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The Excitation, Propagation and Mitigation of Train-Induced Ground Vibrations from the Axle Impulses on the Track

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Abstract

Train-induced vibrations in soft ground usually have a strong low-frequency component. This component has a characteristic spectrum which is related to the axle sequence and the speed of the train. Its attenuation with distance is weaker than the attenuation for higher frequencies, and it always dominates the far-field ground vibration. Narrow-band frequency analyses clearly show that this ground vibration component is due to the static axle loads. Axle box vibrations have a different characteristic where the first out-of-roundness of the wheels is the only remarkable low-frequency component. Therefore, the dynamic axle loads from wheel and track irregularities are not the reason for the strong ground vibration component. The moving static axle loads generate the quasi-static response of the soil at very low frequencies and at very near distances. A part of the original impulse spectrum is scattered when it propagates through an inhomogeneous ballast and soil with a randomly varying stiffness. The axle impulses are smoother for a higher bending stiffness or a lower support stiffness (under sleeper pads, under ballast mats) of the track. This mitigation of the ground vibration will be demonstrated by measurements at three sites in Switzerland as well as the characteristic of the soil and axle-box vibrations.

Keywords: soil and vehicle measurements, train passages, ground vibration, excitation mechanisms, mitigation, under sleeper pads, under ballast mat.

1 Introduction

Train-induced ground vibration can be mitigated by soft elements in the track such as under sleeper pads and under ballast mats (Fig. 1). The reduction effect is established as a frequency-dependent amplitude ratio or level difference usually by one-third octave band spectra in the wide range of 4 to 250 Hz [1]. The dynamic reduction is at high frequencies which are present at the mid-range distances of 8 or 16 m. The lower frequencies, typically between 10 and 30 Hz for passenger trains, become dominant at longer distances (Fig. 2). Reduction effects can also be found in this lower frequency range, and measurement results will be given which clearly demonstrate that this is an effect of the passage of the static loads over an irregular ground.

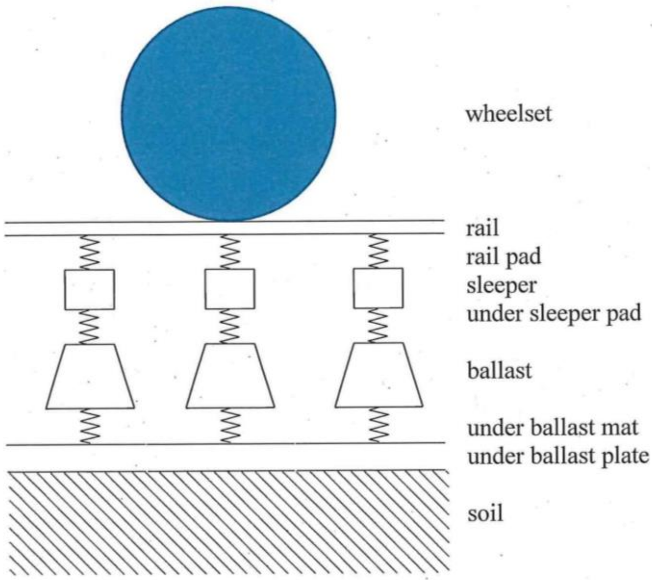
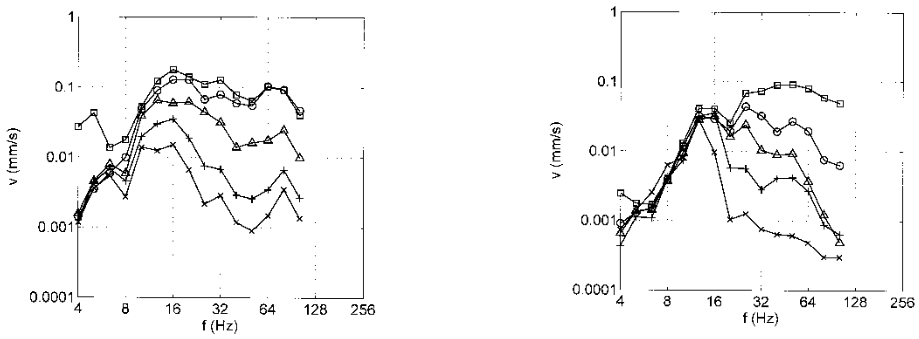


Figure 1: The excitation of ground vibrations by the vehicle-track interaction and its mitigation by rail pads, under sleeper pads, an under ballast mat, and an under ballast plate.



a) b)

Figure 2: Train-induced ground vibrations at a) the Selzach and b) the Lengnau site, one-third octave band spectra measured on an axis of sensors at distances □ 4/6, ○ 8, △ 16, + 32, × 64 m, passenger trains with 120 and 160 km/h.

