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Review Papers

Can Historic Interiors with Large Cubature be Turned Acoustically Correct?

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Historic interiors with large cubature, such as reception, theatrical, and concert halls, need to be renovated periodically if they are to be preserved as cultural heritage for future generations. In such cases it is necessary to maintain appropriate balance between requirements imposed by heritage conservation authorities office which are usually being given a higher priority, applicable safety regulations, and the comfort of use, including good acoustics.

The paper is a presentation of architectural interference in three historic interiors with large cubature leading to changes in their acoustic qualities. In two cases, the changes were beneficial to the functional qualities of the halls to satisfaction of the investors carrying out the renovation work. In the third instance, the architectural interference aimed at showing off the monumental valor of the interior resulted in significant degradation of its acoustics. To remedy the situation impairing the functional program of the facility, corrective measures are proposed neutral with respect to its historic character.

Keywords: room acoustics; acoustic rehabilitation of historic interiors; Schroeder diffusers; microperforated foil.

1. Introduction

Performance halls in historic buildings, if maintained in good technical conditions, can be successfully used in accordance with their original functional program for a long time. This usually involves periodical renovation work to be carried out under supervision of national heritage conservation authorities the objective of which is to maintain historic value of the building.

Requirements set forth by the heritage conservator's office usually restrict the range of construction materials that can be used without negative impact on historic qualities of the refurbished structure. These limitations apply in particular to period theatrical, concert, and lecture halls as well as to other large stately interiors. They are expected to function and serve multiple purposes with the same level of comfort as contemporarily designed and constructed facilities, which means the necessity to meet currently applicable requirements in the area of visibility, acoustics, ventilation, thermal comfort, etc. A natural way of conduct in this case, selected usually under the pressure of applicable building regulations, consists in choosing modern technical infrastructure systems and finishing materials. These solutions are designed with stress put on achieving pre-assumed functional and aesthetic qualities and bear certificates guaranteeing appropriate fire safety, acoustic properties, attractive color schemes, etc. However, in most cases, the use of such materials is considered an excessive interference in historic substance of architectural monuments. Adaptation of period interiors to contemporary functions results therefore in the necessity to look for finishing materials that meet both requirements imposed by heritage conservation principles and contemporary functional standards (Kamisiński, 2010; Ratajczyk-Piątkowska, Piątkowska, 2005).

This paper is a presentation of several undertakings concerning acoustic adaptation of period halls carried out in the framework of renovation projects in which the above-mentioned problems emerged.

2. The Assembly Hall of the Lviv University of Technology

2.1. Acoustics of the Assembly Hall "as it is"

The main building of the Lviv University of Technology (LUT) housing the Assembly Hall has been erected in the year 1877 (Kamisiński *et al.*, 2011). The room has a cuboidal form with dimensions 22 m × 12 m × 13 m (L × W × H) and cubature of 3400 m^3. Alike the whole building, the Hall represents the neo-classical style with walls plastered and richly ornamented with colonnades, well-developed cornices, and figural sculptures. The floor is covered with parquet, and the ceiling is decorated with lavishly carved coffers. Flat wall sections demarcated by the main cornice, the ceiling, and the sculptures carry eleven original paintings by Jan Matejko expressing an apotheosis of technology by depicting in an allegorical way the most important inventions constituting milestones marking out the development of civilization (Politechnika Lwowska, 2015).

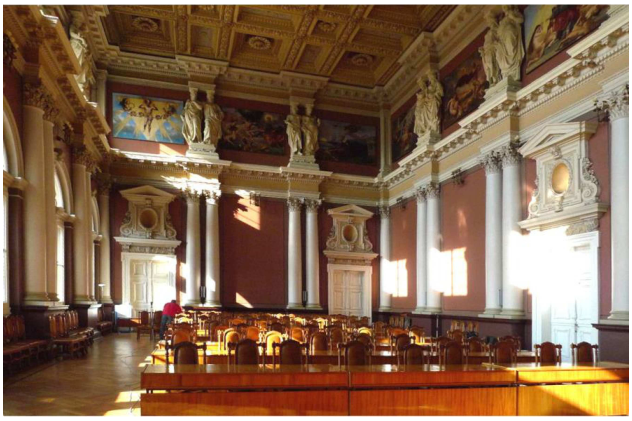

Fig. 1. The Senate Room of the Lviv University of Technology (picture by T. Kamisiński).

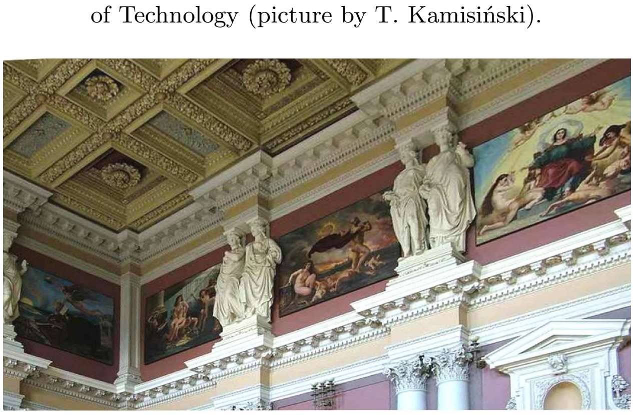

Fig. 2. Jan Matejko paintings in the upper wall panels (Politechnika Lwowska, 2015).

Deeply developed decorations on walls and ceiling are beneficial for the diffusion of sound in the room and produce an overall positive acoustical effect. To assess it quantitatively, measurements of the reverberation time and speech intelligibility have been carried out. The reverberation time in the frequency range 500–1000 Hz was found to be 1.8–2.0 s {1} (cf. solid line in Fig. 5). An acoustic deficiency of the hall was the merely satisfactory and, in most of the observation points, less then satisfactory speech intelligibility (the measured value of the speech transmission index *STI* did not exceed 0.45).

