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14. ABSORBING PROPERTIES OF NOISE BARRIERS MEASURED BY DIFFERENT METHODS

14.1. Introduction

Two methods are applicable for the measurement of the absorbing properties of noise barriers - the laboratory method for the measurement of the sound absorption coefficient in reverberant conditions and a newer method for the measurement of the sound reflection coefficient in-situ. Measurement procedures are given in standards PN-EN 1793 for road barriers and PN-EN 16272 series for railway barriers. Measurement methodologies used in the PN-EN 1793 and PN-EN 16272 series are similar. The main difference lies in the application of a different standardized noise spectrum for the determination of single-number ratings DL_{α} and DL_{RI} respectively. The standards for measurement in a diffuse sound field (PN-EN 1793-1 [21] and PN-EN 16272-1 [23]) are a modified version of the methodology discussed in PN-EN ISO 354 [25].

The development of in-situ measurement of acoustic properties of noise barriers using impulse response technology dates back to the early 1990s [1]. In 1993 Garai [9] proposed a method of measurement of the absorption coefficient with the use of the impulse response technique. The method was based on measurement with a single microphone, for the normal sound incidence to the tested surface. The measurement signal was generated by a loudspeaker powered by an MLS signal. Garai also proposed a method to determine the required sample size. In 1995 Mommertz [18] proposed to modify the Garai method by using a signal subtraction technique to separate the reflected component from the signal and to perform measurement for several wave incidence angles. In the years 1995-1997, the European Adrienne project was

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realised. The result of this project was the measurement method adopted in the technical specification CEN/TS 1793-5. The Adrienne method used an integrated loudspeaker-microphone unit, in which the microphone was located on the loudspeaker axis at a distance of 1.25 m. At the reference position, the loudspeaker-microphone unit is located perpendicularly to the front plane of the noise barrier. The other measuring positions (8 positions) are obtained by rotating the unit every 10º. To improve the Adrienne method, The European project QUIESST (Quietening the Environment for a Sustainable Surface Transport) was implemented in 2009-2012 [10, 11, 12]. The result of the project was the measurement methodology presented in the EN 1793-5 standard (in Poland the standard adopted as PN-EN 1795-5:2016). The SOPRANOISE project (Securing and Optimizing the Performance of Road trAffic Noise Barriers with New MethOds and In-Situ Evaluation) is underway, whose aim is, among others, to develop an improved version of the existing EN 1795-5 standard [4].

Studies presented in the literature show that the results of the evaluation of acoustic properties of noise barriers, determined under laboratory conditions (in diffuse sound field conditions) and the QUIESST method are for many cases incomparable. Laboratory measurement usually results in higher DL_α values compared to DL_{RI} values obtained by in-situ measurement [1, 14, 29, 31]. According to studies presented by Sipari and others [29] for a perforated absorptive metal barriers the differences between DL_α and DL_{RI} values may be over 10 dB, and for concrete noise barriers 2-6 dB. There is also no significant correlation between the DL_α and DL_{RI} values determined for the same noise barriers [31]. The DL_α and DL_{RI} values may range from 0 dB for perfectly reflecting surfaces to 20 dB for perfectly absorbing surfaces. A noise barrier is assumed to have good sound absorbing properties if the DL_α value is at least 8 dB. According to Garai [10] comparative studies, for 5 metal absorptive barriers, the DL_α was between 9 dB and 20 dB and the DL_{RI} was between 4 dB and 5 dB. For 5 tested absorbing concrete noise barriers, the DL_α was from 5 dB to 12 dB and the DL_{RI} was from 2 dB to 6 dB. According to Sipari [29] studies, the *RI* index for typical metal noise barriers is 5-10 dB, and for concrete barriers 3-6 dB. Sipari [29] also notes that the EN 1795-5 method is sensitive to acoustic impedance which results in a noticeable effect of the resonance frequencies of the noise barrier structure and surface on the *RI* reflection index frequency response. The laboratory method of assessing the acoustic properties of noise barriers concerning traffic noise (PN-EN 1793-1) has been used for many years. The value of the DL_α is given in technical approvals of barriers as a parameter characterizing the acoustic class of the barrier and is commonly used to determine the required absorbing properties of designed barriers. Differences in the assessment of the acoustic properties of barriers based on different standards can lead to many misunderstandings.

With this in mind, the paper reviews the measurement methodologies used to assess the absorbing properties of the noise barriers and the relationships between the absorption coefficients determined by the different methods. The reasons for the differences between the assessment of absorbing properties of barriers made based on laboratory tests and the in-situ method are discussed. Next, a measurement setup for in-situ testing of noise barriers developed in the Department of Acoustics, Multimedia and Signal Processing and a setup for testing in an impedance tube are presented. The results of sound absorption measurement of the tested metal noise barrier, made by the in-situ method and in the impedance tube, in comparison with the results of laboratory tests are presented.

14.2. Methods of measuring the absorbing properties of surfaces

The absorption coefficient of materials is classically measured using two laboratory methods: the reverberant room method and the impedance tube method. Under in-situ conditions the sound reflection index is determined using signal subtraction technique. To measure the absorbing properties of noise barriers under laboratory conditions the reverberant room method is used [21, 24].

14.2.1. Measurement in the reverberation room

In the reverberation chamber method, the reverberation absorption coefficient α_s is determined. It is calculated by measuring the reverberation time of the reverberation chamber with a barrier sample T_2, and without a sample T_1. Following the measurement procedure described in PN-EN ISO 354 [25], a reverberation chamber with the required reverberation time and a sample of the tested material with an area of 10-12 m^2 are required for testing. During testing, the sample is on the floor. The reverberation absorption coefficient of the tested sample α_s is determined from dependencies (1) and (2), for each one-third octave frequency band in the range from 100 Hz to 5000 Hz. In (1) A_T is the equivalent absorption area of the sample, V is the volume of the reverberation chamber, c is the speed of sound in the air, T is the reverberation time of the chamber, m is the airborne sound absorption coefficient, indices 1 and 2 refer to the situation without and with the sample respectively. In (2), the symbol S indicates the surface area of the material sample under test.

