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PRACTICAL USES OF SOUND AURALIZATION IN CONFINED SPACES

PRAKTYCZNE ZASTOSOWANIA AURALIZACJI DŹWIĘKU W PRZESTRZENIACH ZAMKNIĘTYCH

A b s t r a c t

Practical aspects of testing confined spaces, especially for the purpose of acoustic adaptations, are presented. The tests were carried out with use of prediction models, showing the possibilities of models that are used at present. Sound auralization, which is a reliable method for the assessment of sound signal quality and the acoustic conditions of tested rooms, is described. The basic criteria for the assessment of acoustic conditions in confined spaces are briefly discussed.

Keywords: *acoustics*, *confined spaces*, *acoustic conditions*, *auralization*, *assessment indices*, *speech clarity*, *reverberation time*

S t r e s z c z e n i e

W artykule przedstawiono praktyczne aspekty badań przestrzeni zamkniętych, zwłaszcza na potrzeby realizacji adaptacji akustycznych. Badania te prowadzono z użyciem modeli predykcji, obrazując jednocześnie możliwości stosowanych obecnie modeli. Opisano auralizację dźwięku, która jest wiarygodną metodą oceny jakości sygnału dźwiękowego, a co za tym idzie, także i warunków akustycznych badanych pomieszczeń. Skrótowo omówiono podstawowe wskaźniki oceny warunków akustycznych w przestrzeniach zamkniętych.

Słowa kluczowe: *akustyka*, *przestrzenie zamknięte*, *warunki akustyczne*, *auralizacja*, *wskaźniki oceny*, *zrozumiałość mowy*, *czas pogłosu*

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1. Introduction

Sound auralization in a confined space is a term relating to the visualization of the distribution of sound intensity in a given testing area, which is frequently used in acoustic tests [8–10, 12, 13]. Auralization enables the audio monitoring of sound generated in a virtual room with the use of calculated methods for the prediction of impulse responses. Thus, it is possible to assess the acoustic conditions of closed rooms, which is especially important in tests carried out for the purposes of acoustic adaptation [12]. Acoustic adaptations enable changing audio conditions and most frequently, they aim to reduce reverberation times (RT) as well as improving speech transmission parameters and speech intelligibility parameters. However, auralization provides a subjective assessment of acoustic conditions, unlike the objective method based on the analysis of parameters [1–3, 8], which is discussed in detail in paragraph 2. Auralization, despite being subjective, enables speeding up the analyses and the additional verification of assessment with use of indicators. For the experienced listener, this method provides a variety of important information, giving the possibility of a reliable assessment of sound signal quality, and in many cases, it is more valuable than an assessment of parameters, because, for example, speech intelligibility is not a physical parameter, but only a measure of how the listeners understand the spoken words. The same applies with assessments of music transmission, assessments of music coding and assessments of audio equipment quality [8].

2. Sound auralization in a confined space – the recreation of acoustic conditions

Predictive tests were carried out in a virtual room for the purposes of acoustic adaptation aimed at improving acoustic conditions through limiting the RT. This room is presented in Fig. 1. This is a precise recreation of the material and geometrical design features of a real sports and entertainment hall. During the initial stage of testing, most frequent and periodically accepted functions of the analysed room were described in detail. This stage is very important from a testing point of view because it directly determines directions of procedures [6, 7]. Different guidelines regarding designing and tests are used for rooms only intended and for sport activities. Other guidelines are used for rooms where music is played as well as where celebrations, performances or training sessions take place [6, 7]. The functions of the rooms can be combined, however, this requires a different approach.

For almost 80% of the time, the tested room is used as a place for sport activities, while for the rest of the time, music is played there during rhythmic classes for children as well as verbal communiqués that are announced during different performances and celebrations. The method of announcing the verbal communiqués as well as the method of playing music is also important. The rooms in which the sound is emitted through audio system are designed without major difficulties. It is more difficult to cover with sound a large room, which is voiced only by a man. However, for some rooms it is necessary to take into account both forms of sound emission, i.e. audio systems and the human voice. The model presented in Fig. 1 was developed in a vector version with use of the standard Computer Aided Design (CAD) software program to an accuracy of 10 cm, and positions of all doors and window niches were recreated in this model as they are important with regard to the propagation of audio waves [4]. The model was transformed to the Odeon acoustic software program and then completed with the material construction features. Acoustic calculations indicate that the tested room has a reverberation time that is too long with regard to the functions that were planned for this room. Such conditions are detrimental to health, people in this room get tired quickly and their concentration ability is reduced.

