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EXPERIMENTAL METHODS FOR TRAIN VIBRATION FORECASTS

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Abstract

Noise and vibrations are considered to be the most disturbing environmental problems of railways. While prediction and abatement of noise are well established techniques, vibrations are more complicated to handle. Reasons are the complex transmission behavior of the underground and the feedback by the dynamic properties of buildings, which control the frequency transfer functions and the level of vibrations experienced by local residents. Therefore reliable vibration forecasts are necessary, especially for shallow sections of new railway tunnels in residential areas. Due to the extremely limited knowledge of underground geodynamics vibration experiments are indispensable to determine frequency transfer functions for the entire transmission path. Refraction seismic profiles for P- and S-waves enable the calculation of eigenfrequency models from the underground before starting construction. As soon as the basic tunnel construction is completed a heavy seismic servo hydraulic vibrator there can synthesize train emissions with frequency sweeps covering the entire spectrum of railway vibrations.

INTRODUCTION

It is unavoidable that moving trains cause vibrations and groundborne noise. When ever emission reduction is required, the vibration characteristics of the source, the local geodynamics of the subsoil and the dynamic behavior of the neighbourhood buildings have to be taken into account. They altogether form an elastic feedback system in a complex manner with significant local variations. Therefore in-situ experiments are indispensable for reliable forecasts.

It is well-known that the human perception of vibrations is twofold. First, vibrations may be felt directly as oscillations and second, the vibration of solid surfaces may reradiate ground-borne noise. Different frequency weighting filters of vibration records are required to get W_m-weighted vibration perception levels and A-weighted sound pressure levels according to ISO standards.

With regard to solid structures, vibrations cause dynamic stress eventually with damaging potential. In addition buildings as well as the subsoil have to be considered as elastic entities, which own specific natural frequencies and corresponding resonance properties. These natural frequencies depend on the elastic properties, dimensions and the shape of the relevant unity.

This behavior is shown in Fig.1 for the example of a single underground layer based on an elastic half-space [1].

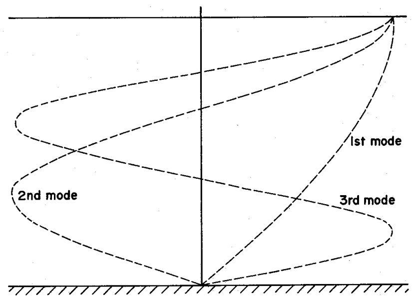


Figure 1 – Modal shapes for a uniform subsoil layer

VIBRATION PROPAGATION

Vibrations are propagated in form of various types of seismic waves which own characteristic vibration patterns and are classified as body-, surface-, channel- and flexural waves. The intensity and propagation velocity is guided by the elastic properties and differs for all wave types. Trains on tracks at the surface will generate primarily far reaching surface waves, while such on tunnel tracks will create predominantly body waves of higher frequencies. It has to be noted, that due to the length of seismic waves the geodynamic behavior of geologic units in rather great depths is important for vibration propagation as well [4].

But the major challenge for vibration forecasts results from the irregularly structured underground, which causes refraction, reflection, diffraction and resonances [2] as it is indicated in Fig.2.

In the planning phase of a new transit line project especially refraction seismic profiles and seismic uphole surveys are suitable as first exploration methods for investigating the geodynamic conditions. The example in Fig.3 presents a refraction seismic profile delivering cross sections of the depths of discontinuities and P- and S-wave propagation velocities of the intermediate layers.

These seismic velocities enable the determination of elastic moduli. Furthermore, based on the theory of Roesset [1] the frequency transfer functions for P- and S-waves of a multilayer-underground cross section can be calculated under some simplifying approximations according to Fig.4.

Thus basic information on the vibration propagation in the underground can be obtained already in the planning phase.

