THEORETICAL PRINCIPLES FOR EFFICIENCY CALCULATIONS FOR THE NOISE BARRIERS ALONG HIGH-SPEED RAILWAYS

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The main contribution to the overall level of noise generated by high-speed trains (with the speed of over 300 km/h) is made by the aerodynamic noise of the train body and pantograph. The separation of contributions from different noise sources located at different heights above the rail head must be taken into account when determining the noise barriers efficiency. The article presents theoretical principles based on the statistical theory of acoustics for efficiency calculations of the noise barriers along single - and multi-track high-speed railways. The improved formulas for noise barriers allowing for their height, material, mutual arrangement with separate train noise sources (with separating a predominant one for a specific height) and other parameters are presented. The formulas are based on the assumption of the quasi-diffusion field generation in the semi-enclosed volume created by the train body, noise barrier and subgrade formation. Comparison with the calculation data with the Fresnel number using the optical-diffraction approach.

Keywords: high-speed train, noise, statistical theory of acoustics, quasi-diffusion sound field.

1. Introduction

The fundamental difference between noise generation processes when trains move at a speed of up to 250 km/h and over is the presence of an aerodynamic noise component. Thus, when assessing the efficiency of the noise barriers (NB) installed along high-speed railways, it is necessary to take into account the multi-component nature of the total noise level. The developed theory applies the principle of energy summation and a high-speed train is represented by a set of several separate incoherent noise sources (NS) of different nature and height (the acoustic center) [1]:
- pantograph (h=5 m, aerodynamic noise);
- nose and body of the train (h=2 m, aerodynamic noise);
- the ‘wheel-rail’ pair (h=0.5 m, rolling noise).

Therefore, the NB efficiency is determined by its efficiency in relation to each individual source: rolling noise, aerodynamic noise of the body and pantograph. Therefore, the NB overall efficiency ($\Delta L_{NB ov}$) for a high-speed train can be represented as:

$$\Delta L_{NB ov} = 10\lg \left(10^{0.1\Delta L_{NB w/s}} + 10^{0.1\Delta L_{NB body}} + 10^{0.1\Delta L_{NB pant}}\right),$$

where $\Delta L_{NB w/s}$ is the NB efficiency relative to rolling noise, dB;
$\Delta L_{NB body}$ is the NB efficiency relative to aerodynamic body noise, dB;
$\Delta L_{NB pant}$ is the NB efficiency relative to aerodynamic pantograph noise, dB.
Depending on the height, the NB can have a screening effect both on individual noise sources (with the height of less than 5 m) and on the whole train.

Depending on the NS height, the conditions for using formula (1) can be represented as:

\[
\Delta L_{NB \text{ov}} = \begin{cases} 
\Delta L_{NB \text{w/s}}, & h < 2, \\
\Delta L_{NB \text{w/s}} + 5, & h = 2 \\
10 \log \left(10^{0.1 \Delta L_{NB \text{w/s}}} + 10^{0.1 \Delta L_{NB \text{body}}}ight), & 2 < h < 5 \\
10 \log \left(10^{0.1 \Delta L_{NB \text{w/s}}} + 10^{0.1 \Delta L_{NB \text{body}}} + 5\right), & h = 5 \\
10 \log \left(10^{0.1 \Delta L_{NB \text{w/s}}} + 10^{0.1 \Delta L_{NB \text{body}}} + 10^{0.1 \Delta L_{NB \text{pant}}}ight), & h > 5 
\end{cases}
\]  

(2)

where \(h\) is the NS absolute height, m.

The term ‘absolute’ refers to the NB height above ground level. In subsequent formulas (7)-(14) the calculations take into account the effective NB height, which is determined as the length of the perpendicular descending from the top NB edge to the line connecting the noise source and the reference point where the noise levels are determined. Thus, the effective NB height depends on the NS and RP heights.

2. Derivation of the calculation formula for determining the NB efficiency

We derive a general formula for calculating the NB efficiency.

A hypothesis that the sound field in front of the noise barrier is quasi-diffusive, characterized by the sound energy isotropy at any point in the space between NS and NB but having the nature of reducing the sound intensity in the space in front of the barrier as its height increases, is accepted as a basic working theory.

The sound field is generated in the equivalent volume formed by the noise barrier, train and supporting surface. In the equivalent volume the top aperture is considered as open with the sound absorption coefficient \(\alpha_{ta} = 1\).

The sound field generated by the NB and subgrade formation is taken as quasi-diffusive. Acoustic efficiency of the NB (\(\Delta L_{NB}\)) is determined as follows [2]:

\[
\Delta L_{NB} = 10 \log \frac{i_{RP/\text{w/o}}}{i_{RP/\text{w}}}, dB
\]

(3)

where \(i_{RP/\text{w/o}}\) is the sound intensity in the reference point (RP) without the NB, W/m²;

\(i_{RP/\text{w}}\) is the sound intensity in the RP with the installed noise barrier, W/m².

