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Sound wave diffraction difference index for noise barrier with added device

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Abstract The diffraction phenomenon at the edge of the acoustic screen is of fundamental importance for forming the acoustic shadow area in the space outside the screen. The so-called added devices construction solutions are increasingly used on plane sound barriers, often used as anti-noise solutions on roads and railway lines. Added devices with various geometric shapes; aim to change the diffraction conditions at the noise-reducing devices' top edge. Adrienne method was developed in a European research project, the aim of which was the measurement on site of sound absorption and sound transmission of any road noise barrier. The European Adrienne project has developed a diffraction difference index at the top edge of an acoustic screen and a method for its determination to compare the effectiveness of the screen with and without the added device. The diffraction difference index is a single-number rating of the design solution mentioned. Measurements for index calculations are made by comparing the impulse response of screens with and without the added device using MLS (Maximum Length Sequence) signals.

Keywords: impulse response, diffraction, noise barrier, added device, MLS method.

1. Introduction

A noise barrier can be any natural or artificial obstacle in the sound propagation path between the noise source and the reception point. Its main task is to create an acoustic shadow zone in which the acoustically protected area is located. The fundamental issue when designing a sound barrier is calculating its acoustic efficiency.

It is determined as a function of the acoustic wave's frequency and the system's geometric configuration: noise source - noise screen - reception point [1, 2]. New solutions are the so-called added devices installed on the top edge of the acoustic screen. Definition of the added device in accordance to [3], "acoustic elements added on top of a noise-reducing device and intended to contribute to sound attenuation by acting mainly on the diffracted sound field".

Diffraction (wave deflection) is a physical phenomenon of changing the direction of wave propagation at the edges of obstacles and in their vicinity. The phenomenon occurs for obstacles of any size but is observed for obstacles with sizes comparable to the wavelength. According to Huygens' principle, the wave propagates so that each point becomes a new source of a spherical wave. Behind an obstacle, the waves overlap according to the principle of superposition. When certain conditions are met, areas of strengthening and weakening of propagating waves appear behind the obstacle [4, 5].

In the study of noise barriers, one can refer to the geometric theory of diffraction (GTD), which extends the idea of rays by introducing the concept of diffracted rays, which differ from the rays of geometric optics in that they are produced when the ray hits an edge or corner of an obstacle [6–8].

According to the manufacturers, the added devices would increase the effectiveness of acoustic screens compared to simple screens made in the same construction and material technology, primarily acting mainly on the diffracted acoustic field. Since it was difficult to justify using these elements at the top edge of the screen, the Adrienne project developed a methodology to determine the diffraction index, the phenomenon responsible for the deflection of the acoustic wave at the edge of the screen with and without an added device. As part of the work on the Adrienne project, several methods were developed for the use of impulse responses to study the acoustic parameters of screens in situ in the free field. Some acoustic measures can be calculated from the captured impulse response [9, 10], such as the sound insulation of panels and pole joints, the sound reflectance of panel elements, and the diffraction at the edge of the screen. The MLS technique generates and acquires impulse response signals [11, 12].

The manuscript describes the test method used to determine the internal sound diffraction characteristics of additional devices installed on the upper edges of noise barriers reducing road noise. The test method is based on measuring impulse responses at several well-defined reference points near the top edge of the noise reduction device with and without an additional device installed on top of it.

The effectiveness of the added device is calculated as the difference between the measured sound pressure values with and without the added devices, with correction for changes in height (the described method indicates the acoustic advantage of the new solution over a simple barrier of the same height; however, in practice, the added device can only increase the height, which can provide additional shielding depending on the mutual position of the noise source and receiver).

2. Measuring system

The measurement signal used for the diffraction measurement was a pseudorandom MLS signal. This signal consists of a pseudorandom sequence of binary values generated recursively by an N-stage digital register. N is called the MLS order. The MLS signal is periodic, with period: $L = 2N\text{-}1$. An essential property of this signal is its nearly flat spectrum.

