

Vibration immission forecast by means of train equivalent synthetic vibration experiments

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Abstract. Vibration abatement measures at a railway track require forecasts before the rails are put into place. Due to the multiple feedback system between train, track, geodynamics of the local underground and the dynamic behaviour of the neighbourhood buildings these prognoses become very elaborate. All the parameters of the dynamic system scatter extremely as the results from numerous investigations prove. This concerns vibration emission spectra, tunnel mobility, geodynamic vibration loss along the transfer through the underground as well as the natural frequencies from buildings and ceilings. Therefore experimental in-situ investigations are indispensable for trustworthy forecasts. In this paper the VibroScan method is presented, whose basic idea is to implement the principle of equivalence between the synthetic vibrations used for the experiments and train vibration emissions at the highest possible degree. This is focused on emission spectra, force of excitation, unsprung wheelset mass and axle load. The necessary experimental provisions are discussed and some examples of results are given like the protection of the Musikverein building in Vienna or the Sagrada Familia basilica in Barcelona against vibrations from tunnels in the immediate neighbourhood.

1 Introduction

Vibrations are part of the most disturbing environmental problems of railways. Also structure borne noise, caused by these vibrations can become very annoying, especially in shallow tunnel sections in residential areas. However, vibration protection measures at the railway line have to be installed before the first train is moving. Therefore vibration immission forecasts are required.

Due to the multiple feedback system, which governs vibrations this requires consideration of:

- the emission source: train, track, tunnel, dam, etc.
- the transmission behaviour: geodynamics, resulting from dimensions and elasticity of geologic units
- the immission response: building dynamics, like natural frequencies and damping.

The reliability of a forecast depends therefore on the degree up to that these parameters are comprehensively taken into account.

2 Problem

As numerous investigations prove, all the above mentioned parameters own considerable, even extreme local variability [1]. Some examples can illustrate this.

2.1 Vibration emission spectra

Frequency spectra of train vibrations own great variabilities with dominating emission frequencies ranging from 0.5 Hz to 230 Hz thus covering 9 octaves (Figure 1). This depends on train speed, axel geometry, roughness of wheel and rails as well as track conditions like straightness, switches or sleeper distance. In addition the feedback with the geodynamics of the underground is involved in the elastic reaction to the acting forces, i.e. the ground volume of load transfer as counterforce is of importance. The latter becomes the dominating effect in the example shown. In addition it is evident that track-related elements like dams, tunnels, bridge-abutments etc. influence the emission spectra as well.

For extreme low frequency train vibrations the tactile perception is often astonishing far-reaching. Cases have been recorded, where in 150 m distance to the track the vibrations exceeded the guidance level for comfort of the Austrian Standard ÖNORM S 9012.

On the other hand high frequency emission spectra favor audible ground borne noise in the same way up to a distance of 300 m.

Altogether it has to be concluded, that universally valid emission spectra like for noise emissions will never be applicable for train vibration emissions.

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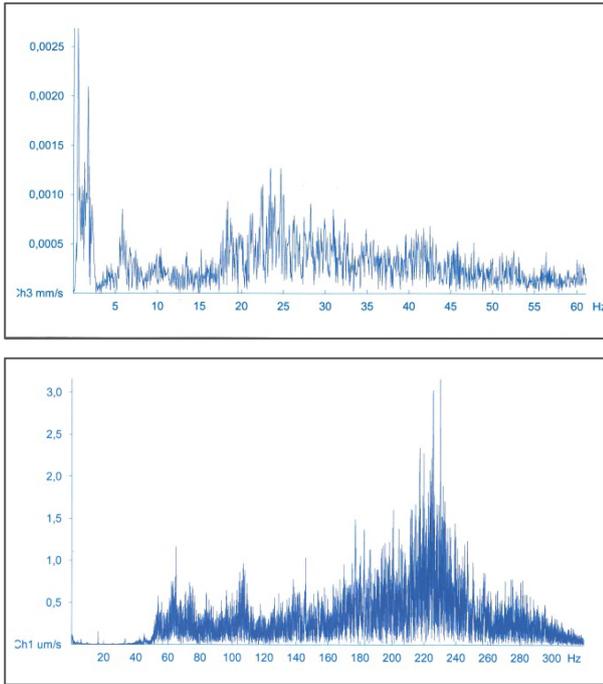


Figure 1. Scope of vibration emission spectra of trains due to different subsoil condition.
 top: soft, swampy
 bottom: stiff, rocky.

