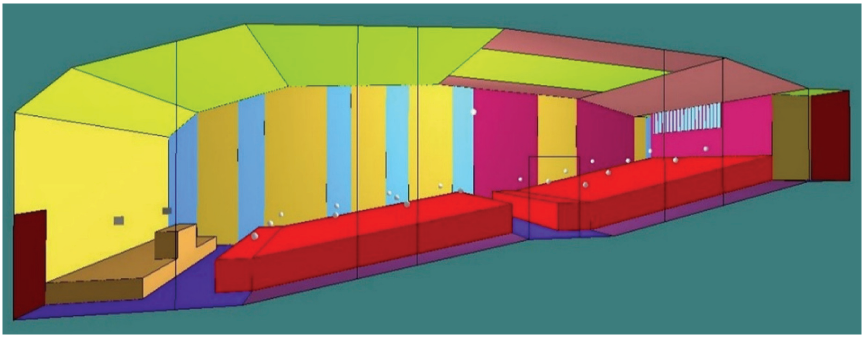

Fig. 6. The 3D model in variant I: an axonometric view (on the wall with windows) of the designed auditorium

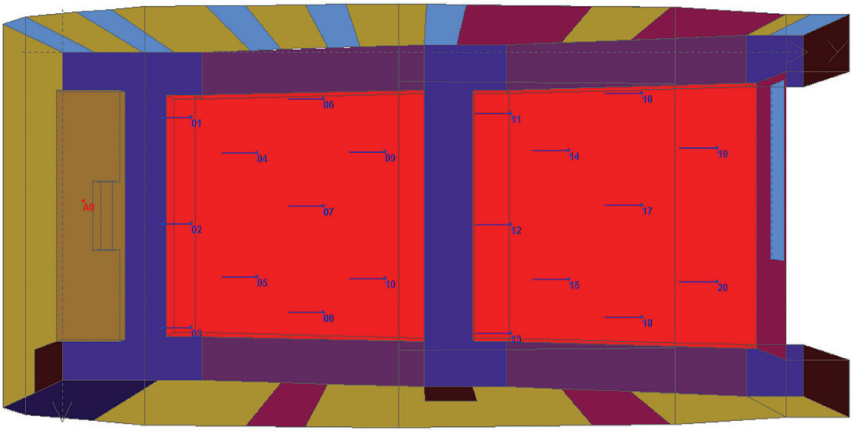

Fig. 7. The model in variant I: a z-direction view of the designed auditorium

The second variant of the auditorium's acoustic adaptation allows changing the shape of the inner surfaces to provide the best visual and auditory contact between a speaker and the audience. The conceptual project assumes the room on a rectangular plan with dimensions of 20.9 m x 9.8 m. Due to the fact that the room is quite long relative to its width, it is important to direct as much of the acoustic energy in the auditorium's rear regions in order to compensate for the sound level over the entire audience. Therefore, it was proposed that the room model should have appropriately shaped side walls. The depth of the cavities is in the range of 15 to 25 cm. Both side walls in the auditorium were uniformly shaped. Such designed reflective and absorbing surfaces do not only affect the uniformity of the sound field in the room, they also reduce some basic acoustic defects, i.e. sound focusing, sound creeping or flutter echo. In comparison with the model in the first variant, some changes in the arrangement of the materials used to cover the walls and ceiling were also made due to the need to ensure the required values of the basic acoustic parameters, e.g. the reverberation time. Figs 8 and 9 show the model of the auditorium in the second variant.