2.2. Corrective measures

For its highly presentable value, the Assembly Hall serves as the venue of important academic celebrations and other occasional events. From the point of view of this function, some reduction of the reverberation time seemed to be advisable in order to improve the speech intelligibility. To emphasize the solemn character of ceremonial meetings and create favorable conditions for musical events, especially choral performances typical for the local culture, it has been decided that the target reverberation time should exceed the values typical for lecture halls and conference rooms. An additional argument in favor of introduction of limited attenuation to the interior were restrictions in using modern sound-absorbing materials imposed by the architectural heritage conservation principles. The reverberation time value recommended for a lecture theatre or a meeting hall with the cubature of 3400 m^3 at the frequency of 1000 Hz would be 0.9 s and 1.1 s, respectively (Rettinger, 1977). Therefore it has been assumed that the optimum design reverberation time for the LUT Assembly Hall would be 1.4–1.5 s.

Historical character of the interior excluded the use of typical materials (such as mineral or glass wool lined with fabric), but it was possible to hang window curtains and additionally, cover the floor with fitted carpet in case of certain events. Presence of 11 large paintings unexpectedly turned out to be a favorable circumstance – they could be lined on the back side with a 50-mm thick layer of mineral wool with density of about 60 kg/m^3. The canvas surfaces covered with a thick layer of oil paint, stretched on thick frames filled in with sound-absorbing materials, have formed a box-shaped acoustic structures absorbing effectively low-frequency sound components. Location of the paintings in upper portions of the walls was also a favorable circumstance (Fig. 3). Acoustic properties of the used materials are listed in Table 1.

Table 1. Sound absorption coefficient values for individual material used in computer simulation.

Material description	Frequency [Hz]					
	125	250	500	1000	2000	4000
A. Oil paintings lined with a layer of mineral wool	0.35	0.35	0.35	0.35	0.40	0.40
B. Fitted carpet on parquet floor	0.10	0.10	0.10	0.20	0.40	0.55
C. Window curtains, 2 layers of velour, 75 mm and 100 mm from the glass pane	0.80	1.00	1.00	0.90	0.95	0.95

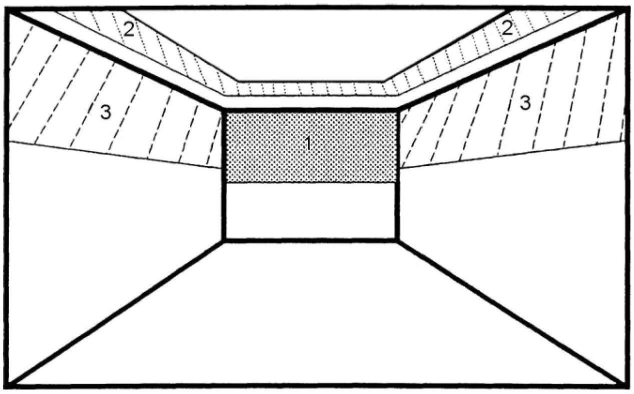

Fig. 3. The recommended sequence in which the sound-absorbing materials should be applied, in the order corresponding to increasing effect on the room acoustics: 1 – rear wall; 2 – ceiling portions bordering to walls, 3 – upper portions of side walls (Kulowski, 2011; Fasold, Winkler, 1976).

2.3. Computer simulation

A graphical representation of the model used to simulate the hall in CATT-Acoustic programming environment is shown in Fig. 4. The model was developed with geometrical dimensions of the hall taken into account together with sound absorption and diffusion coefficients characterizing the existing finishing materials and furniture (4 long tables, a lectern, and 160 upholstered chairs). The model has been calibrated based on the measured reverberation time values.

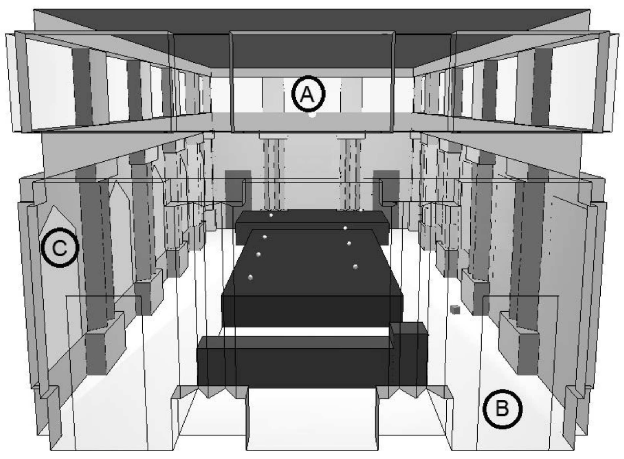

Fig. 4. The Assembly Hall model developed in CATT-Acoustic with arrangement of sound-absorbing materials listed in Table 1.

The aim of the calculations was to determine the effect of individual configurations of sound absorbing materials listed in Table 1 on the reverberation time and the speech intelligibility. Four different variants of the use of these materials were defined according to Table 2. The reverberation time frequency characteristics and the speech transmission index *STI*, averaged over 8 observation points distributed evenly in the hall, are shown for each of these variants in Figs. 5 and 6, respectively. The measurements we made with the use of impulse response method according to ISO 3382-1 standard, using the maximum-length sequence (MLS) signal.

Table 2. Configurations of sound absorbing material adopted in computer simulation.

Variant	Material description	Surface area [m^2]
1	Window curtains, 2 layers of velour, 75 mm and 100 mm from the glass pane	50
2	Oil paintings lined with 50-mm thick 60 kg/m^3 mineral wool layer	60
3	Fitted carpet on parquet floor	240
4	Window curtains Oil paintings lined with mineral wool Fitted carpet on parquet floor	350

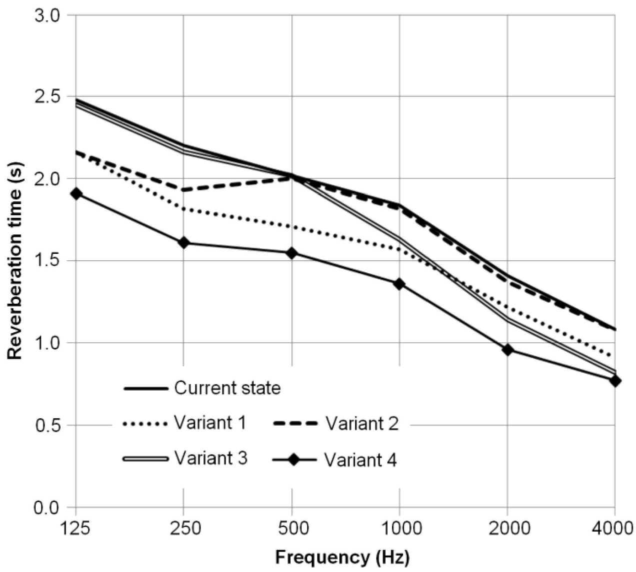

Fig. 5. Reverberation time frequency characteristics for the LUT Assembly Hall (unoccupied, computer simulation).

