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Influence of the reference position on the measured sound reflection for flat homogenous noise barriers

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Summary
The number of measured reference positions for the in situ measurement of the sound reflection under direct sound field conditions according to EN 1793-5 for road traffic noise reducing devices (e.g. noise barriers) depends on the surface structure of the device under test. In the current version of the standard a noise reducing device is considered flat, if the depth of its surface structure is smaller than 85 mm and therefore only one reference position of the measurement grid is required. According to this definition, nearly all installed noise barriers along Austrian motorways are considered flat and should be measured with one reference position only. Nevertheless, the statistical analysis of over 50 sound reflection measurements of typically used flat noise barriers shows partly significant differences for the obtained single and third-band values for different reference positions. These deviations may occur for definite surface structures (e.g. concrete wood noise barriers) as well as for planar surface structures like perforated metal plates (aluminum cassette noise barriers). Therefore, to reduce the measurement uncertainty for the repeatability of the measurement procedure according to EN 1793-5 it may be advisable to use more than one reference position for flat homogeneous noise barriers.

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1. Introduction

The measurement method for the sound reflection properties of noise reducing devices (noise barriers) under direct sound field conditions is described in EN 1793-5 [1]. Its measured quantity is the reflection index RI_j which is basically the ratio of the power of the reflected component to the power of the incident component in one-third octave bands for nine incident angles, which are typically measured with a grid of nine microphones at specified locations. Each set of nine microphone positions is relatively fixed to one source (loudspeaker) position, which defines the reference position.

The method is able to investigate flat and non flat noise barriers, whereas a specific definition is given in the standard. A noise barrier is considered *flat* and *homogeneous*, if the depth of its surface structure is smaller than 85 mm and its surface is constituted by one material. According to this definition the majority of all installed noise barriers in Austria are considered flat and homogeneous and should be measured with one reference position in the horizontal and vertical center of the noise barrier. If the surface structure depth is at least 85 mm or the noise barrier is constituted of more than one material, where each portion of material has a minimum width of least 85 mm the noise barrier is considered non-flat or non-homogeneous and additional reference positions are necessary. For homogeneous and non-flat samples one reference position is in front of the most protruding part of the surface, one reference position is in front of the least protruding part of the surface and the third reference position is between the first two. The reflection index is calculated as average over all reference and microphone positions.

An influence of the reference position on the measured sound reflection for flat homogenous noise barriers according to EN 1793-5 would be a contributing factor to the repeatability and reproducibilty measurement uncertainty of the measurement procedure. At the moment the expanded uncertainty for the single number rating of the reflection index DL_{RI} calculated with the upper bound of the reproducibility is 1.62 dB [2].

During various measurements of the reflection index we found significant differences between the reference positions for *flat* noise barriers. As the effort for an additional measurement position is minimal in comparison to the whole procedure, additional reference positions are recorded, when reflection measurements are performed by the institute. In this paper we examine the influence of the reference position in relation to the surface structure for 58 different reflection index measurements.

2. Measurement Data

The dataset used for the analysis consists of 58 measurements of the sound reflection properties of noise barriers according to EN 1793-5. 33 measurements were performed on aluminium cassette noise barriers with a steel supporting structure (SM), 21 measurements were performed on wood-fibre concrete noise barriers with a steel supporting structure (SC) and 4 measurements were performend on transparent plexi-glass noise barriers with a steel support structure (SG)[1]. In this total 58 measurements 19 different types of noise barriers are measured, where 24 measurements were performed on one specific aluminium cassette noise barrier type. Additionally measurements of the same type were also performed on five different concrete noise barriers with two times two, two times three and one time five repetitions. All other measurements were performed on individual noise barrier types.

2.1. Surface Structure

For 56 noise barriers the surface structure is considered to be homogenous according to EN 1793-5, two of the transparent noise barriers are non-flat and inhomogenous in one direction and can therefore be considered with a small roughness in the QUIESST database naming scheme [3]. All noise barriers can be considered as flat shaped and multi-layered with vertical inclination. Therefore, according to EN 1793-5 only two of the noise barriers must be measured with more than one reference position. Nevertheless, for all measurements multiple reference positions have been recorded. For the 58 measurements a total of 144 reference positions are available, so on average 2.48 reference positions are used per noise barrier measurement. 144 reference positions multiplied by 9 microphone positions equals 1296 impulse responses, on which the analysis is based on.