$$A_T = A_2 - A_1 = \left(\frac{1}{c_1 T_1} - \frac{1}{c_2 T_2}\right) - 4V\,(m_2 - m_1) \tag{1}$$

$$\alpha_s = \frac{A_T}{S} \tag{2}$$

The values of the absorption coefficient, determined according to the procedure given in PN-EN ISO 354 [25], may take values greater than 1. This is the result of adopting the Sabine formula to calculate the sound absorption of the surface of a chamber with and without a sample based on the measured reverberation time, which leads to an overestimation of the sound absorption in certain situations. Several attempts have been made to achieve improvements discussed e.g. by Ducourneau [7]. For the measurement of the absorbing properties of the noise barrier, the single number DL_α is determined from (3) in which: α_{si} is the reverberation absorption coefficient for the *i*-th frequency band, L_i is a corrected level of standardized traffic noise spectrum according to PN-EN 1793-3 or normalized railway noise according to PN-EN 16272-3-2, and *i* is the one-third octave band index. If the summation quotient in (3) is greater than 1.00, the value of 0.99 should be taken for calculation of DL_α value [21].

$$DL_\alpha = -10 \cdot \log\left[1 - \frac{\sum_i^{18} \alpha_{si} \cdot 10^{0.1L_i}}{\sum_i^{18} 10^{0.1L_i}}\right] \tag{3}$$

14.2.2. Measurement in an impedance tube

An impedance tube is an acoustically hard tube with a loudspeaker mounted on one end of the tube and a material sample on the other end. Based on the measurement in the impedance tube, the physical absorption coefficient is determined for the perpendicular incidence of a flat acoustic wave. For the determination of the sound absorption coefficient in an impedance tube the method using the standing wave ratio according to PN-EN ISO 10534-1 [26] and the transition function method according to PN-EN ISO 10534-2 [27] are used. Currently, mainly the second method is used. The measurement consists of determining the transfer function H_{12}, between two microphones, which are placed at a certain distance along the tube.

The standard describes three applicable measuring methods: a two-microphone technique with swapped microphone positions, a two-microphone technique with a predetermined calibration factor and a single-microphone technique. Two-microphone techniques are faster and easier to use (especially with a predetermined calibration factor). The single-microphone technique, on the other hand, requires a time-consuming measurement procedure and is, therefore, less popular. Once the transfer function, H_{12}, reflection factor r is determined and is calculated from (4):

$$r = |r|\mathrm{e}^{\mathrm{j}\Phi_\mathrm{r}} = r_\mathrm{r} + \mathrm{j}r\frac{H_{12} - H_\mathrm{I}}{H_\mathrm{R} - H_{12}} e^{2\mathrm{j}k_0 x_1} \tag{4}$$

where: x_1 is a distance of the sample from the further position of the microphone, k_0 – wave number, H_I and H_R – incident and reflected wave transfer function respectively described in (5a) and (5b).

$$H_{\mathrm{I}} = \frac{p_{2\mathrm{I}}}{p_{1\mathrm{I}}} = \mathrm{e}^{-\mathrm{j}k_0(x_1 - x_2)} = \mathrm{e}^{-\mathrm{j}k_0 s} \tag{5a}$$

$$H_{\mathrm{R}} = \frac{p_{2\mathrm{R}}}{p_{1\mathrm{R}}} = e^{\mathrm{j}k_0(x_1 - x_2)} = \mathrm{e}^{\mathrm{j}k_0 s} \tag{5b}$$

where s is a distance between microphones. The sound absorption coefficient α_{n}, for perpendicular incidents wave, is determined from (6).

$$\alpha_{\mathrm{n}} = 1 - |r|^2 \tag{6}$$

To obtain the value of the sound absorption coefficient over a wide frequency range, measurements are carried out using two pipes with different diameters d, usually 100 mm and 29 mm. The upper limit frequency f_{u} is defined by the relationship $d \leq 0.58\ \lambda_{\mathrm{u}}$; $f_{\mathrm{u}}\, d < 0.58\ c$. For a 100 mm diameter tube, the upper frequency is 1.9 kHz and for a 29 mm tube it is 6.8 kHz. The method of measurement in an impedance tube is convenient as it requires small-size samples of the tested material (10 cm and 3 cm in diameter) and gives the possibility to measure the absorbing properties of different materials and structures relatively quickly.

14.2.3. Measurement of sound reflection index

The in-situ method of testing the absorbing properties of noise barriers is an impulse response method in which the sound reflection index *RI* is determined. The method adopted in PN-EN 1793-5 [22] consists of generating a sound signal in front of the noise barrier and simultaneous recording of reflected sound for nine microphone positions. The minimum dimensions of the noise barrier under test are 4.0 × 4.0 m. The configuration of the measuring system is defined in the standard (Fig. 1). The nine measurement microphones are arranged in a grid at horizontal and vertical intervals of 0.4 m. The central microphone (microphone 5) is located at the reference height h_{S} (typically h_{S} = 2.0 m). The standard distance between the front of the loudspeaker and the reference plane of the noise barrier is 1.50 m, the distance between the measuring grid and the reference plane is 0.25 m.

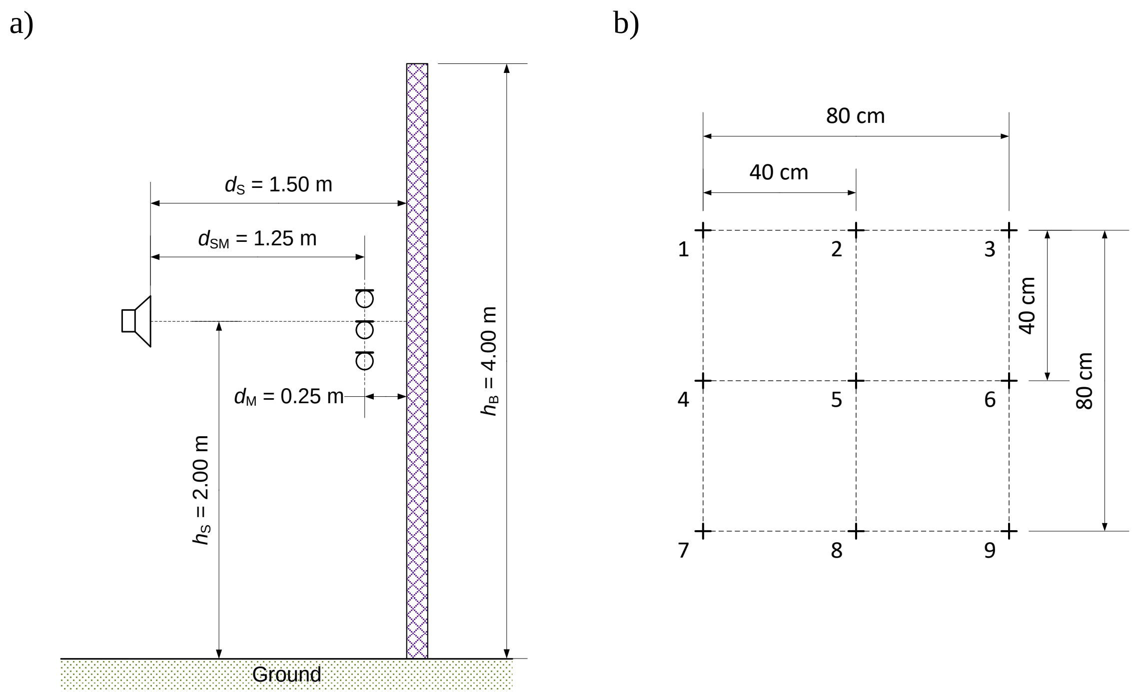


Fig. 1. a) Standard geometry for *RI* measurement, b) arrangement and numbers of measurement microphones (loudspeaker-side view)

