Measures to reduce structure-borne noise emissions induced by above-ground, open railway lines

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Introduction
To date, comparatively little work has been done in the field of protection against structure-borne noise transmission and vibration induced by above-ground railway lines. This stands in contrast to underground railway lines, for which a tried and tested set of advanced measures exists. These measures are well established due to the ability to clearly define the boundary conditions in tunnels, also by means of analytical models ([1] to [6]).

For above-ground, open railway lines, the conditions are generally much more complex, as the parameters and boundary conditions, such as impedance of the subgrade, interaction between the track and the foundation, are often not sufficiently definable or it is not possible to carry out measurements directly.

Nevertheless, it is possible to achieve a reduction of the structure-borne noise transmitted into the foundation of above-ground, open railway lines by improving the substructure by means of installing additional layers of support material beneath the ballast bed, if necessary, in combination with ballast mats.

For more than 20 years now, cellular polyurethane (PUR) elastomers, available on the market under the brand name SYLOMER® (Registered trademark of Getzner Werkstoffe Ges.m.b.H., Bludenz-Bürs, Austria), have been used for solving problems related to vibration and structure-borne noise in general applications and specifically in the field of railway construction.

The publications listed in [7] and [8] provide an insight into the wide range of applications. To the extent that applications in track construction are considered, the focus is on measures related to underground lines and bridges.

A detailed account of special structure-borne noise reduction measures taken during the construction of a ballastless track on a reinforced concrete hollow box girder bridge is given in [9].

This article deals with examples of structure-borne noise reduction for above-ground, open railway lines, as with respect to the extension or reconstruction of these lines there is a growing need for well-founded, tested measures in this field of application.

Literature evaluation
A summarised evaluation of the relevant literature on measures with respect to the reduction of structure-borne noise directly at the track (superstructure/substructure) for above-ground, open railway lines is presented in [10], and referred to in the following.

In [11] and [12] an evaluation of experiments carried out by British Rail is presented. During the research the influence of the following factors was investigated:

> varying ballast bed thickness;
> sleepers of varying weight;
> elastic inserts under the sleepers;
> elastic mats between ballast bed, and a 50 mm layer of sand on the subgrade.

Similar experiments have been carried out at Swiss Railways (SBB), using elastic mats on a gravel formation or on a concrete slab [13]. These experiments were, however, carried out in a tunnel that was open towards the floor (i.e. lacking a tunnel floor).

During the experiments, it was found that neither the variation of the ballast bed thickness of between 25 cm and 50 cm nor the different types of sleeper, had any significant influence on the levels of structure-borne noise adjacent to the test line section. However, substantial improvements were observed when using elastic inserts under the sleepers (sleeper pads) and installing ballast mats.

With respect to the experiments carried out by British Rail, however, it was mentioned in [11] that the use of elastic mats under the ballast led to certain track maintenance problems at a later point. In order to avoid such problems as much as possible, the measures depicted in Fig. 1 (see also [14]) were employed (inter alia) during similar tests carried out by German Rail (DB) on a test section at Altheim, Lower Bavaria, Germany.

The experiments took place on a track section where, due to the extremely poor condition of the track, a so-called protective subgrade layer consisting of sand was installed during track renewal (replacement of track skeleton and ballast bed) in all three types of track construction (Fig. 1).

![Fig. 1: Basic construction of various measures for the reduction of structure-borne noise adjacent to above-ground, open railway lines as per [10]](image-url)
Further, two 100-metre track sections were, in the area of load distribution, provided with a cement-hardened layer of gravel (Figs. 1b + 1c). One of these two sections was also provided with a Sylomer D220 ballast mat (Fig. 1c). The Sylomer D220 ballast mat has a dynamic stiffness of 0.09 N/mm² in the frequency range under investigation and, with a "bedding modulus" of 0.06 N/mm², meets the specifications prescribed by the speed of the line and expected loads (axle load) as per [15].

Test results

The acoustics engineering consulting company Müller-BBM GmbH, Germany, conducted structure-borne noise measurements both before and one year after the track renewal – at exactly the same locations 8 m adjacent to the track axis. Measurements for the type of construction featuring just the protective subgrade layer, i.e. Fig. 1a, yielded the results shown in Fig. 2.

