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Acoustic comfort in atria covered by novel structural skins

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Abstract

In large rooms, where many people gather such as atria, food courts or restaurants, relatively high noise levels can occur, due to so called "Lombard effect". The "Lombard effect" is a reflex of vocal chords that relates to changes of the voice characteristics in noisy background. Typically an increase of the vocal intensity, the fundamental voice frequency, and the word duration will occur. Noise levels in an enclosed place are influenced not only by the amount and character of sound sources present, but also by the overall reverberation of sound in the space.

This article deals with the investigation of the acoustic conditions in three large gathering places covered by glass and foils. We focus on the investigation of the influence of the amount and position of sound absorption in atria on their reverberation time and on the occurrence of various sound phenomena, such as flutter echoes, focusing of sound etc. Results of the measurements are used for calibration of acoustical models. Different architectural solutions simulated in ray-based software are compared.

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Keywords: acoustics, sound, membrane structures, novel structural skins;

1. Introduction

Evolution of public and private gathering places has been in the history influenced by many factors, such as life style, society requirements and priorities, technical knowledge etc. [1-3].

First people used to live in places created by nature (such as caves), later, type and size of buildings was determined by the engineering level and society preferences. Application of natural membranes and textile structures in architecture can be already seen in antique times. Open air theatres were often covered by membranes, to prevent

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audience from rain or strong sunlight. In the middle ages, first closings of windows in buildings (before the usage of glass) were based on different kinds of natural skins.

Nowadays architects like to use hard and polished materials, which look very nice and clean on one hand, but they are the main cause of long sound reverberation and high noise levels inside building on the other hand, Covering of atria or large shopping malls by hard roof structures without any acoustic treatment can lead to acoustic discomfort [6-8]. Furthermore, the high noise levels and long sound reverberation don't influence only the pleasantness of the perceived sound, but can directly influence the vocal output and vocal effort of people present in the room [4] leading to presence of so called Lombard effect. Making architects aware about the consequences of modern design from acoustic point of view became therefore one of the priorities of acousticians of 21st century [5].

In order to reduce long reverberation time, application of sound absorbing material is necessary and it is typically designed under the ceiling. This, generally convenient step will help to reduce reverberation on one hand, but might (depending on situation) enhance some other acoustic phenomena such as flutter echoes or focusing of sound cause by side walls. Choice of convenient structural membrane and its placement on a carefully chosen position in the room can avoid many problems and discussions [6].

This article deals with comparison of three large gathering places with multipurpose function, in the capital of Slovakia (Bratislava). Two of them are atria covered by glass and one is a vestibule of a shopping mall. Acoustic assessment and comparisons are based on measured and simulated room acoustic parameters: Reverberation Time T (s). Several solutions for improvement of the acoustic situation are compared that are based on transparent or removable constructions, such as polycarbonate, micro-perforate foils or textiles.

2. Description of case studies

Cases chosen for this article are typical renovation projects of halls in Slovakia with volume between 4 550 and 14 100 m^3 in which (after the renovation) the room acoustic requirements were not fulfilled. In particular we deal with Atrium in building of Faculty of Arts of Comenius University in Bratislava (Atrium FA), Atrium of building of Slovak Philharmonic in Bratislava (Atrium SP) and Vestibule of shopping center Palace close to Zlaté Piesky lake in Bratislava (SPZP).

2.1. Atrium FA

One of the well known building complex in the city center of Bratislava is the building of the Faculty of Arts of Comenius University. It belongs to monuments of the architecture of 20th century. The main building was erected in 1913 and an atrium has been always a part of the building complex. In 2011 an extended renovation took place, in a framework of which a glass roof structure has been built, to cover the atrium (Fig.1 - left). The height of the new roof with dome shape is between 16,3 - 21,3 m. The total area of interior surfaces is S = 4 600 m^2 and the volume of the atrium is V = 14 100 m^3. The so called „whole year ventilation“ system has been integrated to the new roof construction. Dominant materials used on interior surfaces are glass, plaster, concrete and PVC. This hall can be considered as a typical multipurpose hall where students can spend their time during breaks. However the room is used also for teaching purposes, organization of conferences, performance of music or receptions and banquets.