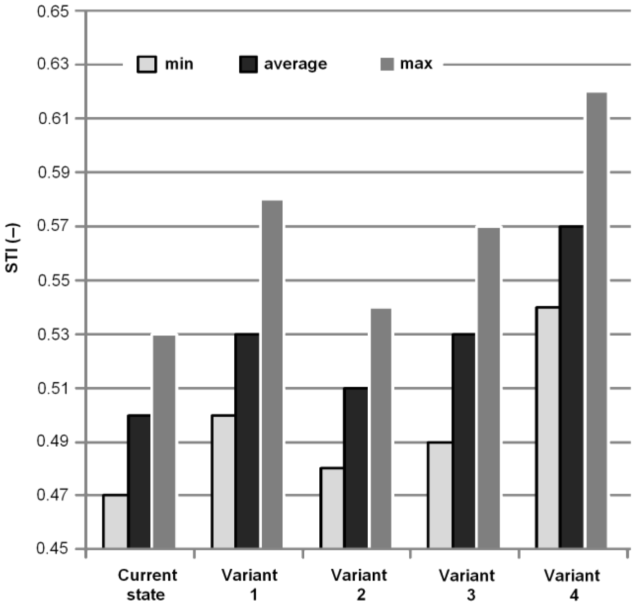

Fig. 6. The sound transmission index in the LUT Assembly Hall (unoccupied, computer simulation).

Table 3. Correlation between *STI* values and speech intelligibility.

STI value	Quality of speech intelligibility in accordance with IEC 60268-16
0–0.30	bad
0.30–0.45	poor
0.45–0.60	fair
0.60–0.75	good
0.75–1.00	excellent

Simulation results closest to the design assumptions correspond to the use of all measures admissible in the hall in view of heritage conservation restrictions (cf. Table 2, Variant 4). The obtained value of $STI = 0.57$ corresponds to a good speech intelligibility (the reverberation time value for frequency 500–1000 Hz is 1.45 s). An interesting feature is the favorable behavior of the sound absorbing material used as lining under the paintings, thanks to which a significant reduction of the reverberation time in the low-frequency range has been obtained.

3. The Theatre of Opera and Ballet in Lviv

3.1. Acoustics of the hall in its original state

The Salomea Kruszelnicka Lviv State Academic Theatre of Opera and Ballet opened in the year 1900 (Kamisiński, 2012). The building is acknowledged the crowning achievement of Zygmunt Gorgolewski, one of the most eminent Polish architects of his time. Architecturally, the building is an example of the eclectic style (Opera Lwowska, 2015). The Opera's auditorium has the volume of 5,500 m^3 and seats 998.

The hall has a horseshoe-shaped layout typical for opera houses, with level floor in the stalls and rows of boxes situated on the semicircular wall (Fig. 7). An acoustically difficult element in rooms of this specific shape are concave underbalcony cavities situated along the rear wall in the stalls. In case of walls being finished with hard materials, such as plaster or wallpaper put up on a hard substrate, the sound reflected from the rear wall focuses in the rear part of the audience area which is considered an important acoustic flaw of any room. At some point in time, the user decided to soundproof the rear wall (Fig. 8) which was also unfortunate because of excessive sound damping in the higher frequency range observed in the last two rows of seats.

Fig. 7. A view of the Lviv Opera House hall.

Fig. 8. The underbalcony space in the Lviv Opera House hall prior to installing the sound diffusing structures. The walls and ceiling were covered with a textile tapestry.

3.2. Corrective measures

The proposed corrective measure provided for introducing a wide-band sound diffusing features with limited absorption effect. Such opportunity is offered by acoustic structures interfering in phase of the reflected acoustic wave known as the Schroeder diffusers.

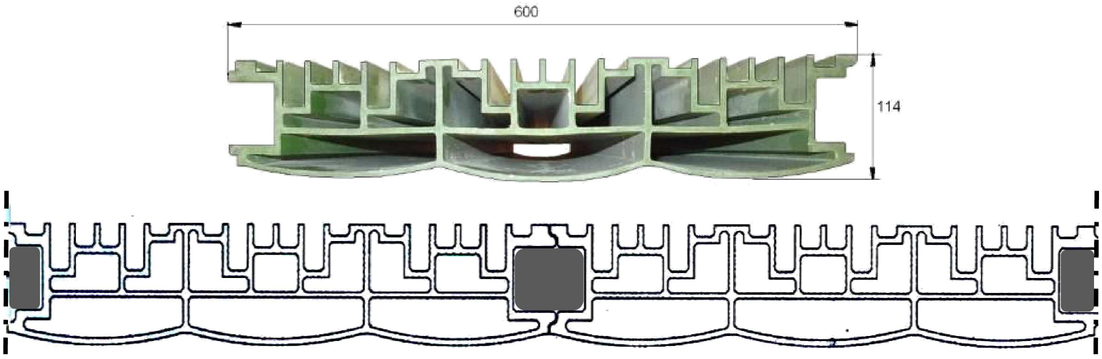

Fig. 9. A cross-section of the sound diffusers (dimensions in mm). The material and manufacturing process is protected as an industrial design (Community Designs Bulletin, 2012).