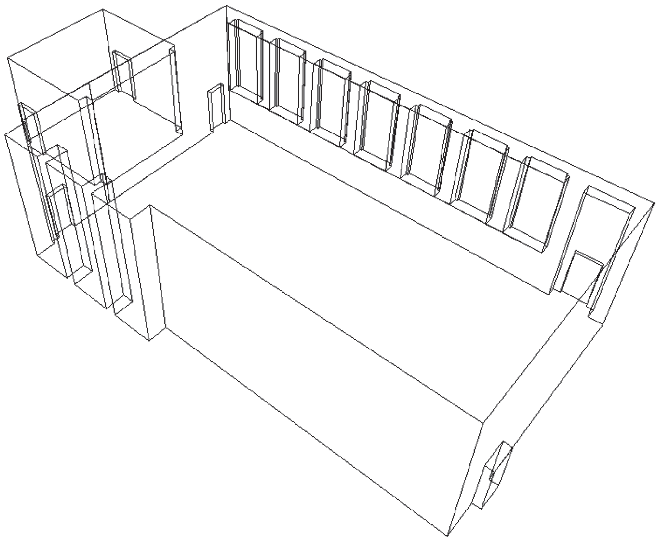
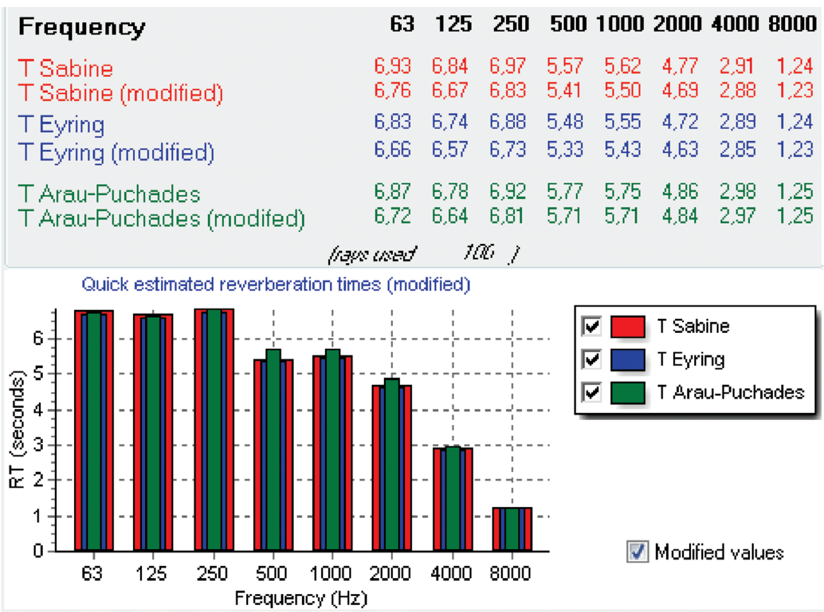


Fig. 1. Model of the geometry of the tested room [9]



Frequency	63	125	250	500	1000	2000	4000	8000
T Sabine	6,93	6,84	6,97	5,57	5,62	4,77	2,91	1,24
T Sabine (modified)	6,76	6,67	6,83	5,41	5,50	4,69	2,88	1,23
T Eyring	6,83	6,74	6,88	5,48	5,55	4,72	2,89	1,24
T Eyring (modified)	6,66	6,57	6,73	5,33	5,43	4,63	2,85	1,23
T Arau-Puchades	6,87	6,78	6,92	5,77	5,75	4,86	2,98	1,25
T Arau-Puchades (modifed)	6,72	6,64	6,81	5,71	5,71	4,84	2,97	1,25

Fig. 2. Reverberation time in the room for the selected frequencies of middle octave bands [9]

Additionally, all parameters describing acoustic conditions of the room were analysed. Some of these parameters are indicated as follows [1, 3, 6–8, 12, 13]:

– reverberation parameters:
  • RT – reverberation time [s],
  • EDT – early decay time [s],
  • T15 – time of sound decay by 15 dB [s],
  • T20 – time of sound decay by 20 dB [s],
  • T30 – time of sound decay by 30 dB [s],
– speech intelligibility parameters:
  • STI – speech transmission index [–],
  • RASTI – rapid speech transmission index [–],
  • Al_{cons} – articulation loss of consonants [%],
– parameters associated with energy ratio:
  • D50 – distinctness index for 50 ms [dB],
  • C50 – clarity index for 50 ms (for speech) [dB],
  • C80 – clarity index for 80 ms (for music) [dB],
– spatial parameters:
  • LF80 – lateral flexion coefficient for 80 ms [–],
  • IACC – interaural cross-correlation coefficient [–],
– parameters determining the sound level:
  • SNR – signal to noise ratio [dB],
  • SPL – sound pressure level [dB].