It can be seen that after renewal the level of structure-borne noise in the frequencies range below approx. 50 Hz was significantly reduced. The increase in structure-borne noise in the higher frequency range, i.e. between approx. 50 Hz and 100 Hz, which can be explained by a "stiffening of the substructure" due to the renewal, would hardly be noticeable at a distance of 30 m to 40 m from the track, because generally higher frequencies are damped much more strongly in their propagation than lower frequencies (see for example [10], page 400).

The results of structure-borne noise measurements for the superstructure without ballast mat (Fig. 1b) are shown in Fig. 3, and for the superstructure with ballast mat (Fig. 1c) in Fig. 4.

As can be seen, the level of structure-borne noise initially saw a decrease in the very low frequency ranges, whereas the values in the frequency ranges which are relevant to the perception of secondary air-borne noise increased by up to 8 dB adjacent to the track section without the ballast mat (see Fig. 3). By installing a ballast mat, however, this deterioration was for the most part rectified (see Fig. 4).

The decline in resonance at 40 Hz must be accepted as being the result of physical and system-related factors. This decline occurs in the resonating frequency range determined by the stiffness of the superstructure and the dynamically effective masses of the "vehicle/superstructure" system. In principle though, it is possible, depending on the requirements of a given situation, to move this decline in resonance (within certain limits) to a higher or a lower frequency by installing harder or softer ballast mats, respectively.

Analytical model

In the experiments described above, the cement-hardened layer of gravel was mainly installed to meet the acoustic requirement of making the input impedance of the substructure as high as possible (see for example [16], [18]). If this condition is met, then it is possible, for example, to expect optimum results with certain ballast mats, due to their specific dynamic characteristics (stiffness, loss factor, etc.). Furthermore, this offers the advantage that the input impedance of the substructure need not be taken into account when calculating the efficiency of the ballast mat - i.e. its insertion loss, as has been proven for the normal installation situations in tunnels (see for example [5] and [6]) or bridges with concrete slabs [17].

If one takes the well-tested analytical model shown in Fig. 5 as a basis, the insertion loss $\Delta L_e$ of a ballast mat, which is solely effective based on its stiffness $s_M$, can be calculated as follows:

$$\Delta L_e = \frac{1}{4} \ln \left( \frac{s_M}{s_0} \right)$$
\[ \Delta L_e = 20 \cdot \log \left| 1 + \frac{j\omega \cdot s_M}{1/Z_i + 1/Z_a} \right| \text{ dB} \quad (1) \]

where:

- \( Z_i \): effective input impedance from the top side of the mat towards the source of the structure-borne noise;
- \( Z_a \): terminating impedance effective at the bottom of the mat (tunnel floor, bridge, substructure);
- \( \omega \): radian frequency;
- \( j \): imaginary unit.

For normal tunnel floors and the track foundations of concrete bridges (not of steel bridges though) \( Z_a \) is large enough in comparison to \( Z_i \), so that the expression \( 1/Z_a \) in the equation for \( \Delta L_e \) can be ignored (see for example [18] and [19]).

The stiffness of the ballast mat is defined by the equation:

\[ s_M = s_M^* \cdot S_w \cdot (1 + jd_M) \quad (2) \]

where:

- \( s_M^* \): dynamic stiffness of the ballast mat;
- \( d_M \): loss factor of the ballast mat;
- \( S_w \): effective area of the ballast, determined by the conical load distribution underneath the sleeper [5].

The following equation provides an approximation of the source admittance \( 1/Z_i \):

\[ \frac{1}{Z_i} = \frac{j\omega}{s_s} \left[ 1 - \left( \frac{\omega_0}{\omega} \right)^2 \right] \quad (3) \]

where, \( s_s \) is the ballast stiffness and \( \omega_0 \) the resonance radian frequency, which is mainly determined by the ballast stiffness \( s_s \) and the unsprung mass of the wheel set \( M \). In this respect, the following equation applies for normal track skeletons and normal ballast beds:

\[ \omega_0 = 1.7 \cdot \left( \frac{s_s}{1/l} \right)^{3/8} \cdot B^{1/8} \cdot m^{1/2} = \sqrt{\frac{s_s}{M}} \quad (4) \]

where

- \( B \): bending stiffness of the rail [Nm²];
- \( l \): reference length [m].