Rys. 1. a) Standardowa geometria układu pomiarowego do wyznaczania *RI,* b) układ i numery mikrofonów (widok od strony głośnika)

The basis for determining the sound reflection index is two nine-channel impulse responses. One is taken in front of the noise barrier and therefore contains both direct and reflected sound. The second impulse response is determined in a free field and therefore contains only direct sound. To determine the energy of the sound reflected from the noise barrier, the difference between the impulse response taken in front of the noise barrier and the free field impulse response is used. In practice, both the impulse response taken in front of the noise barrier and the free field impulse response is determined above the ground. Thus they contain the component related to the reflection from the ground. Moreover, the impulse response taken in front of the noise barrier contains components related to diffraction at the barrier edges. By determining the impulse response for a sufficiently height above the ground surface and a sufficiently large sample, unwanted components can be eliminated by using the Adrienne time window [22].

The *RI* is calculated as the ratio of the energy of the reflected sound to the direct sound in one-third octave bands, taking into account proper correction factors. This is done independently for each microphone. The final result for a given one-third octave band is the arithmetic mean obtained for each of the nine positions. The expression used to compute the *RI* is presented by (7):

$$RI_{\mathrm{j}} = \frac{1}{n_{\mathrm{j}}}\sum_{k=1}^{n_{\mathrm{j}}}[\frac{\int_{\Delta \mathrm{f_j}}\left|F\left[h_{\mathrm{r,k}}(t)\cdot w_{\mathrm{r,k}}(t)\right]\right|^2 \mathrm{d}f}{\int_{\Delta \mathrm{f_j}}\left|F\left[h_{\mathrm{i,k}}(t)\cdot w_{\mathrm{i,k}}(t)\right]\right|^2 \mathrm{d}f}\cdot C_{\mathrm{geo,k}}\cdot C_{\mathrm{dir,k}}\left(\Delta f_{\mathrm{j}}\right)\cdot C_{\mathrm{gain,k}}\left(\Delta f_{\mathrm{g}}\right) \tag{7}$$

where:

$h_{\mathrm{i,k}}(t)$ - the impulse response in the free field at *k*-th measurement point,

$h_{\mathrm{r,k}}(t)$ - the reflected component of the impulse response taken in front of the noise barrier under test at the *k*-th measurement point,

$w_{\mathrm{i,k}}(t)$ - the time window (*Adrienne*) for the free-field impulse response at the *k*-th measurement point,

$w_{\mathrm{r,k}}(t)$ - a time window (*Adrienne*) for the reflected component at the *k*-th measurement point,

F - Fourier transform,

j - the index of the one-third octave frequency bands,

Δf_j - the width of the *j*-th one-third octave frequency band,

n_{j} - the number of microphone positions on which to average,

k - the microphone number,

$C_{\mathrm{geo,k}}$ - the correction factor for geometrical divergence at the *k*-th measurement point,

$C_{\mathrm{dir,k}}\left(\Delta f_{\mathrm{j}}\right)$ - the correction factor for sound source directivity at the *k*-th measurement point,

$C_{\mathrm{gain,k}}\left(\Delta f_{\mathrm{g}}\right)$ - the correction factor to account for a change in the amplification settings of the loudspeaker and in the sensitivity settings of the individual microphones when changing the measurement configuration from free field to in front of the sample under test or vice versa.

To indicate the performance of the noise barrier, a single-number rating of sound reflection DL_{RI}, expressed in decibels, is determined from (8):

$$DL_{\mathrm{RI}} = -10\cdot\log\left[\frac{\sum_{i=m}^{18} RI_{\mathrm{i}}\cdot 10^{0.1L_{\mathrm{i}}}}{\sum_{i=m}^{18} 10^{0.1L_{\mathrm{i}}}}\right] \tag{8}$$

where: m - the number of the lowest one-third octave frequency band, L_{i} - relative A-weighted sound pressure levels of the normalized traffic noise spectrum, as defined in EN 1793–3 (or normalized railway noise spectrum, as defined in PN-EN 162723-2), in the *i*-th one-third octave band. If the summation term in the (8) is greater than 1, the maximum value of 0.99 should be used to calculate the DL_{RI} [22].

14.3. Relationship between absorption coefficients α_s and α_n and *RI* index

Studies show that the results of the absorption coefficient measurement depend on the test method. This means that the absorption coefficient of the same material with the same properties will vary depending on the test method [5, 6, 10, 15, 17, 20, 30]. Due to the method of measurement, two types of conventional absorption coefficients can be distinguished: α_s – reverberant/statistical absorption coefficient, measured under reverberant field conditions for all possible angles of incidence of the acoustic wave on the sample, α_n – physical absorption coefficient, for the normal sound incidence, measured in an impedance tube. There are significant differences in the frequency characteristics of α_s and α_n, especially in the medium frequency range. The α_s is characterized by significantly higher values and measured α_s may take values greater than 1. In the high-frequency range (> 2000 Hz), α_n and α_s are similar.

Studies on the relationship between the physical absorption coefficient α_n, measured in the impedance tube, and the reverberant absorption coefficient α_s have a rich history. The relationship, for materials with a locally reacting surface area, was already given by London in 1950 [16]. Since then, several attempts have been made to develop a better overall formula, but also with moderate success. The relationship between α_n and α_s, based on London's formula, included in Information Annex F of PN-EN ISO 10534-2:2003, is given by (9):

$$\alpha_s = 8\frac{z'}{z'^2+z''^2}\left[1-\frac{z'}{z'^2+z''^2}\ln(1+2z'+z'^2+z''^2)+\frac{1}{z''}\frac{z'^2-z''^2}{z'^2+z''^2}\arctan\frac{z''}{1+z'}\right] \quad (9)$$

where: z' is the real part of normalized acoustic impedance, z'' the imaginary part of the normalized acoustic impedance. The highest possible value of the α_s coefficient, calculated according to the standard dependence is 0.96. For many materials, the compliance of the reverberation frequency characteristics of the coefficient calculated from dependence (9) and measured is not the best [5, 6, 10, 15, 17, 20, 30]. The study of del Ray et al. [6] shows that for porous materials, such as mineral wool, the α_s frequency characteristics measured and calculated from (9) show a similar pattern.