2.2. Atrium SP

Atrium of Slovak Philharmonics is a part of the historical building, which was built on order of Maria Theresia in 1773. Building was later rebuilt in a neo-Baroque style with Rococo and Art Nouveau elements and during the last 200 years has been renovated several times. In 2005, the atrium SP has been covered by transparent (glass based) roof structure supported be metal trusses, resting on four steel columns (Fig.1 - middle). The most used materials on the interior surface in atrium SP is plaster, glass and natural stone. Total area of interior surfaces is S = 1 900 m^2, volume is ca V = 4 550 m^3 and the height of the ceiling is varying between 12,8 - 13,6 m. The main function of the hall is its usage for a gathering of people and for organization of different types of events, such as receptions, small conferences and meetings. Sometimes, a small scale concerts or theatrical performances take place here as well.

a b c

Fig. 1. (a) Atrium FA; (b) Atrium SP; (c) Vestibule SPZP;

2.3. Vestibule of SPZP

The third case that is analyzed in this paper is a large vestibule, which is a part of the Shopping center Palace in Bratislava. Also in this space, many different types of activities take place. Besides the shopping hall function, cultural events, theatres or concerts are organized here as well. The main volume of the space is V = 5 750 m^3 and the total surface area of interior surfaces is S = 1 850 m^2. Place has a round shape with a diameter of 24 m. Roof is a dome-shaped object, with partly transparent material (glass), with a maximal height in the middle h = 14.5 m. The most materials used as finishing of interior surfaces are plaster, marble and glass.

Building complex was built in 2004. Shortly after it was given to users, several acoustical problems (such as high background noise levels, long reverberation time and flutter echoes) have popped up.

3. Measurements

In order to get a basic information about room acoustical properties of each case study, the standardized impulse response measurements were performed according to the ISO 3382-1 [10,11]. Measurement results were compared with requirements listed in the Slovak technical norm STN 73 0525 [12].

3.1. Atrium FA

Atrium FA has a typically long reverberation, which was confirmed also by measurements. Measurements were performed using gunshots (6 mm) in order to increase the signal to noise ratios (*S/N*), which has reached values 50 to 70 dB. Flutter echoes have been confirmed by measurements too. Results of measured reverberation time are shown in the Fig.2. Reverberation time $T_{30,1000Hz}$ = 6,1s, is far too high value for the room of its purpose. Normally, the values of T_{opt} = 0,95 - 1,2s are required for speech, T_{opt} = 1,2 - 1,4s for chamber music, and T_{opt} = 1,6 - 1,9 s for orchestra music.

3.2. Atrium SP

In the atrium SP, detailed measurements of integrated impulse responses were performed by means of omnidirectional loudspeaker and omnidirectional microphone using Dirac software. Measurements were done on over 30 microphone position and two positions of sound sources [13]. During the measurements, a temporarily stage construction was present in the room, based wooden plates mounted on metal profiles. Measurements were performed for two variants: *Variant*$_1$ and *Variant*$_2$, with and without absorptive curtain hanged above the stage. The total surface of the curtain was S = 38,7m^2 and it was placed in the height of 5 m (above the temporary stage). Results of reverberation time are given in the Figure 2. According to the STN 73 0525, the reverberation time

($T_{30(1000Hz,V1)}$ = 5,4 s and $T_{30(1000Hz,V2)}$= 4,5 s) is much too long for speech (T_{opt} = 0,85) and very long even for music (T_{opt} = 1,7 s).

3.3. Vestibule SPZP

Vestibule SPZP has a cylindrical shape and most of the complaint of users relate to occurrence of flutter echos and bad speech intelligibility during the cultural events. Typical are also high background noise levels in the room. Impulse response measurements were conducted on seven microphone positions, showing the average reverberation time of $T_{30,1000Hz}$ = 4,3s (Fig. 2a). The optimal values for a room with the given volume is according to STN T_{opt} = 0,95 - 1,15s (for speech), T_{opt} = 1,15 - 1,35s (chamber music), T_{opt} = 1,55 - 1,85s (orchestra).

3.4. Comparisons

For sake of illustration, and better understanding of differences between the 3 cases, the average sound absorption coefficient α (-) of interior surfaces have been determined based on Sabine formula (1) [14]. Absorption coefficient has been calculated for relative humidity of 50% and temperature of 20°C [15].

$$\alpha = \frac{0{,}164V - 4mVT}{TS} \tag{1}$$

where α (-) is the average sound absorption coefficient, T (s) in the reverberation time, m (m^{-1}) is a total attenuation coefficient due to air absorption, S (m^3) is the overall surface area and V (m^3) is the volume of the room interior.

