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SOPRANOISE

D2.1 – Review of the physical significance of EN 1793-1, EN 1793-2, EN 1793-5 and EN 1793-6

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1 Overview of SOPRANOISE WP2

The objective of work package 2 of SOPRANOISE is to provide theoretical and practical background information on the measurement of the acoustic performance of noise barriers.

This report shows the achievement of milestone M2.1 (State of the Art on the physical significance of the different measurement methods) and is the final output of task 2.1 (Review of the physical significance of EN1793-1, -2, -5 and -6), providing the state of the art regarding correlations and possible trends between diffuse and direct sound field methods. A database of the EU noise barrier market, including manufactured products and already installed noise barriers has been created. This database aims to show facts and figures about acoustic performances obtained from both the diffuse sound field and direct sound field methods, together with a better understanding of the respective significance, similarities and differences of these standardized methods. The final results will be presented in the report T2.2, which is the second part of deliverable report D2.2.

Moreover, in WP2, the effect of acoustic degradation on the global noise barrier performance will be carefully considered and documented to objectively understand the long-term ability of noise barriers to reduce noise immissions. The results of this work are reported in the report T2.3, which is the third and last part of D2.2.

This deliverable presents the current state of the art of the standardized measurement methods for assessing the intrinsic acoustic performances of noise reducing devices.

It starts with short summaries of the diffuse sound field measurement methods for sound absorption [1] and for airborne sound insulation [2], followed by descriptions of the direct sound field measurement methods for sound reflection [3] and for airborne sound insulation [4]. These descriptions are not complete manuals for the measurement methods, but they contain the general measurement procedures as well as some physical background information.

Subsequently, the differences between the diffuse sound field methods, requiring (laboratory) reverberant rooms, and the direct sound field methods, which can be applied everywhere the direct sound field conditions are met, including alongside roads, are investigated. This will be done first in general, and then specifically for the sound absorption under diffuse sound field conditions and the sound reflection under direct sound field conditions, as well as for the diffuse and direct sound field measurement methods for airborne sound insulation.

Finally, a short conclusion about the presented information is given.

2 Current methods for assessing the acoustic performance of European NRD

There are four standardized methods for assessing the intrinsic properties of sound absorption and airborne sound insulation of NRD. They can be categorised into two classes: the diffuse sound field methods and the direct sound field methods.

Diffuse sound field measurement methods were the first used to determine the intrinsic acoustic properties of NRD: at the early stages (the seventies), they were the only measurement methods available, but the sound field used by those methods does not correspond to the effective sound field for noise barriers (except for closed field and tunnels).

Since 2015, with the final publication of the respective standards describing measurement methods for sound reflection and airborne sound insulation under direct sound field conditions, a clear distinction is made on the scope of application for those different methods.

It is now mandatory to characterize the NRD with the appropriate sound field that corresponds to their effective intended use, i.e.: direct or diffuse sound field.

In the following sections, an overview of the existing diffuse sound field and direct sound field measurement methods for intrinsic NRD properties is given and their possible relations to each other is explained.

2.1 Acoustic properties of NRD

The acoustic properties of NRD can be divided into two categories:

- intrinsic properties of NRD
- extrinsic properties of NRD

Intrinsic properties are inherent to the (product) NRD and are independent of the environment. Examples of intrinsic properties are the sound absorption and the airborne sound insulation, which depend only on the specific make-up of the NRD itself.

Extrinsic properties, on the other hand, depend on the specific environment in which the NRD is used. An example of an extrinsic property is the insertion loss, which can depend on the terrain or even on meteorological circumstances, but also the dimensions of the NRD: it compares the sound immissions at specific points with and without the NRD.

This state-of-the-art report is only addressing the measurement methods for intrinsic properties, i.d., sound absorption/reflection and airborne sound insulation.

EN 1793-4 describes a measurement procedure for testing the intrinsic property of sound diffraction at the top of the NRD [5]; however, as sound diffraction is not in the focus of SOPRANOISE, the measurement procedure is not addressed in this report.

2.2 Diffuse sound field measurement methods

Diffuse sound field measurement methods require special infrastructure, i.e., reverberation rooms, to be performed, as well as test-specimen which must be mounted inside these rooms. The main property of a diffuse sound field is that it has no privileged direction of the energy, i.d. for a NRD the incident sound energy is equally spread over all angles of the hemisphere.

The following two subsections summarise the standards EN 1793-1 for sound absorption and EN 1793-2 for airborne sound insulation to describe their measurement principles.

2.2.1 Diffuse sound field method for testing sound absorption (EN 1793-1)

The diffuse sound field measurement method for sound absorption is based on the change of the reverberation time inside a reverberation chamber (as measured with ISO 354 [6]) after installation of a test sample of the NRD at the surface of the room.

The reverberation time of a room can be calculated with Sabine's law.

$$T = k\frac{V}{cA} \tag{1}$$

With the constant $k = 24\ln(10) \approx 55.3$, the volume of the reverberation room V, the speed of sound c and the effective absorption area A. Inversion of this law allows the calculation of the effective absorption area from the reverberation time.

To calculate the absorptance α of the test sample, the reverberation time before (T_1) and after (T_2) its installation in the room must be measured. From these reverberation times the effective absorption areas A_1 and A_2 can be calculated. Each effective absorption area A depends on all individual surfaces S_i of the room and their absorptances α_i. Additionally, a term for the sound absorption of air itself (m according to ISO 9613-1 [7]) must be considered.

$$A = \sum_{i=1}^{N} S_i\,\alpha_i + 4mV \tag{2}$$

The effective absorption area (A_T) of the test specimen can therefore be calculated with the following equation:

$$A_T = A_2 - A_1 = 55.3V\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - 4V(m_2 - m_1) \tag{3}$$

The absorptance of the NRD (α_{NRD}) with the surface S is then given by

$$\alpha_{NRD} = \frac{A_T}{S} \tag{4}$$

Finally, a single number rating $\mathrm{DL}_{\alpha,\mathrm{NRD}}$ can be calculated by averaging over all third-octave band values of the absorptance weighted with the third-octave band values of the standardised traffic noise spectrum (L_i) according to EN 1793-3 [8].