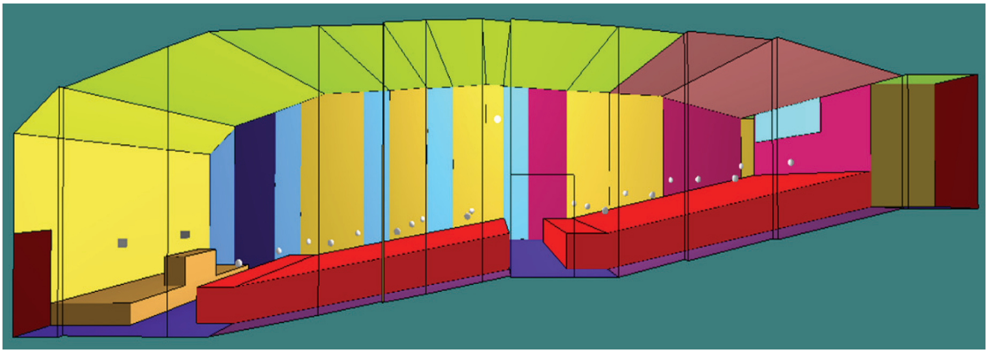

Fig. 8. The 3D model in variant II: an axonometric view (on the wall with windows) of the designed auditorium

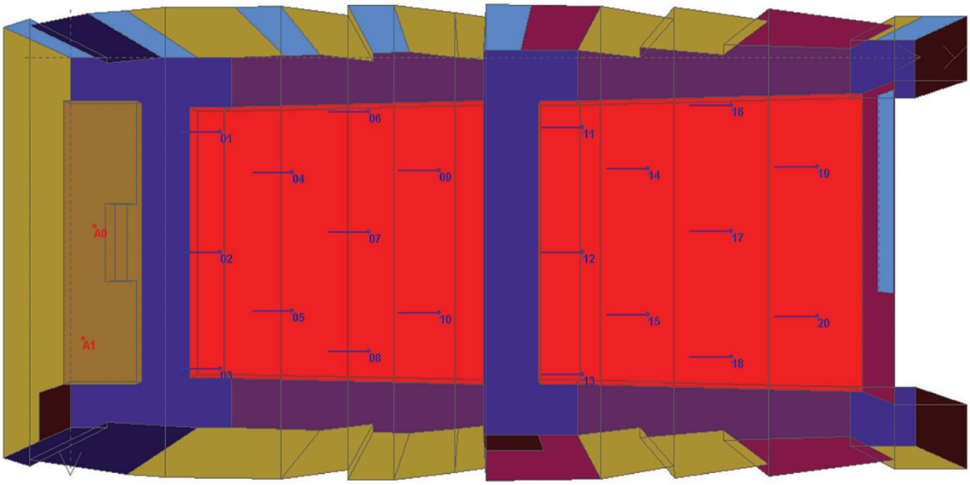

Fig. 9. The model in variant II: a z-direction view of the designed auditorium

Both proposed solutions to the auditorium's acoustic adaptation required the use of the same finishing materials, however, their placement was varied. To cover the walls, panels from Gustafs Panel System combined with mineral wool were used with an air-gap width of 30 mm. The side walls and the front wall, marked on the drawings in a brown-orange colour, were covered with plain panels characterized by a low sound absorption coefficient (Fig. 10). On the rear wall and some parts of the side walls, perforated panels PG5 were used, these have a moderate absorption coefficient (Fig. 11). In the drawings, these panels are marked in purple. At the front of the room, on the walls next to the lectern (the wall marked in dark blue), Gustafs RS8-C40 panels were placed – these have a linear perforation, characterized by a high sound absorption coefficient (Fig. 12). Strong sound absorption in the high frequency band might reduce the unfavourable flutter echo phenomenon that could occur in the region of this room where the sound source is located.

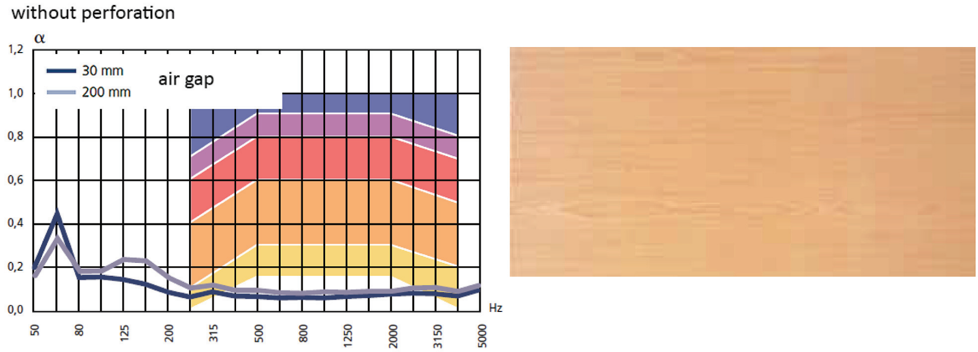

Fig. 10. The plain Gustafs panels (on the right) and their sound absorption characteristic as a function of frequency (on the left) (according to the the product catalog)