Figure 1 depicts the surface structure dimensions for the whole data set separated for the noise barrier material. The structure width is the spatial period length of the most relevant periodicity in the surface structure. Typically, two reference positions are half structure width apart. For aluminium cassettes (SM) the structure width is the height of the single elements. The structure depth is the distance between

[1] For a detailed description of the used abbrevations see [3].

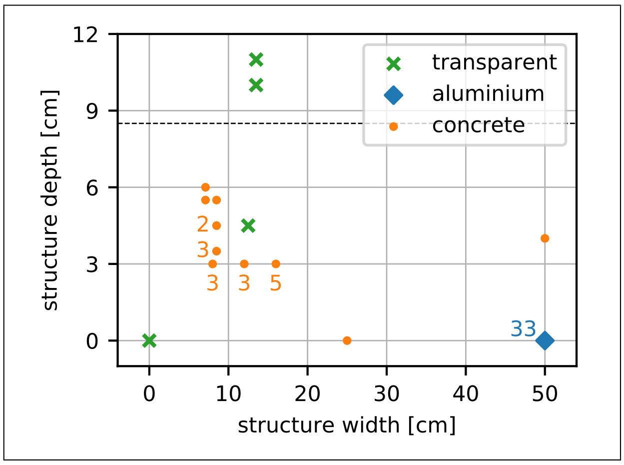

Figure 1. Surface structure dimensions in the data set. Each marker represents a measured structure geometry, multiple measurements of the same structure dimensions are additionally marked with the numeric annotations. The dashed line depicts the border for a *flat* noise reducing device according to EN 1793-5.

the outer-most point of the noise barrier (i.d. reference plane for the measurement) to the inner-most point. Gaps in the surface structure with a width under 0.5 cm are not considered. Also, for aluminium cassette noise barriers the perforated metal plates are considered as acoustically relevant and define therefore the reference plane for the measurement. Therefore, the structure depth is zero. Concrete noise barriers typically have a small but distinct structure with a structure depth between 3 and 6 cm in this data set and a structure width between 7 and 16 cm. One concrete noise barrier consisted of a structure depth of 4 cm but a structure width of 50 cm. As a repeatable dependency between the reference positions to the reflection properties could be found for this type a detailed analysis if given in section 4.2.

2.2. Location of the Reference Positions

Figure 2 shows the distribution of the location of the reference positions in the data set in reference to the center of the measured noise barrier. For nearly all measured noise barrier one reference position is located in the center (i.d. origin in the graph). For the 33 aluminium cassette measurements one additional reference position 25 centimeters above the center is used. If only one reference position is used for a 4 m aluminium cassette noise barrier consisting of eight elements, the three vertically centered microphone positions 4, 5 an 6 are in front of the gap between two elements. As this position is most likely not most relevant for the sound reflection the other reference position is additionally measured.[2] For the concrete noise barriers reference positions are chosen as for a non flat

[2] For an insulation measurement the gap between two elements is more relevant.

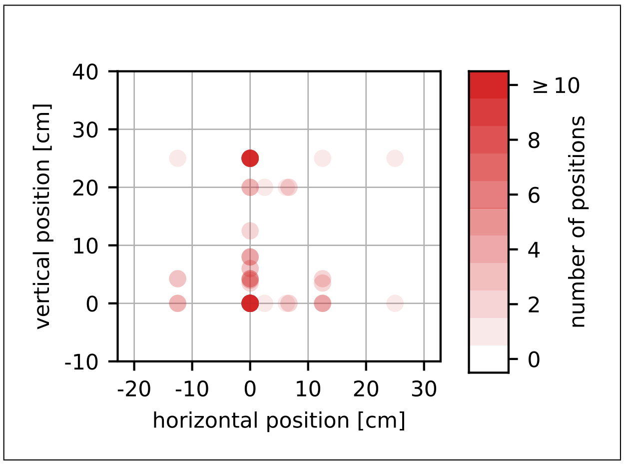

Figure 2. Distribution of the location of the reference positions in the dataset. The origin is located at the horizontal and vertical center of the noise barrier.