$$\mathrm{DL}_{\alpha,\mathrm{NRD}} = -10\log_{10}\left[1 - \frac{\sum_{i=1}^{18}\alpha_{\mathrm{NRD},i}\,10^{0.1L_i}}{\sum_{i=1}^{18}10^{0.1L_i}}\right] \tag{5}$$

2.2.2 Diffuse sound field method for testing airborne sound insulation (EN 1793-2)

The diffuse sound field measurement method for airborne sound insulation according to EN 1793-2 is based on EN ISO 10140-2 [9] and requires two adjacent reverberation rooms, the "source room" and the "receiving room". The "source room" contains one or multiple loudspeakers which generate a diffuse sound field and the "receiving room" contains one or multiple microphones. The rooms are linked by a window in which the test-specimen is placed.

The comparison of the averaged sound pressure levels in the source (L_1) and the receiving (L_2) room then yields the airborne sound insulation R of the specimen.

$$R = L_1 - L_2 + 10 \log_{10}\left(\frac{S}{A}\right) \quad (6)$$

The quantities S and A are the size of the connecting window (about 10 m^2) containing the test specimen and the effective sound absorption area in the receiving room, respectively.

The airborne sound insulation in third-octave bands can also be summarised in a single number rating DL_R by a weighted average using the third-octave band values of the standardised traffic noise spectrum L_i from EN 1793-3 [8].

$$\mathrm{DL}_R = -10 \log_{10}\left[\frac{\sum_{i=1}^{18} 10^{0.1L_i}\, 10^{-0.1R_i}}{\sum_{i=1}^{18} 10^{0.1L_i}}\right] \quad (7)$$

2.3 Direct sound field measurement methods

The direct sound field measurement methods for airborne sound insulation and sound reflection are based on the measurement of impulse responses between the loudspeaker and dedicated microphone positions. Since a loudspeaker emits a spherical wave in the first approximation, the incident sound energy on the NRD is concentrated in distinct directions. Impulse response measurement techniques (MLS, Sweeps) [10] are able to omit disturbing sound sources, hence these methods can be performed also in environments with acoustic harsh conditions, e.g. alongside roads under traffic. The most limiting requirement of the methods is sufficient dimensions of the NRD under test, to allow the removal of spurious reflections (on the ground, at the top, and on lateral edges) outside the time window used for the post-processing (signal analysis).

The directional sound field used in these measurement methods also better emulates the directional sound of traffic noise in open area, which makes the results more relevant to real-world conditions for noise barriers.

2.3.1 Direct sound field method for testing sound reflection (EN 1793-5)

The direct sound field measurement method for sound reflection according to EN 1793-5 is based on a comparison between the sound energy reflected from the NRD and the sound energy emitted towards it.

The sound is generated by a loudspeaker positioned 1.5m in front of the NRD at half of its height. The corresponding microphones are positioned in-between, in a 3x3 grid with a distance of 0.25m to the NRD and with a spacing of 0.4m to neighbouring ones. Multiple impulse response measurements are performed with this setup to average out noise from the environment.

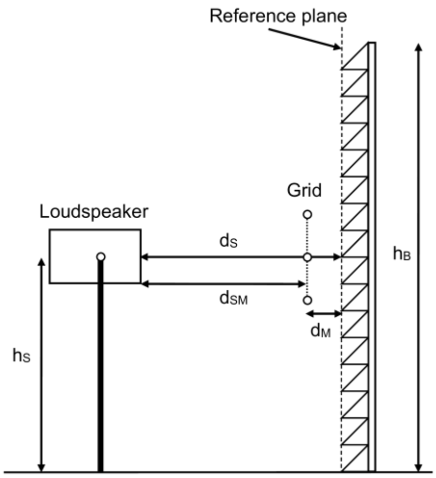

Figure 1: Setup of a direct sound field reflection measurement

The measured signal of the actual measurement comprises the impulses of the sound towards the NRD and the reflection coming back (Figure 2, left). To separate the reflected sound from the received signal of the actual measurement, an additional free-field measurement has to be performed. The subtraction of the free-field measurement from the actual measurement results in only the reflected component of the impulse response, as well as spurious reflections from the surroundings which can be removed by time-windowing (Figure 2, right).

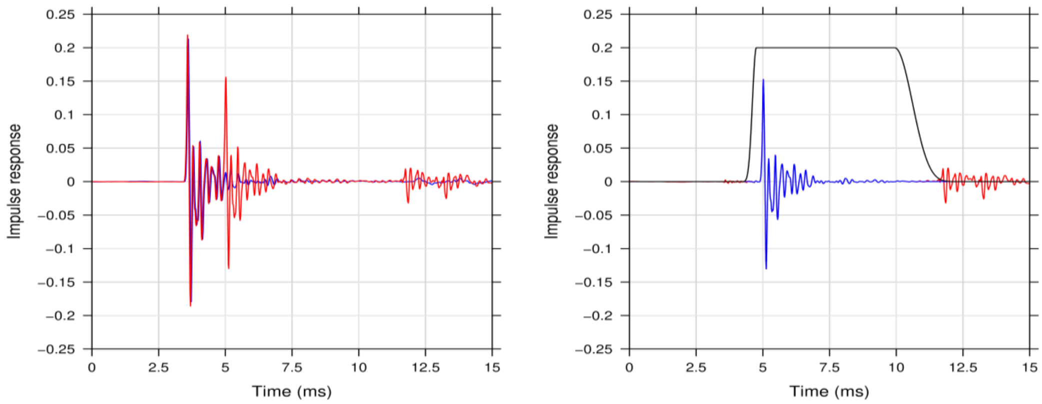

Figure 2: Impulse responses before and after subtraction and time-windowing. Left: free-field (blue) and actual (red) impulse response. Right: reflected component before (red) and after (blue) time windowing.