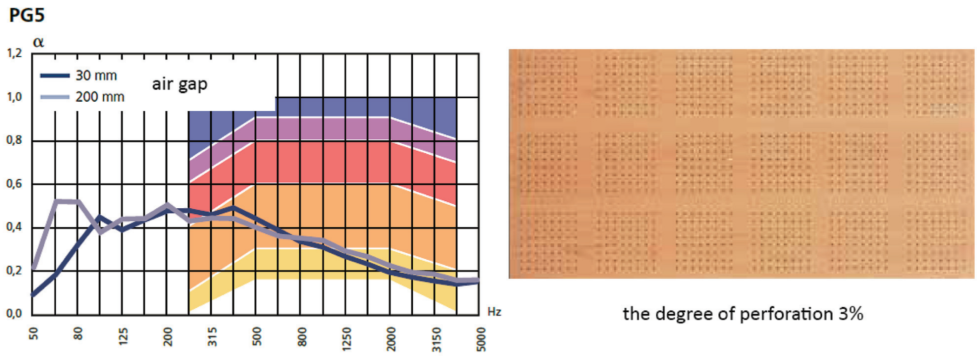

Fig. 11. The perforated PG5 Gustafs panels (right) and their sound absorption characteristic as a function of frequency (left) (source: product catalogue)

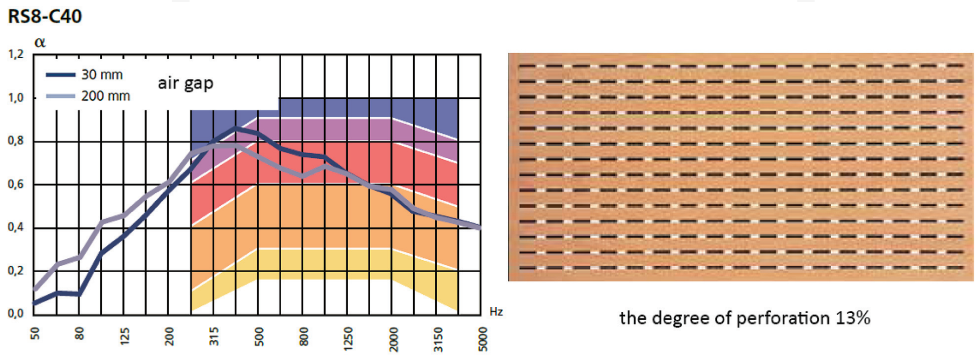

Fig. 12. The perforated RS8-C40 Gustafs panels (right) and their sound absorption characteristic as a function of frequency (left) (source: product catalogue)

The suspended ceiling is designed with two different technologies. The greater part of the surface is covered with a plain plasterboard on the system mounting with mineral wool filling having a thickness of 5 cm (the surface marked in green). Such a constructed ceiling provides the sound reflections towards the audience. Moreover, the ceiling also reduces the time when first reflections reach the listeners and ensures uniform sound distribution in the entire room [10, 11]. At the back of the auditorium, the ceiling was made with plasterboards with slotted perforations (surfaces marked in violet). Rigips panels were used (Gyptone Line 4) at a distance of 200 mm, additionally covered by the acoustic fabric. These panels have a high average sound absorption coefficient $\alpha_w = 0.65$ and the arrangement and size of the holes provide the uniform sound absorption throughout the frequency range (Fig. 13). Owing to such a characteristic, the panels used had a positive effect on reducing the reverberation time in the designed auditorium and they minimised sound reflection from the rear wall.