2.2 Geodynamics

The depth range influencing the seismic waves transferring the emissions through the underground is considerably greater than that one relevant for the static load transfer of building foundations [2]. This sphere is by no means homogeneous but at least stratified into several horizons thus forming a complex elastic system with appropriate natural frequency bands and allowing refraction and reflexion at discontinuities.

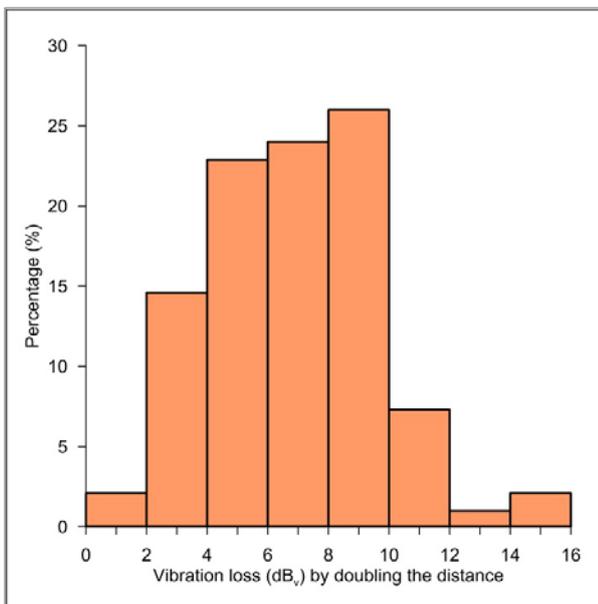


Figure 2. Statistics of geodynamic vibration loss by doubling the distance at various project sites in dB_v.

Statistics for approximately 100 profiles demonstrate the scatter consequently inherent to parameters relevant for vibration transmissions. Geometric damping of vibration propagation in the underground is shown in Figure 2 as the vibration loss by doubling the distance to the source.

The bandwidth of this geometric damping is ranging from 1 to 16 dB_v. This indicates how delicate the transmission behaviour reacts on variations of the interacting elements like source spectra, source location (surface, underground), underground geodynamics (elasticity, dimensions and arrangement of layers) and wave type (body, surface, channel).

2.3 Building dynamics

Variability of building dynamics can be demonstrated by the spread of building eigenfrequencies in relation to building height (Figure 3). The bandwidth of natural frequencies broadens rapidly with decreasing construction heights. While for high-rise buildings the natural frequencies correlate very well with the building height, for low-rise buildings there exists a broad scatter. Unfortunately the latter ones represent the vast majority of buildings.

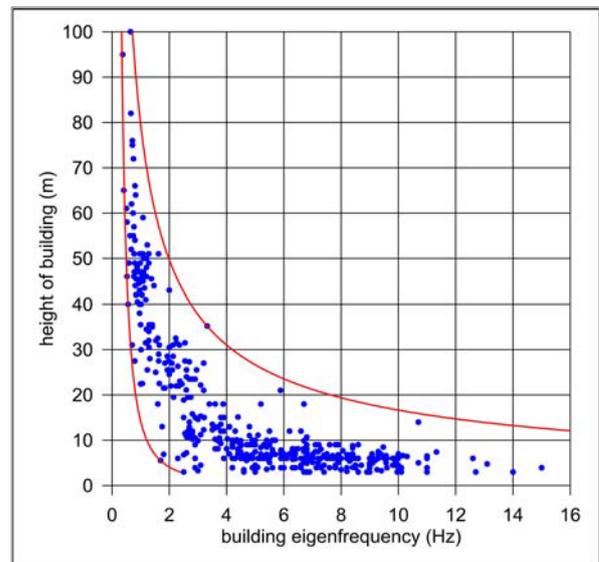


Figure 3. Spread of building eigenfrequencies and building height.

Even greater is the bandwidth of natural frequencies of ceilings (Figure 4). The lowest frequencies own ceilings in protruding building parts, followed by ceilings resting on wooden beams, while solid ceilings are characterized by the highest natural frequencies. Altogether the ceiling-eigenfrequencies cover a band of at least 4 octaves.

As a consequence the local vibration propagation and response behaviour of residential buildings has to be investigated by in-situ experiments. Some success has been obtained already by using backfill rammers or vibratory compactors as vibration source [3]. But by these investigations it became also evident that the comparableness of artificial vibrations to those of trains

(frequency band, ground loading etc.) is essential for a higher prediction accuracy.