Consequently, for any period, the autocorrelation function is a Dirac function. Another property is a good signal-to-noise ratio without the need for significant crest factors that can cause non-linearities. The system's impulse response was obtained by amplifying the measuring system with the MLS signal. The frequency response was received through appropriate computational algorithms (correlation function) using the original MLS signal as input data and the impulse response of the measured system excited by this signal. An essential advantage of measurements made using the MLS signal is high resistance to ambient noise (background noise), which is particularly important during measurements made in the presence of traffic noise [12].

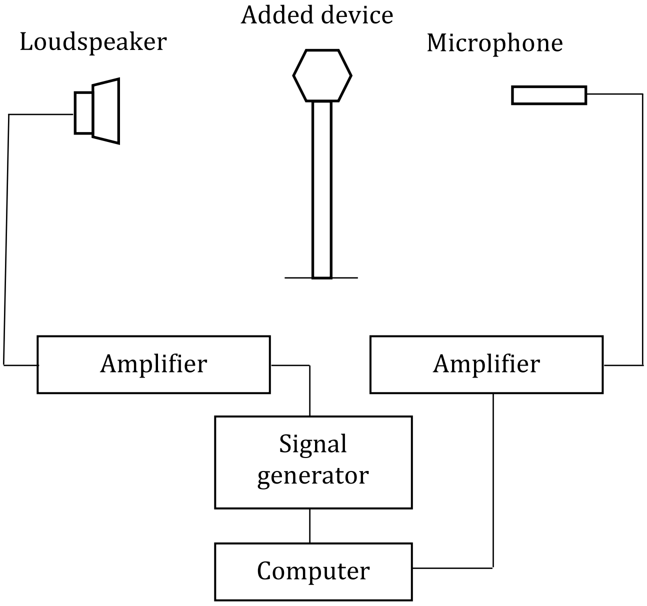

Figure 1. Components of the measuring system (sketch).

The system shown in Fig. 1 was excited by the MLS signal (signal parameters: order N = 16, length L = 65,535 samples, sampling frequency f_s = 48 kHz, signal duration T_s = 1.37 s, the cut-off frequency of the filter (anti-aliasing filter) f_{oc} = 10 kHz). At the reception points, the signal was recorded using a ½" GRAS type 40AN free-field microphone. By applying appropriate mathematical transformations (correlation function), using as input data the primary MLS signal and the response of the measured system to this signal, the response of the measured system, and consequently its frequency response, can be obtained [13–16]. Then, the cross-correlation of the emitted and received signals was determined, and the signal was separated using the Adrienne temporal window. The windowed impulses were subjected to spectral analysis using the FFT algorithm. The spectral data obtained from the FFT are converted to 1/3 octave or 1/1 octave frequency bands to get information about the spectral characteristics. From the obtained values in 1/3 octave bands in the range from 100 Hz to 5000 Hz, the difference in sound diffraction occurring at the upper edge of the screen is calculated. A self-developed program written in the LabView environment was used for the calculations.

The experimental study presented here focuses on the differences between impulse responses for wave propagation in the free field and over the top of the barrier by using the sound level difference relationship $\Delta L(f)$ for a given frequency f and a given observation point for sound wave transmission in space with and without a sound barrier:

$$\Delta L(f) = -10\log\left(\frac{H_{dk}(f)d_{dk}}{H_i(f)d_i}\right)^2 \tag{1}$$

where H_{dk} is the impulse response for a wave diffracted over the top edge of the barrier, H_i is the impulse response for a wave in a free field, d_{dk} is the distance between the loudspeaker and the microphone for the diffracted wave, and d_i is the distance between the loudspeaker and a microphone for the direct wave.