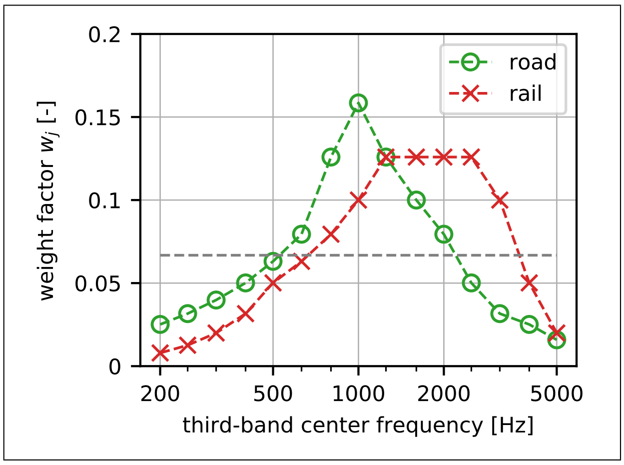

Figure 3. Linear weighting factors of the road traffic noise spectrum (green) and the railway noise spectrum (red). The grey dashed line is the linear average of the weighting factors.

or non-homogeneous noise barrier in one direction. All reference positions are far less away from the origin than the distance between two microphone positions (40 cm).

2.3. Data Preparation

The measured reference positions have been processed according to EN 1793-5 with a temporal Adrienne window with a total length of 6.0 ms, the lowest usable third-octave frequency band is also set accordingly to the measured height. The analysis in this paper is based on the averaged reflection index over all microphone positions for one reference position for each measurement. The single-number rating of sound reflection DL_{RI} can be calculated from the reflection index with

$$DL_{\mathrm{RI}} = -10\log_{10}\left[\frac{\sum_{j=m}^{18} RI_j \cdot 10^{0.1L_j}}{\sum_{j=m}^{18} 10^{0.1L_j}}\right] \qquad (1)$$

according to EN 1793-5 with the traffic noise spectrum L_j according to EN 1793-3. j is the index for the third-octave band. RI_j can either be the average over the microphone positions only to get the DL_{RI} of the reference position or the average over the microphone and reference positions to get the DL_{RI} of the whole measurement.

3. Global Data Analysis

In this section the qualitative and quantitative difference in the reflection index between reference positions in the whole data set is examined. As the measurement result of a single reference position can either be a single value (DL_{RI}) or multiple values (RI_j) suitable measures must be defined to assess the difference between two reference positions.

3.1. Distance Metrics

In the one dimensional case it is intuitive to use the absolute difference as suitable metric, which can be seen as distance between two points in one dimension. Therefore, for the single number ratings of the reflection index DL_{RI} a suitable metric for the difference between two measurements might be

$$\Delta_{\mathrm{DL}_{\mathrm{RI}}} = |DL_{\mathrm{RI}}^{(1)} - DL_{\mathrm{RI}}^{(2)}|. \qquad (2)$$

This single number difference $\Delta_{\mathrm{DL}_{\mathrm{RI}}}$ has a major drawback due to the averaging process in the calculation of the DL_{RI}. Two measurements with different reflection index third-band values can have the same DL_{RI}, which result in a $\Delta_{\mathrm{DL}_{\mathrm{RI}}} = 0$. Nevertheless, the similarity between two reference positions can be better analyzed with the third-octave band values of the reflection index RI_j. A more suitable measure is the weighted mean absolute difference distance d_{MAD} between two reflection index measurements $RI_j^{(1)}$ and $RI_j^{(2)}$:

$$d_{\mathrm{MAD}} = \frac{\sum_j |RI_j^{(1)} - RI_j^{(2)}| \cdot w_j}{\sum_j w_j}. \qquad (3)$$

As weighting factors the road traffic and railway noise spectra according to EN 1793-3 [4] and EN 16272-3-2 [5] respectively are used with $w_j = 10^{0.1L_j}$, where L_j are the given weighting terms in dB. The two possible weighting factor sets are shown in Figure 3. Additionally, the average of the weighting factors is shown. Therefore, for the road traffic noise spectrum the frequency range from 630 Hz to 2000 Hz is weighted above average. The term $\sum_j |RI_j^{(1)} - RI_j^{(2)}|$ can be interpreted as the L_1 distance between the multi-dimensional RI_j values.