Structures of that type are composed of geometrical elements arranged in repeatable series. However, cyclical form and "technocratic" appearance of the diffusers impose serious limitations as far as their applicability to interiors with clearly exposed architectural style is concerned. Especially in rooms designed and finished in the eclectic style, where interiors are decorated with irregular carvings inspired by plant-like forms, pieces of figural sculpture, and highly diversified geometrical motifs following the canon of specific stylistics, any modern finishing element with highly technical form can be perceived as an alien feature. However, high efficiency of Schroeder diffusers invented four decades ago encourages designers to use them to correct acoustics of highly renowned historic concert halls, such as the Carnegie Hall in New York which opened in 1891 (Cox, D'Antonio, 2004). An important factor in this case is the technological awareness of contemporary architects and heritage conservation officers who, unlike their counterparts operating in the 19th century, accept interference of that kind into appearance of period halls. The economic aspects play also an important role in making such decisions, because when a hall representing the quality of a historic monument retains its original function and realizes it successfully in line with contemporary technical standards, it becomes very attractive to both the public and the owner.

Schroeder diffusers are usually constructed by craftsmen in the course of interior finishing work or are offered in short series by specialized manufacturers. A solution concerning both the material and technological process used to fabricate the diffuser elements on an industrial scale has been patented in the European Union as an industrial design (Fig. 9). The diffuser has a form of a pressing continuously extruded out of a composite based on epoxy resin (EPD) filled with wood dust. The system is mounted on 60 mm × 60 mm posts inserted into holes provided in the diffuser's structure.

A distinctive acoustic feature of Schroeder diffusers is the high degree of sound scattering. The measure of the effect is the sound scattering coefficient s, defined as the ratio of the sound energy reflected in the diffused way to the total reflected sound energy. Values of the coefficient s depend strongly on the sound frequency (Fig. 10). The frequency range $[f_0, f_g]$ within which the sound diffusion is particularly effective is a derivative of the sequence of wells constituting the structure. The sequence, i.e. the number of wells per cycle, their width, and depth, is determined by an algorithm developed by Manfred Schroeder (1975). The lower limiting frequency f_0 is related to maximum depth of the wells. The value adopted in the present case (2234 Hz) followed from technological limitations and the fact that for deep wells, the diffuser is characterized with high absorption coefficient at low frequencies (Kamisiński *et al.*, 2012a).

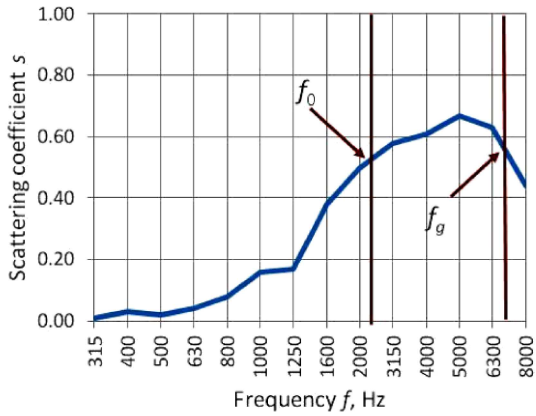

Fig. 10. The sound scattering coefficient s for the diffuser of Fig. 9 obtained from acoustics measurements (third-octave resolution, frequency range 314–8000 Hz). f_0 and f_g are the lower and the higher sound diffusion limiting frequencies, respectively. It is assumed that sound diffusion occurs at frequencies above 0.5 f_0 (Kamisiński *et al.*, 2012b).

3.3. Computer simulations

To assess effectiveness of the corrective measures described in the preceding subsection, a computer simulation of the acoustic field in the hall was performed with the use of CATT-Acoustic software. The digital model has been calibrated based on acoustic measurements taken previously (Kamisiński *et al.*, 2009).Calibration is based on such a selection of finishing materials in a computer model to achieve compliance of reverberation time frequency characteristics obtained by the simulation with the characteristics of a real object, measured prior to use diffusers. The objective consisted in determining distribution patterns of the sound strength G and the sound clarity C_{80} in selected regions of the auditorium (cf. Kulowski, 2011, Eqs. (1) and (2)). This allowed to examine the effect of diffusers on the sound focusing phenomenon and the perceived music quality. The sound strength was calculated from the formula

$$G = 10 \log \frac{\int\limits_0^{\infty} p^2(t)\,\mathrm{d}t}{\int\limits_0^{t_{\mathrm{dir}}} p^2_{10\mathrm{m}}(t)\,\mathrm{d}t}, \tag{1}$$

where $p(t)$ is the impulse response (acoustic pressure as a function of time), $p_{10m}(t)$ is the impulse response in free field at the distance of 10 m from a sound source with the same acoustic power as the source used in the measurements, and t_{dir} is the time after which the direct sound reaches the receiver. The sound clarity was calculated as

$$C_{80} = 10 \log \frac{\int\limits_0^{80\ \mathrm{ms}} p^2(t)\,\mathrm{d}t}{\int\limits_{80\ \mathrm{ms}}^{\infty} p^2(t)\,\mathrm{d}t}. \tag{2}$$

The calculated distribution pattern of the sound strength G indicates that after covering the originally smooth and hard rear wall with a sound scattering structure, distribution of the parameter became significantly more even (Fig. 12). The effect is particularly prominent for frequencies above 1 kHz, as in this very range, the sound absorption introduced by the diffuser is lower, while the scattering effect is stronger (Fig. 11). Even more favorable is the forecasted change in the clarity factor C_{80} (Fig. 13). This is especially

