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The index method of acoustic design of sports enclosures

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Summary
The science of interior space acoustics essentially consists in creating adequate acoustic conditions that are necessary for speech and music reception in spaces. The intended use of a particular interior space implies the use of specific acoustic quality criteria which, in turn, are related to respective levels of speech intelligibility. Enclosed sports facilities, such as gyms and indoor swimming pools, are spaces where speech intelligibility and noise level determine, to a large extent, the working comfort or even the safety of occupants. The use of acoustic treatment is often a necessary solution, but in fact is rarely employed. In the paper it is presented a method which develop rules and criteria for the assessment of interior space acoustics in sports facilities, and in particular, the assessment of acoustic conditions in terms of reverberation time and speech intelligibility in enclosed sports facilities, with particular consideration given to school gymnasiums. Presented method increases an accuracy and clarity of the criteria used to assess the acoustic properties of sports facilities. The goal of it is to raise designers' and facility owners' awareness of acoustical problems in such spaces, and of the necessity to apply acoustic treatment.

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1. Introduction

The science of interior space acoustics essentially consists in creating acoustic conditions that are necessary for adequate reception of speech or music in spaces. The intended use of an interior space is connected with specific, appropriate acoustic quality criteria which are divided in subjective and objectives ones.

Subjective criteria are based on the opinions of spectators, and are very important in assessing the acoustic properties of a given space. On the other hand, objective criteria are based on acoustic measurements and play a very important role in the entire design process.

Objective assessment criteria fall into the following categories:

- criteria that can be taken into account and verified during the design stage,
- criteria that can be taken into account in a design, on the basis of model tests, computer simulations, and that can be verified by means of measurements at various stages of the project delivery (project stage control), and those that cannot be verified during the design stage,
- criteria that can only be verified after a given facility has been built.

At present no unambiguous criteria exist relating to factors significantly affecting the acoustic properties of spaces in enclosed sports facilities:

- special intended use of an interior space,
- geometric proportions of an interior space,
- fitting the interior space with sound-scattering objects, sound-absorbing components as well as those that channel sounds (noise),
- arrangement of noise sources in a long interior space, installing (or failure to install) a public address system in the interior space.

There are also several issues related to acoustic properties of sports spaces:

- very high reverberation times resulting from the widespread use of hard, reflective materials. It is indeed difficult to install sound-absorbing materials in sports spaces, but it should be stressed that it is not impossible.
- a phenomenon called "flutter echo" – a phenomenon where a sound is reflected back and forth from two flat, hard parallel surfaces, even though in the room or space there are other surfaces that absorb or scatter sounds. This phenomenon was

References [1 – 9]

found to occur in the spaces tested and it was demonstrated that the flutter echo adversely impacted speech intelligibility in the spaces and actually increased sound levels there.

– high level of sound resulting in excessive noise levels in the spaces concerned, posing a serious problem for those frequently using sports spaces (PE teachers, coaches).

What is of interest to the architect or interior spaces acoustic designer is the parameters that can be used in design and that will take into account the specific character of spaces in enclosed sports facilities. Of the many objective assessment criteria used in the science of acoustics of spaces, it is reverberation time that is the most critical criterion, particularly from the designer's point of view. It is the most reliable criterion, as it can be established as early as in the design stage.

2. Development of assumptions for acoustic design guidelines applicable to sports spaces, intended for architects

Reverberation time is one of the main parameters determining the acoustic quality of long spaces. Requirements relating to protection against reverberation noise boil down to specifying the required maximum reverberation time. With respect to sports spaces (gymnasiums, sports halls and other spaces intended for similar purposes), relevant requirements are set out in polish standard prPN – B – 02151 – 4 *Building Acoustics. Protection against noise in buildings. Requirements for reverberation and speech intelligibility in spaces* [11]. This standard is connected with the basic requirement of "protection against noise" provided for under building regulations (the Construction Law Act and the Ordinance on Technical Guidelines for Buildings and Building Localisation [10]), and in particular addresses protection against reverberant noise. The requirement to reduce reverberant noise in sports spaces is expressed as the maximum value of reverberation time T_{max} for a given volume of a space.

There are separate regulations addressing the requirement to use sound warning systems (DSO) [12, 13]. According to the provisions of standard prPN–B–02151–4, if the requirement relating to reverberation time is met, in most cases it should be possible to correctly design such systems and these should later operate as required. In the case of some sports spaces it might be necessary to decrease the value of reverberation time relative to maximum values set out in the standard, which is allowable under the requirements of this standard.

According to the provisions of standard prPN–B–02151–4, in view of the necessity to reduce reverberant noise in sports spaces, maximum reverberant times were set with respect to octave bands with center frequencies of 50, 500, 1000, 2000 and 4000 Hz. In the band with the center frequency of 125 Hz reverberation time may exceed the given value by up to 25 %. Moreover, in spaces (particularly those with a large volume) where an additional PA system is to be installed, reverberation time for the low frequency band (63-125 Hz) should be similar to the value of reverberation time for the intermediate frequency band (500-1000 Hz).