2 Methods to assess the reduction effects of mitigation measures

The reduction effects of mitigation measures are usually measured from train passages before and after the construction of the measure or at different isolated and un-isolated

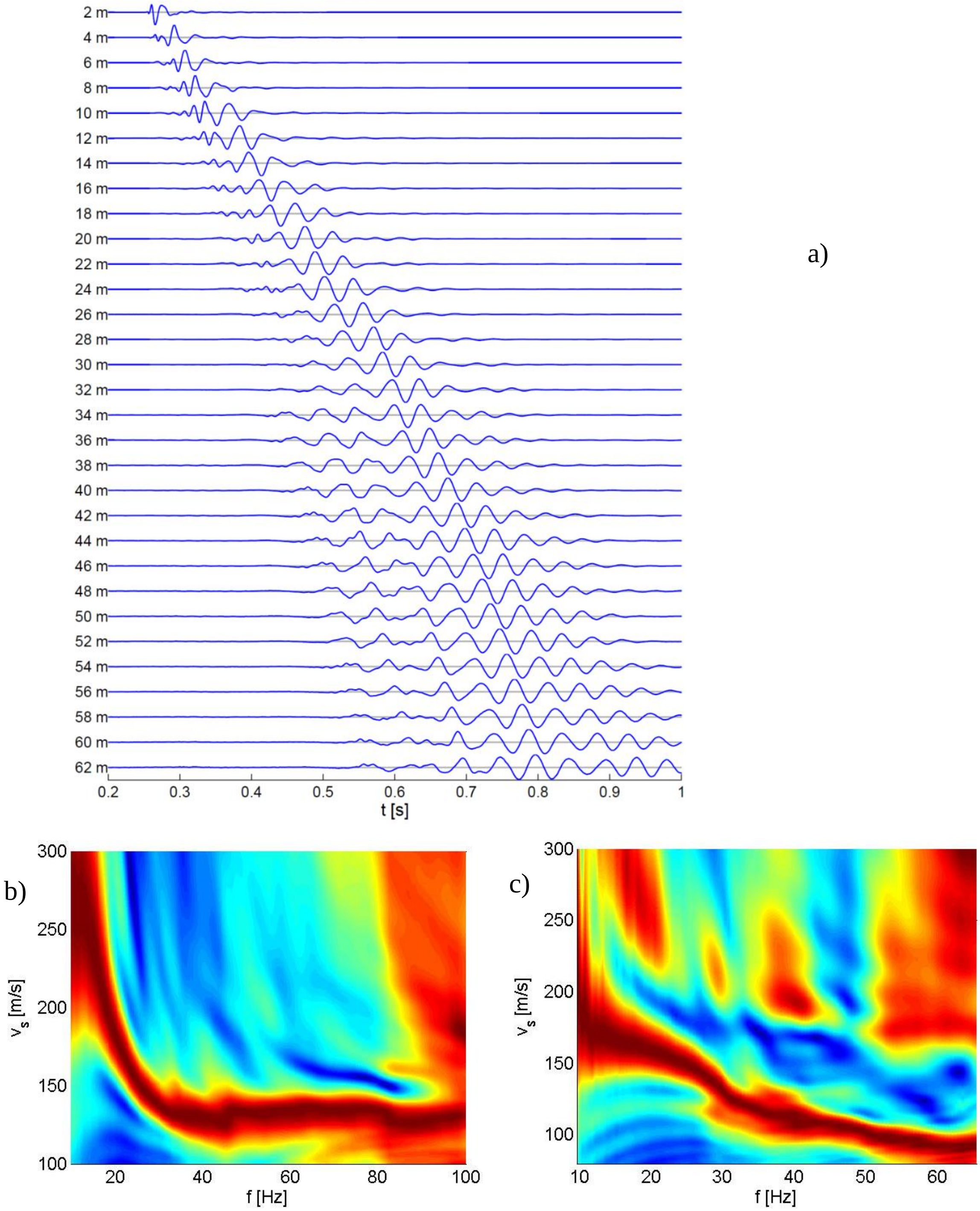
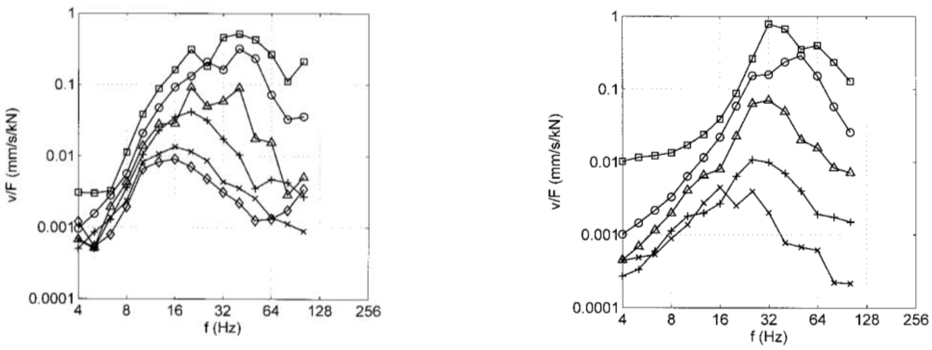


Figure 3: Soil properties at the Pieterlen site, wave velocities from a) the time histories (seismogram), and from the frequency-wavenumber transform at the section without (b) and with (c) under sleeper pads.

track sections. The following recommendations can be given:
1. The original ground vibration spectra for the isolated and un-isolated track should be reported for to check if the established reduction is for the main amplitudes or for smaller and more random amplitudes.
2. The reduction should not be measured in the near field of the track (for example at the tunnel wall or at 5 m distance from the track) as the quasi-static response could lead to a too positive mitigation effect.
3. It is better to measure not only one measurement point but a line of measurement points for to check the regularity of the soil.
4. The reduction depends strongly on the reference system. A stiff reference track would give the “best“ mitigation effect.
5. It is recommended to analyse the reduction separately for different train types and train speeds.
6. It is always useful to measure the properties of the soil at each track section. Even nearby track sections can have different soil properties.
7. If the soil is different at the isolated and un-isolated track section, a correction should be made [4].