In the in-situ method, the *RI* reflection index is determined from the impulse response. It is assumed that the absorption coefficient α_I is determined from the relation $\alpha_I = 1 - RI$. For in-situ measurement of noise barriers (PN-EN 1793-5), the sound reflection index *RI* is measured under near-field conditions for a narrow angle of incidence of sound wave. The angles of acoustic wave incidence on the barrier, for which the measurement is made, result from the obligatory geometry of the measuring system and are within the range of 0 - 20°. Literature reports show that the values of the absorption coefficient α_I are close to the value of the absorption coefficient α_n measured in the impedance tube [13, 20].

14.4. Experimental research

Within the framework of the conducted experiments, measurement of the sound absorption coefficient α_n in the impedance tube, and measurement of the sound reflection index *RI* with the in-situ method were performed on a specially built test setup. A metal one-sided absorption barrier was selected for the test (Fig. 2). The barrier cassettes were made of 1.2 mm thick profiled aluminium sheet, perforated on one side (23% degree of perforation, 5 mm diameter holes) and solid on the other. The cassette is filled with absorbing material in the form of mineral wool panels with a thickness of 50 mm and a density of 100 - 120 kg/m^3. The mineral wool panels are fixed to the perforated cassette wall and protected by a glass veil. The depth of the barrier surface profiling is 12 mm. According to the manufacturer's data, the single number rating of sound absorption DL_α = 12 dB (according to PN-EN 1793-1:2001, for a normalized traffic noise spectrum). For the normalized railway noise spectrum (standard PN-EN 16272-3-2:2010) DL_α = 9.5 dB.

14.4.1. Test setup for *RI* measurement

The in-situ test setup has been built in an acoustic chamber (Fig. 2). The dimensions of the acoustic chamber are 14 × 10 × 7 m and the volume is 980 m^3. The walls and ceiling of the chamber are sound absorptive, the floor is reflective. A metal noise barrier with dimensions of 4 × 4 m was assembled in the chamber and during measurement, it was positioned so that no reflective surfaces are present within 2 m of the barrier.

For measurement, a self-made measuring system was used [8]. The system has been designed to meet the requirements of PN-EN 1793-5:2016, i.e. the entire measurement system should meet the requirements for the first class accuracy meters [28], except for microphones, which should meet the requirements for the second class devices and should have a diameter not exceeding ½". Microphones with a diameter of 1/4" and meeting the requirements for first-class microphones have been used. The microphones are placed on a designed metal frame. In the system, a popular audio interface with 12 microphone inputs was used, which, for measurement with nine channels, enables signal processing with sampling frequency up to 96 kHz. Electrical parameters of the interface and power amplifier used were measured, confirming that the devices meet the requirements for first-class meters according to PN-EN 61672-1 [28].

A single loudspeaker driver in a closed enclosure designed for these measurements, was used as a sound source. The impulse responses were measured using the EASERA software and processed using DIRAC and self-made programs.

In the standard there are no special requirements for frame construction on which the microphones are mounted. However, in the case of measurement of the sound reflection index, the frame is a very important part of the system. Frame elements have an effect on the sound field in front of the barrier and can be a source of unwanted reflections and diffraction. Consequently, the frame construction can influence the measurement results. Various frame elements and geometry have been tested. A frame made of pipes with a diameter of 12 mm was selected for research. Such a solution provided the results closest to expected for the concrete surface [8].

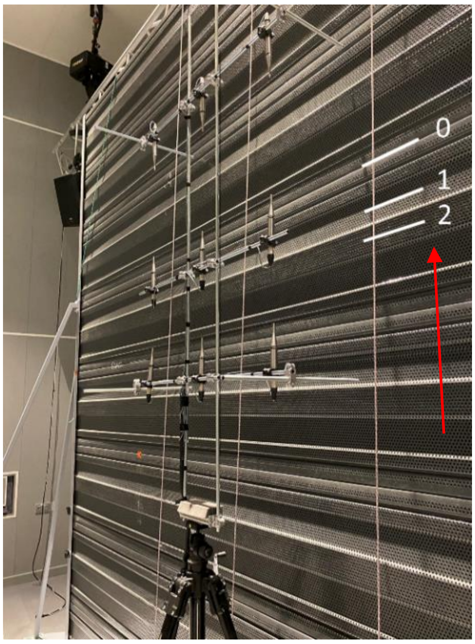


Fig. 2. View of the tested barrier in the acoustic chamber with marked the hight of microphone No. 5 of the measuring matrix on different segments of the barrier surface
Rys. 2. Widok ekranu testowego w komorze akustycznej z zaznaczoną wysokością mikrofonu nr 5 matrycy pomiarowej na różnych segmentach powierzchni ekranu

System for impulse response measurement presented in PN-EN 1793-5:2016 and some of the related requirements seem to be somewhat archaic. So, more modern measurement principles were used in determining the impulse responses [19]. Different measurement signals with different sampling frequencies, times and levels were tested [8]. Ultimately, the e-sweep signal with a sampling frequency of 96 kHz and a length of 2.7 s was used in the measurement. An Adrienne time window of $T_w = 6.0$ ms was used for the analysis, hence the lower frequency range of reliable *RI* measurement is 200 Hz. Results for lower frequencies should be treated as informative.

The research focused on the analysis of the influence on the measured values of the *RI* of the microphones' location in relation to barrier elements of different structure. For this purpose a vertical scan was performed for three locations of the measurement grid (Fig. 2): position 0 – microphone 5 of the grid in front of the barrier panel join, where there is 8 cm of a solid sheet, position 1 – microphone 5 in front of the concave segment (cross-section A in Fig. 6), position 2 – microphone 5 in front of the convex segment (cross-section B in Fig. 6). According to the criterion given in PN-EN 1793-5, the surface of the tested barrier is flat and homogeneous (the sample is not flat when the depth of the barrier surface structure is at least 85 mm, the sample is not homogeneous when its front surface consists of different materials and the width of the strip of each material is at least 85 mm). In this case, it is sufficient to measure for one location of the microphone grid, located in the centre of the barrier under test, i.e. microphone 5 should be located at a height equal to half the height of the barrier at a distance of 2 m from each edge of the barrier. For the tested barrier, following the above rules, the loudspeaker axis and microphone 5 of the grid shall be located exactly in the front of connection of panels of which the barrier is made. For a 4.5 m barrier height, microphone 5 should be located at half the barrier panel height, which corresponds to measurement position 2 in Figure 2. It should be noted that the required location of microphone 5 results from the measurement methodology requirements concerning the elimination of unwanted reflections and the length of the time window T_w used, not the barrier design requirements.