a b

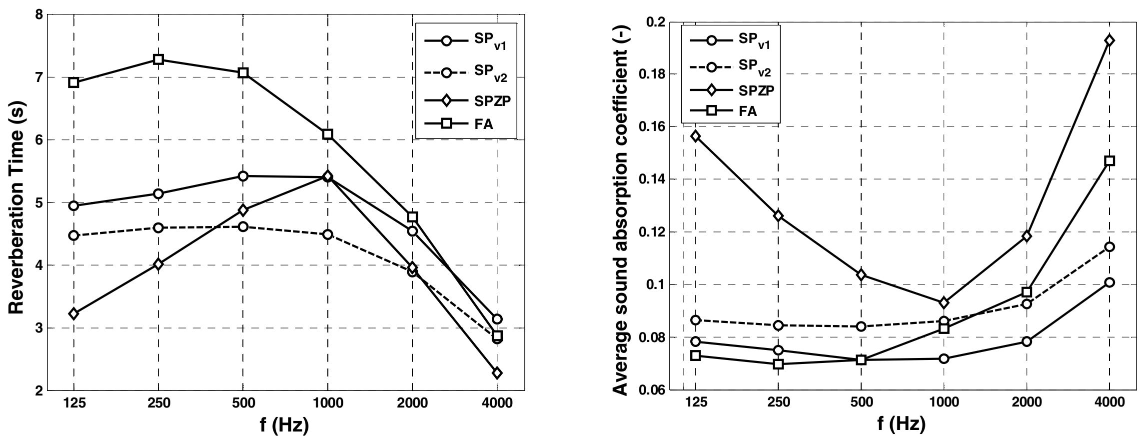


Fig. 2. (a) Measured reverberation time T_{30} (s); (b) average sound absorption coefficient α (-);

Average sound absorption coefficient of interior surfaces is in general better indicator for fast estimation of the amount of acoustic absorption in the space and consequently acoustic conditions in the rooms. Mainly when comparing rooms with different volumes. For instance, in the Figure 2 we can see, that although the reverberation time at low frequencies is almost double as long in case of the atrium SP in comparison with the Vestibul SPZP (Fig.2a), the vestibule SPZP will subjectively sound less reverberant and will be also less noisy at low frequencies then atrium SP. It is because its interior surfaces in SPZP are in general more absorptive (Fig.2b) and the longer reverberation is caused by larger volume. Interestingly, all the investigated case studies have very similar average sound absorption of interior surfaces at 1 kHz, with values of average α between 0,07 – 0,09. Atrium SP and Atrium FA are very similar over all frequency bands, while the vestibule is in general more absorptive then the rest. But the real pleasantness of soundscape in the 3 cases would need to be confirmed in listening tests or surveys in situ.

4. Simulations

Simulations were performed in CATT Acoustic v.9 software [16], which is using a ray-based algorithm. Models were calibrated based on measured average reverberation time (Fig.3) and followed by several simulated alternatives, in which different acoustic solutions were presented. Simulated variants were based on variations in absorption properties and/or on changes in shape of reflective surface in order to eliminate the flutter echoes and to reduce the reverberation time. Summary and description of sound absorbing materials and their properties used in the simulations are given in the Tab.1.

a b c

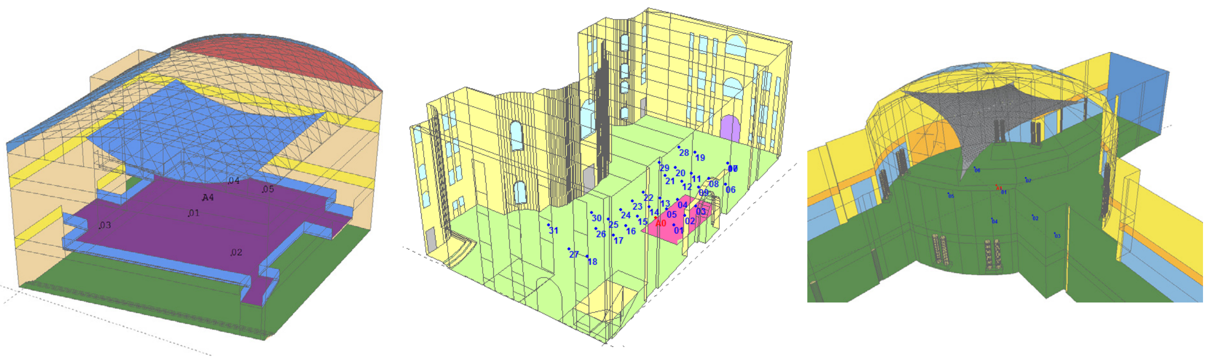


Fig. 3. Spatial acoustic models created in CATT Acoustic. (a) Atrium FA; (b) Atrium SP; (c) Vestibule SPZP.

Table 1. Overview of sound absorption coefficients of the individual materials used as input data for simulations.