a) b)

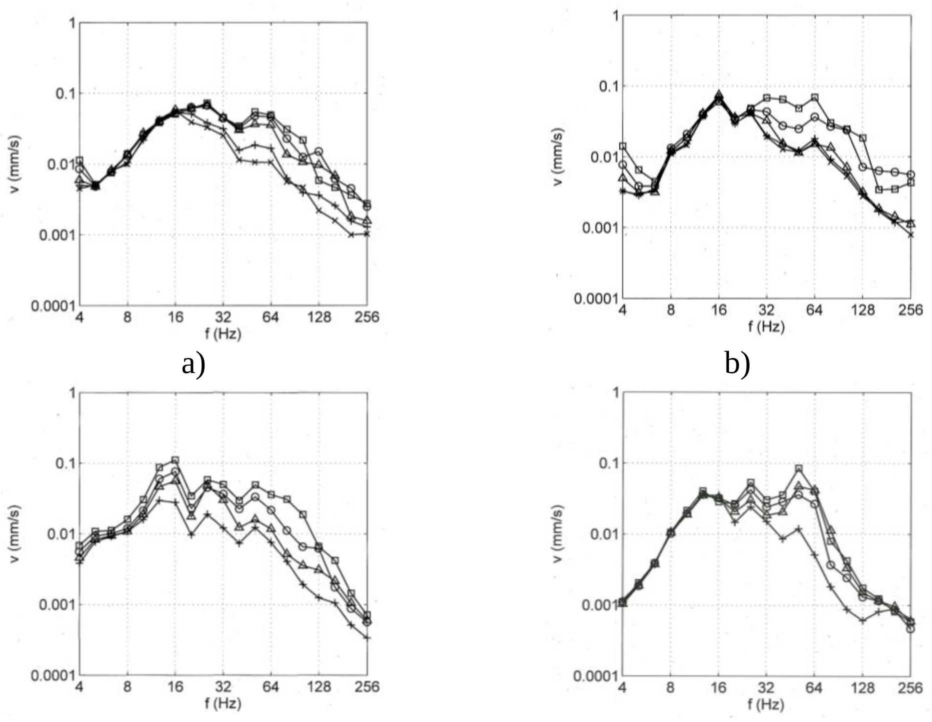
Figure 4: Ground vibrations from hammer impacts at a) the Selzach and b) the Lengnau site, transfer functions measured on an axis of sensors at distances a) □ 4, ○ 8, △ 16, + 32, × 48, ◇ 62 m and b) □ 4, ○ 8, △ 16, + 32, × 64 m.

The properties of the soil can be measured with an additional axes of equidistant measurement points (along or transverse to the track). The time history plot (Fig. 3a) gives a first information about the wave velocity and the stiffness of the soil. The spectra of the time histories can be evaluated for the frequency-dependent wave velocity (the dispersion) of the soil (Fig. 3b,c) [2]. These measurements indicate that the soil at the Lengnau axes (including the reference track without under sleeper pads)) is stiffer than at the Pieterlen axes (the isolated tracks with under sleeper pads) while the corresponding north and south axes in Pieterlen give similar results. Moreover, the transfer function of the soil can be measured (Fig. 4) and evaluated for a layered soil model [3]. It can be concluded that the Selzach and the Lengnau site have the same wave velocities v_{S1} and v_{S2} for the upper layer and the underlying half-space, but that the soft upper layer at Selzach (Fig. 4a) is thicker and therefore there is a lower layer frequency (at about 10 Hz compared to 20 Hz at Pieterlen) with a strong increase of the amplitudes. There is also more damping at the Lengnau site what can be concluded from the stronger attenuation with distance (the stronger spread of the curves). The original or the approximated transfer functions can be used for a correction if the soils are different at the different sections [4]. It is also advantageous if axle-box accelerations are measured and give some information about the dynamic vehicle-track excitation of the ground vibration [5].

3 Mitigation results from three measurement sites in Switzerland

3.1 The Pieterlen/Lengnau site with under sleeper pads

The Federal Institute of Material Research and Testing has performed ground vibration measurements at 12 sites in Switzerland [3] where four sites (Selzach, Lengnau, Pieterlen, and Le Landeron) are near the Bieler See. On a 1 km long line segment between the villages Pieterlen and Lengnau, test sections with different under sleeper pads have been constructed. BAM has measured the soil properties on several axes along both sides of the track (Fig. 3 and 4), and the train-induced ground vibrations on axes perpendicular to the railway line (Fig. 2 and 5) [6]. The train-induced results are quite similar for the north and the south side of the line (Fig. 5a,b), but differences along the 1 km test track could be observed. The amplitudes are higher for the softer Pieterlen sites (Fig. 5a,b) compared to the stiffer Lengnau sites (Fig. 2b, 5c,d). The mitigation effects (Figure 6) have been hidden (under-estimated) [7] as the



a) b) c) d)

Figure 5: Train-induced ground vibrations at the un-isolated tracks in a) Pieterlen North, b) Pieterlen South, c) Lengnau, and d) the track with under sleeper pads in Lengnau, one-third octave band spectra measured on an axis of sensors at distances of a,b) □ 5, ○ 6, △ 7, + 10, × 12 m and c,d) □ 8, ○ 10, △ 12, + 16 m.

reference track is on a stiffer soil than most of the isolated track sections. To correct this, the comparisons have been done between the isolated southern track and the un-isolated northern track using the same sensor, and a high-frequency as well as a low-frequency reduction has been established (Fig. 6, triangle markers) [8].