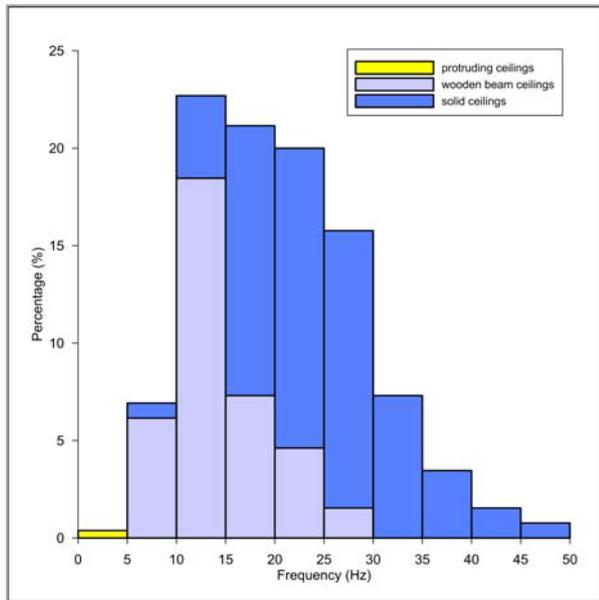


Figure 4. Statistics of natural frequencies of ceilings.

In order to receive reliable vibration characteristics of the entire dynamic system the VibroScan prediction method has been developed, which is based on experimental investigations following the principle of equivalence.

The intention was to design experiments for synthesizing the input parameters of real train vibrations at its best. This approach for the vibratory source guarantees a feedback of geodynamics and building dynamics equivalent to that one of real train emissions. Knowledge of specific characteristics like the propagation depth range or the underground elasticity and the dynamic behaviour of adjacent buildings and their constructive elements is not required as all their relevant back coupling effects are included in the experimental results.

3. VibroScan forecasting method

Successful experiments require the highest possible degree of equivalence between test conditions and reality. With train vibrations this concerns especially [4]:

- frequency spectrum of emissions
- force of excitation
- unsprung wheelset mass
- axle load
- area of load transfer to the underground

The back coupling reaction between excitation frequency and the unknown natural frequencies from the underground and constructive building elements is of prime interest. The experimental emission spectrum therefore has to cover all relevant frequencies. That means that broadband frequency excitation equivalent to that one of trains is necessary.

The dynamic behaviour of the vibrating system „vibration source – underground“ is controlled by its

physical dimensions, as the size of the surface area under load governs the volume and consequently the mass of the cone of load transfer. While the elastic behaviour of this cone causes the reaction force of the underground, the inertia of this mass acts as system damping. Corresponding force transfer functions are shown in Figure 5 for different types of trains as well as of vibrators.

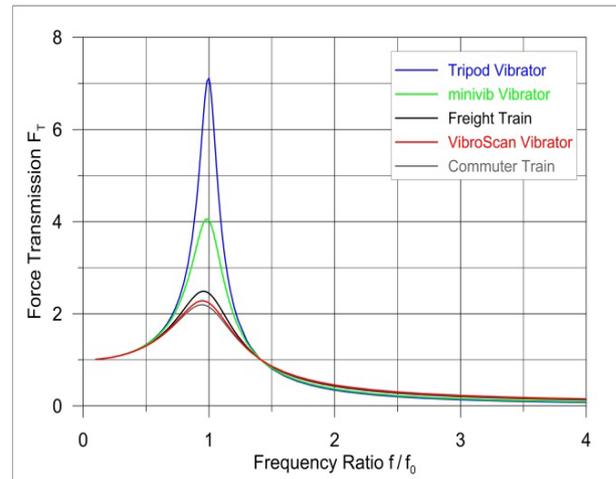


Figure 5. Resonance plots for different vibrator types; f excitation frequency; f_0 natural frequency of vibrating underground.

First of all, Figure 5 reveals that both, light-weight and heavy-weight trains own high damping ratios on a ballast track and consequently low resonance peaks. The transfer function from the VibroScan vibrator fits excellent to these transfer functions of trains.

Tripod vibrators in general rest on three small-sized bearings causing relative high surface loads, while the minivib vibrator [5] has a base plate size of 0,6 m² resulting in a medium size surface load. In both cases the outcome is a higher amplification peak of force transmission as with the VibroScan vibrator.