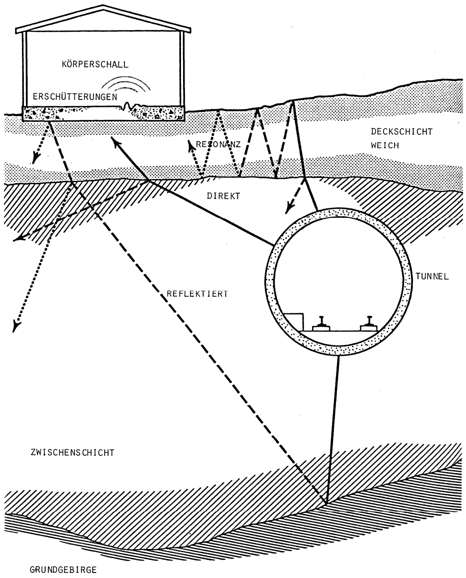


Figure 2 – Manifold transmission paths in the underground

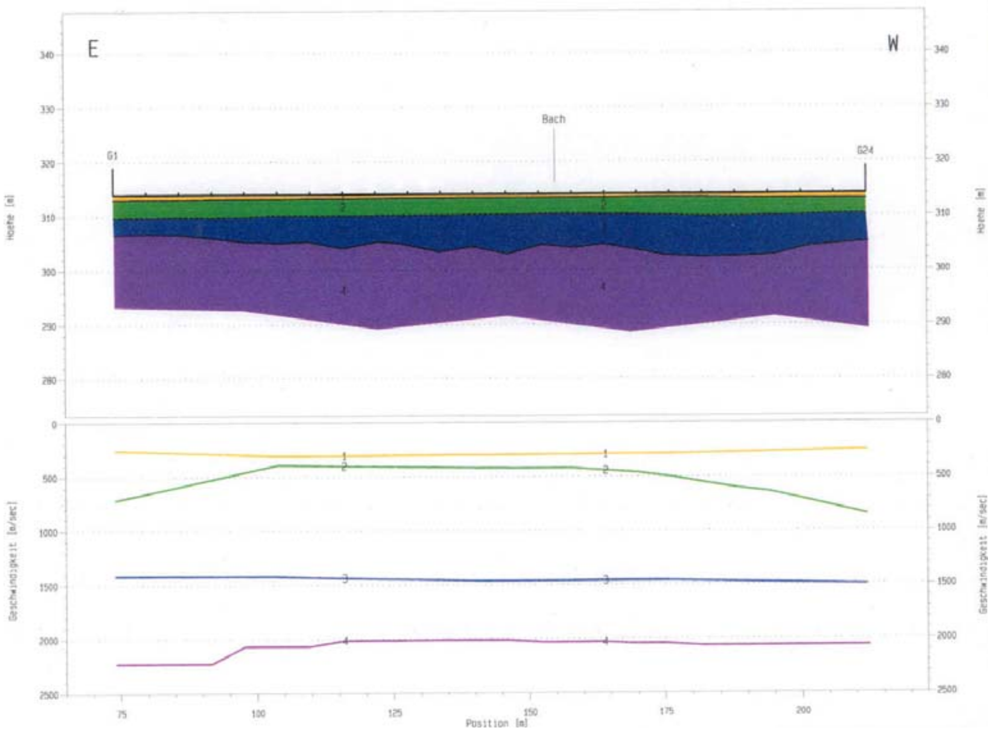


Figure 3 – Refraction seismic cross section

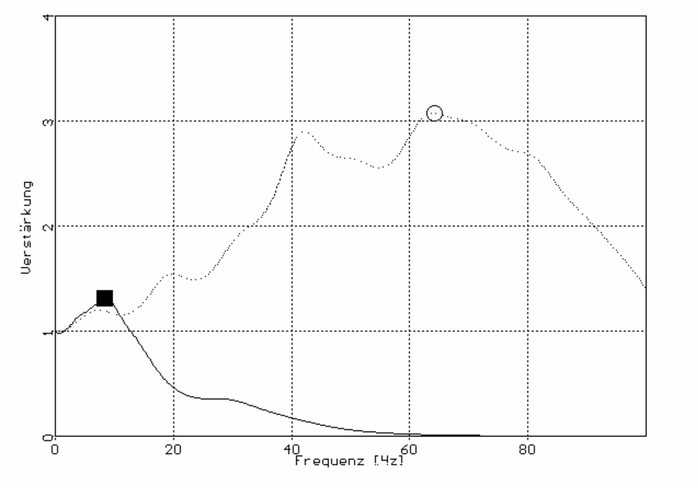
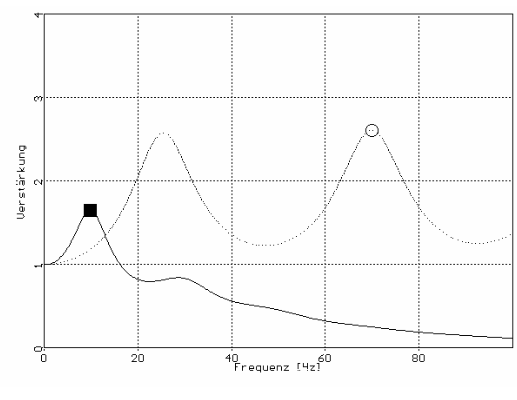