The diffraction index DI for j-th one-third octave frequency band is determined by equation (2):

$$DI_j = -10\log\left\{\sum_{k=1}^{n}\left[\frac{\int_{\Delta f_j}|F[h_{dk}(t)w_{dk}(t)]|^2 df}{\int_{\Delta f_j}|F[h_{ik}(t)w_{ik}(t)]|^2 df}\right]\right\} \tag{2}$$

where F is the symbol of the Fourier transform; $h_{ik}(t)$ is the component of the free-field impulse response received at the k-th measurement point ($k = 1, \ldots, n$), $h_{dk}(t)$ is the part of the impulse response diffracted by the top of edge of the test construction and received at the k-th impulse response; $w_{dk}(t)$ is the Adrienne temporal window for the diffracted component at the k-th measurement point; $w_{ik}(t)$ is the incident reference free field component time window; j is the index of the one-third octave frequency bands between 100 Hz and 5 kHz, Δf_j is the j-th one-third octave frequency band (from 100 Hz to 5 kHz), and $n = 10$ is the number of microphone positions [17, 18].

The sound diffraction index should be determined two times: for the barrier with (DI_{ad}) and without the added device (DI_0). Then the sound wave diffraction index difference ΔDI shall be calculated as the difference:

$$\Delta DI = DI - DI_0. \tag{3}$$

The single-number rating of sound diffraction index difference $DL_{\Delta I,}$ for a reflecting or absorbing wall is given by:

$$DL_{\Delta DI} = -10\log\left[\frac{\sum_{i=1}^{18} 10^{0.1Li}10^{-0.1\Delta DI_i}}{\sum_{i=1}^{18} 10^{0.1Li}}\right], \tag{4}$$

where L_i is relative A-weighted sound pressure levels of normalized traffic noise spectrum in the i-th one-third octave band, dB [18, 19].

3. Impulse response measurements

The speaker emits a transient sound wave that travels toward the acoustic screen under test and is partially transmitted, partially reflected, and partially diffracted. A microphone placed on the other side of the acoustic screen records the transmitted sound pressure wave passing from the sound source through the acoustical screen and the sound wave diffracted by the top edge of the sound wall under test [20].

Measurements were made on a measuring stand. These were two segments of the acoustic screen specially prepared for a series of measures. The length of the screen was 10 m (3 support pillars filled with panels 5 m long each), and the screen's height was 4.0 m. One side of the barrier was a sound-reflecting wall, and the other was a sound-absorbing wall. The screen was placed on a concrete base. All elements of the screen (panels) and the added device were brand new with no signs of wear or damage.

There were no sound-reflecting surfaces at a distance of 4 m and less from the measuring stand. The picture of the stand is shown in Fig. 2.

Figure 2. The noise barrier with the added device installed on the top edge.

During the field measurements, the meteorological conditions were excellent and did not affect the obtained impulse responses (average temperature 20 °C, humidity 61%, wind 0.6 m/s, atmospheric pressure 995 hPa).

Acoustic measurements were made following the methodology developed in [1] for two positions of the loudspeaker relative to the top edge of the screen and five positions of the microphone, respectively. The reference height of the noise screen $h_{ref,0}$ = 4.0 m. Then the system was rotated by angle $45^{0,}$ and the measurement sequence was repeated. Such two series were carried out for a loudspeaker placed in front of a sound-reflecting wall (20 measurement points) and then for a sound-absorbing wall. For each of the measurements, a series of reference measurements were made (in the open space, without an acoustic screen) - also 20 measurement points. The diagram of all microphone positions (designations M1 – M5 and M6 -M10) and the loudspeaker (designations S1 – S2 and S3 - S4) is shown in Figure 3.

After installing the added device on the upper edge, the new height of the screen increased by the height of the added device was taken into account h_{add} = 0.41m. For such a total height of the screen, a series of measurements were assuming $h_{ref,0}$ = 4.41 m. No sound-reflecting surfaces were in the surrounding area at a distance of 4 m and less from the test construction.