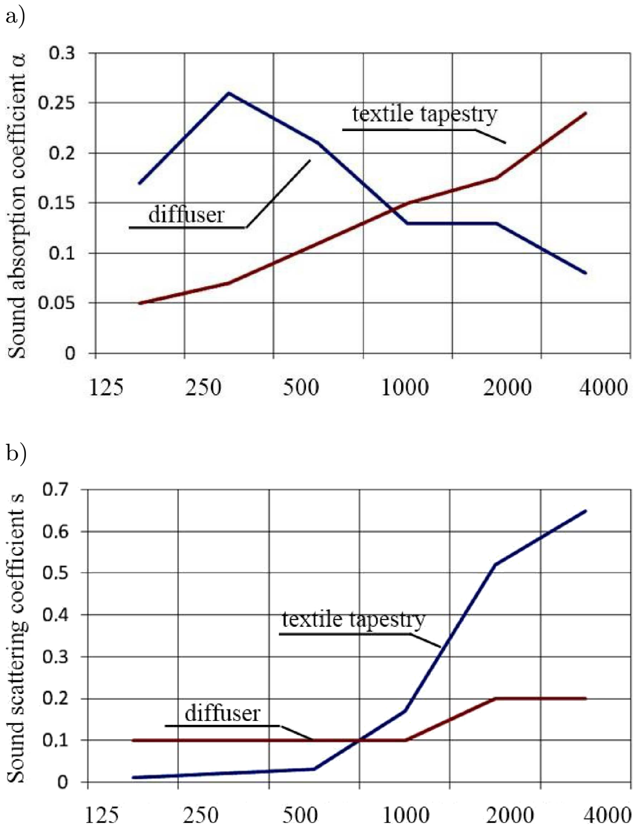

Fig. 11. Acoustic parameters of the textile tapestry and the diffuser of Fig. 9 used in computer simulation (octave resolution, frequency range 125–4000 Hz): a) sound absorption coefficient α, b) sound scattering coefficient s (Kamisiński *et al.*, 2012b).

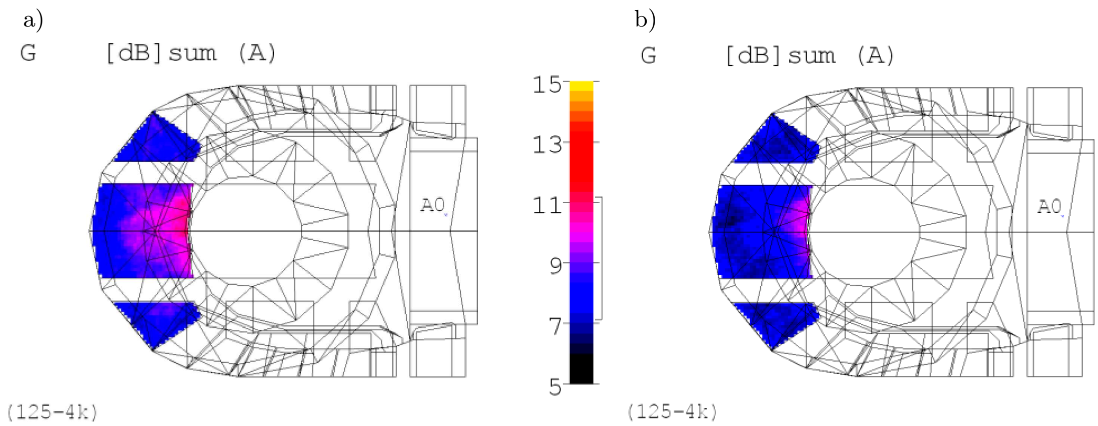

Fig. 12. The forecasted distribution of G values in the underbalcony area for the rear wall covered with: a) textile tapestry, b) sound diffuser.

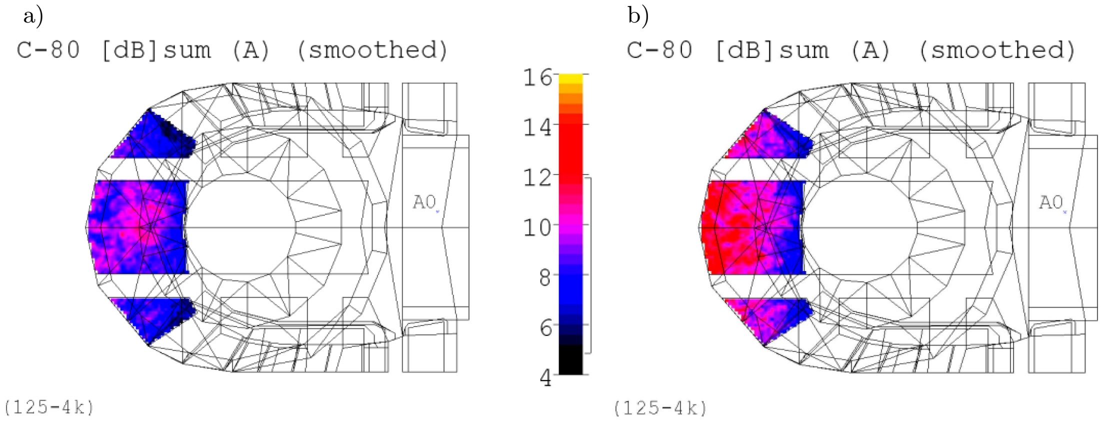

Fig. 13. The forecasted distribution of C_{80} values in the underbalcony area for the rear wall covered with: a) textile tapestry, b) sound diffuser.

true for the last rear rows where acoustic deficiencies were most uncomfortable. In this area, C_{80} increases by as much as 5 dB, and what is more, distribution of this increased value remains even in the whole underbalcony zone. In view of the complex measurement procedure (ISO 17497-1, ISO 17497-2), sound scattering coefficients are rarely published. Graphs shown in Fig. 11 a come from the authors' own measurements (Kamisiński *et al.*, 2012b), while scattering coefficients of other materials have been adopted as suggested in the instructions for the program CATT-Acoustic.

3.4. "As-built" measurements

Unlike the computer simulations, which were performed only for the underbalcony area, acoustic measurements covered the whole stalls. The measurements were taken in the unoccupied hall. From among all parameters that were examined, the sound strength G was the one which demonstrated the most noticeable effect related to mounting the diffuser on the rear wall. The increase was particularly high in the medium ($G_{0.5-1\text{ kHz}}$) and high ($G_{4\text{ kHz}}$) frequency regime in the whole area of stalls (Fig. 14). The other parameters noticeably improved in the underbalcony cavity and in the areas close to proscenium, at the expense of a slight reduction of their values in the auditorium center (Figs. 15 and 16). A view of the underbalcony cavity with the diffusers installed on the rear wall is presented in Fig. 17.