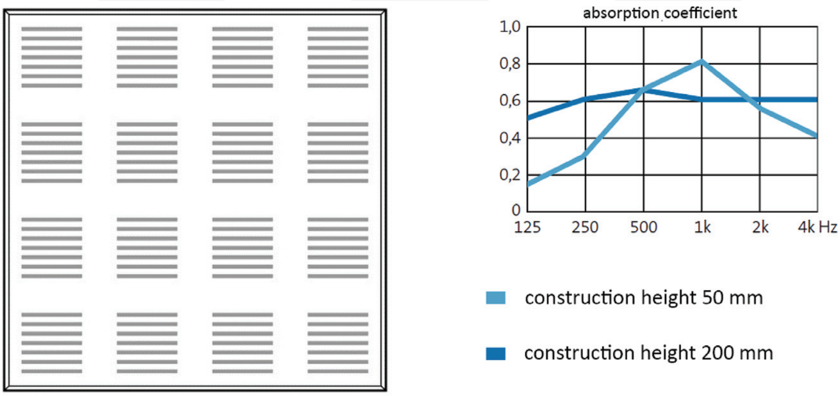

Fig. 13. The perforated Rigips panels – Gyptone Line 4 (left) and their sound absorption characteristic as a function of frequency (right) (source: product catalogue)

The floor is the next modelled surface. It was covered with a flocked lining which is durable and easy to clean and has an aesthetic appearance. Moreover, such a covering has a positive influence on reducing impact noise thereby improving the acoustic comfort in used rooms. Furthermore, the lectern and the doors were modelled as solid wood, the windows have double glazing and the seats for the audience were assumed as slightly upholstered.

5. The comparison of results of the auditorium sound field simulation in two variants

The prepared model of the discussed auditorium was used to carry out a computer simulation of sound propagation in this interior with the use of the aforementioned software CATT-Acoustics. Figs. 7 and 9 show the locations of the sound source and twenty receivers in the analysed model. It was decided to model two positions of the sound source which represent the typical orientations of the speakers. The virtual omnidirectional sound source generated a white noise signal of 94 dB for the octave band with a center frequency of 1 kHz. Furthermore, twenty receivers were placed uniformly over the entire surface of the audience at a height of 1.30 m.

The first step in the analysis was to check the inclination angles and positions of the ceiling's reflective surfaces. For the purposes of this study, the spatial geometry method was applied. The analysis was performed for the sound source position A0, i.e. for the source located near the lectern. Such a position refers to the typical location of the speaker and also to the point of the apparent sound source for wall-mounted loudspeakers spaced symmetrically on both sides of the audience. Based on these results, it can be concluded that the proposed shape of the ceiling provides proper sound distribution in the room (Fig. 14). Moreover, it is confirmed that there exists a need for using some sound absorbing panels in the rear areas of the auditorium due to the large amount of acoustic energy reflected from these planes towards the rear wall (Fig. 15).

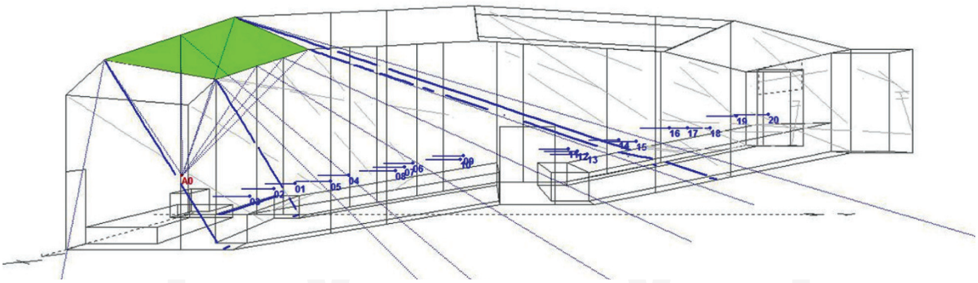

Fig. 14. An analysis of the first sound reflections from the sample ceiling's surface – the front surface (reflective) – variant I