Name	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Textile membrane	0,15	0,40	0,75	0,85	0,65	0,65
Mineral wool	0,60	0,90	0,90	0,95	0,90	0,90
3D absorber	0,45	0,91	0,99	0,99	0,99	0,99
Micro-Perforated foil	0,33	0,29	0,37	0,48	0,57	0,47
Polycarbonate	0,08	0,04	0,03	0,03	0,02	0,02
Cotton plush 0,4kg/m^2	0,24	0,39	0,75	0,80	0,80	0,85
3 layer ETFE cushion system	0,41	0,21	0,26	0,17	0,08	0,02

Table 2. Overview of materials used in different cases.

	Atrium FA									Vestibule SPZP				
Variant	v.1	v.2	v.3	v.4	v.5	v.6	v.7	v.8	v.9	v.1	v.2	v.3	v.4	v.5
Textile membrane										●[1]	●[1]	●[7]		
Mineral wool					●[2]	●[2]	●[3]				●[4]			
3D absorber	●[5]	●[6]												
Micro-Perforated foil			●[7]	●[7]	●[7]									
Polycarbonate						●[8]	●[8]							
Cotton plush 0,4kg/m^2								●[7]						
3 layer ETFE cushion system									●[9]				●[9]	●[10]

Acoustic solutions and their combinations were chosen according to the situation in each atrium case. The choice of the simulated alternatives was not based purely on acoustics. The design decision were taking into account also requirements of architect and other indoor comfort parameters, such as daylight quality [17-19]. For an overview of all simulated alternatives see Tab.2. (v.1 - Diagonally stretched membrane hanged in a square grid shape; v.2 - Continuous facing zone in a line above windows; v.3 - Continuous facing zone in two lines above windows; v.4 -

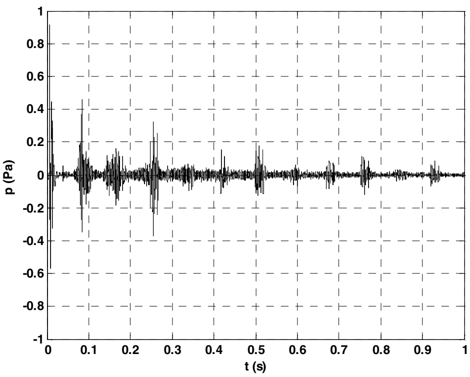
Facing in the top of the dome; v.5 - 3D absorbers of cube shape hanged under the ceiling; v.6 - Rectangular 2D absorbers on the ceiling surface; v.7 - Large area overlay hanged under ceiling; v.8 - Inverse shape to the shape of the roof; v.9 - Glass roofing replaced by ETFE system; v.10- Dome structure replaced by ETFE system).

5. Results and discussions

Results and discussions are based on measurement, simulations and feedback from users. The relatively high background noise levels in the atria are typically caused by two factors: external noise due to natural ventilation system and hard surfaces, which produce multiple reflection of outdoor noise and internal sound sources. In the large halls different resonances and sound effects might occur, which are out of the assessment frequency range required by technical standards in room acoustics. However, low frequencies, although they will not influence speech intelligibility, might also cause acoustic discomfort and consideration of standards revision to this respect is advised. Simulation results have confirmed that halls with large volumes and hard parallel walls or circular shape with distance between walls ca 9 m (e.g. > 50 ms) will cause audible flutter echos. (Fig. 4b). Summary of a chosen simulated variants are shown per case in the Figure 5.

In case of atrium FA, nine different variants were simulated. For this article, only 5 out of 9 variants (v.1.v.3. v7, v.8 and v.9) were taken for comparisons. Small objects, people and furniture were in simulations neglected. Table 4 summarizes all simulated variants and shows the result of reduction in reverberation time in octave bands thanks to the acoustical solutions. Variant 7 turned out to be the most optimal in terms in reverberation time reduction to less then 2.5 s at 1 kHz. This variant was based on (hanged polycarbonate plate in inverse shape to the roof shape) together with application of highly absorptive material (based on mineral wool and porous plaster of a thickness 70-100 mm) on the two parts of the side walls.

a



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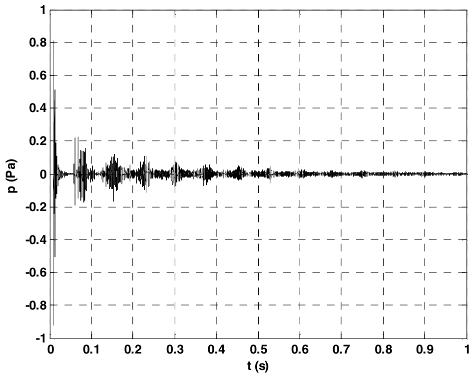