Figure 4 – Frequency transfer function for the cross section of Fig.3
circle: maximum amplification of P-waves
square: maximum amplification of S-waves

A sufficient depth resolution of geodynamic investigations is necessary for obtaining realistic vibration transfer spectra. Geotechnical knowledge from the uppermost 7-10 m of the underground will be sufficient for static considerations of the construction work, but will be misleading for dynamic problems like vibration propagation as Fig.5 demonstrates. At left the model calculation for geologic structures resolved only to 8 m depth is shown, while at right layers down to 80 m below surface are considered in the model [3]. This expansion of the model domain shifts the natural frequencies significantly to lower frequencies – thus increasing the efforts for damping considerably.



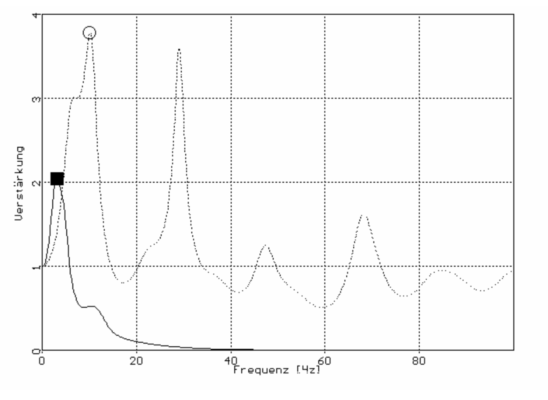


Figure 5 – Models from natural frequencies of the underground with a model domain of 8 m depth (left) and 80 m (right)

INSERTION LOSS CALCULATION AND GEODYNAMICS

The usual insertion loss calculations for ballast mats or floating slabs are done assuming a rigid base of the resilient system [5]. It is evident that this assumption is not fulfilled for tracks based on a soft layered substratum. But also for tunnels embedded in soft sedimentary layers significant differences to a rigid basement exist and an elastic feedback can be observed.

In combining the frequency transfer functions from a seismic cross section with the insertion loss equation it is possible to take this elastic feedback quantitatively into consideration. The example of Fig.6 gives at left the seismic derived model of natural frequencies from a sedimentary layered underground and compares at right the standard calculation for the insertion loss of a ballast mat with the calculation taking into account the geodynamics as well: the soft layered substratum causes a reduction of the insertion loss of about 6-14 dB.

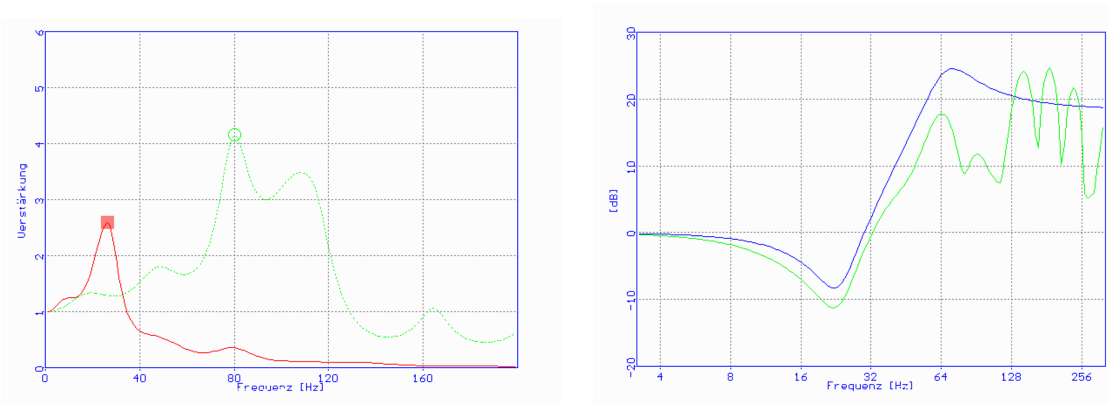


Figure 6 – Geodynamic frequency transfer function (left) and its effect on the insertion loss calculation (green); blue: insertion loss for rigid base