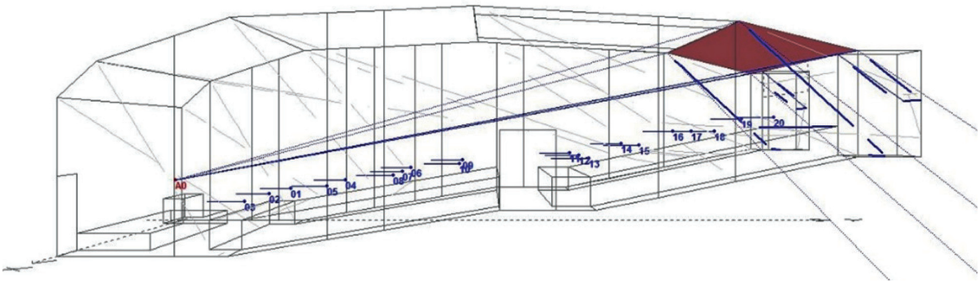

Fig. 15. An analysis of the first sound reflections from the sample ceiling's surface – the back surface (absorbing) – variant I

Calculations of the selected room acoustic parameters were performed for a full room. Sound masking effect was also included by introducing external noise at a level of 35.8 dB (28 NCB curve) to the model. The accuracy of numerical calculations was verified by Schroeder's decay curves. If some disturbances in the decay curve occurred, the number of rays increased until a smooth characteristic was obtained.

Reverberation time T_{60} is the first analysed room acoustic parameter. Fig. 16 shows the average reverberation time in the designed auditorium after adaptations in two variants against the assumptions given in the third chapter. On the basis of the presented results, it can be concluded that the reverberation time obtained from the simulation of both models meets the previously defined requirements, i.e. it has a flat characteristic in the whole analysed frequency band and its values are in accordance with the guidelines. In order to compare two of the proposed auditorium's acoustic adaptations, the convergence of obtained reverberation times for both solutions with the required values were determined. The comparative criterion was a minimum root mean square distance. In the first case, it was 0.0069, while for the second variant, it was equal to 0.0031. Therefore, it may be stated that the acoustic adaptation in the second variant provides a reverberation time closer to requirements. Moreover, the values of the reverberation time are slightly lower for the second model which can be considered as favourable due to the function of the room.

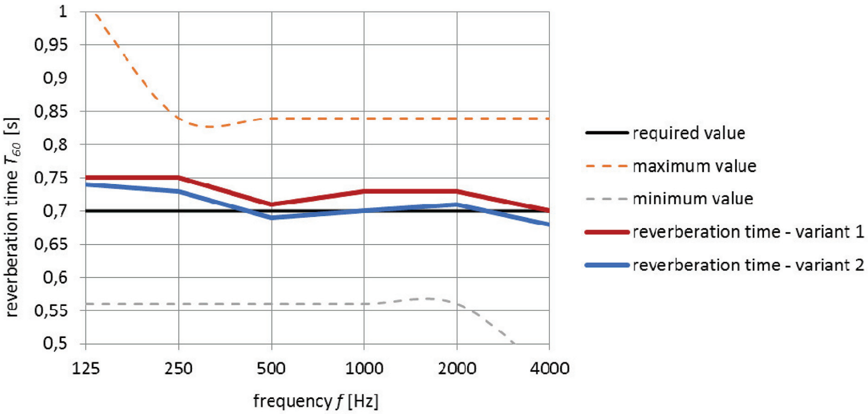

Fig. 16. The average reverberation time in the designed auditorium after adaptations in two variants against the assumptions

The speech transmission index *STI* is the next analysed acoustic parameter of the designed auditorium. Figs. 17 (variant I) and 19 (variant II) show the sample distribution of the values of this parameter in the audience for the A0 sound source location. In relation to these maps, Figs. 18 and 20 present the areas in the audience with the best speech intelligibility (E – 'excellent', G – 'good'). Based on the results obtained from the simulation, it can be concluded that both proposed acoustic adaptations of the auditorium meet the requirements for high speech intelligibility. Nevertheless, the average value of *STI*, calculated for twenty receivers' points, is slightly higher for the model in the second variant. In the first variant, it is equal to 0.74 and the minimum and maximum values of *STI* are 0.72 and 0.77 respectively. On the other hand, the average value of *STI* in the second variant is 0.76 and the minimum and maximum values are equal to 0.71 and 0.78 respectively. Furthermore, the differences between both models are even more visible on the adequate maps (e.g. Figs. 18 and 19). It is clear that in the case of the second variant, a larger area of the audience has 'excellent' values of the *STI* parameter.