A characteristic feature worth noticing is a similarity of the sound strength distribution patterns in the 4 kHz octave band, observed for the first 80 ms and for

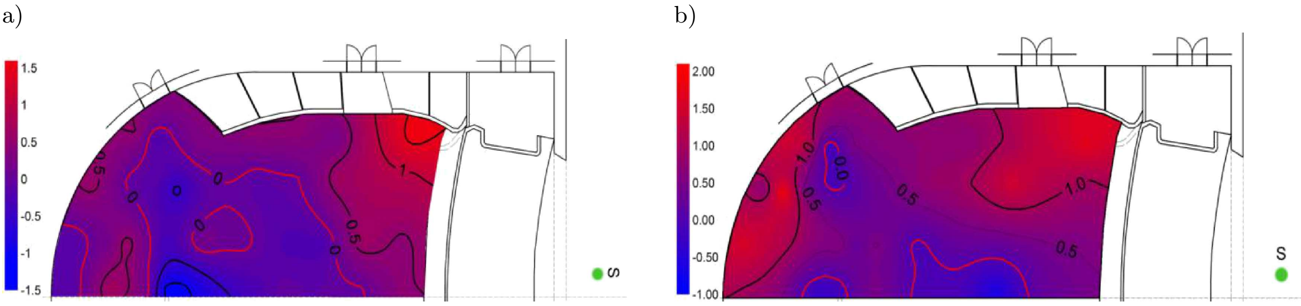

Fig. 14. The effect of mounting the diffusers on the sound strength G in octave bands: (a) 0.5–1 kHz and (b) 4 kHz.

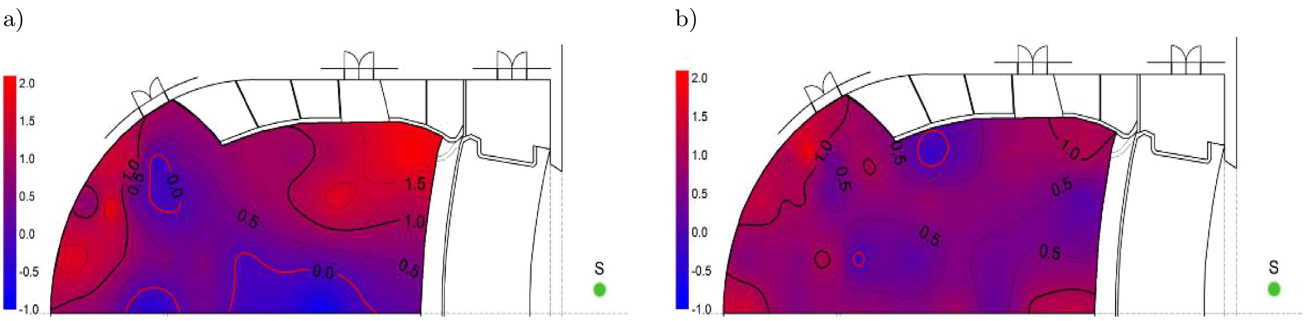

Fig. 15. The effect of mounting the diffusers on the sound strength G: a) $G_{80\text{ ms},\,4k}$ and b) $G_{\text{Late},\,4k}$.

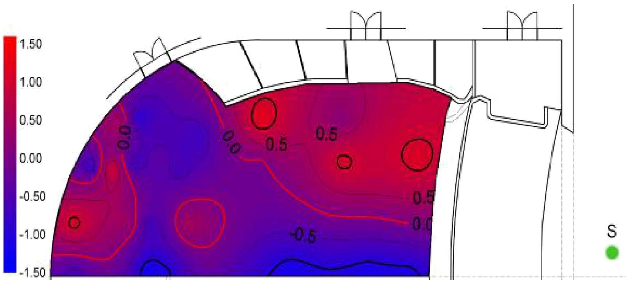

Fig. 16. The effect of mounting the diffusers on the sound clarity $C_{80,\,4k}$.

Fig. 17. The underbalcony space in the Lviv Opera House after mounting the sound diffusers.

the whole impulse response decay period (cf. Fig. 15a and 14b, respectively). This means that the impression of sound strength in the auditorium and the parameter G corresponding to sensation related to this quantity is created in the initial stage of formation of the impulse response. The observation is consistent with the generally accepted regularity concerning enhanced response of the human ear to early high-energy sound reflections.

According to subjective assessment of the acoustics articulated by the polled audience members, acoustical deficiencies of the underbalcony cavity have disappeared after installation of sound diffusers, and the overall acoustic quality of the hall has noticeably improved. Apart from getting rid of the undesired sound focusing effect and the music gaining in clarity, it has been found that the degree of sound diffusion in the hall also improved.

4. Courtyards of the Gdańsk University of Technology's main building

4.1. Original state of the courtyards

The main building of the Gdańsk University of Technology (GUT) was constructed in the years 1900–1904 according to the design of Albert Carsten (born 1859, died 1943 in Theresienstadt), professor of architecture and the first vice president of the then *Technische Hochschule*. From the architectural point of view, the building is an example of the style known as the historicism, with references to Netherlandish neo-Renaissance and some interiors decorated in Art Nuveau style (Kulowski, Kamisiński, 2012) The mass of the building contains twin inner courtyards, originally designed as unroofed spaces to be used mainly as venues for occasional academic ceremonies. In 2010, the courtyards have been given the names of Johannes Hevelius and Daniel Gabriel Fahrenheit.

The original acoustics of the courtyards was characterized with a short reverberation time (cf. Fig. 23, the lowest curve). The original acoustics of the courtyards was distinguished with a short reverberation time and high degree of sound diffusion. This followed from diversified structure of the brick elevation with significantly resolved stone decorations and resulted in good speech intelligibility. Such characteristics was favorable from the point of view of the functional program of the courtyards despite exposition of the space to the elements.

Table 4. Geometrical parameters of the courtyards.