14.4.2. Measurement of the absorption coefficient in the impedance tube

The measurements of the absorption coefficient were made on a test setup, made in the Department of Acoustics, Multimedia and Signal Processing, which consists of two 29 mm and 100 mm impedance tubes, a sound source, which is a dynamic loudspeaker placed in a housing and two 1/4 inch diameter measuring microphones connected to a signal conditioner and an external audio interface. This interface also functions as a power amplifier powering the sound source and analogue-to-digital and digital-to-analogue converters enabling measurement to be made via appropriate computer software. A two-microphone measurement method with a predetermined transmittance between H_{12} microphones, described in PN-EN ISO 10534-2, has been applied. The distance between the microphones, used in measurement: 80 mm in a large tube, 22 mm in a small tube. The upper measuring frequency limit, resulting from the diameter of the impedance tube, is 1.9 kHz for a 100 mm tube and 6.8 kHz for a 29 mm tube. The lower limit of the measuring frequency resulting from the distance between the measuring microphones and the loudspeaker used shall be 215 Hz for 100 mm tube and 780 Hz for 29 mm tube.

In the impedance tube, samples of a layered structure, similar to the tested barrier, and for comparison, samples of homogeneous absorbent material, mineral wool of various densities (50-120 kg/m^3) were tested. Samples of materials comprising the structure of the noise barrier were obtained from the manufacturer. The samples were placed in an impedance tube to reproduce the arrangement of layers in the real barrier panel. Samples corresponding to sections A and B were tested (Fig. 6). The layout of tested samples was as follows (sample components are shown in Fig. 3):

– A cross-section: 1.2 mm thick perforated aluminium sheet with stucco structure, glass veil, 50 mm mineral wool with a density of 100 kg/m^3, 50 mm air void, 1.2 thick solid aluminium sheet with stucco structure,
– B cross-section: 1.2 mm thick perforated aluminium sheet with stucco structure, 12 mm air gap, glass veil, 50 mm mineral wool with a density of 100 kg/m^3, 62 mm wide air gap, 1.2 mm thick solid aluminium sheet with stucco structure.

When measuring the properties of a complex structure, the accuracy of placing successive layers of the structure under test in an impedance tube, including leaks in the circumference of the sample, the angle of the front layer (perforated sheet layer) or the distance between the layers may have a significant impact on the measurement result. The accuracy of matching the dimensions of the samples to the diameter of the impedance tube may also be important [0]. Therefore, for both complex and homogeneous structures, the measurements have been repeated many times. Each time the samples were taken out of the impedance tube and reassembled. Taking into account that the real barriers may differ in geometrical parameters and accuracy of execution, the influence of the air gap width behind the wool in the barrier panel on the frequency characteristics of the absorption coefficient α_n was also examined.

Fig. 3. Components of a barrier for testing in an impedance tube: 1.2 mm thick perforated aluminium sheet, glass veil, 50 mm mineral wool, 1.2 mm thick unperforated aluminium sheet
Rys. 3. Elementy składowe próbki struktury ekranu do badań w rurze impedancyjnej: blacha o grubości 1.2 mm perforowana, welon szklany, wełna mineralna 50 mm, blacha o grubości 1.2 mm bez perforacji

14.5. Measurement results

Fig. 4 shows the measurement results of the *RI* reflection index obtained for the individual microphones of the microphone grid (microphones 1-9) for the different microphone 5 positions and the mean value of *RI*, which is the result of measurement according to the measurement procedure in [22]. It can be seen that for high frequencies, above 1250 Hz, the measured *RI* values for the individual microphones vary considerably. For position 0 (microphone 5 opposite the solid sheet metal at the barrier panel connection), the *RI* value for microphones 4, 5 and 6 increases with frequency and for the band f = 5 kHz takes the value of 1. For the other microphones, the increase in *RI* with frequency is much smaller, for f = 5 kHz $RI \leq 0.36$. For position 2 (microphone 5 at half the height of the barrier panel), there is no such increase in *RI* values for the high frequencies, but significant differences in the frequency characteristics of *RI* for microphones 4, 5 and 6 and others can be observed.