Based on detailed assessment of the above parameters, the acoustic conditions inside the tested building were classified as either bad or very bad, depending on the type of assessment criterion. Unacceptable values of RT and EDT were the basic problem. These resulted from both the room geometry and from its layout (including material characteristics). The relatively low ceiling with its low absorption of acoustic wave energy was the reason for multiple unwanted wave reflections. As a consequence, speech intelligibility in almost all points of the room was abnormally low, while the STI did not exceed 0.1. Such difficult acoustic conditions required the development of assumptions for the improvement of these conditions through the adaptation of the most significant components of the interior decoration.

After the stage of objective assessment based on the parameters described above, the conclusions were additionally verified through the auralization of sound in the tested sports and entertainment hall. Sample audio material was listened to, and subjective impressions associated with listening to this material fully corresponded with the objective assessment based on the assessment criteria. Among other findings, it was found that the long reverberation time makes correct reception of voice messages impossible and the messages merge into a sequence of unintelligible sounds. This observation is reflected in the objective assessment of the RT, EDT and mainly STI, RASTI and Al_{cons} indices. A set of impulse responses for the receiving point P1 located at the centre of the hall at an appropriate height for signal reception in a sitting position, is given in Fig. 3 to image the auralization process.

Binaural Room Impulse Response (BRIR) – a set of two impulse responses determined for left and right auditory channels can be seen in the above figure. This method is very sensitive as it refers to sound pressure levels for a wide range of frequencies. Thus, changes of acoustic pressure almost undetectable to human ears can be seen in the BRIR and seem to be significant [12, 13]. It should be emphasized that prediction models used at present are not ideal and even in the case of symmetry in the system: closed room, sound source, receiver, can give differences in BRIR for left and right auditory channel, what makes analyses difficult.

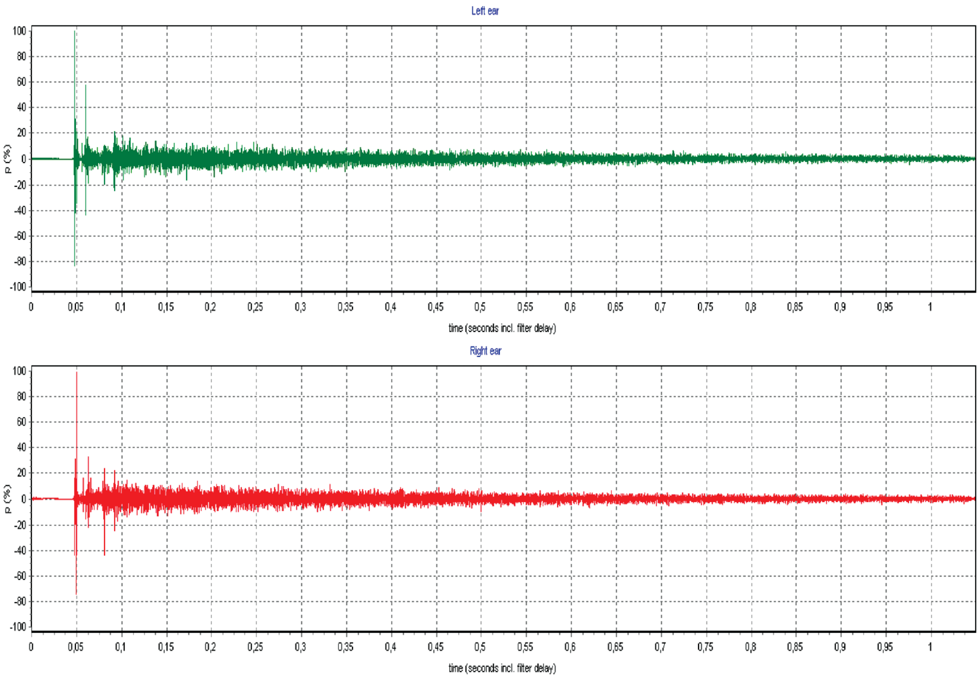


Fig. 3. Impulse response for left and right auditory channels determined in point P1 of the tested hall [9]