Feature	Value
Floor surface area	487 m^2
Height	27 m^1
Cubature	13,423 m^3
Windows	384 m^2
Textural plaster	1190 m^2
Face brick walls	340 m^2
Glazed roof	695 m^2

4.2. Acoustics of the courtyards after covering with glazed roof

The courtyards remained open-air spaces until 2004 when glazed roofs were installed over both of them. The load-bearing structure is based on arched steel trusses with the span reaching about 22.5 m. The roof shell is made of double-pane insulation glass units with voids filled with argon. The outer panes made of tempered glass are 10-mm and 8-mm thick, while the inner pane is a 2×4 mm glass laminate with plastic film glued between the layers (Figs. 18–20).

The rationale behind installation of the glass roof is a clearly readable architectural idea consisting in protecting the courtyards against elements with the impression of staying in an open-air space created and emphasized by large cubature of the structures and transparency of the roofing covering the whole of their surfaces. Unfortunately, the decision to increase visual attractiveness of the complex was taken without sufficient awareness of acoustic consequences accompany-

Fig. 18. Glazing roofs over Gdańsk University of Technology's main building courtyards (Google maps, 2015).

Fig. 19. Transferring glazed roof framework from the assembly site onto the Hevelius Courtyard (Cywiński, 2012).

Fig. 20. A view of the Fahrenheit Courtyard.

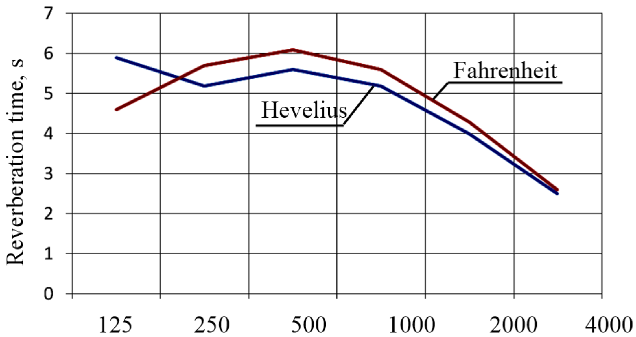

Fig. 21. Reverberation time of the courtyards after textural plaster renovation and face brick cleaning (July 2007).

ing transformation of open or semi-open spaces into confined interiors. While the functional program of the object was changed towards events demanding good acoustic conditions, the materials typical for outdoor elevations were used which are resistant to elements, but acoustically are undesirable as neither absorbing nor diffusing the sound. As a result, the all-year-round availability of the courtyards was created at the expense of serious degradation of their acoustics. The reverberation time characterizing both courtyards increased more than 2.5 times (cf. Fig. 23), which resulted in significant deterioration of speech intelligibility parameters.

The courtyards are subject to further renovation work improving their qualities of fine historic objects. According to requirements imposed by monument conservation authorities, the work consists in reconstruction of original disposition of finishing materials, i.e. filling in the cavities in brick facing, repairing stone elements of the elevation, renovating plastered surfaces, etc. In view of the fact that the used materi-

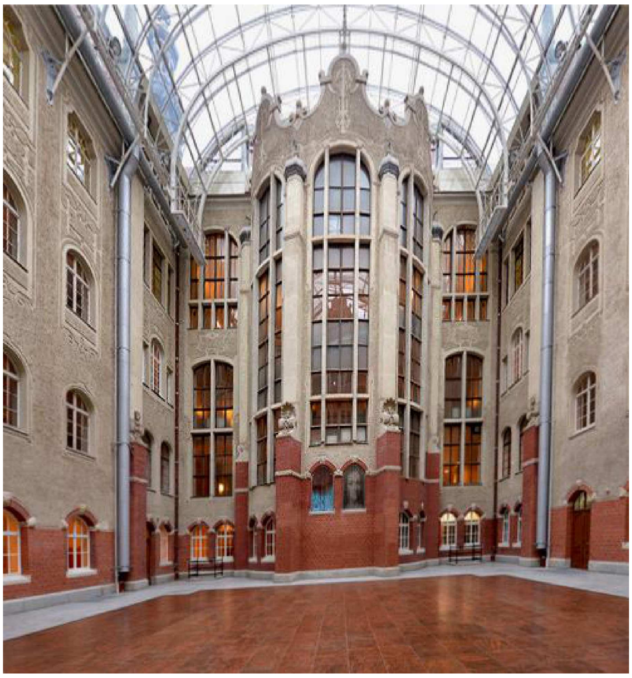

Fig. 22. The Fahrenheit Courtyard after laying a stone floor, June 2014. From Dziedziniec Farenheita (2015).

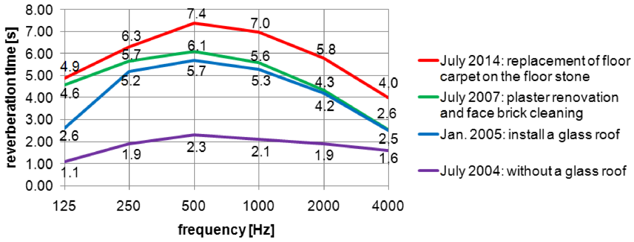

Fig. 23. The Fahrenheit Courtyard reverberation time after successive renovation stages.

als are intended mainly for outdoor applications, such repairs result in further deterioration of acoustic conditions prevailing in the courtyards. For instant, the recent stage of renovation included laying a stone floor (Fig. 22) which was the cause of further increase of the reverberation time, as the stone, alike the glass used for the roofing, is a material reflecting virtually the whole of incident acoustic energy. After subsequent work stages, the reverberation time increased gradually and from the initial 2.5 s, it increased up to the current 7.5 s, whereas the value recommended for the official functional program of the interiors should not exceed 2.0–2.5 s (Fig. 23).

The presented example illustrates how a seemingly neutral, from the purely architectural point of view, modification of a semi-opened space by covering it with a glazed roof can radically deteriorate its acoustic qualities. The reason consists in ignoring the rules of physics applicable to the sound propagation in confined spaces, constituting the fundamentals of the room acoustics.