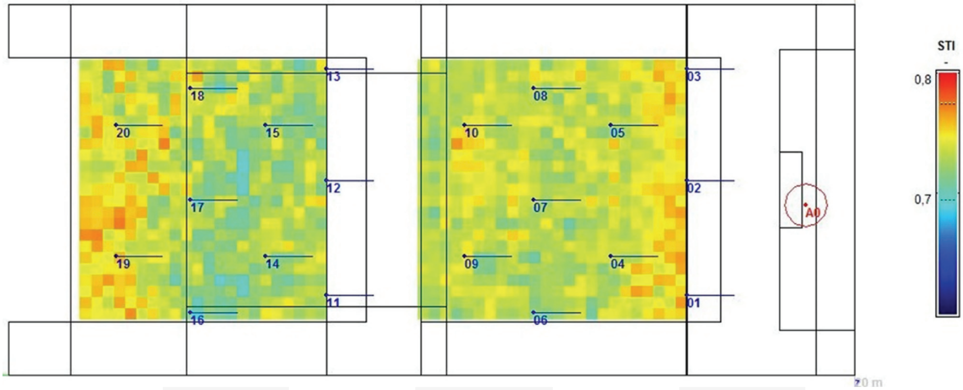

Fig. 17. Map showing the distribution of the speech transmission index *STI* values in the audience and for the A0 sound source location – Variant I

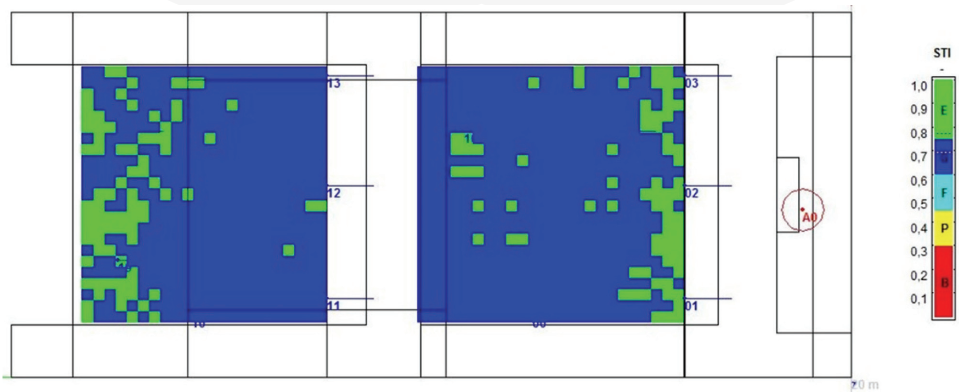

Fig. 18. Map showing the areas in the audience with the best speech intelligibility – the A0 sound source location – Variant I

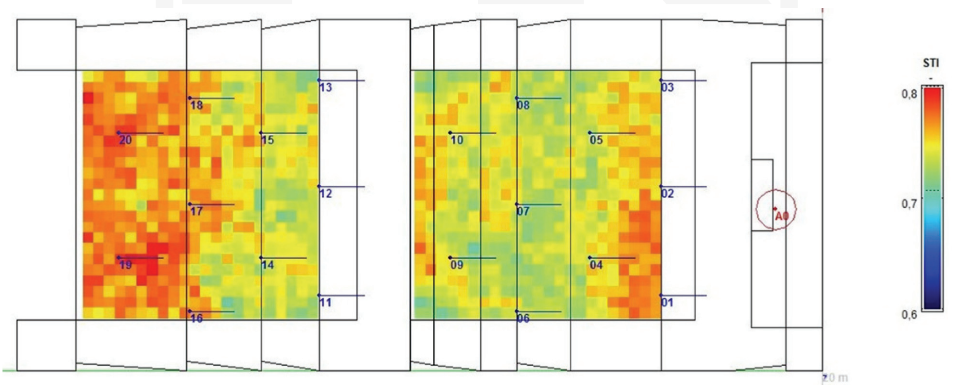

Fig. 19. The map showing the distribution of the speech transmission index *STI* values in the audience and for the A0 sound source location – Variant II