3. Acoustic adaptation and prediction of its results

Acoustic adaptation is understood as a series of activities undertaken to change acoustic conditions (mainly investments), to adapt them to the planned function of the room. The increase of acoustic absorption of the room by use of sound-absorbing materials is a typical acoustic adaptation procedure [9, 10]. Most frequently, these materials are placed below the ceiling, due to its dominating role in shaping the acoustic conditions of large rooms. Thus, material having the reverberant sound absorption coefficients described in Tab. 1 was used to improve the acoustic conditions of the analysed room (Fig. 1).

Table 1

Reverberant sound absorption coefficient of material used in acoustic adaptation

f [Hz]	63	125	250	500	1,000	2,000	4,000	8,000
αp [–]	0.10	0.55	0.90	1.00	0.90	0.95	0.75	0.10

The impact of adaptation on RT is presented in below figure (Fig. 4). It was found that after increasing the acoustic absorption, this time significantly decreased for almost all frequencies, excluding 63 Hz and 8 kHz for which the time decreased slightly.

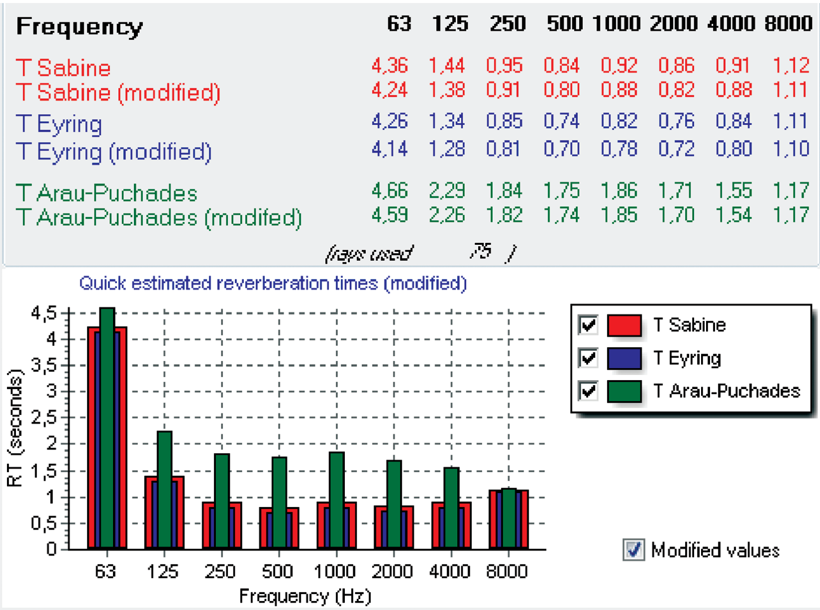


Fig. 4. Reverberation time of the tested room for selected frequencies of middle octave bands after acoustic adaptation [9]

EDT also significantly decreased as a result of adaptation. General STI increased to 0.61 for the speaker (audio system based only on human voice), including:

– 0.63 for speaking woman,
– 0.62 for speaking man.

Use of an adequate audio system would enable STI to increase to 0.68. It would improve the speech intelligibility in almost each point of the tested hall. It should be emphasized that STI at a level exceeding 0.6 refers to good acoustic conditions in the room regarding speech intelligibility. Al_{cons} also significantly increased to 6.98% – conditions classified as good according to the Peutz scale. As in the assessment of present state, also in the prognostic studies on acoustic adaptation, the sound auralization was made through a virtual listening to the sample sound material. It was found that speech intelligibility was significantly improved. Before acoustic adaptation, it was difficult to understand the sentences spoken by the lecturer and most of the words were unintelligible. However, after increasing the acoustic absorption of the room, and thus limiting the number of unwanted reflections of acoustic waves, the repeated speech became intelligible. Sound auralization enables the listener to use the percentage assessment of speech intelligibility [5, 11]:

$$Z = P/Q \cdot 100\%$$

where:

Z – speech intelligibility,

P – number of understandable words,

Q – number of all spoken words.

For such tests, it was assumed, according to the PN-EN ISO 9921:2005 Standard [11], that speech intelligibility is perfect when Z > 98 %, and it is sufficient when *Z* is in the range of 80% to 93%. Speech intelligibility is assessed as bad when 40% of all spoken words are not understood by the listener. For the analyzed example, the speech intelligibility is assessed as good. The impact of acoustic adaptation on hearing ability is also presented in a form of BRIR impulse responses in Fig. 5.