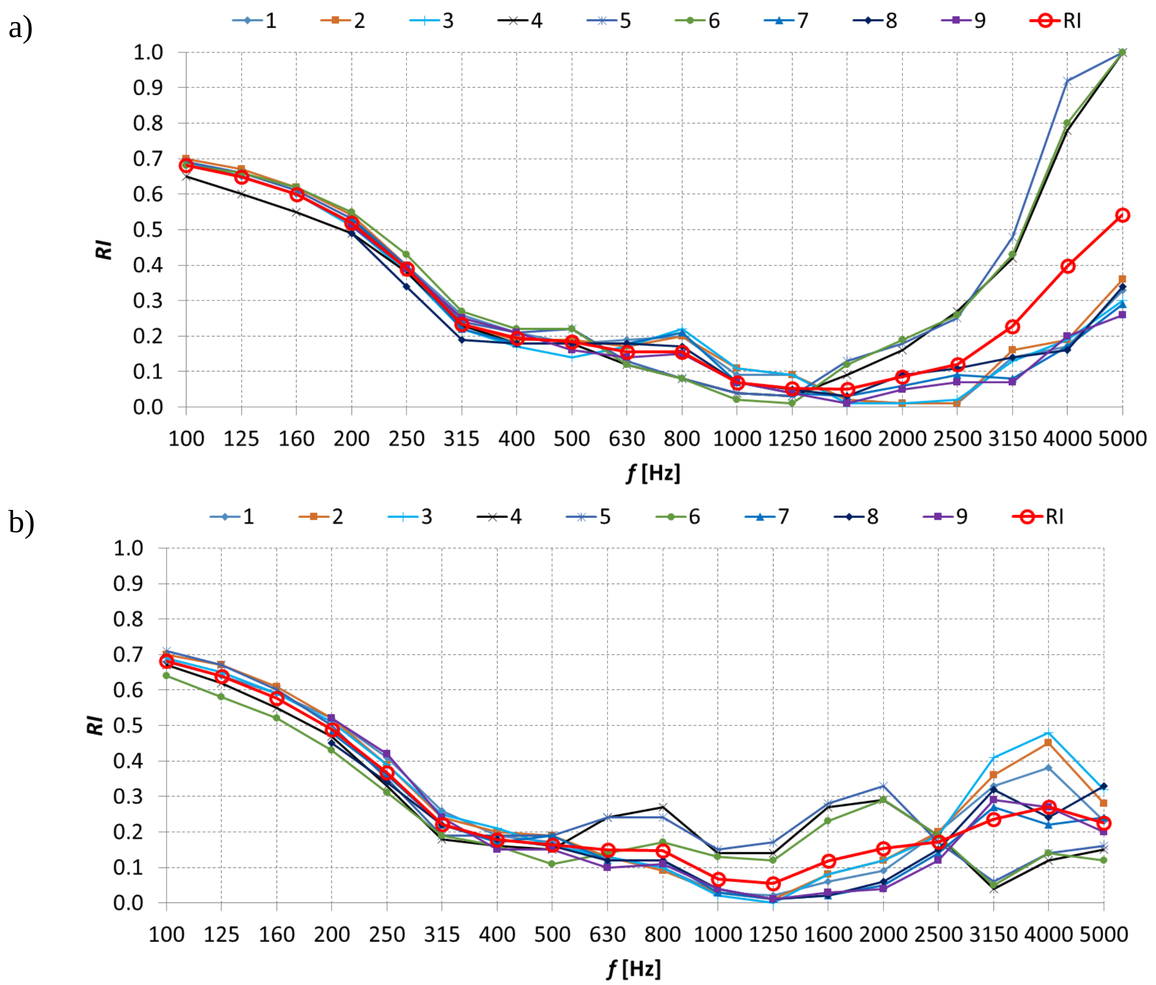


Fig. 4. *RI* indicator for individual microphones of the microphone grid and average *RI* value measured for different microphone 5 locations (Fig. 2): a) position 0, b) position 2; 1-9 – microphone numbers (Fig. 1)

Rys. 4. Wskaźnik *RI* dla poszczególnych mikrofonów matrycy i wartość średnia *RI*, zmierzone dla różnej lokalizacji mikrofonu nr 5 (rys. 2): a) pozycja 0, b) pozycja 2; 1-9 numery mikrofonów (rys. 1)

In Fig. 5, the frequency characteristics of the calculated *RI* are presented for the three locations of the microphone grid. The *RI* characteristics determined for position 0 and position 1 differ significantly from those determined for position 2 in the high-frequency range (f = 4 kHz and f = 5 kHz). For f = 4 kHz the difference in *RI* values between position 2 and positions 0 and 1 are 0.13 and 0.17, respectively, and for f = 5 kHz they are 0.31 and 0.34. These differences are probably the result of the influence of piece non-perforated sound reflective metal element. Measurement problems resulting from the influence of even small highly sound reflective surfaces were pointed out by Sipari and others [29].

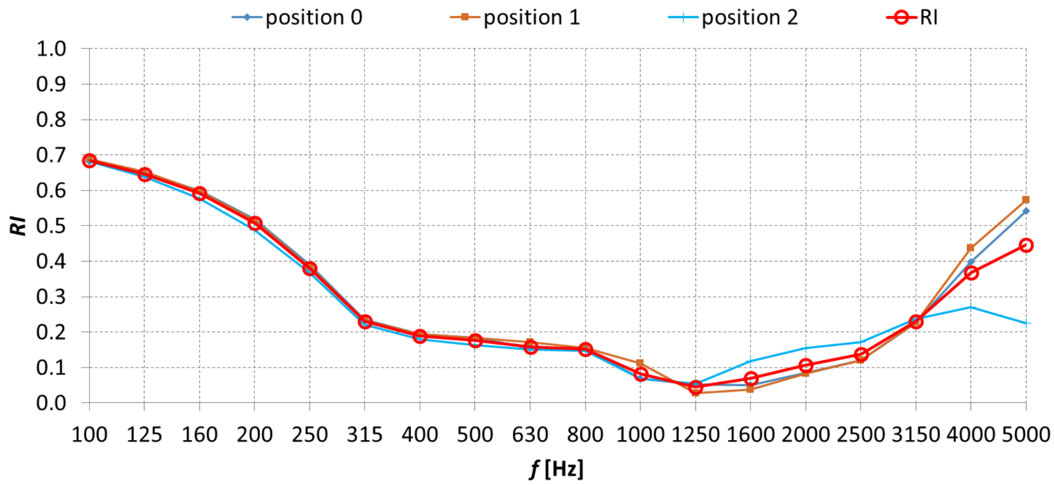


Fig. 5. Sound reflection index *RI* of the metal barrier test measured by in-situ method, for different locations of the microphone grid as in Fig.2

Rys. 5. Wskaźnik odbicia *RI* testowego ekranu metalowego zmierzony metodą in-situ, dla różnej lokalizacji matrycy pomiarowej jak na rys. 2

Table 1 presents the values of the *RI* index determined for the tested barrier based on measurement made for different microphone grid locations, for *RI* frequency characteristics as shown in Fig. 5. The *RI* indexes determined for the normalized traffic noise spectrum (PN-EN 1793-3) and the normalized railway noise spectrum (PN-EN 16272-3-2) are given. For comparison, the values of DL_α index, determined based on laboratory tests provided by the manufacturer, are also included. The differences between the *RI* values are small, despite visible differences in *RI* frequency characteristics for different locations of the microphone grid. For traffic noise, the DL_{RI} values are 3.7-3.8 dB lower than the DL_α value determined for railway noise, the differences are 1.1-1.4 dB.

Table 1

Sound reflection index *RI* specified for the tested barrier for different positions of the microphone grid

Type of noise	DL_{RI} [dB] 200 - 5000 Hz			DL_α [dB] 100 - 5000 Hz
	position 0	position 1	position 2	-
Normalized traffic noise	8.3	8.2	8.2	12
Normalized railway noise	8.4	8.3	8.1	9.5

The results of in-situ measurement on the test setup also showed good repeatability. In the frequency range from f = 200 Hz to f = 5 kHz, the spread of RI values for the individual bands is between 0.00 and 0.02. The determined DL_{RI} value is within the limit of 0.09 dB.