When comparing the energy content of the reflected and the impinging sound several influences have to be considered. The main one is the longer propagation path of the reflected sound, which causes a decrease of the sound pressure approximately equal to $1/r$ (for point sources), which is corrected by the factor $c_{\mathrm{geo},k}$. Additionally, correction factors for the directivity of the loudspeaker ($c_{\mathrm{dir},k}(\Delta f_j)$) and a possible change of the gain settings ($c_{\mathrm{gain},k}(\Delta f_g)$) between the actual and the free-field measurements are taken into account.

With these correction factors, the reflectance in third-octave bands (RI_j), can be calculated as follows:

$$RI_j = \frac{1}{n_j} \sum_{k=1}^{n_j} \left[\frac{\int_{\Delta f_j} \left| F[h_{r,k}(t) w_{r,k}(t)] \right|^2 \mathrm{d}f}{\int_{\Delta f_j} \left| F[h_{i,k}(t) w_{i,k}(t)] \right|^2 \mathrm{d}f} \; c_{\mathrm{geo},k} \; c_{\mathrm{dir},k}(\Delta f_j) \; c_{\mathrm{gain},k}(\Delta f_g) \right] \quad (8)$$

Here, F denotes the Fourier transform, $h_{r,k}(t)$ and $h_{i,k}(t)$ are the reflected and the incident components of the measured impulse responses, $w_{r,k}(t)$ and $w_{r,k}(t)$ are window functions (specific windows, having Blackman-Harris leading and trailing edges and a flat central part are used), n is the number of microphones and j is the index of the third-octave bands.

It has to be noted that the currently valid EN 1793-5:2016+AC:2018, also called QUIESST method after the project in which it was developed, is the successor of the former CEN/TS 1793-5 also known as Adrienne method, which was similar but not identical. The main differences between the methods are the microphone positions and the handling of the correction factors. While the centre microphone position was identical, instead of using a measurement grid, the centre microphone was attached to the loudspeaker with a cantilever and the whole microphone – loudspeaker construction was rotated around the loudspeaker position in 10° increments, in the horizontal and vertical plane, from -40° to +40°, for 17 independent microphone positions in total. Additionally, instead of the correction factors mentioned above, a time multiplication was performed which counteracts the approximate $1/r$ decline in sound pressure.

$$RI_j = \frac{1}{n_j}\sum_{k=1}^{n_j}\left[\frac{\int_{\Delta f_j}\left|F[t\cdot h_{r,k}(t)w_{r,k}(t)]\right|^2 \mathrm{d}f}{\int_{\Delta f_j}\left|F[th_{i,k}(t)w_{i,k}(t)]\right|^2 \mathrm{d}f}\right] \tag{9}$$

For flat and homogenous noise barriers a very good correlation could be found between the QUIESST and the Adrienne method [11], where the values of the QUIESST method were found to be slightly smaller.

Similar to the diffuse sound field methods, the third-octave band values are then averaged and weighted according to the standardised traffic noise spectrum (L_i) in EN 1793-3, to get a single number rating for the NRD.

$$\mathrm{DL}_{RI} = -10\log_{10}\left[\frac{\sum_{i=1}^{18}\mathrm{RI}_i\,10^{0.1L_i}}{\sum_{i=1}^{18}10^{0.1L_i}}\right] \tag{10}$$

As RI_j, as well as α_{NRD} , is defined as an energy ratio, its meaningful range for a flat homogeneous surface is between 0 and 1. Nevertheless, for non-flat surfaces the RI_j can take values larger than 1 at some frequencies, due to focusing and interferential effects. By contrast, for highly absorbing samples, α_{NRD} can take values larger than 1, due to the approximations underlaying the reverberation room method. Special care must be taken, as these two quantities are defined in a complementary way. A highly reflective NRD (e.g. transparent panels) will have an α_{NRD} close to 0 and a RI_j close to 1. On the other hand, a highly absorptive NRD should reach an α_{NRD} close to 1 and a RI_j close to 0.

Nevertheless, for the calculated single-number ratings $\mathrm{DL}_{\alpha,\mathrm{NRD}}$ and DL_{RI} a higher value denotes a higher sound absorption, the property which is generally desired for a NRD.

2.3.2 Direct sound field method for testing airborne sound insulation (EN 1793-6)

The measurement method for airborne sound insulation according to EN 1793-6 is based on a comparison between the sound energy arriving at the microphone positions with and without the NRD. The setup is comparable to the direct sound field measurement method for sound reflection, using a similar source position and the same microphone grid, but the grid is positioned on the opposite side of the NRD. Since the distance between the NRD and the grid is the same as for testing sound reflection (0.25m), the absolute distance between the source and the microphones is now dependent on the thickness of the NRD. This has to be taken into account when performing the measurement under free-field conditions.

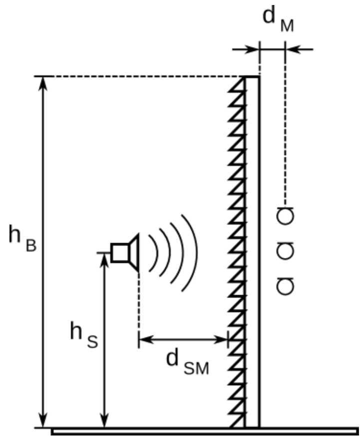

Figure 3: Setup of a direct sound field measurement of airborne sound insulation

The measured impulse response now consists of two major components: the first one is the sound that travelled through the NRD and the second is the sound that e.g. travelled over or around the NRD. To separate them and to get rid of spurious reflections from the ground, time windowing is used.