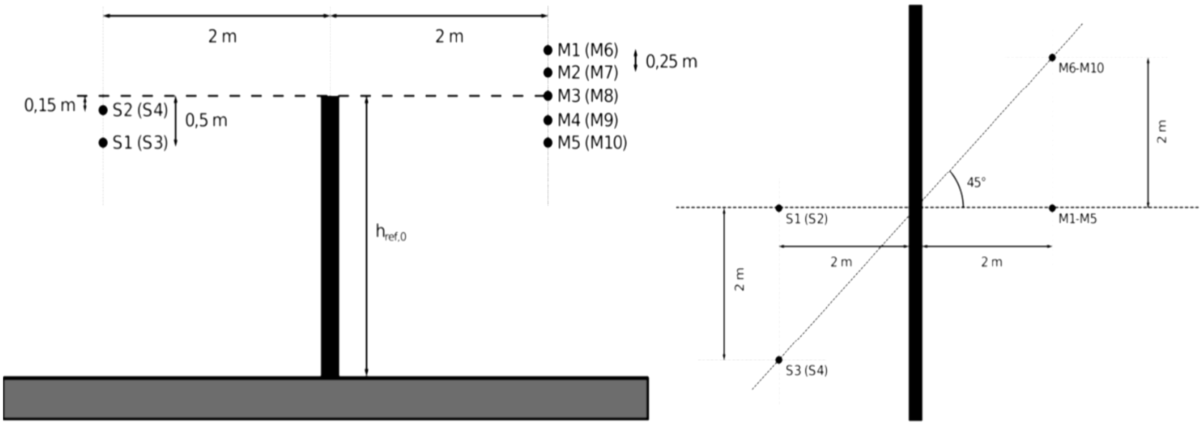

Figure 3. Loudspeaker and microphone position diagram during a testing session [1].

Impulse responses in the direction perpendicular to the edge of the screen were compared: reference measurement without the acoustic screen and situations in the presence of the noise screen without an added device and with the added device mounted on the upper edge of the screen. Two angles of acoustic wave incidence 90^0 and 45^0 should be used. In the analysis of impulse responses, the Adrienne window described by the function w(t) was used following the standard [18].

4. Results and discussion

The power spectra of the direct components and the diffraction component at the top edge, corrected to account for the difference in paths of the two components, form the basis for calculating the sound diffraction index. Example impulse responses of the measurement system are shown in Figure 4.