EXPERIMENTAL FREQUENCY TRANSFER FUNCTION DETERMINATION

Once a tunnel is driven through the underground the frequency transfer function for the entire transmission path from the tunnel bottom to local residents can be determined directly by the VibroScan method before the permanent way is built. This method synthesizes the train vibrations by frequency sweeps covering the entire spectrum of railway vibrations (Fig.7) generated by a seismo hydraulic vibrator. The goal is to substitute train vibration emissions as realistic as possible. This concerns vibration source type, vibration intensity, frequency spectra, vibration duration and the ratio of static to dynamic load. Only the intensity of vibrations is intentionally oversized in case of high background vibration levels at a construction site.

Figure 7 – VibroScan vibrator

The comparison train – vibrator proofs the similarities of both vibration sources according to Table 1.

Table 1 – Comparison of dynamic parameters train – seismic vibrator

Parameter	train	seismic vibrator
unsuspended axle mass/actuator mass	2000-4000 kg	3500 kg
peak excitation force	100 kN	225 kN
surface under load	2,9 m^2	2,8 m^2
ratio dynamic/static load	≤1,6	≤2,2
peak ground pressure	9-12 N/cm^2	15 N/cm^2
frequency band	1-120 Hz	1-250 Hz
spectral characteristic	broadband	sweep

As the human vibration perceptivity is proportional to the vibration velocity for the largest part of the frequency spectrum a constant vibration velocity output of the vibrator for the entire frequency range is desirable. This is obtained by tuning the upward sweep from low driving forces in the beginning to high driving forces at the end. But of course, good seismic coupling between vibrator and underground is essential. This priority can cause deviations up to ± 2 dB from a flat velocity output, which is acceptable. Fig.8 shows an example for a VibroScan investigation with frequency spectra from the emissions at the tunnel bottom, the foundations of a nearby building and the second floor sleeping room.

Especially the equivalence of source types seems to be important for the success of such experiments. Train vibrations act as surface load to the underground and the same has to be true for vibrators. In case of a tripod mounting of the vibrator high punctual loads occur and it can be shown that in this case the vibration propagation depends on the area of the base plate.

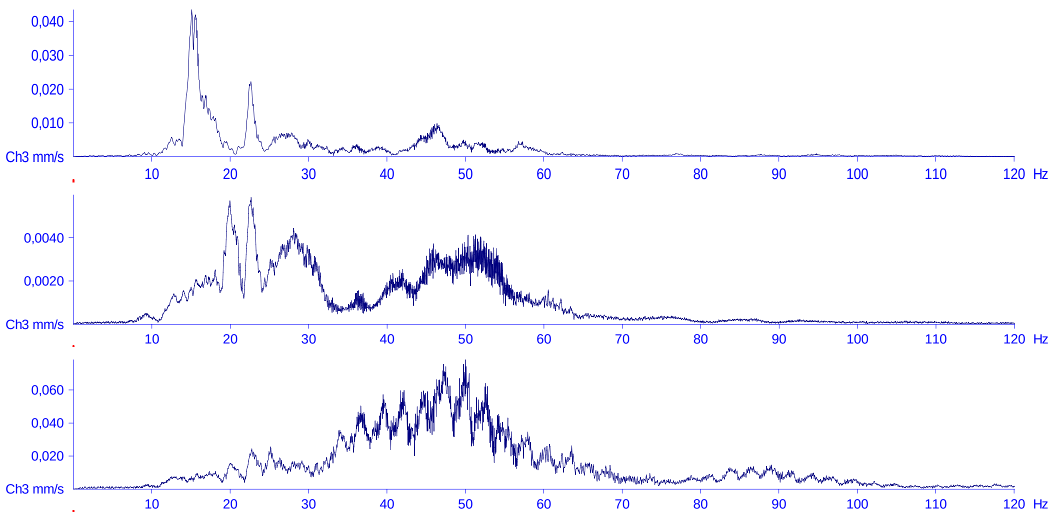


Figure 8 – VibroScan analyses example
(Top: sleeping room floor, center: building foundation, bottom: tunnel)