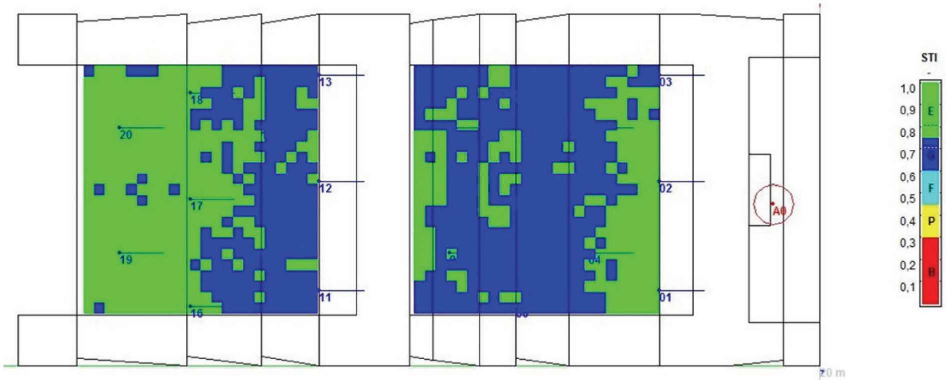

Fig. 20. The map showing the areas in the audience with the best speech intelligibility – the A0 sound source location – Variant II

The sound strength *G* is the last analysed room acoustic parameter. Figs. 21 (variant I) and 23 (variant II) show a sample distribution of its values in the audience for the A0 sound source location and an octave band with a center frequency of 1 kHz. Moreover, in Figs 22 (variant I) and 24 (variant I), the appropriate percentage shares of specific values of the sound strength *G* in relation to all data were also presented. Naturally, the final analysis was based on all the results obtained in the simulation. On the basis of the results, it was found that the assumed room's acoustic adaptations provide a basic sound dispersion throughout the room space with a uniform distribution of the sound field. The differences in the values of the sound strength for both models do not exceed the assumed 5 dB between the seats situated near the sound source and the seats located far from it. Moreover, the sound reaching the audience is properly amplified by the reflections. The analysis of the sound strength parameter confirmed the uniform distribution of sound throughout the audience for both variants and showed no significant difference between these two acoustic adaptations.

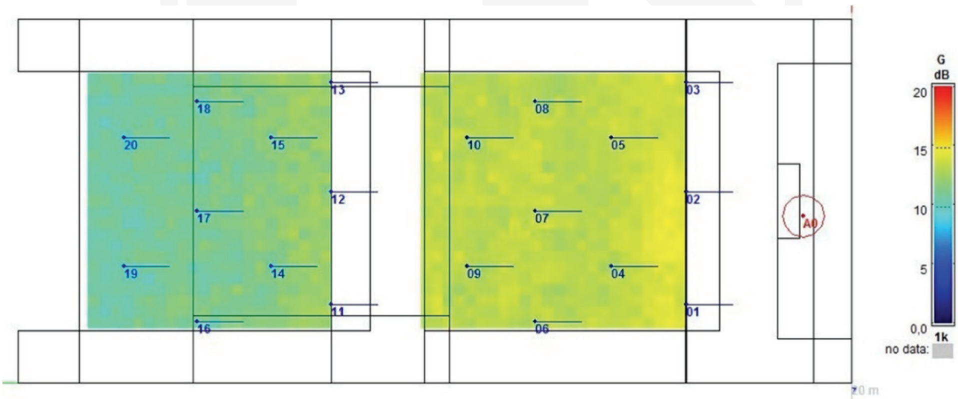

Fig. 21. Map showing the distribution of the sound strength *G* values in the audience for the A0 sound source location and the octave band with a center frequency of 1 kHz – Variant I