Fig. 6 shows the frequency characteristics of the physical absorption coefficient α_n, measured in an impedance tube for the tested barrier structure, for cross-sections A and B. The characteristics show a different course in the frequency range 1.6 - 3.15 kHz. For section B, the α_n values are 0.12 - 0.14 higher. The results of α_n measurement in the impedance tube show good repeatability for both homogeneous material (mineral wool) and complex metal barrier structure.

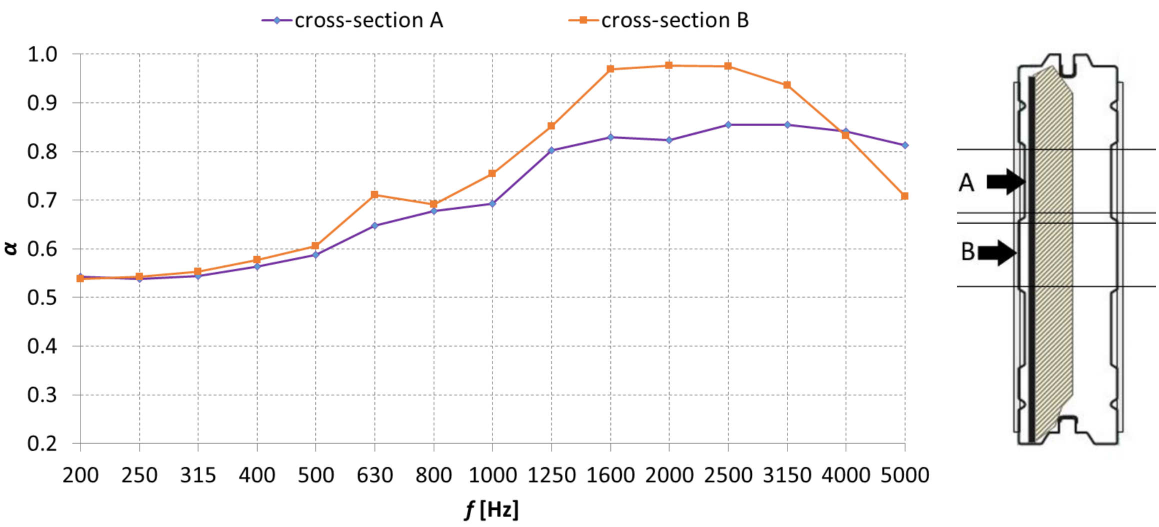
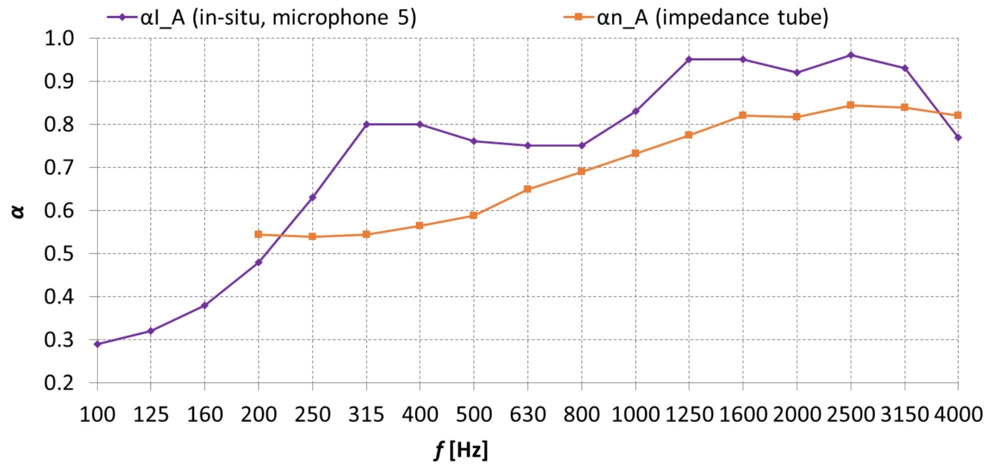


Fig. 6. a) Absorption coefficient α_n measured in the impedance tube for a tested barrier structure, b) barrier structure and tested cross-sections

Rys. 6. a) Współczynnik pochłaniania α_n zmierzony w rurze impedancyjnej dla struktury jak ekranu testowego, b) przekrój struktury ekranu i badane przekroje

Fig. 7 shows a comparison of the α_n factor characteristics measured in the impedance tube for section B with the α_I factor characteristics measured in-situ for microphone 5, i.e. for the normal incidence. The course of the characteristics is different. For frequency bands from 250 Hz to 500 Hz, differences greater than 0.2 occur for measurements in both sections. For section B, where there is a 12 mm wide air gap between the front perforated sheet and the mineral wool, in the frequency range 1.6 - 2.5 kHz the characteristic curve is different and the differences are up to 0.31.

a)



b)

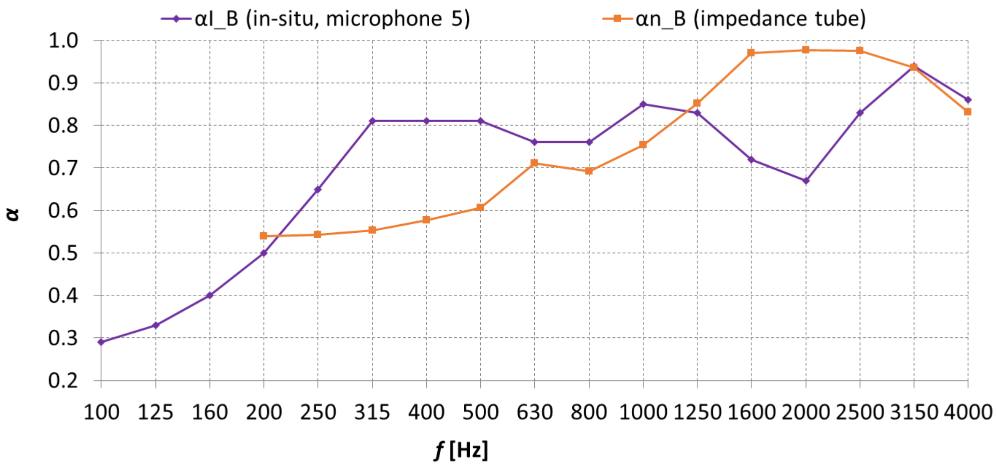


Fig. 7. Comparison of α_I measurement results by the in-situ method for microphone 5 and α_n in the impedance tube for the tested barrier: a) position 1/section A, b) position 2/section B

Rys. 7. Porównanie wyników pomiaru α_I metodą in situ dla mikrofonu 5 i α_n w rurze impedancyjnej dla ekranu testowego: a) pozycja 1 /przekrój A, b) pozycja 2 /przekrój B

Fig. 8 presents the frequency characteristics of absorption coefficients of the tested barrier, determined by various methods: reverberant absorption coefficient α_s measured under laboratory conditions (data from the manufacturer), indicator $\alpha_I = 1–RI$, determined based on in-situ measurement (mean from three positions), coefficient α_n measured in an impedance tube and reverberant coefficient, α_s calculated from (9).