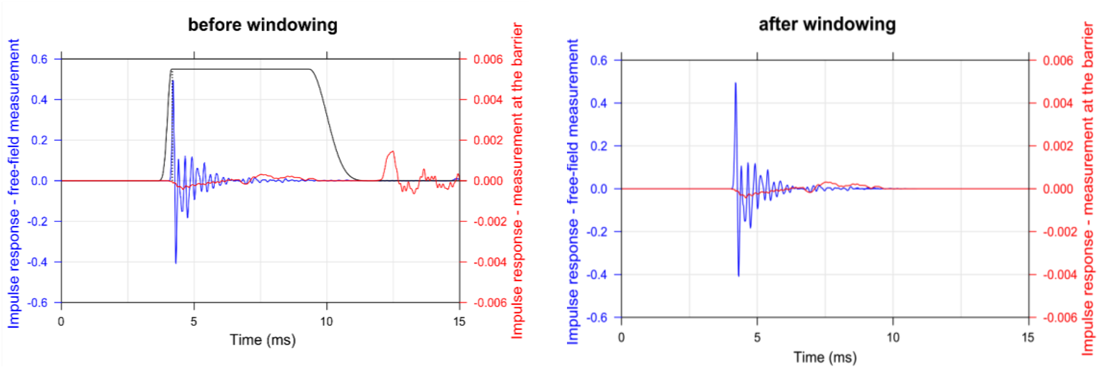

Figure 4: Impulse responses before (left) and after (right) time windowing; the blue curve depicts the free-field, the red curve the actual measurement at the NRD

The comparison between the sound energy of the direct component from the free-field measurement and the sound energy transmitted through the barrier from the measurement at the NRD is then performed similar to the reflection measurement method.

$$\mathrm{SI}_j = -10\ \log_{10}\left[\frac{1}{n}\sum_{k=1}^{n}\frac{\int_{\Delta f_j}\left|F[h_{t,k}(t)w_{r,k}(t)]\right|^2 \mathrm{d}f}{\int_{\Delta f_j}\left|F[h_{i,k}(t)w_{i,k}(t)]\right|^2 \mathrm{d}f}\right] \tag{11}$$

The resulting SI_j are then summarised as a single number rating by a weighted average with the standardised traffic noise spectrum (L_i) according to EN 1793-3.

$$\mathrm{DL_{SI}} = -10\log_{10}\left[\frac{\sum_{i=1}^{18} 10^{0.1L_i}\, 10^{-0.1\mathrm{SI}_i}}{\sum_{i=1}^{18} 10^{0.1L_i}}\right] \tag{12}$$

3 Relation between the measurement methods

As the two kind of methods (diffuse and direct sound field) coexist, notwithstanding the fact that their correspond to different physics, it is interesting to investigate up to what extent they can be compared: this section highlights the main similarities and differences between the methods if pairwise comparisons are made. In the following subsections the state of the art of the relation between the measurement methods are presented.

Scope of application

The scope of application for each measurement method depends on the relevant sound field. The diffuse sound field measurement methods should be applied to describe the NRDs intrinsic properties if it is to be installed in a reverberating environment, e.g., tunnels, otherwise the direct sound field measurement methods should be used. In the respective standards reverberant conditions are defined based on geometric considerations. Figure 5 shows typical examples of where reverberant conditions of noise reducing devices alongside roads can occur, as they are given in the standards.

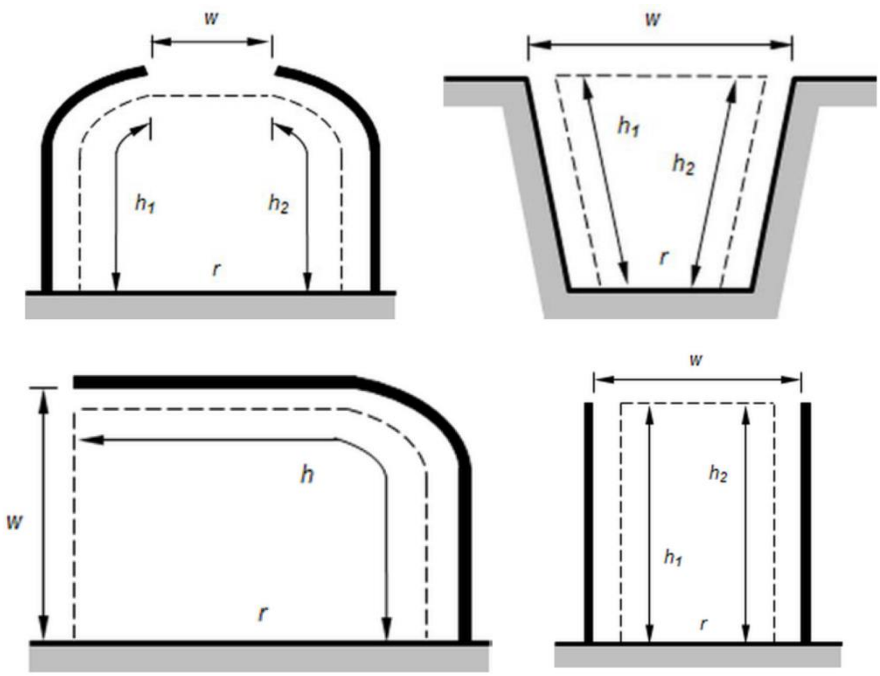

Figure 5: In natural reading order; Partial cover on both sides of the road; Deep trench envelope; Partial cover on one side of the road with $h = 2 * h1$; Tall barriers or buildings; from [3], [4]

An environment is considered reverberating, if $w/e \leq 0.25$, where $e = (w + h1 + h2)$. In other words, the non-enclosed length (w) must be at maximum 1/4 times the sum of the enclosing envelope (e, h_1 and h_2) without the road surface r. For the typical case where the two enclosing heights are equal, Figure 6 shows the relationship between the open width and the height of the noise reducing device for assessing reverberant conditions. It can be easily seen that even for a very small width of 5 meters (viz. less than two lanes), the noise reducing devices can be up to 7.5 meters high to be in a non-reverberant condition. Thus, for the most common conditions alongside roads, only the direct sound field methods according to EN 1793-5 and EN 1793-6 are applicable. Additionally, these methods have the advantage that they can assess the properties of already installed NRDs, which makes them suitable for the evaluation of recently installed NRDs, based on their predefined specification, and for the long-term monitoring and evaluation of NRDs.