The reference track (Fig. 5c) shows a dominating low-frequency part at 12 to 16 Hz which is clearly reduced by the under sleeper pads (Fig. 5d). The high frequency maximum at 50 to 60 Hz is therefore more dominant for the isolated track, and the

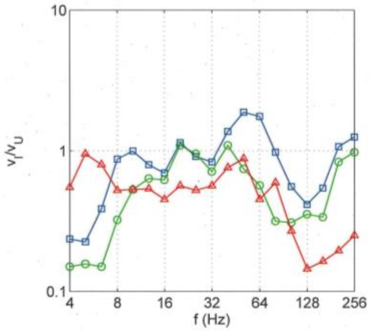
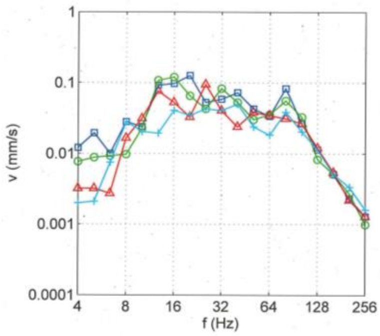
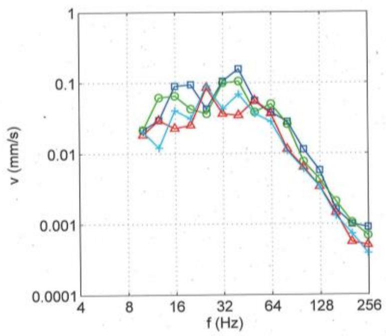


Figure 6: Ground vibration reduction by under sleeper pads at □ Lengnau track with under sleeper pads type 1, ○ Lengnau track with under sleeper pads type 2 (BAM measurements), △ average of all Pieterlen/Lengnau isolated tracks (RIVAS evaluation using the northern track as reference) [8]



a)



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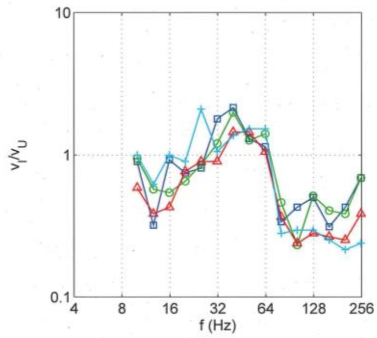


c)

Figure 7: Train-induced ground vibrations at the Raron site at 8 m distance from a) the un-isolated track, b) the track with under ballast mat, c) the ground vibration reduction; different train speeds of □ 175, ○ 160, △ 120, and + 80 km/h.

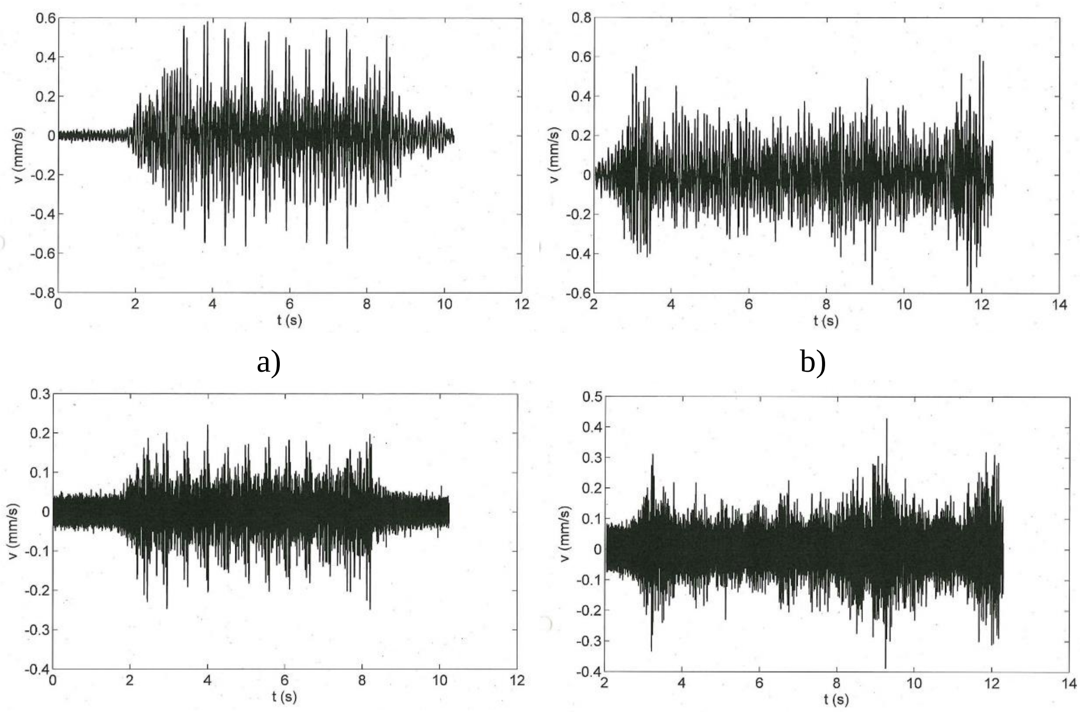
vehicle-track resonance may be expected here. The higher frequencies are then also reduced by the under sleeper pads.