Fig. 4. (a) Measured flutter echo in atrium SPZP; (b) Simulated flutter echo in atrium SPZP;

Table 3. Reduction of Reverberation time T_{30} (s) thanks to different acoustic solutions

		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Atrium FA	v.1	1.48	2.6	2.61	1.99	1.44	0.7
	v.3	2.23	2.36	2.61	2.21	1.73	0.74
	v.7	2.35	3.06	2.88	2.3	1.49	0.7
	v.8	1.72	2.82	3.51	2.59	1.89	1.08
	v.9	2.39	2.37	2.4	1.49	0.49	0
Atrium SPZP	v.1	0.80	1.76	3.08	3.73	2.31	0.95
	v.2	0.98	1.87	3.08	3.72	2.31	0.94
	v.3	0.84	1.57	2.20	2.98	1.79	0.64
	v.4	0.16	0.20	1.09	1.67	0.54	0
	v.5	1.11	1.26	2.18	2.36	0.72	-0.32

a b

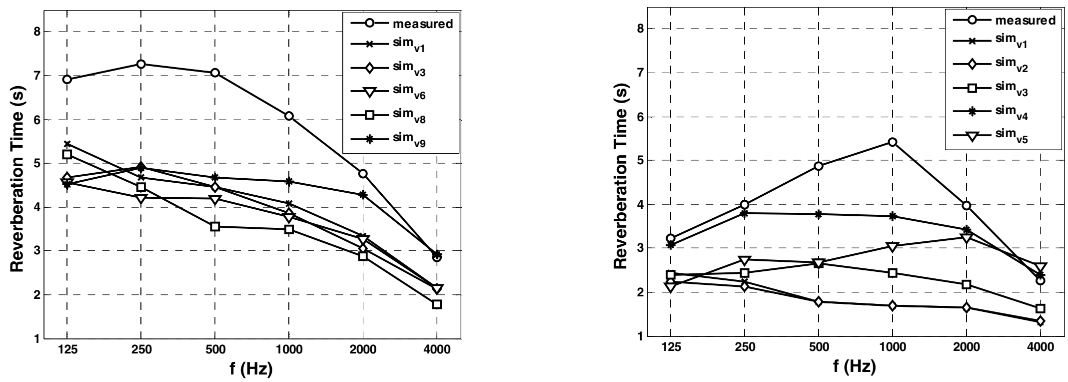

Fig. 5. Simulated results of reverberation time (T_{30}) in different variants in (a) Atrium FA and (b)Vestibule SPZP;

Simulations have shown, that the application of micro-perforated foils in the atrium will significantly improve the conditions in terms of noise levels and sound reverberation. However, it will still not completely solve the problems regarding speech intelligibility. Sufficient speech intelligibility can be achieved only in combination of membrane structure and placement of other acoustically absorptive material on vertical surfaces (such as interior walls).

Simulations of Atrium FA have shown, that the substitution of glass roofing by a transparent ETFE foil system significantly contributed to the reduction of reverberation in low and middle frequencies.

In case of Vestibule SPZP, the replacement of the glazed openings by ETFE foil (v.4) had impact mainly in middle frequencies, where the differences between absorption of glass and foil system are largest. The differences were smaller at low frequencies, because the Vestibule already has relatively low reverberation time in the current state, due to different low-frequency absorbing surfaces present in the hall.

In the simulated situation in which a dome structure was replaced by ETFE system (v.5), reverberation time has dropped at low frequencies. In this situation (v.5) a slight increase of T_{30} at 4 kHz can be seen as a logical consequence of a replacement of hard material but slightly porous material by foil membrane. This increase of T_{30} is anyway not significant.

Results have confirmed, that the application of ETFE will thanks to its acoustic properties contribute to the enhanced room acoustic comfort. In comparison with a glass or polycarbonate, rooms covered by structural skins have shorter reverberation time at low and middle frequencies. However acoustic comfort in large halls cannot be completely reached by roofing structure due to its relatively small surface area (in comparison with overall surface area of interior structures). Finally, it is important to realize, that although typical membrane structures have a higher sound absorbing properties than hard materials such as glass, they have usually poorer sound insulation. This might result in an increase of the background noise levels inside the halls, in cases in which buildings are located in noisy areas. Also the drumming effect caused by heavy rain should be mentioned as a case of disturbance in any cases. Fortunately a rain suppression system are more and more applied in practice. The rain drumming noise can be nowadays dumped by 10dB.

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