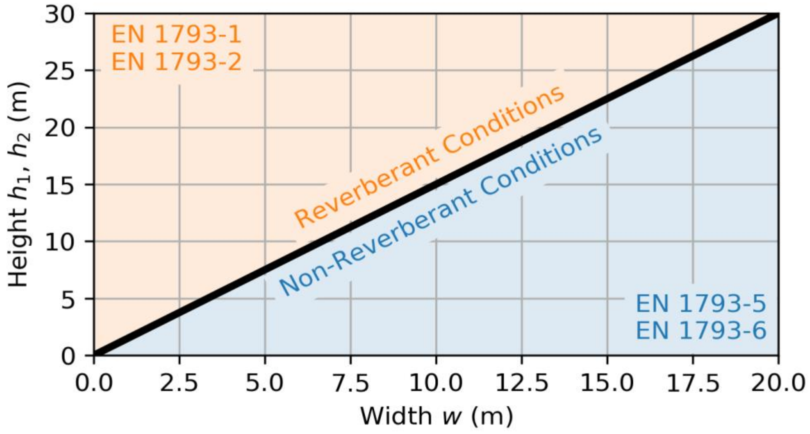

Figure 6: The boundary of reverberant conditions, separating the areas of application of the diffuse and direct sound field measurement method, based on the width and height of the enveloping geometry. For simplicity $h_1 = h_2$ is assumed.

Type of the sound field: "diffuse" versus "direct"

The diffuse sound field methods, which are carried-out in reverberant rooms, give an averaged response of the performances at all angles of incidences and over the whole sample. In contrast, the direct sound field methods incorporate only incident angles close to normal incidences at specific points of the sample.

Therefore, if the intrinsic property of airborne sound insulation is measured both with the diffuse sound field method and with the direct sound field method, similar but not identical physical quantities are measured.

The importance of the angle of incidence is even bigger for sound absorption: that will lead to bigger differences between diffuse and direct sound field measurement.

Artificial boundary conditions for diffuse sound field method

To highlight another difference between the measurement methods, consider the following equation for the ratios of the absorbed (α), the reflected (ρ) and the transmitted (τ) sound energy to the incident sound energy.

$$\alpha + \rho + \tau = 1 \tag{13}$$

Since energy is never lost, their sum must always be 1. In noise protection, only the reflected and the transmitted sound are relevant for the environment. The direct sound field measurement methods determine these quantities directly, while the diffuse sound field measurement methods determine τ directly, but not ρ.

In the sound absorption measurement method under diffuse sound field conditions the transmission path artificially set to zero as the transmitted energy is reflected at the floor and is remaining in the reverberant room after a second transmission through the barrier. The reflected sound is assumed and calculated with $\rho = 1 - \alpha$ (compare also Eq. (5)), see left part of Figure 7. In contrast to this, in the direct sound field method, the ratio of the reflected sound energy to the incident sound energy ρ is measured directly, see right part of Figure 7. As the test setup artificially adds energy to the reflected sound for the diffuse sound field Figure 1method that would normally be transmitted, it is only a valid approximation for NRD where the energy of the transmitted sound is much lower than the reflected energy. Usually, this is a valid simplification to make, but for the extreme example of an acoustically almost fully transparent NRD, the diffuse sound field methods would give an inconsistent picture of the properties of the NRD, with almost full transmission and full reflection at the same time.

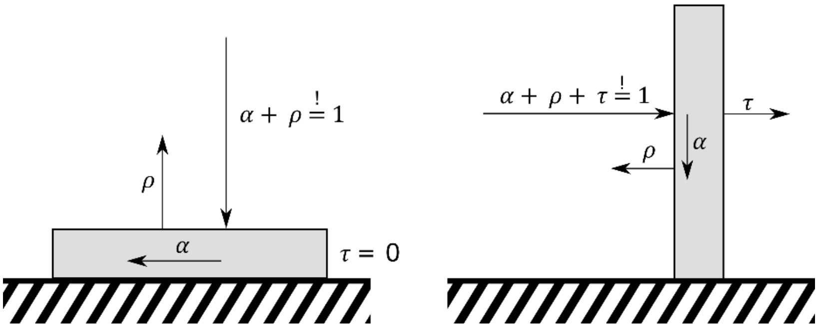

Figure 7: Relationship between the ratios of the absorbed (α), the reflected (ρ) and the transmitted (τ) sound energy for the measurement set-ups of the diffuse sound field method for measuring sound absorption (left) and the direct sound field method for sound reflection (and airborne sound insulation) (right).

Condition of the test sample

As the diffuse sound field methods can only be performed inside of reverberation rooms, always distinct test samples are used, which are carefully prepared and mounted inside the test chambers. On the other hand, the direct sound field measurement methods have much lower demands on the acoustic environment during the test. If the NRD is mounted specifically for testing (e.g. inside a laboratory hall or outside), then approximately the same diligence of installation of the test sample as for the diffuse sound field methods can be assumed. Nevertheless, as one of the major advantages of the direct sound field methods is the possibility to test alongside roads under real-world conditions, the test sample might not be in perfect laboratory condition due to mounting errors, wear or contamination. Moreover, for the diffuse sound field method for sound absorption, the sample has free edges that give rise to the so-called “edge effect” artificially increasing the measured sound absorption (see [12]).

Facilities used, and conditions for a measurement

The methods for measurements under diffuse sound field conditions are depending on reverberation rooms, where it is possible to generate a nearly diffuse sound field. The diffuse sound field measurement method for airborne sound insulation even requires two reverberation rooms that are linked by a window for the test sample. When a strongly absorbing sample is placed in a reverberation room, the sound field is not diffuse any longer, because the sound intensity vectors tend to flow towards the absorbing sample. This is one of the causes of the systematic overestimation of sound absorption with the diffuse sound field method (ISO 354).