3.2 The Raron site with under ballast mats

At Raron in the Wallis, different test tracks with under ballast mats have been constructed [9, 10]. The measurements had shown a low- and high-frequency reduction and are now analysed in more detail by looking at the original spectra (see appendix) for different train speeds. In Figure 7a it can be clearly seen that the different train speeds generate amplitude maxima at different frequencies - at 20 Hz for 175 km/h, at 16 Hz for 160 km/h, at 12 Hz for 120 km/h and at 8 Hz for 80 km/h - and Figures 7b,c show that the low-frequency reduction of up to 10 dB correlates well with these maxima. An amplification around 40 Hz can be observed in Figure 7b and 7c, and the frequencies above 64 Hz are reduced by about 10 dB. On the other hand, an amplification of the sleeper vibration is observed with an under ballast mat, see the Appendix. This clearly indicates that the vibration of the track is not the emission quantity, and that the force transferred from the track to the ground must be analysed for to predict the ground vibration of the track with ballast mat [11].

3.3 The Sempach site with under sleeper pads

North of Luzern near Sempach, the Swiss Confederation has built a monitoring station with several test sections for noise and vibration measurements of isolated and un-



a) b)

c) d)

Figure 8: Train-induced ground vibrations at the Sempach site at 8 m distance, a,c) time histories from an articulated and b,d) from a conventional passenger train, track a,b) without and c,d) with under sleeper pads.

isolated tracks. Some results from tracks with and without under sleeper pads are shown for two train types in Figures 8 and 9. The passenger train with shared bogies (articulated train) has clearer maxima for each bogie (Fig. 8a), whereas the conventional passenger train (with two bogies per carriage) results in higher amplitudes for the locomotives (Fig. 8b). The ground vibration at the isolated track is clearly lower than at the un-isolated track section, in time domain (Fig. 8) as well as in the linear (Fig. 9a,b) or one-third octave frequency domain (Fig. 9c,d). Especially at low frequencies, the differences are very big and reach values of more than 20 dB (Fig. 9e).