Table 5. Acoustical parameters of the courtyards (July 2007).

Courtyard name	C_{50}	C_{80}	*STI*	*RASTI*
D.G. Fahrenheit	−4.8 dB	−3.3 dB	0.38	0.31
J. Hevelius	−3.9 dB	−3.0 dB	0.40	0.34
Recommendations (Marshall, 1996; IEC 60268-16; Carvalho, 1999)	2–7 dB	3–6 dB	0.60	

4.3. Corrective measures

The courtyards are subject to strict supervision of the heritage conservation authorities; moreover, they are used for educational purposes – currently, the Hevelius courtyard plays a role of a physical laboratory with a 26-meter long Foucault pendulum suspended under the roof. For this reason, it will be impossible to apply standard methods of reducing the excessive reverberation by using e.g. sound absorbing materials available commonly on the market or suspending acoustic structures under the ceiling.

A favorable circumstance allowing to plan for effective corrective measures is the large area of glazed surfaces including the roofing and portions of inner walls of the courtyards (about 35% of the total inner surface area – cf. Subsec. 4.1). The surfaces are protected against elements and this creates the possibility to screen them with the so-called microperforated foil. This is a completely translucent material stretched usually at a distance of several centimeters from glass panes creating thus an effective sound-absorbing system. The microperforated foil is an up-to-date high-tech material (500,000 micro-holes per square meter), available on the market only recently. The foil is barely visible, and the mounting/tensioning system is visually discreet which allows to have the great hopes for acceptance of the solution by the heritage conservation office.

The effect of application of the microperforated foil on the reverberation time can be coarsely estimated from the well-known formula (calculations are valid for the frequency 1000 Hz):

$$T = 0.161V/A, \tag{3}$$

where T is the courtyard's reverberation time with the foil applied, $V = 13{,}423\ \mathrm{m}^3$ is its cubature, and A is the total acoustic absorptivity of the courtyard with the foil, which can be represented as the sum

$$A = A_0 + \Delta A, \tag{4}$$

where A_0 is the acoustic absorptivity of the courtyard in its present state. Its value can be estimated from the formula analogous to (3):

$$A_0 = 0.161V/T_0, \tag{5}$$

where $T_0 \approx 7.0$ s is the currently observed reverberation time (cf. Fig. 23), and ΔA is the acoustic absorptivity increase relating to application of the foil, value of which can be calculated as

$$\Delta A = \alpha S, \tag{6}$$

where $\alpha = 0.85$ is the absorption coefficient of the foil (cf. Fig. 24) and $S = 1.079\ \mathrm{m}^2$ is the total area of glazed surfaces (cf. Subsec. 4.1).

After substituting actual numerical values to Eqs. (3)–(7) for the case of the microperforated foil being applied on both roofing and windows, the result yields $T = 1.76$ s. Assuming that the foil will be applied only on the glazed roof ($S = 695\ \mathrm{m}^2$), one obtains $T = 2.40$ s. Idealized conditions for which formulae of Eqs. (3) and (5) are valid assuming complete diffusion of the acoustic field mean that the real-life values should be corrected towards higher figures, but even then, the obtained result is surprisingly positive.

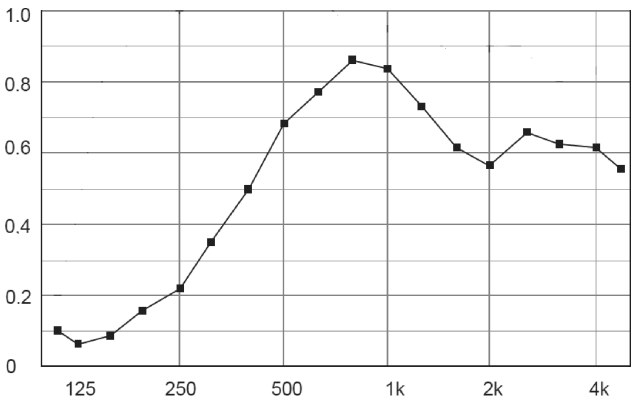

Fig. 24. The sound absorption frequency characteristic for the microperforated foil stretched at a distance of 10 cm from glass pane. Film parameters: thickness 0.18 mm; 500,000 Ø0.1 mm holes per m^2; perforation rate 1%; sound absorptivity class D, $\alpha_w = 0.55$ (Nocke, 2014).

Making plans for the future, the user of the courtyards takes into account the possibility to develop them partially, including introduction of a functional program demanding limited reverberation (Fig. 25). Other plans provide for replacement of windows with new ones; this would be an excellent opportunity to screen them with the above-mentioned acoustic structures based on the microperforated foil. It is also possible to stretch the foil on selected portions of plastered walls. Arrangement of sound-absorbing materials throughout the courtyards should be preceded by an acoustical study, including numerical modeling carried out with the use of computer software dedicated for room acoustics simulations. The above-described corrective measures represent a realistic method of restoring the courtyards to functionality in scope of applications demanding good acoustical conditions.

Fig. 25. A conception of developing the Fahrenheit Courtyard – a computer visualization (Cywiński, 2012).

5. Conclusions

The paper presents some specific problems in the area of room acoustics encountered when renovation projects are carried out in historic performance halls and large stately interiors. Usually, intervention in acoustics of such rooms poses specific problems which result in the scale of work much larger and related costs much higher than those typical for modern objects because of worse technical condition of the ancient building substance. The issues of special importance include acoustic insulation properties of walls, ceilings, doors, and windows; disturbances generated by various infrastructure systems (such as elevators and heating, air conditioning, water supply, and wastewater disposal systems), resistance of the building structures to transportation-induced vibrations transmitted by the ground, etc. The ability to find proper solutions to such problems under the strict discipline imposed by requirements of the art of monument conservation is a key factor decisive for possibility to continue the use the renovated interiors in the most desirable way, i.e. according to what they were originally intended. At the same time, it is very important that after any renovation and functional modernization, these precious buildings retain their status of historic monuments remaining both attractive and useful to the public.

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