One advantage of the VibroScan method is that vibration forecasts are possible without knowing details of the dynamics of the tunnel and the residential buildings or the geodynamics. Another advantage is that changes in the vibration propagation conditions due to construction work can be detected. Fig.9 demonstrates the increase of vibration intensity and the broadening of the spectrum due to a "vibration bridge" between tunnel and building foundations caused by cementation injections in the underground while tunnel driving, detected by VibroScan.

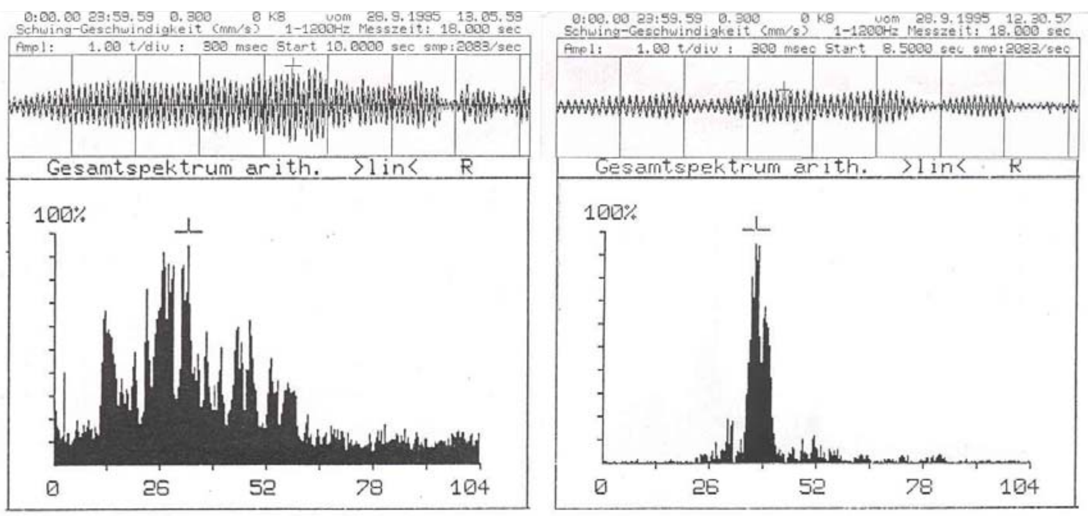


Figure 9 – Effect of "vibration bridges" on intensity and spectra of vibrations
left: building with vibration bridge contact to the tunnel
right: building without contact

CONCLUSIONS

Due to the limited knowledge of the geodynamic behavior of the local underground vibration experiments are indispensable for reliable vibration prediction and abatement. The advantages can be summarized as follows:

- Refraction seismic profiles deliver elastic parameters (P- and S-wave velocities) and the cross-section geometry (size and depth of layers), thus enabling the calculation from analytical models of the natural frequencies of the underground.
- Sufficient model-depth domains are required to receive realistic geodynamic models which cover also the lower part of the vibration transfer spectra.
- Insertion loss calculations can be improved by taking into account the elastic feedback from the tunnel with soft sediments by adding the geodynamic model of natural frequencies to the calculation procedure.
- Synthesizing train vibrations by a VibroScan vibrator enable the determination of the vibration transfer functions from a future railway line to neighborhood buildings without any need for information about the local geology and building dynamics.
- VibroScan sweeps can be tuned in equivalence to train vibrations concerning excitation force, ground pressure, frequency spectrum and duration.
- Vibrator sweep investigations are carried out under the final environmental vibration transfer conditions as the tunnel is built. Thus all changes produced by tunnel driving are taken into account. Even unintentionally created “vibration bridges” to residential buildings can be detected and considered in insertion loss calculation.
- The vibrator design as automotive machinery with 4-wheel steering allows high mobility even under narrow conditions as in a tunnel.

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