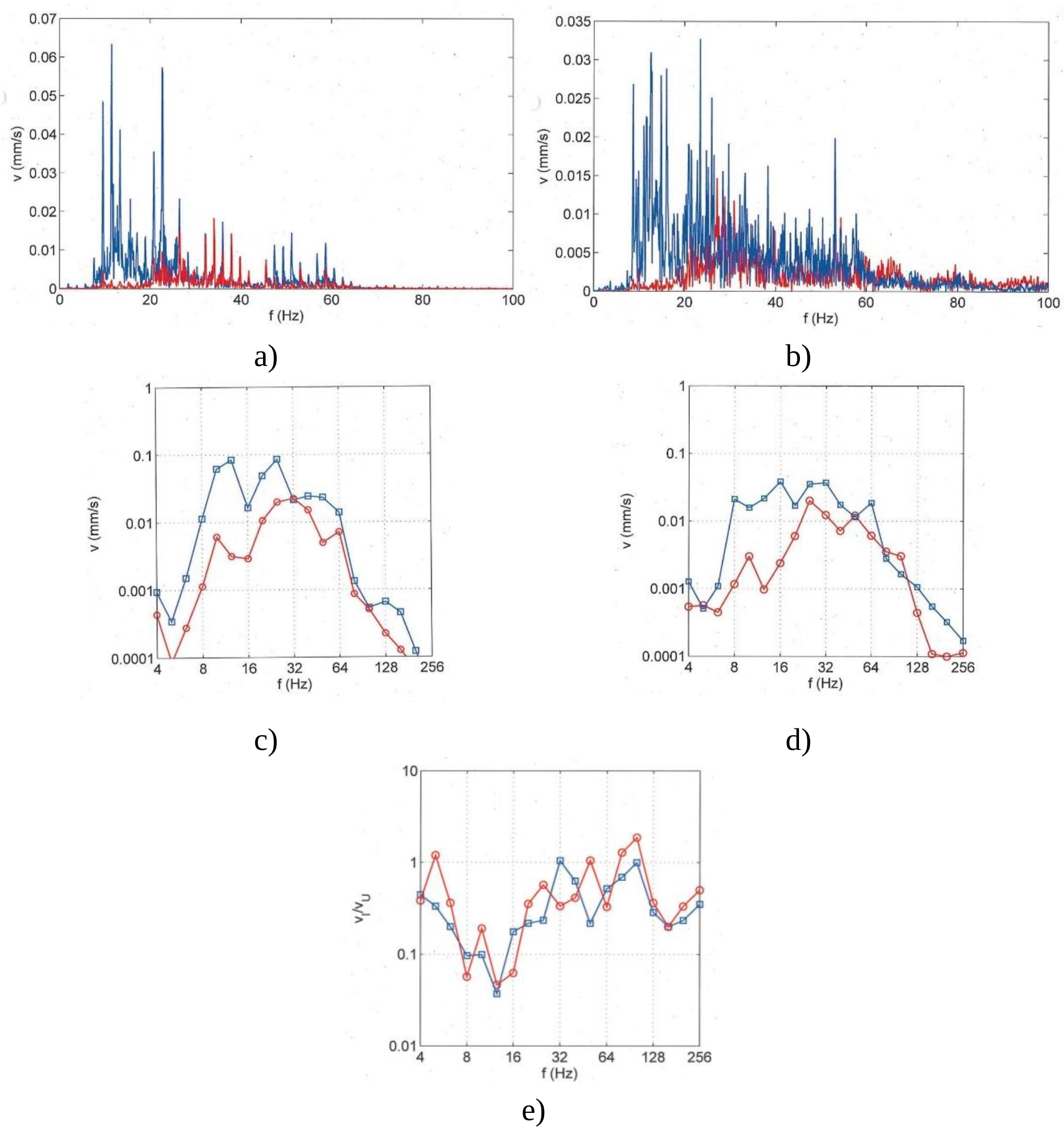


Figure 9: Train-induced ground vibrations at the Sempach site at 8 m distance, a,b) linear and c,d) one-third octave band spectra, a,c) from an articulated and b,d) a conventional train, without (blue) and with (red) under sleeper pads, e) ground vibration reduction for ☐ the articulated and ○ the conventional train with 120 km/h.

The ground vibration is confronted with the measured axle-box accelerations in Figure 10 as linear spectra, one-third octave band spectra, and as a spectrogram. In all these presentations, no relevant differences between the track without and with under sleeper pads can be found. Moreover, the linear spectra of the axle box (Fig. 10a) and the ground vibration (Fig. 9a) have little similarity. Whereas the ground vibrations have a wide frequency band between 10 and 25 Hz, the axle-box accelerations have a strong peak at 10 Hz for the first out-of-roundness of the wheel and at 55 Hz for the sleeper-passage component, see also the spectrogram in Figure 10c. It can be clearly concluded from these observations that the specific low-frequency ground vibration component is not generated by dynamic axle loads but by the passage of the static axle loads.

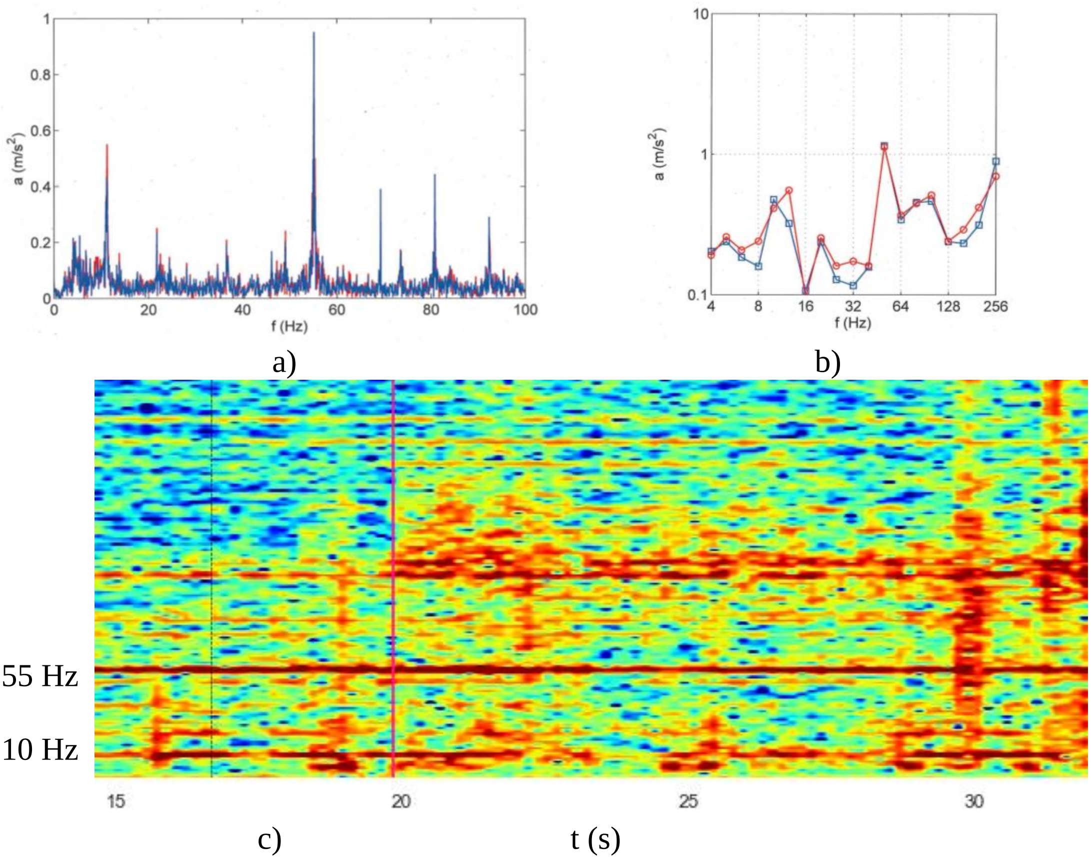
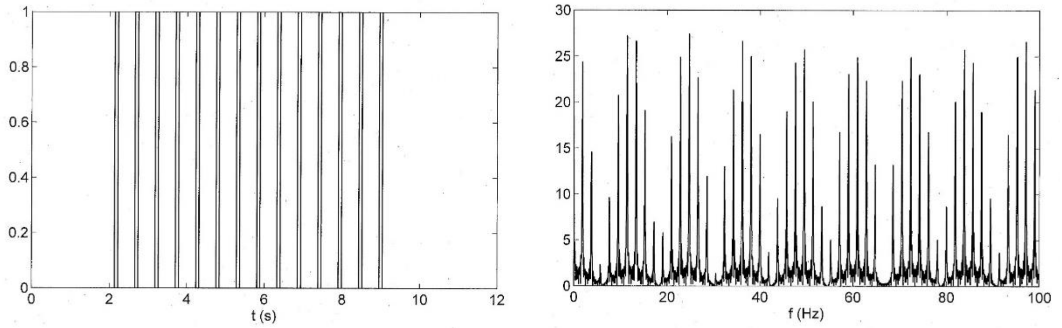