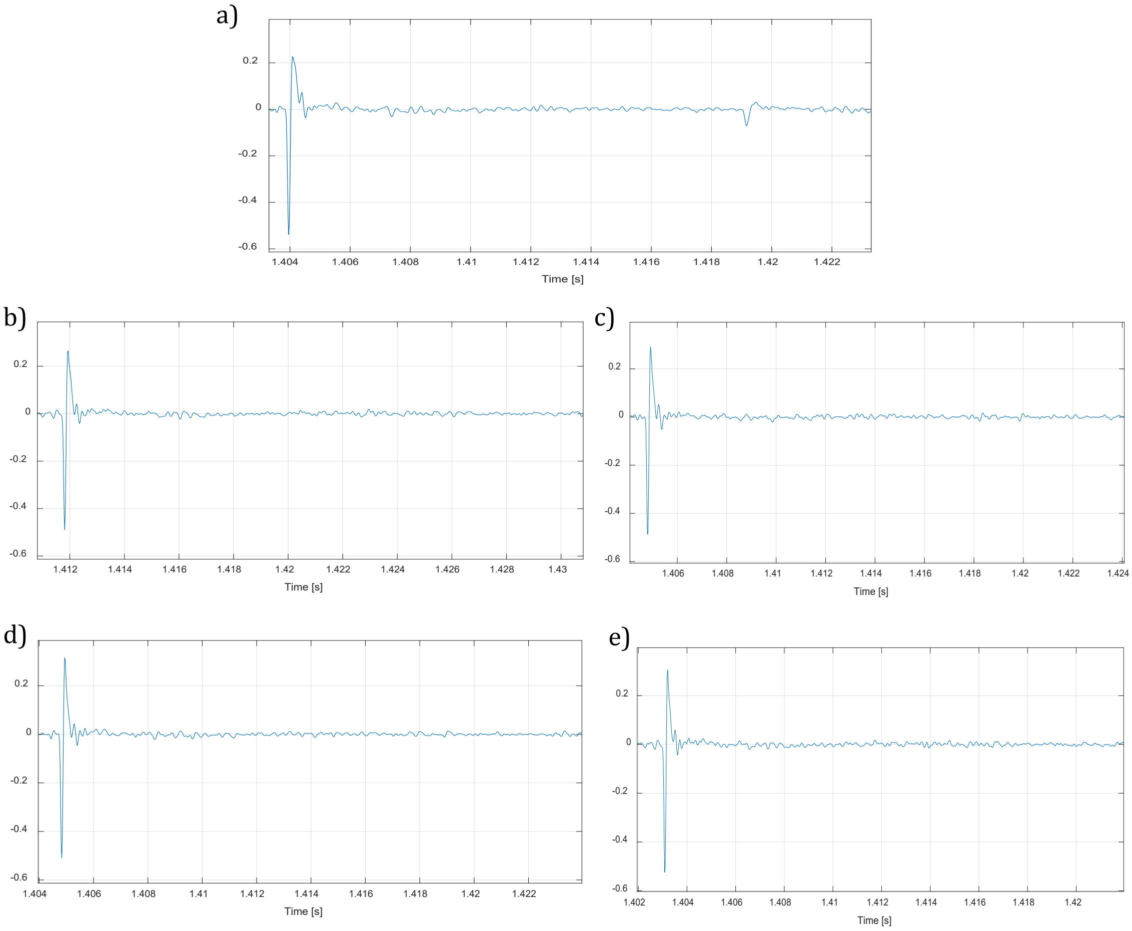

Figure 4. Examples of impulse responses for various configurations of measurement systems: a) reference signal, b) without an added device with reflecting wall, c) without an added device with absorbing wall d) with added device with on the absorbing wall, e) with added device on the reflecting wall.

The sound diffraction index difference is derved from the difference between the results of sound diffraction tests on the same reference barrier with and without an added device on the top.

Table 1. The sound diffraction difference indices for 1/3 octave frequency bands for a wall with sound-reflecting and sound-absorbing panels.

	One-third octave centre frequency (Hz)																	
f	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
ΔDI_{abs}	0.7	0.7	0.8	0.8	0.8	0.0	-0.1	0.0	0.0	0.2	0.7	0.4	0.7	0.8	0.9	1.0	0.2	0.5
$\Delta DI_{\mathrm{refl}}$	0.6	0.6	0.7	0.7	0.8	0.4	0.0	-0.1	0.3	0.5	0.6	0.6	0.6	0.6	0.8	0.9	1.0	0.3

The single-number diffraction difference index $DL_{\Delta DI,\mathrm{abs}}$ for the added device under test was placed on the top edge of the wall with sound-absorbing panels:

$$DL_{\Delta DI,\mathrm{abs}} = 1 \text{ dB},$$

and the single-number diffraction difference index $DL_{\Delta DI,\mathrm{refl}}$ for the added device under test placed on the top edge of the wall with sound-reflecting panels:

$$DL_{\Delta DI,\mathrm{refl}} = 1 \text{ dB}.$$

The single-number rating of the diffraction index difference should be reported after being rounded to the nearest integer.

The test results in the form of a graph are presented in Figure 5. The values of diffraction index difference in the 1/3-octave frequency bands between 100 Hz and 5 kHz for the reflective and absorptive wall construction are presented. The diffraction index difference values are rounded to one decimal place (see Table 1).