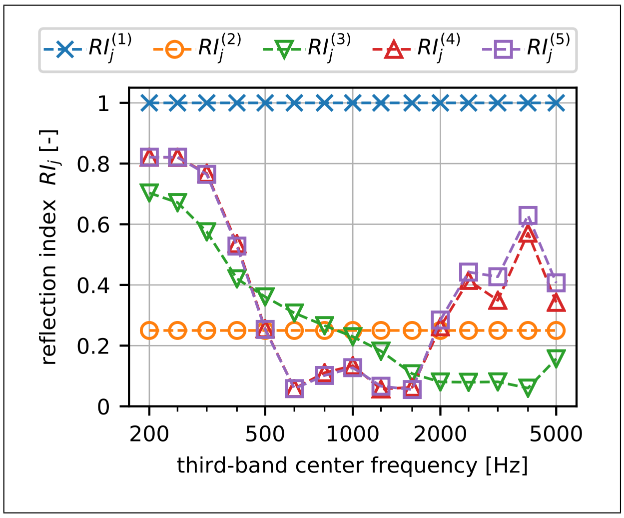

Figure 4. Five exemplary reflection index values for comparing the distance metrics. $RI_j^{(1)}$ stand for zero absorption ($DL_{\mathrm{RI}} = 0$ dB). All other curves have a $DL_{\mathrm{RI}} = 6$ dB.

The weighted mean absolute difference distance d_{MAD} is a measure for the weighted absolute difference between the reflection index values, whereas the single number difference $\Delta_{\mathrm{DL_{RI}}}$ is the absolute difference of the averaged reflection index values. From the weighted mean absolute difference distance d_{MAD} between two measurements the maximum DL_{RI} difference for the occurring deviations can be calculated with

$$D_{\mathrm{MAD}} = -10\log_{10}\left[1 - \frac{d_{\mathrm{MAD}}}{\beta}\right] \tag{4}$$

with

$$\beta = \max(10^{-0.1 DL_{\mathrm{RI}}^{(1)}}, 10^{-0.1 DL_{\mathrm{RI}}^{(2)}}). \tag{5}$$

It can be shown that $D_{\mathrm{MAD}} = \Delta_{\mathrm{DL_{RI}}}$ if the RI_j values of one measurement are all higher or all smaller than the values from the other measurement.

Table I compares these two metrics for exemplary reflection index values from Figure 4. The upper right half of the table shows the D_{MAD} for all possible combinations of the five exemplary reflection index values, the lower left half shows the $\Delta_{\mathrm{DL_{RI}}}$ for all possible combinations. The values of $RI_j^{(1)} = 1$ can be seen as baseline with a $DL_{\mathrm{RI}} = 0$ dB. $RI_j^{(2)} = 0.25$ are also artificial values as reference with a $DL_{\mathrm{RI}} = 6$ dB. $RI_j^{(3)}$ values are a measurement of an aluminium cassette noise barrier, $RI_j^{(4)}$ and $RI_j^{(5)}$ are the measurements of two close reference positions of the same concrete noise barrier. All curves except $RI_j^{(1)}$ have an approximate DL_{RI} of 6 dB and the RI_j values are all smaller than $RI_j^{(1)}$. Therefore, D_{MAD} and $\Delta_{\mathrm{DL_{RI}}}$ are equal and also close to 6 dB. From the curves 2, 3 and 4 and the resulting distance metrics in Table I it can be seen, that the simple difference between the DL_{RI} values ($\Delta_{\mathrm{DL_{RI}}}$) is not a suitable metric, whereas the weighted mean absolute difference D_{MAD} is a suitable similarity measure.

Table I. Distance metrics D_{MAD} and $\Delta_{DL_{\mathrm{RI}}}$ in dB for the reflection index values of Figure 4 weighted with the road traffic noise spectrum.

D_{MAD} / $\Delta_{DL_{\mathrm{RI}}}$	1	2	3	4	5
1		6.0	6.0	6.1	6.0
2	6.0		2.8	5.7	6.3
3	6.0	0.0		4.3	4.8
4	6.1	0.1	0.1		0.2
5	6.0	0.0	0.0	0.1	

Table II. Distance metrics d_{MAD} and d_{RMS} for the reflection index values of Figure 4. d_{MAD} is weighted with the road traffic noise spectrum.

d_{MAD} / d_{RMS}	1	2	3	4	5
1		0.75	0.75	0.75	0.749
2	0.750		0.119	0.183	0.193
3	0.745	0.215		0.158	0.167
4	0.684	0.293	0.220		0.013
5	0.671	0.303	0.244	0.032	

Another common metric is the root mean squared deviation, which can also be used here to assess the difference between two reflection index measurements. It is defined without any weighting to directly measure the deviations between the third-octave band values for the two measurements. The root mean squared deviation d_{RMS} is defined as

$$d_{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_j \left(RI_j^{(1)} - RI_j^{(2)}\right)^2}. \tag{6}$$

In comparison to the d_{MAD} the d_{RMS} will give more weight to higher deviations and less weight to smaller deviations. This can also be seen in Table II. Both measures seem to be suitable to assess the differences in the reflection index curves. The d_{RMS} can be interpreted as a (scaled) euclidean (L_2) norm of the difference of the reflection index independent from any weighting. The d_{MAD} has a similar definition to the calculation of the DL_{RI} and with the D_{MAD} a direct interpretation.