Figure 10: Axle-box accelerations of a train with 120 km/h, the Sempach track sections without (blue) and with (red) under sleeper pads, a) linear spectra, b) one-third octave band spectra, and c) spectrogram (the un-isolated track starts at t = 20 s).

The characteristic spectrum of the ground vibrations is compared with the axle-sequence spectrum of the articulated train in Figure 11. The passage of the 12 bogies in a distance of L_C = 17.5 m gives a series of peaks at df = v_T/L_C = 1.9 Hz which have minima at $f_i = v_T/L_A$ 1/2, 3/2, 5/2, … = 6, 18, 36, … Hz according to the axle distance L_A =2.75 m in a bogie. This pattern of the articulated train can clearly be identified in the measured spectra in Figure 9a. (The axle sequence spectrum of the conventional train with locomotives is less significant with wider frequency bands and little higher frequencies for the minima due to the shorter bogies with L_A = 2.5 m, see Figure 9b). The maximum amplitudes between the first and the second minimum at 6 and 20 Hz are strongly reduced by the track with under sleeper pads.



a) b)

Figure 11: Sempach site, calculated axle sequence for the articulated train with shared bogies, a) time history, b) linear spectrum.

4 Conclusions and Contributions

A low-frequency reduction of ground vibrations by soft track elements such as under ballast mats and under sleeper pads has been found for three measurement campaigns in Switzerland. It is important to measure the soil properties for each site, and a correction could be necessary as has been demonstrated for the Lengnau/Pieterlen site. It was proved by axle-box measurements at the Sempach site that the strong low-frequency ground-vibration component is due to the passage of the static axle loads. The regular response, the quasi-static down- and upward motion is limited to the very low-frequencies in the near field (for example the maximum at 5 Hz for the 4 m point in Fig. 2a). At 8 m distance, it can only be the irregular response to the passing static loads which are the axle impulses on the track scattered by a randomly varying stiffness of the ballast and the soil [12]. This scattered impulse component is also found in the characteristic linear spectra of the articulated train in Sempach, as a maximum in the one-third octave band spectra in Pieterlen/Sempach/Selzach, and in its clear speed dependency at the Raron site. The scattered impulses are reduced by a track with mitigation measure where the axle impulses are reduced (wider distributed) by under sleeper pads and under ballast mats.

Acknowledgements

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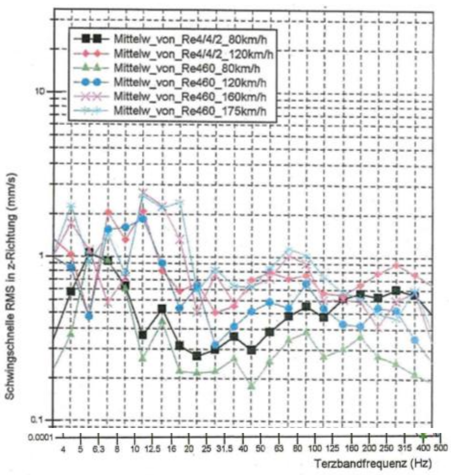
Appendix. Original spectra from the Raron site with under ballast mats

The original one-third octave band spectra from two un-isolated reference and two isolated track section, for the sleeper, the 8 and 16 m distance and for all measurement trains and train speeds are shown in Figure 12. At the sleeper, the low-frequency range below 20 Hz is clearly dominating. There are typically three thirds of octave depending on the train speed: 6.3 to 10 Hz for 80 km/h, 8 to 12.5 Hz for 120 km/h, and 12.5 to 20 Hz for 160/175 km/h. This vibration component is due to the passage of the static axle loads and the axle sequence in a bogie. This speed-dependent component can also be found in the ground vibrations. At 8 m distance, the ground vibration has a wide spectrum from 8 to 100 Hz (Fig. 12c,e). The higher frequencies are damped out at 16 m distance (Fig. 12d,f) so that the special speed-dependent low-frequency component is dominating. This ground vibration component is reduced for the tracks with under ballast mats (Fig. 12g,h,i,j). On the other hand, there is an amplification around the new vehicle-track resonance at 40 Hz. Higher frequencies are reduced by the under ballast mat, see for example the sleeper-passage component.