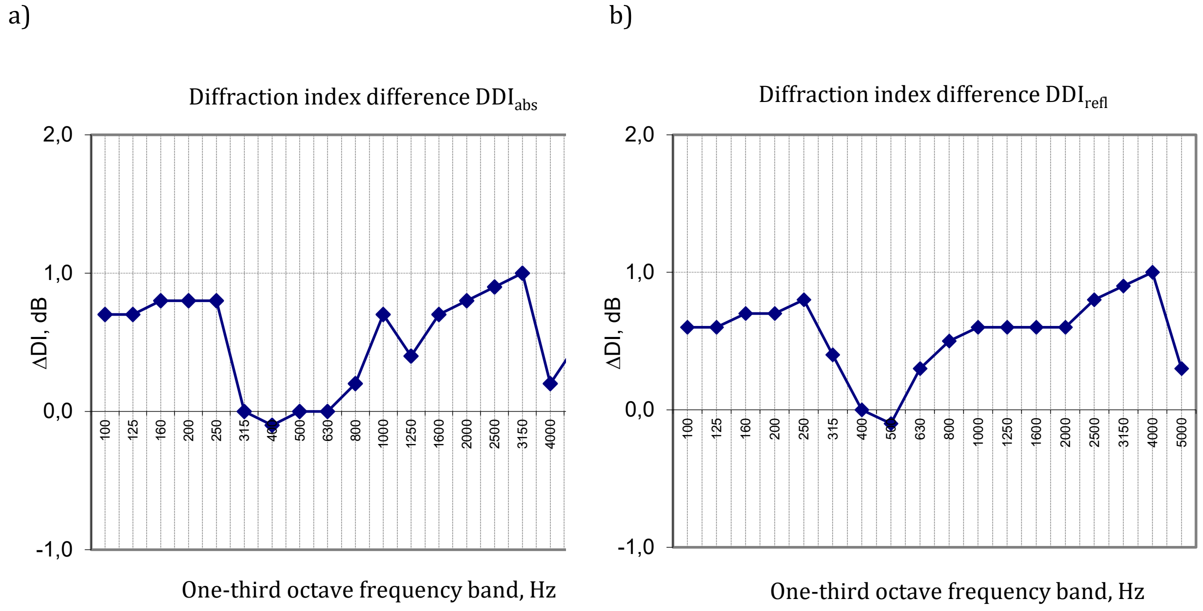

Figure 5. The values of diffraction indices in the 1/3 octave frequency bands for a) absorbing panels, b) reflecting panels.

The final diffraction index is a weighted average of diffraction indices measured at different points loudspeaker and microphones positions.

5. Conclusions

Sound diffraction tests on the upper edge of the noise barrier screen are issues related to the design of effective anti-noise solutions such as acoustic screens. How the acoustic wave is diffracted at the edge directly affects the acoustic efficiency of the screen. This research shows that many commonly used devices placed on the upper edge of the noise screen practically have a diffraction difference index equal to 0 or 1, which may explain that such a device is almost insignificant or insignificant in shaping the acoustic field in the zone behind the screen - the improvement in the effectiveness of sound shielding results from increasing its height. Of course, the diffraction difference index value is the average value of 20 observation microphone points, two positions of the sound source relative to the top of the screen, and the frequency bands range from 100 Hz to 5000 Hz. By analyzing the results at individual measurement points in the frequency bands for various shapes of added devices (based on my research), it is possible to indicate results in which the difference in noise reduction levels between the screen with and without the added device is a few dB higher or lower. The final diffraction index is a weighted average of the diffraction indices measured at different points for the normalized traffic noise spectrum. The obtained power spectra of the direct component and the diffraction component on the upper edge, corrected to account for the difference in path lengths of both components, provide the basis for calculating the diffraction index.

In order to get the impulse response of the device, the MLS method was chosen mainly for its excellent signal/noise ratio.

It is crucial that diffraction at the top edge is most significant and that diffraction from the vertical edges of the wall construction being tested must be delayed enough to be outside Adrienne's time window.

The described test method can be applied in situ, i.e. where road noise reduction devices and devices added to them are installed. This method is non-invasive. It also allows you to monitor the current technical condition of noise-reducing devices during use.

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Additional information

The author(s) declare no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited, and that appropriate permits are obtained.

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