For direct sound field measurements, the loudspeaker has to be capable of generating enough sound power to reliably detect the sound transmitted through a noise barrier over unwanted noise. This requirement is released considerably using deterministic signals, like MLS or ESS, which can get a very high signal-to-noise ratio even with a relatively low sound pressure level. Additionally, the direct sound field methods require a noise barrier that is high enough to enable time windowing for the removal of spurious reflections from the measured signal. When the noise barrier height is progressively lowered below 4m a progressive reduction of the valid frequency range applies (see EN 1793-5 and EN 1793-6). If measurements are taken outside with the direct sound field methods, naturally additional requirements regarding the environmental conditions for temperature, wind and humidity must be considered.

3.1 *Relation between diffuse sound field and direct sound field methods concerning sound absorption/reflection*

The correlation between the measurement method for sound reflection under a direct sound field and the measurement method for sound absorption under a diffuse sound field is generally low [13], [14].

Figure 8, taken from QUIESST report [14], shows a linear regression for the correlation of the single number ratings of the diffuse sound field absorption measurement method (horizontal) and the direct sound field reflection measurement method (vertical), for all NRDs in the QUIESST database, for which both measurement results exist.

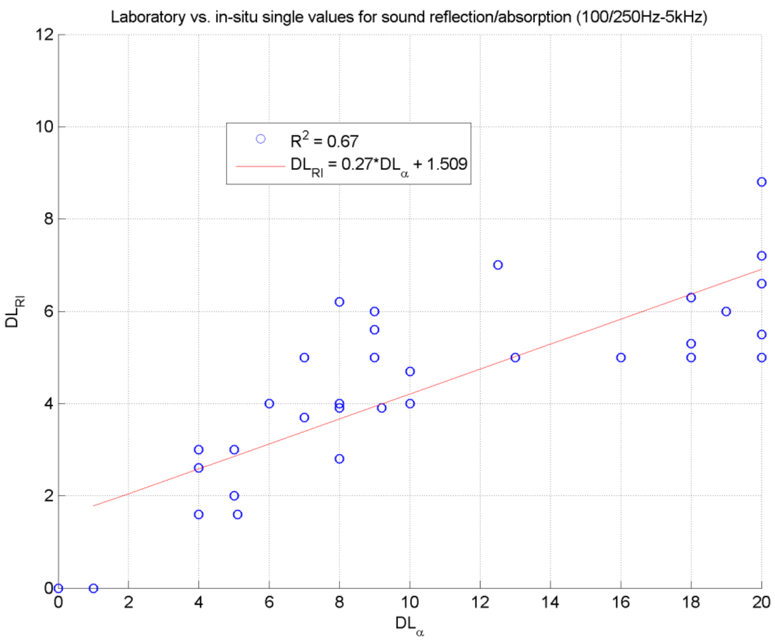

Figure 8: Correlation between the single-number ratings in dB of the diffuse sound field method for sound absorption (horizontal) and the direct sound field method for sound reflection (vertical) for all NRDs in the QUIESST database for which both measurement results exist; from [14].

It can be seen that the correlation is relatively poor and while it is slightly better when only looking at NRD consisting of concrete ($\mathrm{DL_{RI}} = 0.35\mathrm{DL_{\alpha}} - 0.86$ with $R^2 = 0.73$), it is even worse when only looking at metal barriers ($\mathrm{DL_{RI}} = 0.20\mathrm{DL_{\alpha}} - 2.27$ with $R^2 = 0.47$). The number of NRDs made of timber in the QUIESST database, for which measurement results of both methods are available, is only 4 which makes a linear regression not meaningful.

In [15] a theoretical approach for the relationship between the single number-ratings for sound absorption under diffuse sound field conditions (DL_{α}) and sound reflection under direct sound field conditions (DL'_{RI}) is presented, where the absorption coefficient of the diffuse sound field is derived by integration of the absorption coefficient of a plane wave over the hemisphere. For calculating the DL'_{RI} only the centre microphone according to CEN/TS 1793-5 is used. The result of both theoretical calculations is a good linear correlation (see Figure 9). For values not too high (up to 6 or 7 dB of the single-number rating for sound reflection DL'_{RI}) the theoretical estimation is

$$DL'_{RI} \approx \frac{2}{3} DL_{\alpha}. \qquad (14)$$

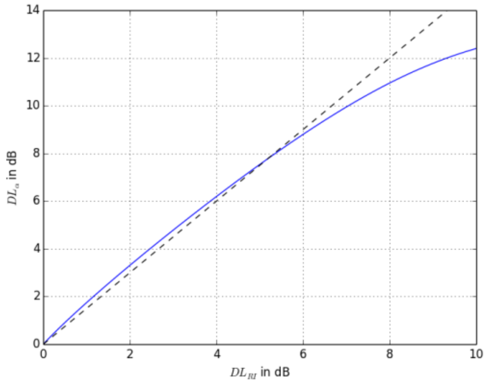

Figure 9: Theoretical curve for single number rating of absorption coefficient DL_α against single-number rating of sound reflection DL'_{RI} (blue) and a linear slope of 3/2 (dashed); from [15]

In comparison to Figure 8 this simplified relationship only holds for NRDs with a low absorption, and even then mainly overestimates the DL'_{RI}. Beside the different correction method for geometric divergence in CEN/TS 1793-5, the omission of the non-perpendicular microphone positions is a significant deviation to the measurement results presented in Figure 8.

This means, that there is currently no accurate way of converting measurement results to make useful comparisons. The reasons for that are manifold, below are some of the probable causes listed for this disparity.

Uncertainties measuring sound absorption under diffuse sound field conditions

One main cause for the poor correlation is the generally low repeatability of the diffuse sound field method, as described in [16], where a meta-analysis of several round-robin tests was performed. Especially the almost linear relationship between the standard deviation and the absorptance of the test sample, which moreover varies strongly by frequency, could cause sufficient variations to cause a low correlation to the direct sound field method. One reason for this is the curvature of the decay curve. For low frequencies (below the Schröder frequency), where the mode density is low, this curvature is caused by the different decay of axial, tangential and diagonal modes. For high frequencies the uneven absorption, which is usually the case for diffuse sound field absorption measurements where the sample is mounted on the ground, also causes a curvature. Since reverberation times are usually calculated with a linear regression, a curvature resp. nonlinearity of the decay curve can negatively influence the accuracy and repeatability of the method. [17] presents this curvature for multiple measurements and shows that it is even dependent on the placement and number of diffusors used in the reverberation room. To mitigate this problem, the use of a multi-exponential fit instead of a conventional linear regression is suggested.