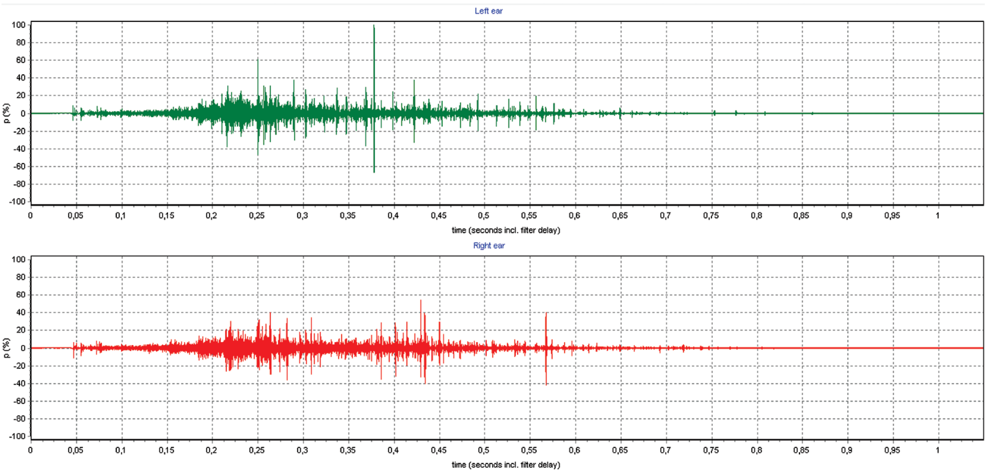


Fig. 5. Impulse response for left and right auditory channels determined at point P1 of the tested hall [9]

This response significantly differs from the response presented in Fig. 3 describing the condition before acoustic adaptation. The acoustic field was also identified during the tests regarding the acoustic system in the tested hall based on the human voice alone as well as on the human voice accompanied by an audio system. It was noticed that the use of an audio system ensures excellent sound coverage of the whole reception area with almost the same SPL indicator. Also on the stage, where speakers and vocal groups present themselves, the sound reception is correct and consistent with expectations. Much worse sound coverage occurs in situations, where in the tested hall the human voice is the only sound source. However, even in this case, acoustic conditions are acceptable.

The sequence of animation frames of acoustic wave propagation in the tested hall is presented in the figure below to show the possibilities of prediction models. The most representative images showing distribution of acoustic wave, only in the horizontal plane, were selected.

In Fig. 7, the acoustic wave coming directly from the source of sound was marked with ‘0’, while reflections of this acoustic wave were marked from ‘1’ to ‘12’ with colours according to the figure legend. The animation shows the scale of the impact of changes to the room shape, caused by window and door niches and similar elements, on the distribution of acoustic waves. Reflections of acoustic waves generated by these elements have a significant impact on the acoustic field.