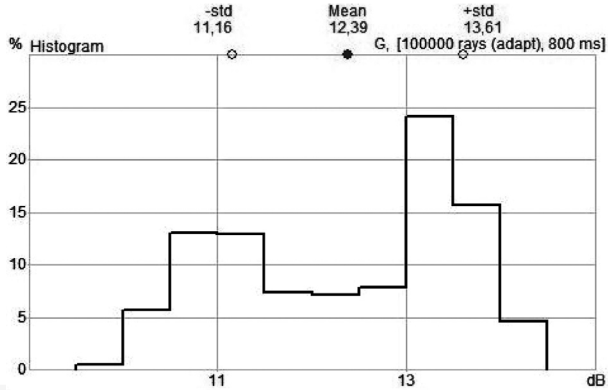

Fig. 22. The percentage share of specific values of the sound strength *G* in relation to all data for the A0 sound source location and the octave band with a center frequency of 1 kHz – Variant I

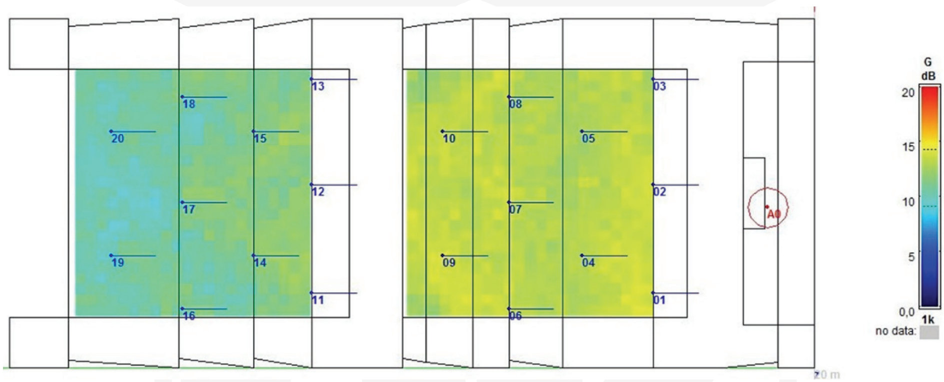

Fig. 23. Map showing the distribution of the sound strength *G* values in the audience for the A0 sound source location and the octave band with a center frequency of 1 kHz – Variant II

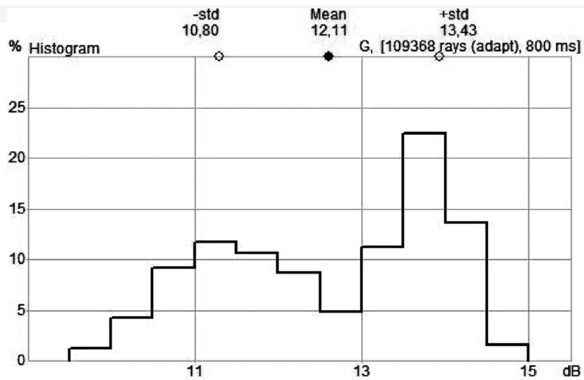

Fig. 24. The percentage share of specific values of the sound strength *G* in relation to all data for the A0 sound source location and the octave band with a center frequency of 1 kHz – Variant II

6. Conclusions

This paper presents an acoustic study of the auditorium hall located in the designed building of the Applied Acoustics Laboratory of Cracow University of Technology. The aim of this study was to demonstrate that having a given room shape and finishing materials, it is possible to optimize the sound quality in the interior through changes of some architectural details, for example, by the appropriate arrangement or formation of finishing elements. The study shows a comparative analysis of two solutions to the acoustic adaptation of the analysed auditorium. The first variant assumes that the shape of the room's inner surfaces is the same as shown in the conceptual project. The second variant allows changing the shape of the inner surfaces. Hence, it was proposed the room model having appropriately shaped side walls. After an appropriate analysis, it was found that although both solutions satisfy the previously defined guidelines for some acoustic parameters, i.e. the reverberation time, speech intelligibility and sound strength, the adaptation in the first variant gave worse results for the room's acoustic field simulation than the adaptation in the second variant. First of all, the values of *STI* parameter are more favourable in the latter model; additionally, the reverberation time in the whole band is closer to the recommended value. Moreover, an adaptation in the second variant is more interesting architecturally. For example, there is the possibility of non-standard illumination of walls by hiding the luminaires in the folds.

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