Limitation of $\mathrm{DL}_{\alpha,\mathrm{NRD}}$ to 20 dB

Another cause for the poor correlation could be the artificial limitation of the $\mathrm{DL}_{\alpha,\mathrm{NRD}}$ to a maximum value of 20dB. This limitation is performed in order to ensure the argument of the logarithm being positive, even when a slight measurement error would make it close to zero or even negative. In Figure 8 it can be seen that several measurement results have a DL_α of exactly 20dB, while those same NRD have different DL_{RI} values. In combination with the faulty energy comparison as described after Equation 1, this has the effect that the diffuse sound field method might be inaccurate or at least not comparable to the direct sound field methods for very high values of $\mathrm{DL}_{\alpha,\mathrm{NRD}}$. This, of course, is a problem when calculating a linear regression.

Non-linearity of single-number rating calculation

Additionally, the non-linearity of the logarithm for calculating the single-number ratings can cause a poor correlation between the methods. Figure 10 compares the measured third-octave band spectra of the direct sound field method (old method according to CENT/TS 1793-5) with $1-\alpha$ of the diffuse sound field method for seven different NRD.

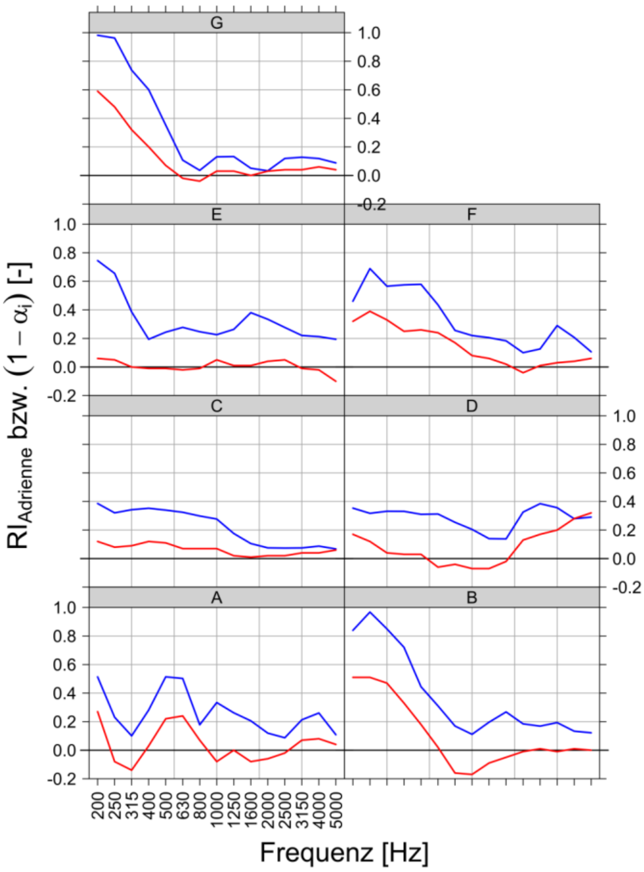

Figure 10: Spectra of seven different noise barriers measured with the CEN/TS 1793-5 (Adrienne) method (blue) and the diffuse sound field absorption method (red); from [11]

It is apparent that most of the spectra have a very similar shape, although they show a (possibly frequency-dependent) offset. An offset alone, even if the shape of the spectra would otherwise be identical, is enough to prevent a linear relationship between the results because of the non-linearity of the logarithm. Additionally, when looking at Figure 8, it is apparent that a non-linear log-shaped regression might fit the data more accurately. Although a correlation with a multi-variate non-linear model might be found for these seven NRD shown in Figure 10, the correlation would only be valid for these noise barriers, which are all considered to be flat and homogenous according to [3].

Interference patterns for highly structured surfaces under direct sound field conditions

As mentioned before, the direct sound field method uses only one loudspeaker position, which essentially approximates a single point source (just one wave front) instead of the diffuse sound (infinite point sources and wave front). For direct sound field conditions, this can cause strong interference patterns for certain NRD shapes, and therefore an under- or overestimation of the reflected sound, which might be smoothened by the integration over all angles of the diffuse sound field. For example, an NRD shape that focuses multiple reflected waves at one microphone position can even cause a sound reflection index larger than one. This effect is technically not a measurement error since it is a repeatable property of the method itself, but nevertheless it can cause over- or underestimations of the total reflected sound energy. This effect may be tackled by an increased number of microphone and/or reference positions.

Most of the mentioned reasons for the disparity between the direct sound field and the diffuse sound field method are based on possible inaccuracies of the diffuse sound field method, but there are also some physical differences between the measurement methods which make a comparison between them very difficult. Due to the mentioned differences a precise calculation from the results from one method to the other is not feasible, especially as measurement uncertainties must be considered. Nevertheless, road operators, civil engineers and the NRD industry itself are used to the range of values of the diffuse sound field method for sound absorption. As the range of values for the direct sound field for sound reflection differ significantly, Task 2.2 shall examine the relationship between these two measurement methods more closely as to support road operators and civil engineers in choosing appropriate minimum requirement values for NRDs for the direct sound field method for sound reflection, as it is the more precise and practical method to use for NRDs alongside roads.

3.2 Relation between diffuse sound field and direct sound field methods concerning airborne sound insulation

Generally, the results of the diffuse sound field measurement method and the direct sound field measurement method for airborne sound insulation have a good correlation, although, depending on the type of the NRD, the results can have quite a bit of an offset.