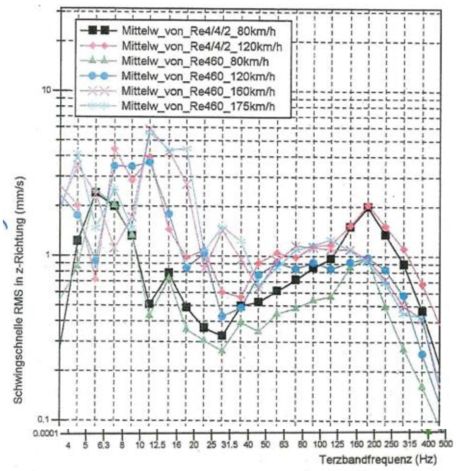
Whereas the ground vibration amplitudes are reduced by the under ballast mats, the sleeper vibrations (Fig. 12a,b) are amplified because of the higher compliance of the track. This indicates that the sleeper vibrations are not relevant for the far field and not an emission quantity. The frequency-dependent reduction effect should be generally similar for different distances. As the reduced low-frequency part is more dominating at longer distances, the total reduction (of the rms-value for example) would be stronger at 16 m than at 8 m.



a)

U

0 m

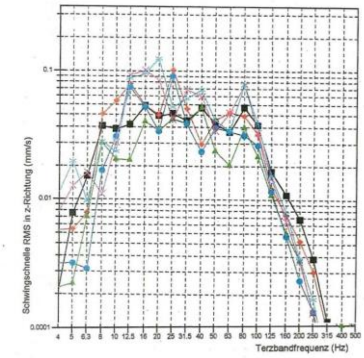


b)

I

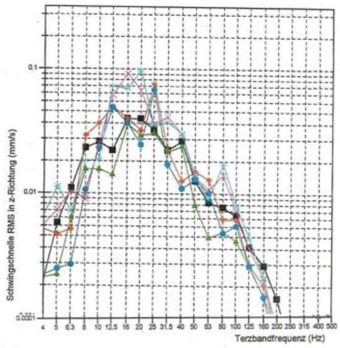
0 m

Figure 12: Raron site with under ballast mat, train induced vibrations as one-third octave band spectra, a,b) at the sleeper (0 m) without and with under ballast mat, c,d,e,f, next page) two un-isolated track sections U1 and U2 at 8 m and 16 m, g,h,i,j) two isolated track sections I1 and I2 at 8 m and 16 m, different trains and train speeds □,△ 80, ◇,○ 120, × 160,∗ 175, [9].



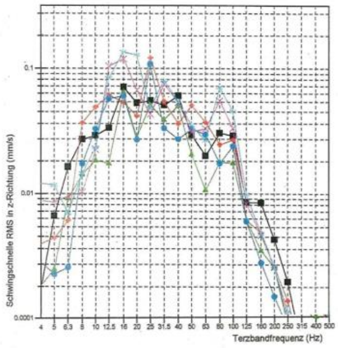
c)

U1 8 m



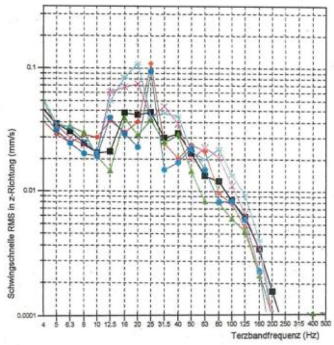
d)

U1 16 m



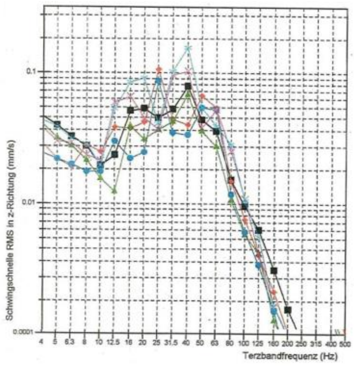
e)

U2 8 m



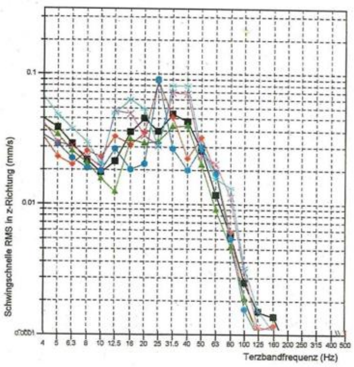
f)

U2 16 m



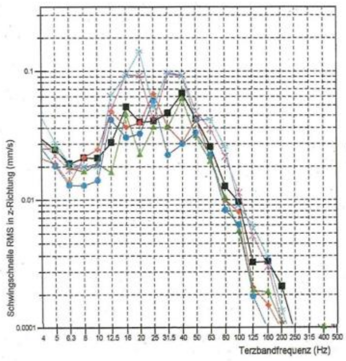
g)

I1 8 m



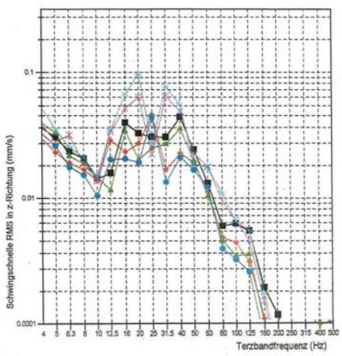
h)

I1 16 m



i)

I2 8 m



j)

I2 16 m