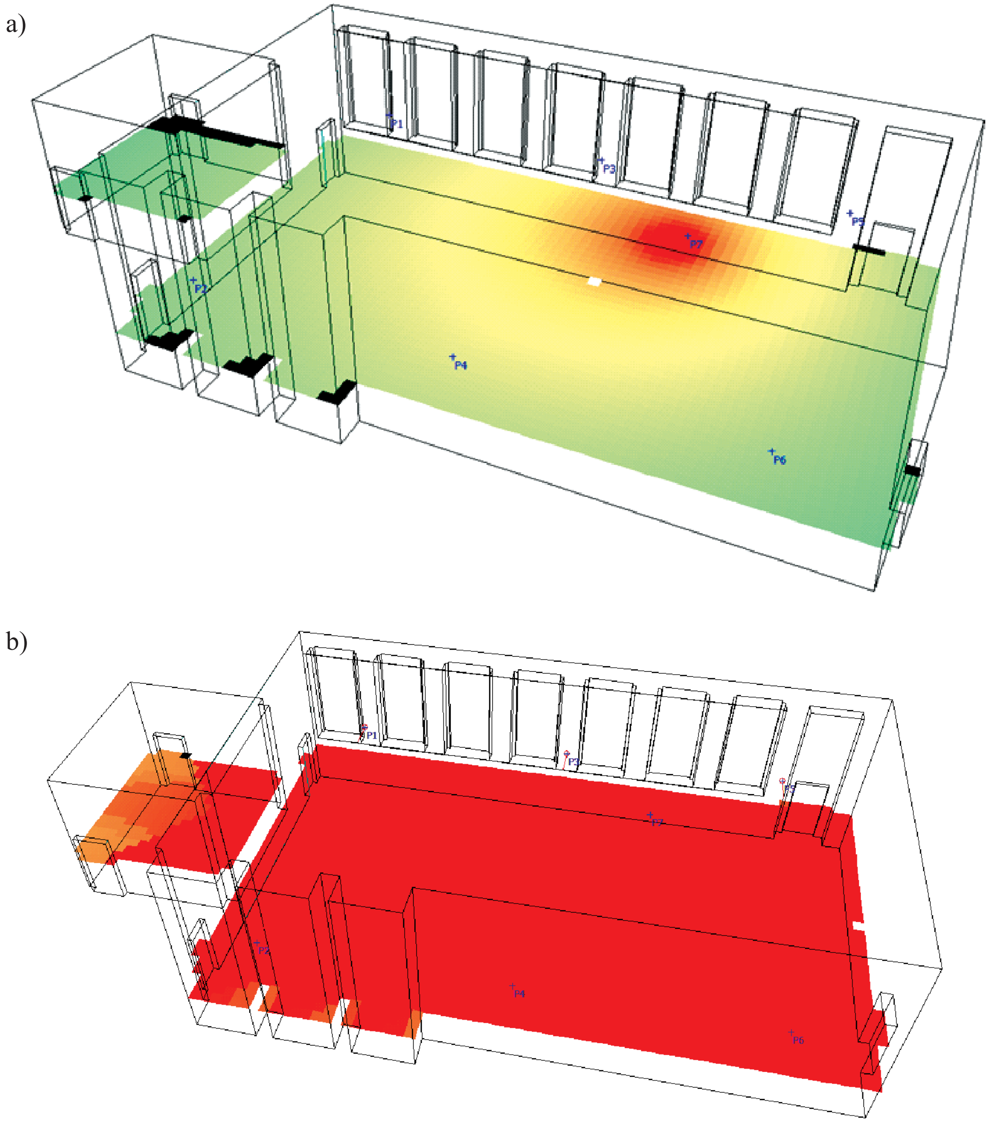


Fig. 6. Distribution of the acoustic field in the tested hall on the reception plane for the following acoustic system variants [9]: a) human voice, b) audio system