The sound intensity in the RP from a linear source is reduced as a result of divergence in the absence of NS:

\[
i_{RP/\text{w/o}} = \frac{W_{NS}}{2\pi l_{NB}(R+r)} \arctg \frac{l_{NB}}{2(R+r)}
\]

(4)

where \(W_{NS}\) is the NS acoustic power, W;

\(l_{NB}\) is the NB length, it is assumed that NS length (\(l_{NS}\)) is equal to NB length \(l_{NB}\) (\(l_{NS} = l_{NB}\)), m;

\(r\) is the distance from the NS to the NB, m;

\(R\) is the distance from the NB to the RP, m.

As it was shown above, the sound field in front of the noise barrier in the equivalent volume is quasi-diffusive and the intensity of the sound incident to the noise barrier is determined in the bottom part:

\[
i = \frac{4W_{NS}(1-\tilde{\alpha})}{\Psi_{\nu} A_{\nu}} , W/m²
\]

(5)
where $\bar{\alpha}_v$ is the average sound absorption coefficient in the equivalent volume;

$\Psi_v$ is the coefficient showing the sound field diffusion ratio in the equivalent volume;

$A_v$ is the equivalent area of sound absorption of the equivalent volume, $m^2$.

Acoustic power in the bottom part of the barrier is determined on the accepted assumption that sound radiation occurs as a reference band with the width of 1 m:

$$W_{bot} = I_l l_{NB} \cdot 1$$  \hspace{1cm} (6)

The intensity of the sound at the top free edge of the barrier is determined using the assumption of sound divergence by the pitch and is determined with the condition of the sound radiation in $\frac{1}{4}$ of the space:

$$I_e = \frac{w_{bot}}{\pi l_{NB} h_{NB} \rho_{diff} l_{NB}} \arctg \frac{l_{NB}}{2h_{NB}^{eff}}$$  \hspace{1cm} (7)

where $h_{NB}^{eff}$ is the NB effective height, m.

Acoustic power at the free edge of the barrier is determined:

$$W_e = I_e \lambda \rho_{diff} l_{NB}$$  \hspace{1cm} (8)

where $\lambda$ is the sound wave length, m;

$\rho_{diff}$ is the sound diffraction coefficient on the top free barrier edge.

The sound intensity in RP with the installed noise barrier:

$$I_{RP}^{w/\text{NB}} = \frac{w_e}{2\pi l_{NB} R} \arctg \frac{l_{NB}}{2R}$$  \hspace{1cm} (9)

Let’s substitute (5)-(8) into (9)

$$I_{RP}^{w/\text{NB}} = \frac{4W_{NS}(1-\bar{\alpha}_v)l_{NB} l_{NB} \lambda \rho_{diff} l_{NB} \arctg \frac{l_{NB}}{2h_{NB}^{eff}} \arctg \frac{l_{NB}}{2R}}{2\pi l_{NB}^{2} \Psi_v A_v \pi h_{NB}^{eff} \pi R}$$  \hspace{1cm} (10)

After conversion and denoting the cofactor as A:

$$I_{RP}^{w/\text{NB}} = \frac{2W_{NS}(1-\bar{\alpha}_v)\lambda \rho_{diff} l_{NB}}{2\pi l_{RB}(R+r)2\Psi_v A_v \pi h_{NB}^{eff} \pi R} A$$  \hspace{1cm} (11)

Let’s substitute (4) and (11) into (3), we will obtain the NB acoustic efficiency as:

$$\Delta L_{NB} = 10 \log \frac{W_{NS} \Psi_v A_v \pi h_{NB}^{eff} \pi R \arctg \frac{l_{NB}}{2h_{NB}^{eff}} \arctg \frac{l_{NB}}{2(R+r)}}{2\pi l_{NB}^{2} (R+r)2\Psi_v A_v \pi h_{NB}^{eff} \pi R}$$  \hspace{1cm} (12)

After reductions and other transformations, the acoustic efficiency of the barrier is:

$$\Delta L_{NB} = 10 \log \frac{R}{(R+r)^2} 10 \log \frac{h_{NB}^\alpha h_{NS}^\alpha + h_{NS}^\alpha h_{NS}^\alpha + \alpha_{surf}^\alpha}{(R+r)^2} + 10 \log \Psi_v + 10 \log \frac{h_{NB}^{eff} \lambda}{\lambda} - 10 \log (1-\bar{\alpha}_v)$$  \hspace{1cm} (13)

where $r_0 = 1$ m.