3.2. Reference Position Distance

The defined metrics can now be used to examine the difference in the reflection index measurements between the measured reference positions. The pairwise metrics are calculated between the reference positions of one sample[3]. Figure 5 shows all combinations of the

[3] e.g., for a sample with three reference positions these are three combinations (1-2, 1-3, 2-3).

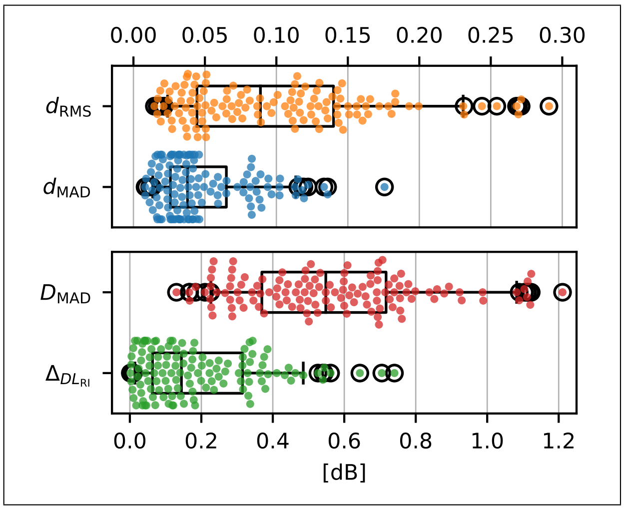

Figure 5. Distribution and boxplot for the distance metrics between the reference positions of a single measurement for all measurements with flat surface. The box shows the median and inter-quartile range, the whiskers expand to the 5 and 95 percentiles.

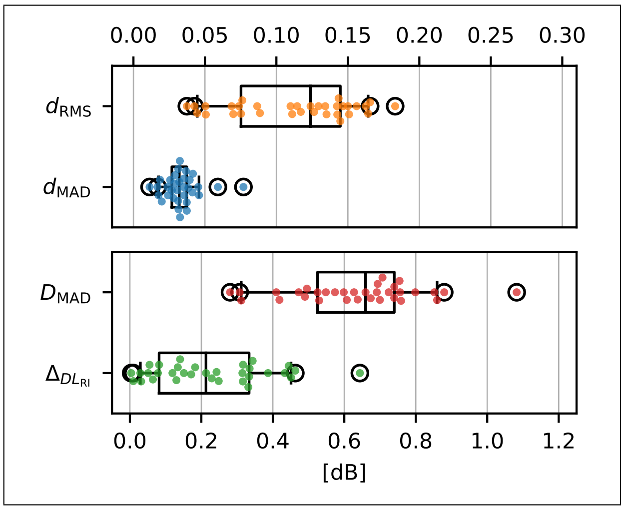

Figure 6. Distribution and box-plot for the distance metrics between the reference positions of a single measurement for all aluminium cassette measurements. The box shows the median and inter-quartile range, the whiskers expand to the 5 and 95 percentiles.

pairwise metrics for all measurements in the data set, which surface is considered flat according to EN 1793-5 (no roughness). For the 56 measurements and 136 reference positions these are 124 combinations. Where applicable the road traffic noise spectrum is used.

For the d_{RMS} and d_{MAD} two clusters can be seen. The first cluster is below 0.05 and can be seen as very similar measurement results (compare to $RI_j^{(4)}$ and $RI_j^{(5)}$ in Figure 4). The second cluster lies between 0.1 and 0.15 for the d_{RMS} and between 0.07 and 0.1 for the d_{MAD}. For some combinations of reference positions these two distance metrics are even higher than for reflection index measurements of two noise barriers of a different material with the same DL_{RI} ($RI_j^{(3)}$ and $RI_j^{(4)}$ in Figure 4 and Table II).