The frequency characteristics of the absorption coefficient α_I and the absorption coefficient α_s are different in for frequencies below $f = 1$ kHz. The values of α_s are significantly higher than the α_I. For the one-third octave frequency bands 200 Hz and 250 Hz the differences between them are 0.45 and 0.34 respectively, and in the range from 315 Hz to 630 Hz from 0.18 to 0.26. In the range from 1000 Hz to 2500 Hz the results of both methods are very similar and the differences between them do not exceed 0.04. For bands 3.15 kHz and 4 kHz the differences increase to 0.08 and 0.07.

For the one-third octave frequency bands from 200 Hz to 1 kHz, the absorption coefficient values determined in the impedance tube α_n are significantly lower than the reverberation coefficient α_S. The differences between α_S and α_n in this range are between 0.25 and 0.51. For frequency 1.6 kHz the values of α_S and α_n are equal, and at higher frequencies the values of α_n are 0.03 to 0.06 greater than α_S.

Formula (9) to calculate the reverberant sound absorption coefficient from the acoustic impedance measured in the impedance tube $\alpha_{s,calc}$ gives good results for frequencies from 1.6 kHz to 4.0 kHz. The values $\alpha_{s,calc}$ and α_s for frequency 1.6 kHz are equal and for the range 2.0 kHz to 4.0 kHz the values $\alpha_{s,calc}$ are by 0.02 greater than α_S. For frequencies below 1.25 kHz, the differences between α_S and $\alpha_{s,calc}$ are large - from 0.18 to 0.41.

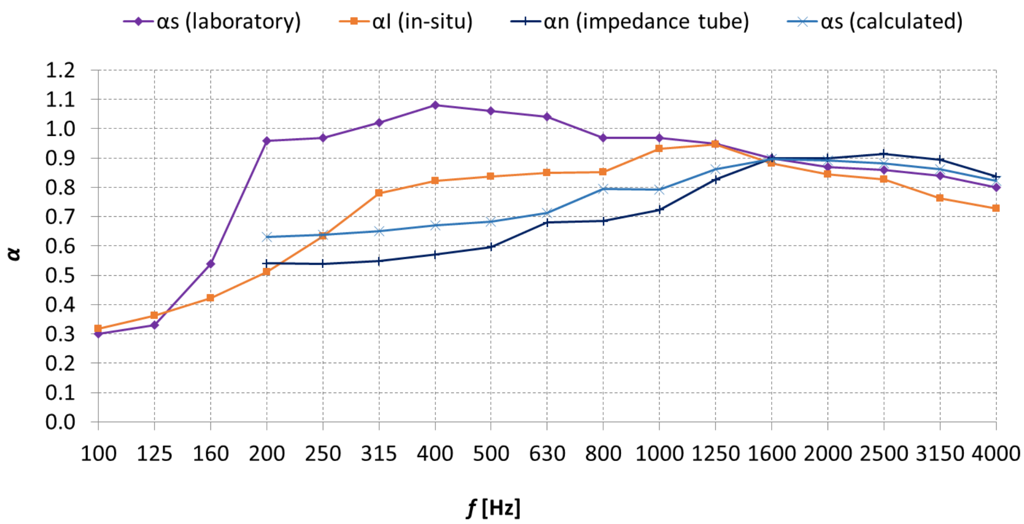


Fig. 8. Absorption coefficients of the tested barrier, determined by different methods: α_s – under laboratory conditions (PN-EN 1793-1, data from the manufacturer), $\alpha_I = 1$ - *RI* – in-situ method (PN-EN 1793-5), α_n – measurement in an impedance tube (PN-EN ISO 10534-2), $\alpha_{s,calc}$ – calculated according to the formula (9)

Rys. 8. Współczynniki pochłaniania badanego ekranu, wyznaczone różnymi metodami: α_s – w warunkach laboratoryjnych (PN-EN 1793-1, dane od producenta), $\alpha_I = 1$-*RI* – metoda in-situ (PN-EN 1793-5), α_n – pomiar w rurze impedancyjnej (PN-EN ISO 10534-2), $\alpha_{s,calc}$ – obliczony wg wzoru (9)

14.6. Summary

The results of in-situ measurement of absorbing properties of barriers differ from those measured under laboratory conditions. The reason is the different measurement conditions – free field and diffuse sound field and the different definitions of the measured values – reverberation absorption coefficient α_S, and reflection index *RI*. In the frequency characteristics of the sound absorption coefficients, the greatest differences are in the low and medium frequencies, below 1000 Hz. For the same type of barrier, the DL_{RI} value is less than the DL_{α} value. For the tested noise barrier, the difference depending on the location of the microphone grid is 3.7 - 3.8 dB for the normalized traffic noise spectrum and 1.0 - 1.4 dB for the normalized railway noise spectrum. The differences obtained at the tested setup for the normalized traffic noise spectrum are smaller than those presented in the literature for similar barriers installed in real conditions. The frequency characteristics of the absorption coefficient determined by the in-situ method and in the impedance tube also show significant differences, which is probably due to the small dimensions of the sample tested in the impedance tube. London formula (9) to calculate the reverberant absorption coefficient from the acoustic impedance measured in the impedance tube is not applicable for frequencies below 1.25 kHz, however gives similar results to reverberant absorption coefficient α_s measured in laboratory for higher frequencies.

The measurement uncertainty of the *RI* measurement methodology presented in PN-EN 1793- 5:2016 is relatively high. It seems that this is partly due to imprecise requirements for the loudspeaker used for measurement and especially the lack of requirements for the construction of the frame on which the microphones are mounted. It seems that the influence of the loudspeaker used on the results could be smaller after digital equalization of its linear distortions. However, the standard excludes the use of active or passive components which can affect the frequency response of the system. On the other hand, the requirements of the standard for the impulse response measurement system seem to be archaic or unfounded. An important disadvantage of the method is its sensitivity to the accuracy of the measuring geometry. The standard gives relatively few restrictions on its use. During the tests, a significant influence on the results obtained was noticed, e.g. even small elements with sound reflective properties. Therefore, it seems necessary to improve the measurement methodology presented in the PN-EN 1793-5:2016 standard.

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