The numerical coefficient is obtained:

$$10 \log \frac{\pi}{4} = -1 \text{ dB}$$  \hspace{1cm} (14)

Note that in formula (13) the values $h_{NS}$, $h_{NB}^{eff}$, $\rho_{diff}$, $\alpha_{NS}$ are defined separately for each noise source.
3. Calculations and results comparison

Comparison of the results, obtained by the derived formula and formulas with Fresnel number according to Maekawa [3, 4] and Kurtze [5] for three different NB heights, was performed: 1.5 m, 3.5 m, 5.5 m, 7 m.

It was assumed that the barrier is located at a distance of 4.5 m from the railway axis, residential development is located at a distance of 75 m. The barrier is assumed as sound-absorbing, $\alpha_b=0.2-0.7$ [6], the surface between the NB and RP is mixed and represents areas of asphalt concrete and a lawn, $\alpha_{surf}=0.1-0.3$.

A high-speed train moving at a speed of 340 km/h was taken as a noise source. Noise performance was calculated in accordance with the guidelines SP ‘High-speed railways noise protection. Design and construction regulations’ [7]. Thus, when determining sound levels (SL), the total maximum LS, calculated for a low-noise train with the length of 250 m with a streamline train nose shape, enclosed undercarriage and intercar spaces (total reduction of 10 dBA), low-noise pantograph and the local screens on the roof of the train (total noise reduction of 10 dBA), noise-absorbing coating on the train bottom (total reduction of 6 dBA), was 85.8 dBA, of which the rolling noise was 81.9 dBA, the body noise was 80.1 dBA, the pantograph noise was 81.0 dBA (without the described measures maximum total SL is 94.6 dBA).

Table 1 shows the calculations for determining the NB efficiency separately for each noise source and a total for the train. The total noise reduction was determined by the energy summation of the characteristics, taking into account the noise reduction of each NS due to NB, and comparing the obtained values with the initial total sound level.

<table>
<thead>
<tr>
<th>Obtained results</th>
<th>Acoustic efficiency, dB</th>
<th>Acoustic efficiency, dBA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>63</td>
<td>125</td>
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<tr>
<td>NB 1.5 m high</td>
<td></td>
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<tr>
<td>NB efficiency for the pantograph</td>
<td>-</td>
<td>-</td>
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<tr>
<td>NB efficiency for the body</td>
<td>-</td>
<td>-</td>
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<td>NB efficiency for the rolling noise</td>
<td>-</td>
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<td>Total efficiency</td>
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<td>-</td>
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<tr>
<td>NB 3.5 m high</td>
<td></td>
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</tr>
<tr>
<td>NB efficiency for the pantograph</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NB efficiency for the body</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NB efficiency for the rolling noise</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NB 5.5 m high</td>
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<tr>
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<td>-</td>
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<tr>
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<td>1</td>
<td>2</td>
</tr>
<tr>
<td>NB efficiency for the rolling noise</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>-</td>
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</table>

Table 1. The NB acoustic efficiency calculation results
When performing similar calculations using the optical diffraction theory using Maekawa [3, 4] or Kurze [5] formulas, the result is the overestimated NB efficiency levels of up to 10 dBA not taking into account the noise sources height and taking as the initial the train noise characteristic at a height of 3.5 m above the rail head level according to ISO 3095:2013 [8], and up to 4 dBA when the sources are separated. The performed calculations show a greater convergence with the experimental results, when a straight barrier mounted on a flat terrain provides noise reduction from the HSR by 5-15 dB depending on the height. A sail-shaped NB and NB of the other shapes increasing the diffraction index, as well as barriers installed on the embankment or in the cutting, as well as on the overpass, can provide a reduction of up to 20 dBA and above.

With a multi-track railway, it is proposed to carry out calculations in the same way with a corresponding change in the formulas (3)-(13) of the distance $r$. When carrying out calculations of the maximum sound level, the worst case from the acoustic point of view of the simultaneous trains passage on parallel tracks and generation of the quasi-diffusive field between the adjacent trains and the train closest to the NB and the NB directly. When performing the calculations to determine the equivalent sound levels, it is proposed to consider the alternate trains passage on parallel tracks and generation of the quasi-diffusive field only between the NB and the closest train.

### Conclusion

To calculate the NB acoustic efficiency, it is proposed to use the statistical theory of acoustics with separation of the high-speed train noise sources into rolling, body and pantograph noise and taking the sound field as quasi-diffusive in the resulting equivalent volume formed by the boundary surfaces (train, barrier and supporting surface). The results of the calculation show a greater convergence with the average results obtained in full-scale conditions.

### REFERENCES