The effect on the final DL_{RI} can be conservatively estimated by the distribution of the D_{MAD} and $\Delta_{DL_{\mathrm{RI}}}$ metric. For the above mentioned first cluster the effect will be marginal. The second cluster shows deviations in the range of the standard deviation of repeatability for the D_{MAD}. Again, some combinations show significant deviations of up to 0.74 dB in the DL_{RI}. For the worst case scenario of the D_{MAD} even a difference between 1.2 dB between the reference positions of a single measurement can be found. It should be noted that according to EN 1793-5 only one reference position should be sufficient to fully describe the sound reflection properties of the noise barrier.

3.3. Distance for Aluminium Cassette Noise Barriers

As the internal and surface structure of all measured aluminium cassette noise barriers is identical a deeper analysis is possible due to the high number of comparable measurements. As the holes in the perforated metal plate of an aluminium cassette must be considered acoustically relevant, the surface structure of a noise barrier consisting of aluminium cassettes must be considered flat with zero structure depth. Nevertheless, in the data set all aluminium cassette noise barriers are measured with two reference positions as mentioned in section 2. The distance metrics between the two reference positions for all 33 measurements are shown in Figure 6. Again, only the road traffic noise spectrum is used. The occurring deviations are in the range or below of the measurement uncertainty. If this deviations are caused by the measurement uncertainty the differences of the DL_{RI} would be symmetrically centered around zero. This is the H_0 hypothesis of a Wilcoxon signed-rank test, which was performed on the not normally distributed data. With a test statistic of $W = 26$ the H_0 hypothesis can be safely rejected ($p < 10^{-5}$), therefore a significant difference between the two reference positions exist.

This can also be seen in Figure 7 where the DL_{RI} values for the two reference positions are plotted against each other. From the regression line parameters it can be derived that the average difference is smaller than 1 dB, but even a small difference may cause unwanted effects: A noise barrier consisting of nine aluminium elements with a element height of 50 cm and a total height of 4.5 m meters will have a significantly higher assessed[4] DL_{RI} than a noise barrier with 8 elements with a total height of 4 m, although the same elements are used in a qualification test. This is because the reference position according to EN 1793-5 lies in the first case in front of the element,

[4] Assuming the same frequency range and time windows are used.

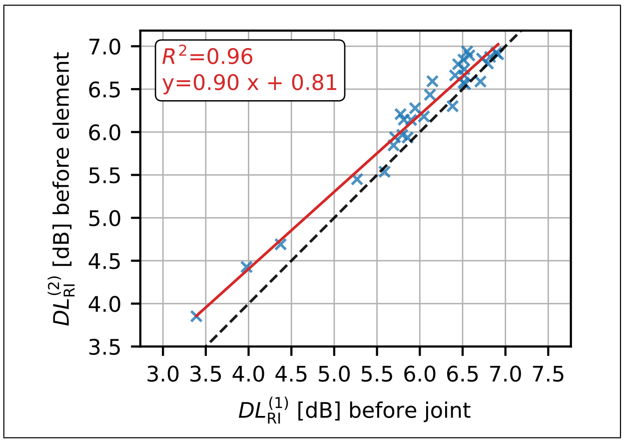

Figure 7. DL_{RI} for the two measured reference positions for aluminium cassette measurements. $DL_{\mathrm{RI}}^{(1)}$ is located in front of the joint of two cassettes, $DL_{\mathrm{RI}}^{(2)}$ is located in front of the vertical center of an element. The black dashed line is the 45° line. The red line is a linear regression of the data points.

in the second case the measurement is performed directly before the joint. This difference is lower than the given expanded uncertainty of the measurement procedure but may be a contributing factor for the (inter-laboratory) repeatability.

4. Device Specific Analysis

The global analysis in the data set showed substantial differences in the measurement of the reflection index for various reference positions. In this section specific measurements are examined, which due to repeated measurements of the same barrier type or sample can further evaluate the influence of the reference position on a flat (and homogeneous) noise barrier.

4.1. Case Study I: Aluminium Noise Barrier

The reflection properties of 24 noise barriers with aluminium cassettes within the same construction section where measured in a period of 4 days. [6] All noise barriers are from the same type and have the same dimensions. Again, two reference positions where used: One at the exact half height of the noise barrier (joint between to elements) and one reference point 25 cm higher (vertical center of an element). For all except two measurements the calculated DL_{RI} is higher at the second reference position in front of the element. As this data is a subset of the analysis shown in section 3.3 the Wilcoxon signed-rank test still shows a significant difference for the two reference points ($W = 19$, $p < 0.001$).