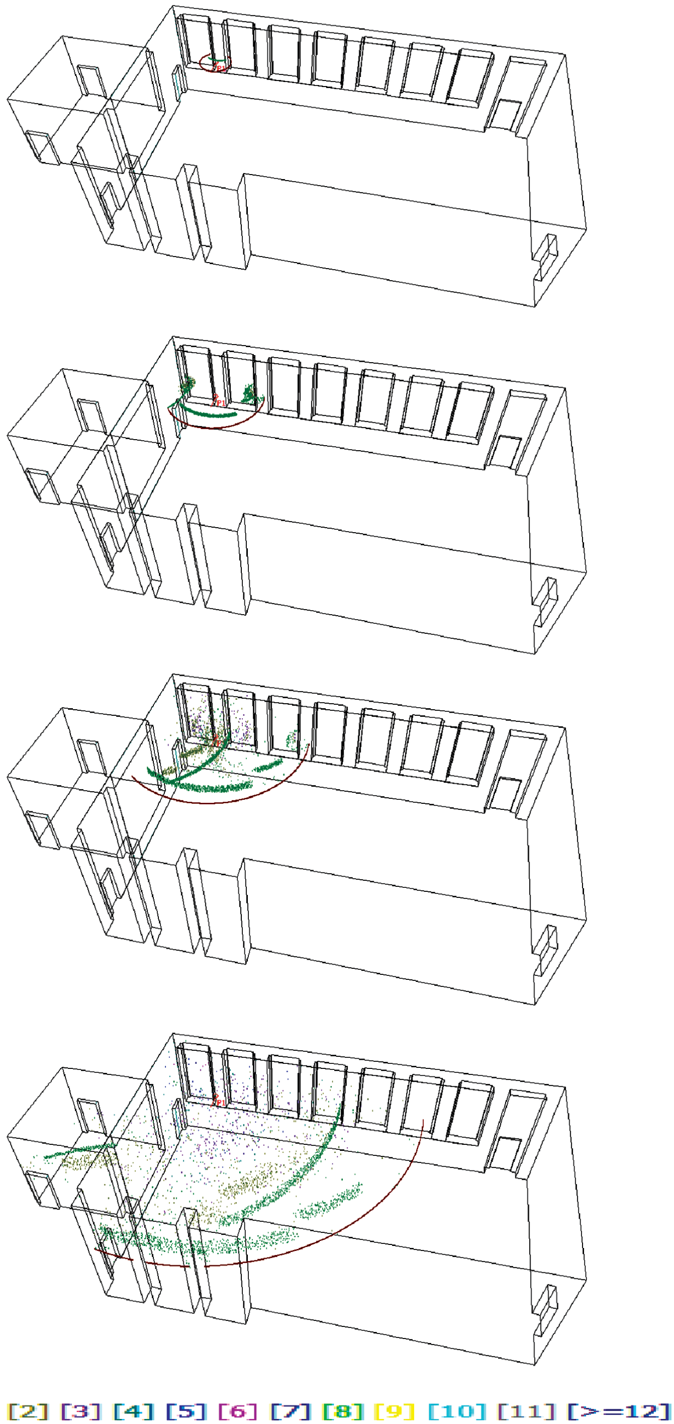


Fig. 7. Animation of acoustic wave distribution from one of the loudspeakers [9]

4. Summary

The tests of confined spaces are much more complex than other tests and analyses in acoustics. Such tests require a broad knowledge of room acoustics, and especially the ability to assess acoustic parameters. Sound auralization is an alternative method for such assessment. This method, despite its subjectivity, is highly valuable due to its assessment reliability. However, the development of numerical methods still introduces new tools enabling, among other things, the virtual tracking of propagation routes of single radius vectors of propagating waves, analyses of impulse responses (BRIR), and even animations of the propagation of acoustic waves. All these tools enable the precise assessment of the impact of changes in the room shape or material features of acoustic conditions of the tested rooms, enabling the design of more and more perfect interiors (i.e. interiors that fully realize their planned functions). The presented example shows that it is possible to change the acoustic conditions even for rooms with extremely unfavourable acoustic parameters regarding the functions planned for these rooms. The tests can be carried out not only to adapt the room for the planned functions, but also to analyse, for example, the listening conditions for the variant where human voice is the only sound source and for the variant where the audio system is used.

References

[1] Cremer L., Müller H.A., *Principles and Applications of Room Acoustics. Applied Science*, London 1982.

[2] Crocker M., *Handbook of noise and vibration control*, John Wiley & Sons Inc., New Jersey 2007.

[3] Engel Z., Engel J., Kosała K., Sadowski J., *Podstawy akustyki obiektów sakralnych*, ITE-PIB, Radom 2007.

[4] Gołaś A., *Metody komputerowe w akustyce wnętrz i środowisku*, AGH, Kraków 1995.

[5] Kotarbińska E., Kozłowski E., *Prognozowanie zrozumiałości mowy w hałasie podczas stosowania ochronników słuchu*, Bezpieczeństwo Pracy, 2004, nr 7–8, 16–20.

[6] Kulowski A., *Akustyka sal*, Wydawnictwo Politechniki Gdańskiej, Gdańsk 2007.

[7] Kulowski A., *Akustyka sal: zalecenia projektowe dla architektów*, Wydawnictwo Politechniki Gdańskiej, Gdańsk 2011.

[8] Long M., *Architectural Acoustics*, Elsevier Academic Press, USA 2006.

[9] Pierchała M., *Charakterystyka i ocena warunków akustycznych. Projekt instalacji systemu nagłośnienia. Analiza akustyczna W53.066LA. KOMAG*, Gliwice 2012 (not published).

[10] Pierchała M., Augustyn A., *Zastosowanie modelowania pól akustycznych w zwalczaniu ponadnormatywnej emisji dźwięku*, Masz. Gór., 2010, nr 3–4, 133–138.

[11] PN-EN ISO 9921:2005. Ergonomia. Ocena porozumiewania się mową.

[12] Rindel J., Christensen C., *Room acoustic simulation and auralization – how close can we get to the real room?*, Melbourne: WESPAC 8, The Eighth Western Pacific Acoustics Conference, 2003, 1–8.

[13] Rindel J., Christensen C., *Odeon, a design tool for noise control in indoor environments*, Lille, France, Solutions for Managing Occupational Noise Risk: Noise at work, 2007, 1–9.