Thus, the insertion loss for a ballast mat on a foundation with extremely high input impedance (tunnels, concrete bridges) follows from equation (1), together with the equations (2), (3) and (4):

\[ \Delta L_e = 20 \cdot \log \left| 1 + \frac{s_s / s_M}{1 - \left( \frac{\omega_0}{\omega} \right)^2} \right| \text{ dB} \quad (5) \]

This is due to the fact that certain key criteria of the simple calculation model are not fulfilled in this frequency range.

Fig. 6 shows the measured insertion loss for the ballast mat in the rapid transit tunnel in Munich near the Philharmonic Hall, as set against values calculated according to equation (5). The minimum requirements determined in the planning phase have also been included (see [4] and [20]).

As can be seen, the calculated and the measurement values agree quite well. At very low frequencies the measured values and the calculated values are no longer in agreement.

This condition for a calculation of the insertion loss of a ballast mat are more complex, if the mat is to be installed directly on the compacted subgrade, i.e. without a support layer of cement-hardened gravel as described above. In such cases, the terminating admittance \( 1/Z_a \) versus the source admittance \( 1/Z_i \) in the equation above cannot gener-
ally be ignored (admittance = reciprocal value of impedance). This means that the terminating admittance of the subgrade must be defined, for example, in the form described in [18], and taken into account in the calculation. In [18], the subgrade is considered to be an elastic half space with the spring stiffness \( s_p \), which, amongst others, is also dependent on the radius \( a \) of the area of force excitation:

\[
s_p = \frac{3.2 \cdot G \cdot a}{1 - \mu}
\]

where:
- \( G \) shear modulus of the ground;
- \( \mu \) Poisson's Constant;
- \( a \) radius of the force excitation area.

Under certain conditions, which are discussed in detail in [16], the terminating admittance of the subgrade can be calculated according to following equation:

\[
\frac{1}{Z_a} = \frac{j \omega}{s_p} \left( 1 - \frac{4 \cdot a}{\lambda_T} \right)
\]

where:
- \( \lambda_T \) length of the transversal waves propagating into the ground.

With the help of equations (7) and (3), the insertion loss of a ballast mat installed on a compacted subgrade can be calculated according to equation (1). The result of such a calculation are shown in Fig. 8, using the example of a Sylo-Dyn DN335 ballast mat with a dynamic stiffness of \( s''_m \approx 0.052 \text{ N/mm}^3 \) in the relevant range of frequency and load. As a comparison, Fig. 8 shows the calculated insertion loss, which could be expected when installing a ballast mat of the same type on a normal tunnel floor, whereby the calculation is based on a ballast stiffness of \( s_x = 5 \cdot 10^8 \text{ N/m} \) (1 + j·0.5) and an unsprung mass of the wheel set of \( M = 3000 \text{ kg} \).

The influence of the substantially lower terminating impedance on the expected insertion loss of the ballast mat when installed on the subgrade, as compared to a tunnel floor, is clearly evident.

The effect described in detail in [18] is also particularly evident, according to which, as a result of the relatively "soft" subgrade, a shift of the resonance frequency

\[
f_0 \approx \frac{1}{2\pi \sqrt{\frac{s_p}{M}}} = 65 \text{ Hz}
\]

(see also equation 4) to the lower frequency \( f_m \approx 42 \text{ Hz} \) has taken place. This shift can be calculated using the aforementioned values for ballast stiffness \( s_x \) and subgrade stiffness \( s_p \) according to the following equation:

\[
f_m = \frac{f_0}{\sqrt{1 + \frac{s_x}{s_p}}}
\]

Fig. 8 also shows that, in order to achieve maximum efficiency when installing ballast mats on subgrade, it is on the one hand necessary to make the mats dynamically as soft as possible for a given static bedding modulus - a goal that should also be aimed towards in general. On the other hand, care must be taken that the terminating impedance on the bottom of the mat is as high as possible, i.e. the subgrade should be compacted as densely as possible.

Example of results achieved on a track section in Austria

A good opportunity for a comparison of the calculated insertion loss values of a ballast mat, as determined on the basis of the previously described analytical model for installation in an above-ground, open track section, with corresponding values measured for an actual operating track occurred at Austrian Federal Railways (ÖBB) at the beginning of 1995.