As the 24 noise barriers have very similar reflection properties also the distance metrics show the difference between the reference points in Figure 8, where the road traffic noise spectrum is used as weighting factors. In the figure the box-plots for the calculated

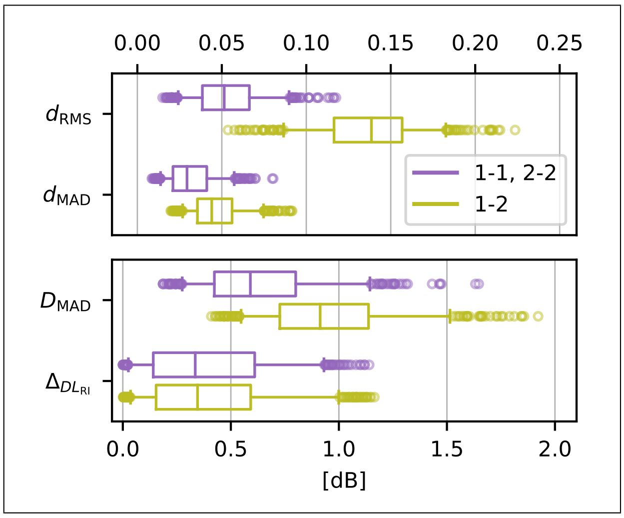

Figure 8. Distance metrics between all reference points for the 24 aluminium cassette measurements for case study I separated, if the distance is calculated between the same reference positions (purple) or between different reference positions (olive).

distance metrics are shown for two cases. For the first case (purple) 552 combinations of the same reference positions are shown (so the distances between all reference positions 1 and the distances between all reference positions 2). For the second case (olive) 576 combinations of the distance between the two reference positions are shown. It can be seen that the on the reflection index based distances d_{RMS}, d_{MAD} and D_{MAD} in the first case are significantly smaller than in the second case, especially the d_{RMS}. Therefore, the reference point location has a significant influence on the measurement of the reflection index, as the difference between different samples but same reference position is smaller than different reference positions on the same sample. For the $\Delta_{DL_{\mathrm{RI}}}$ no relevant difference can be found due to the averaging (of the not absolute values of the reflection index) in the calculation.

4.2. Case Study II: Wood-Fibre Concrete Noise Barrier

Inside the data set one measurement of a flat homogeneous noise barrier according to EN 1793-5 showed significantly high deviations between the reference positions. The absorbing material was wood-fibre concrete with a surface structure depth of 4 cm and a spatial period length of 50 cm in horizontal direction. Four elements of 1 m height were stacked on each other. Although, the surface structure depth is below 85 mm, three reference positions (1,2,3) with a distance of 12.5 cm between each other and at a height of 2 m, i.d. at the joint of two elements, were chosen as if the noise barrier is non-flat or non-homogeneous in one direction according to EN 1793-5. Additionally, another three reference positions (4,5,6) were recorded

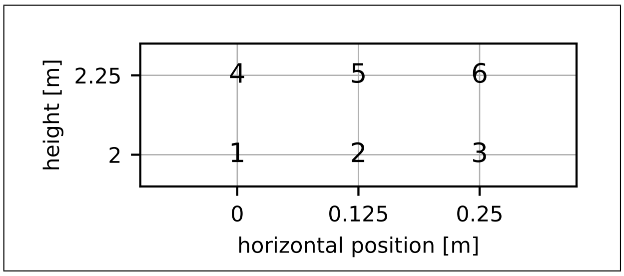

Figure 9. Reference positions for the flat homogeneous concrete noise barrier. Reference position 1 is located in the center of the noise barrier.

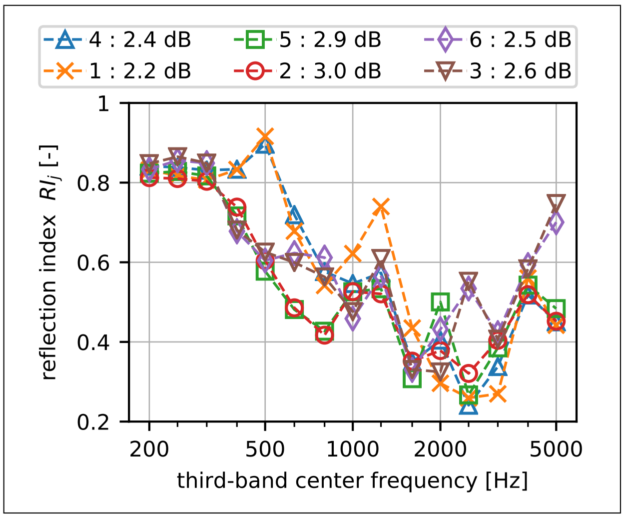

Figure 10. Reflection index and DL_{RI} value for the six reference points for a flat homogeneous wood-fibre concrete noise barrier (case study II) with structure depth 4 cm.