Figure 11 from [14], shows a linear regression between the single number ratings of the diffuse sound field method (horizontal axis) and the direct sound field method (vertical axis), for all NRDs in the QUIESST database for which both measurement results exist. It can be seen that the correlation coefficient ($R^2 = 0.954$) is very high, which indicates a very good accordance between the methods overall. However, when looking at different types of NRD separately, the parameters of the linear regression are not as clear. On page 60 of [14] the regression parameters and the correlation coefficients for multiple types of NRD consisting of concrete metal and timber are shown, see Table 1. While all results have a decent correlation coefficient ($R^2 \geq 0.52$), the parameters of the linear regression are clearly different. One caveat of these results is the relatively low number of NRDs in each category (e.g. only 7 for timber), so the statistics might not be very robust. Nevertheless, they show that there possibly are additional physical effects at play, whose magnitude depend on the material of the NRD. In the following, a few reasons for this disparity are listed.

Table 1: Linear correlation models between the single-number ratings for airborne sound insulation under diffuse sound field conditions ($\mathrm{DL_R}$) and direct sound field conditions ($\mathrm{DL_{SI}}$), [14]

NRD MATERIAL	LINEAR REGRESSION	R^2
CONCRETE	$\mathrm{DL_{SI}} = 1.33\mathrm{DL_R} - 7.53$	0.7
METAL	$\mathrm{DL_{SI}} = 0.75\mathrm{DL_R} - 10.38$	0.52
TIMBER	$\mathrm{DL_{SI}} = 1.04\mathrm{DL_R} - 7.38$	0.78

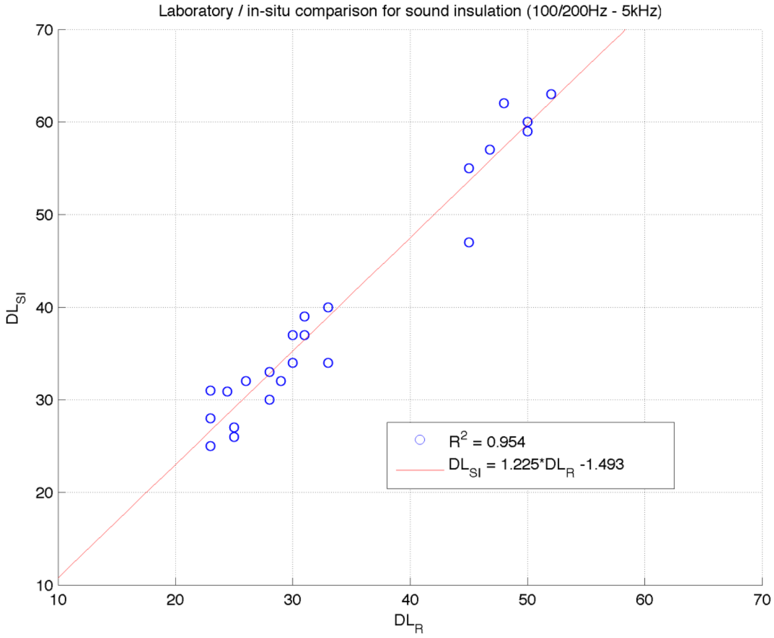

Figure 11: Correlation between the single-number ratings in dB of the diffuse sound field (horizontal) and the direct sound field (vertical) method for airborne sound insulation for all NRD in the QUIESST database for which both measurement results exist; from [14]

Averaging of acoustic element and post measurement

The sensitivity to installation errors and spots of locally lower insulation is different, since the direct sound field method includes separate measurements at the posts, which are especially susceptible to mounting errors on site, whereas the diffuse sound field method always assesses the whole sample consisting of acoustic element and one post, carefully mounted and sealed in the laboratory. Using the energetic mean of the acoustic element and the post measurement for the global single-number rating of the direct sound field method, this value might not properly reflect the actual average over the whole NRD, as measured in the diffuse sound field method.

Artificial set-up in reverberation room

The different boundary conditions regarding the fixation of the NRD elements can have an influence on the vibration modes and therefore the transmitted sound. In the measurement method under diffuse sound field conditions the sample is clamped at all four edges inside the reverberation room, while the noise barrier is clamped only at the two lateral edges, blocked by the gravity on the bottom edge and free on the top edge when measuring under direct sound field conditions.

Maximum of sound transmission at coincidence frequency

Sound impinging under oblique angles can cause a maximum of sound transmission at the coincidence frequency, where the wavelength in air projected on the barrier and the wavelength in the material of the NRD are the same. This has been shown in [18], where the measurement results of both methods are compared for noise barriers consisting of thin acrylic sheets.

4 Conclusions

In this report, the state of the art regarding the measurement of intrinsic properties of NRD was presented. The main focus was on the methods for the measurement of sound absorption and airborne sound insulation under a diffuse sound field, as well as on the measurement methods for sound reflection and airborne sound insulation under a direct sound field. A brief summary of each measurement method was presented, before their differences were discussed in more detail.

Apart from the obvious different scope of application, the differences between the measurement procedures can be traced back to the used sound field (diffuse vs. direct), condition of the test sample (localized defects have different consequences) and the necessary facilities to perform the measurements (reverberation chambers vs portable loudspeaker/microphones).

These differences cause also a disparity in the measurement results, and while the results from the two different airborne sound insulation methods correlate quite well (compare Figure 11), the diffuse sound field absorption method and the direct sound field reflection method do not (compare Figure 8).

Several influencing factors were presented, where the main contributing factor is the difference in measuring the reflected component for specific (direct sound field) angles to artificially obtaining the reflected component by measuring the absorbed sound energy for all angles (diffuse sound field). Additional influences regarding the diffuse sound field absorption method are probably its bad repeatability overall [16], the clipping of the results for high absorptances at $\mathrm{DL}_{\alpha} = 20dB$ and the blockage of transmitted sound energy. Additionally, the logarithms used in the equations for the $\mathrm{DL}_{\mathrm{RI}}$ and the DL_{α} cause a non-linear relationship between the results for offset but otherwise similar spectra and therefore a poor correlation.

Finally, as an outlook, these differences will be analysed in more detail in Task 2.2 of this project.

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