In the course of a noise reduction project in the vicinity of the Nüziders station on the double-track line Feldkirch-Bludenz, ballast mats were installed between the ballast bed and the gravel subgrade in sections of varying length totaling approx. 450 m. ÖBB indicated a compaction modulus (so-called \( E_{v2} \) modulus) of 180 MN/m², from which a subgrade stiffness of \( s_p \approx 3.5 \cdot 10^6 \text{ N/m} \) was determined, on the basis of experience and the assumptions in [18].

Measurements for structure-borne noise were conducted during the passing of intercity trains before and after the installation of the ballast mats [21]. Fig. 9 shows an example of the measurement results, which were determined at a measurement point next to the track section before and after installation of SYLODYN DN335 ballast mats (energetic mean values with scatter boundaries for several passing trains).

The insertion loss of the ballast mat was calculated as the arithmetical mean value of the 1/3-octave-band level differences, which were determined by combining the individual spectra measured during the measuring procedure both before and after the installation of the ballast mat. The result is shown in Fig. 10 along with the scatter boundaries as a function of the 1/3-octave band centre frequency.

Fig. 10 also shows the results of calculations, which were carried out for two different masses of wheel set, i.e. \( M = 3000 \text{ kg} \) and \( M = 1000 \text{ kg} \). Whereby for the ballast stiffness a value of \( s_x = 4.7 \cdot 10^8 \text{ N/m} \) (1 + j·0.5) was applied, and for subgrade stiffness a value of \( s_p = 3.5 \cdot 10^6 \text{ N/m} \).
It can be observed from Fig. 10 that, on average, the measured values and the calculated values agree relatively well in the higher frequency ranges above approx. 63 Hz, at which frequencies the stiffness of the ballast, the ballast mat and the subgrade are the determining factors.

In the lower frequency ranges the result of calculations is strongly dependent on whether one assumes an unsprung mass of wheel set of $M = 3000 \text{ kg}$ or $M = 1000 \text{ kg}$. The first case - 3000 kg - would be applicable for the passing of a locomotive, which during the measurements described was the ÖBB Class 1044 locomotive. According to experience, the latter case – 1000 kg - approximates the dynamic load that would be caused by passing of passenger stock.

Nevertheless, in this frequency range, the two curves for the calculated values, shown in Fig. 10, define quite well the limits within which the measured results were recorded. It can thus be concluded that in the future a tentative prognosis regarding effectiveness is possible for cases where ballast mats are to be installed on compacted subgrade. Due to the more complex set of boundary conditions, however, this prognosis will for the present not achieve the level of accuracy possible for calculations with respect to the use of ballast mats in tunnels.

On behalf of ÖBB structure-borne noise was measured inside residential buildings next to the track section after installation of the ballast mats. Respective measurements were also carried out in the same buildings during construction prior to the installation of the ballast mats. The results of these measurements revealed that the difference in structure-borne noise level was beyond expectation [22].

Conclusions

In the past, measures to reduce structure-borne noise, such as the installation of ballast mats, mass-spring systems, elastic rail fasteners etc., have primarily been applied in railway tunnels in urban areas or on railway bridges. The need for such measures to be applied in above-ground, open railway lines is increasing though, as a result of the extension and renewal of these lines, often in heavily populated areas and near residential buildings.

However, in contrast to underground railway lines, for which a tried and tested set of measures is available that has been developed over the years, little is known with respect to above-ground, open railway lines. The information that is available is often inconsistent, with the exception for tunnel sections. Furthermore, conditions for above-ground, open railway lines are generally more complex as a result of the fact that certain key parameters and boundary conditions can often not be determined with the required or desired level of certainty.

The measures described in this article related to the use of ballast mats, which were also tested under operating conditions, should serve to show that it is possible to achieve good results at a reasonable technical expense, in spite of the more complex set of boundary conditions found here.

Long-term experience gained with respect to track stability at the DB test track section at Altheim, Lower Bavaria, has been very positive [12].

Due to the relatively recent date of installation, long-term results are not yet available for the ÖBB track section with installed ballast mats on subgrade. Nevertheless, after approx. one and a half years of operation no negative effect with respect to the track geometry have been observed.

ÖBB has announced that it will monitor the track geometry of this track section, as very soft ballast mats of the type SYLODYN DN335 have been used, the bedding module of which is substantially lower than 0.06 N/mm² which would have been normal for the given speed and load (axle load) of the line. Detailed information concerning this will thus not be available until a later date.

References