25 cm above the first three. This geometric relationship can be seen in Figure 9.

Figure 10 shows the reflection index for the six reference points. In the range 400 to 800 Hz the reference points are grouped pairwise relative to the surface structure, which can also be seen in the DL_{RI} values. Interestingly enough is for the reference positions 1 and 4 the center microphone 5 before the least protruding part of the surface and for the reference positions 3 and 6 the center microphone 5 is in front of the most protruding part of the surface. The reference positions 2 and 5 are midway between the reference positions 1 and 3 or 4 and 6 respectively.

This similarity can also be seen in the distance metrics shown in Table III and IV. Especially the d_{RMS} clearly shows the difference or similarity in the reference positions, but also the the d_{MAD} and D_{MAD} are smaller for the 3 pairs (1-4, 2-5, 3-6) than for the other combinations. Table IV also shows the occurring deviations (absolute or not) of up to 1 dB in the DL_{RI}, which are induced by the reference position.

The measured noise barrier is considered flat homogeneous according to EN 1793-5, which requires one reference position in center of the noise barrier. With

Table III. Distance metrics d_{MAD} and d_{RMS} for the reflection index values of Figure 10. d_{MAD} is weighted with the road traffic noise spectrum.

d_{RMS} \ d_{MAD}	1	2	3	4	5	6
1	╲	0.122	0.115	0.065	0.133	0.136
2	0.130	╲	0.080	0.083	0.026	0.082
3	0.156	0.116	╲	0.086	0.088	0.029
4	0.065	0.113	0.146	╲	0.089	0.082
5	0.143	0.040	0.124	0.119	╲	0.082
6	0.160	0.112	0.037	0.139	0.133	╲

Table IV. Distance metrics D_{MAD} and $\Delta_{DL_{\mathrm{RI}}}$ for the reflection index values of Figure 10 weighted with the road traffic noise spectrum.

$\Delta_{DL_{\mathrm{RI}}}$ \ D_{MAD}	1	2	3	4	5	6
1	╲	1.0	0.9	0.5	1.1	1.1
2	0.7	╲	0.7	0.7	0.2	0.7
3	0.4	0.4	╲	0.7	0.8	0.2
4	0.2	0.6	0.2	╲	0.7	0.7
5	0.7	0.0	0.3	0.5	╲	0.7
6	0.3	0.4	0.0	0.2	0.4	╲

a spatial period length of 50 cm, seven and a half periods are present on a 4 m wide noise barrier. Therefore, the exact surface structure (most protruding part, the least protruding part or some kind of edge or ramp) at the center reference position can be considered random. Nevertheless, this phase shift will not have any significant effect on the global sound reflection properties of the noise barrier. Contrary to this assumption the measured DL_{RI} values for the reference positions 1 and 2, which are 12 cm apart from each other, are 2.2 dB and 3.0 dB, which differ considerably by 0.8 dB.

5. Conclusions

In this study a significant influence of the reference position on the reflection index for flat homogeneous noise barriers according to EN 1793-5 could be found. As the standard requires that only one reference position is used this may result in increased measurement uncertainties. Although a great number of measurements were used in the analysis, additional measurements should be performed to investigate the found differences. Especially repeated measurements for various reference positions on the same noise barrier for various surface properties would be beneficial. As this means a considerable effort, numeric simulations may also produce valuable results.

The available data suggests that more than one reference position for flat and homogeneous noise barriers is, due to averaging effects, beneficial for the repeatability, as even for a flat homogeneous noise barrier the relative location between the reference position and the surface structure can significantly influence the measurement. Especially in the case of a noise barrier with a total height of 4 m of stacked elements (with 50 cm or 1 m height) the default reference position lies at the joint of two elements. As for aluminium cassettes a significant lower reflection index could be found in front of the joint than in front of the element, it must be discussed if for the overall performance of the noise barrier a measurement in front of the element is the more relevant location. Also it may be discussed, if the standard should demand a minimum of two measurement positions or allow more than one reference position for flat and homogeneous noise barriers.

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