The maximum reverberation times given in Table 1 refer to spaces completely finished, with items of furniture and fixtures permanently attached, but without occupants.

Reverberation conditions in spaces can be controlled with appropriate amounts of sound-absorbing materials or number of sound-absorbing structures mounted on space dividers (walls, ceiling, floor), depending on the value or characteristics of reverberation time.

The author's analysis of the test results and the theoretical discussion indicate that at present no simple and quick methods are available for the assessment of the acoustic quality of sports spaces at the design stage. Measurement and simulation methods require expensive devices and acoustic expertise. That is why an index-based method for the assessment of acoustic quality of sports spaces is proposed, being specifically intended for architects, designers and users of sports spaces. With this method, architectural and acoustic parameters are gathered (including reverberation time, arrangement of sound absorbing structures or sound scattering objects) and their combinations are analysed in terms of correctness. As a result, a single number is obtained – acoustic quality assessment index for sports spaces W_{PS}, for use during the sports spaces design stage. This method will allow for preliminary and quick assessment of acoustic properties of sports spaces and will identify ways to solve acoustic problems.

Table 1 Respective maximum reverberant times T_{max} in various sports spaces

Item	*Space*	T_{max}, *s.*
1.	Gymnasiums, sports halls and other spaces intended for similar purposes, with a volume of up to 5.000 m^3	≤ 1.5
2.	Gymnasiums, sports halls and other spaces intended for similar purposes, with a volume exceeding 5.000 m^3	≤ 1.8
3.	Indoor swimming pools, water parks and other facilities intended for similar purposes, with a volume of up to 5000 m^3	≤ 1.8
4.	Indoor swimming pools, water parks and other facilities intended for similar purposes, with a volume exceeding 5000 m^3	≤ 2.2

3. Architectural and acoustic parameters describing sports spaces.

Based on the tests carried out to date in actual sports spaces and on theoretical analyses, it has been found that the following parameters affect the acoustic properties of sports spaces:
architectural:

- shape of the ceiling of the sports space,
- cross-sectional shape of the space,
- volume of the space,
- architectural elements scattering sounds.

acoustical:

- sound-absorbing objects mounted on the ceiling and the walls of the space,
- presence of sources of constant noise.

3.1. Architectural parameters describing sport spaces

The shape of the ceiling of a sports space determines, to a large extent, the acoustic conditions prevailing in a given sports space. When selecting the shape of the ceiling, one should definitely avoid elliptical, semi-circular, rounded shapes. It is recommended to seek a solution whereby sound is scattered (trusses, irregularly shaped objects…) – see Figure 1.
The shape of the cross-section of a sports space has a significant effect on the acoustic properties of the space. When making a decision on the shape of a long space, one should avoid semi-circular shapes, and should seek to obtain a shape that is as rectangular as possible. Above all, it is necessary to avoid smooth, parallel walls, which contribute to the undesirable flutter echo, thus significantly hampering communication (both direct and through the public address system). It is recommended to employ solutions designed to scatter sound: seats for spectators, indoor climbing walls, climbing frames, etc. – see Figure 2.

Figure 1. Examples of incorrectly (upper picture) and correctly (bottom picture) designed ceiling shapes in sports spaces.

Volume has a significant effect on reverberation time in all spaces, including sports spaces. Excessive volume adversely impacts verbal communication as well as musical sound reception, and that is why this architectural parameter should be taken into consideration in the assessment of acoustic quality of sports spaces. The volume of a space may also negatively contribute to increased reverberant noise. The assessment criteria adopted were developed on the basis of literature data and the author's own research.

Figure 2. Examples of incorrectly (upper picture) and correctly (bottom picture) designed sidewalls in sports spaces

The presence of sound scattering elements in sports spaces (trusses, curtains separating fields etc.) results in the subdivision of the space into smaller spaces, and consequently, in the transformation of non-diffuse sound fields, typical of sports spaces, into diffuse fields. However, it should be remembered that in such a case an undesired acoustic coupling will be created between the smaller spaces, i.e. poor acoustic conditions in one of the spaces are likely to adversely impact the neighboring spaces.

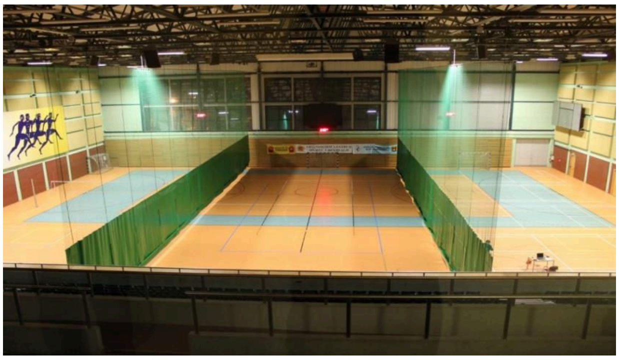


Figure 3. Example of how curtains can be used to subdivide a sports hall

3.2. Acoustical parameters

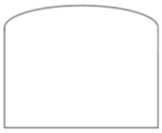
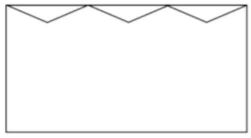
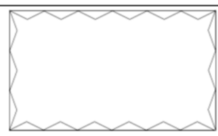
The presence of sound – absorbing objects determines to a large extent the acoustic quality of a sports space. Such objects contribute to decreased reverberation time (and thus reduce reverberant noise) as well as decreased interfering noise levels. As the measure of such quality we should adopt the percentage coverage, of ceiling and walls (separate parameters W_{P1} and W_{P2}, respectively, will be used), with sound- absorbing material of the highest class – A (materials having a sound absorption coefficient $\alpha w \geq 0.9$). If sound-absorbing materials of a lower class are used (B – E or unclassified products), this will accordingly decrease the number of marks for a given partial index.

The presence of constant, active noise sources, such as ventilation and air-conditioning systems, increases sound levels in spaces, and this markedly compromises acoustic quality, especially that of sports spaces. High levels of noise may render verbal messages unintelligible (both in the case of direct communication and through public address systems), and spectators may find it uncomfortable to watch events in such a space because of the aural experience involved. The adverse impact of increased background noise levels is taken into account in the assessment of the acoustic quality of sports spaces, because this phenomenon has been widely described in existing literature and is taken into account in acoustic quality assessments relating to many other types of spaces.

4. Method for assessing the acoustic quality of sports spaces

As a way to conclude the discussion on the effect of architectural and acoustic parameters on the acoustic quality of sports spaces, one could develop an index – based method for assessing the acoustic quality of sports spaces in an effort to develop a quick and uncomplicated method for a tentative assessment of acoustic conditions in such spaces so that adequate comfort for those inside the space and speech intelligibility should be ensured.

Table 2. Values of partial indexes given in Formula (1).

W_n	**Partial index**		
W_{KS}	Ceiling shape index,		
			
value	0	1	2
W_{KP}	Cross-sectional shape index		
			
value	0	1	2
W_O	Space volume index		
	>8 000 m^3	2 000 – 8 000 m^3	< 2 000 m^3
value	0	2	4
W_{P1}	Index relating to sound-absorbing objects, based on ceiling surface area (A-class sound absorbing materials)		
	0 %	50%	100%
value	0	3	5
W_{P2}	Index relating to sound-absorbing objects, based on side wall surface area (A-class sound absorbing materials)		
	0 %	50%	100%
value	0	3	5
W_R	Index relating to sound-scattering architectural elements,		
	Absence		presence
value	0	1	2
W_H	Acoustic background index, based on the presence of constant noise sources.		
	presence		absence
value	0	1	2

The method involves the assumption that an acoustic quality index for a sports space is the sum of partial indices:

$$W_{PD} = W_{KS} + W_{KP} + W_O + W_{P1} + W_{P2} + W_R + W_H, \qquad (1)$$

where:
W_{PS} – rating index for the acoustic quality of sports spaces
partial indexes:
W_{KS} – ceiling shape index,
W_{KP} – cross-sectional shape index
W_O – space volume index,
W_{P1} – index relating to sound-absorbing objects, based on ceiling surface area,
W_{P2} – index relating to sound-absorbing objects, based on side wall surface area,
W_R – index relating to sound-scattering architectural elements,
W_H – acoustic background index (noise level).
The indexes should assume values as set out in Table 2.

The acoustic quality index for sports spaces can take on values within the 0 – 20 range, where each value corresponds to a specific acoustic class:
W_{PS} = 20 ÷ 16 – a sports space of good acoustic quality: in a sports space of good acoustic quality speech intelligibility is sufficient. Direct communication is effective, and there is large potential for installing public address systems. In such a space no typical acoustic problems, such as

too long reverberation time, will be encountered. Architectural and acoustic parameters have been selected correctly.

W_{PS} = 9 ÷ 15 – a sports space of satisfactory acoustic quality: in a space of this category speech reception can be sufficient provided that architectural and acoustic parameters are properly selected, but still acoustic problems might occur, such as too long reverberation time or too high background noise levels. Where sound-absorbing materials are properly selected, and space is appropriately designed (sound-scattering objects), the acoustic quality of the long space under consideration can be satisfactory.

W_{PS} = 0 ÷ 8 – a sports space of poor acoustic quality: in a sports space of poor acoustic quality the occupants will have difficulty understanding speech in direct communication and messages transmitted by the public address system. If a space is found to belong to this category, this means that architectural and acoustic parameters were wrongly selected, which adversely impacts the acoustic properties of such a space by intensifying noise levels.

5. Conclusions

Presented method might be treated as a guide for architects, designers as well as sports facilities managers and users to help them prepare estimates of acoustic conditions and identify ways to improve these.

The guide is intended for:

- designers and architects,
- building owners and/or managers,

This guide is intended to be used when:

- designing and carrying out refurbishments and extensions to existing sports spaces,
- carrying out preliminary, general assessments of the acoustic properties of sports spaces after complaints have been voiced by the users (e.g. PE teachers…),
- carrying out corrective actions aimed at improving acoustic conditions in sports halls.

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