Following the SDOF model the 3 vibrators are characterized by the amplification factors and percentages of critical damping as shown in Table 1.

Table 1. Vibration transfer parameters of vibrators

Vibrator type	Resonance amplification factor	Damping percentage
VibroScan vibrator	2.29	22%
minivib vibrator	4.06	12%
tripod vibrator	7.10	7%

While the tripod and minivib vibrators [5, 6] own low-level damping and therefore high resonance-force peaks, the VibroScan vibrator (Figure 6) is tuned to broadband transmission with a low resonance peak. Consequently the minivib and tripod vibrators limit the force transfer to a narrowband around resonance frequency, while the VibroScan vibrator enables wide-

band vibration transfer experiments. This can cause misleading or inconclusive results thus increasing abatement costs by otherwise available elongations and/or higher effective floating slab systems [7].



Figure 6. Heavy duty VibroScan vibrator operating in a Swiss tunnel.

The comparison of a train to the VibroScan vibrator proves the equivalence of both vibration sources according to Table 2.

Table 2. Comparison of dynamic parameters train – seismic vibrator

Parameter	Train	VibroScan
unsprung wheelset mass/actuator mass	1200-4000 kg	3505 kg
peak excitation force	~ 100 kN	225 kN
area under load/baseplate size	2.1 m ²	2.0 m ²
peak ground pressure	≤ 15 N/cm ²	≤ 19 N/cm ²
frequency band	1-230 Hz	1-250 Hz
spectral characteristic	broadband	Sweep

The actuator mass corresponds for example to the unsprung wheelset mass of a Siemens EuroSprinter locomotive.

As it is already recognizable from Figure 5 it is essential for the success of the sweep experiments to keep the force constant within the entire frequency range. But it is well known that the underground has to react depending on its elasticity and damping behaviour. This feedback will be nonlinear depending on the actuated frequency.

In order to obtain nevertheless constant force input to the underground being independent from the frequency it is necessary to implement a real-time output regulation of the actuator force.

For delivering this gain control it is necessary to measure the VibroScan actuator output continuously which is done by several accelerometers and LVDT force sensors with a sampling interval of 250µs (Figure 7)

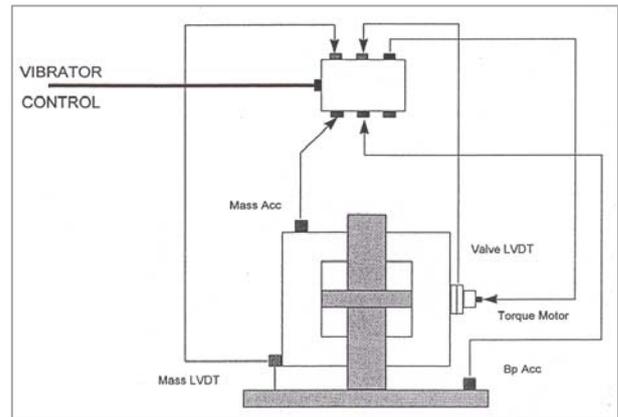


Figure 7. Scheme of sensor configuration for real time force regulation.

Via a Kalman filter the underground reaction is forecasted for the next time increment and thus the output force is regulated by an auto-adaptive servo-mechanism.

This procedure reduces the variation of the force input to the underground considerably to typically +1 dB as it is shown in Figure 8.

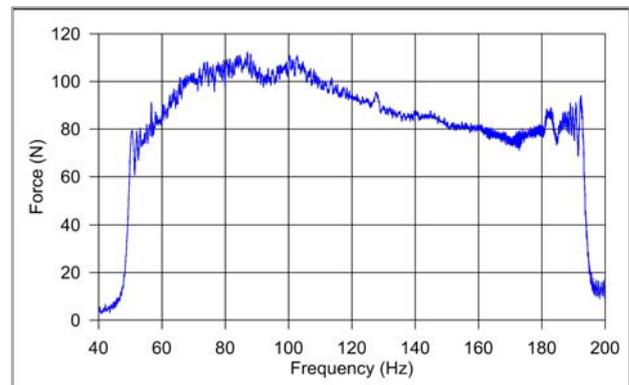


Figure 8. Force input to the underground with auto-adaptive controlled actuator force for a 51-192 Hz sweep.

4. Results

The main result of a VibroScan investigation consists in vibration transfer functions from the future railway track to the living rooms of nearby residents, as Figure 9 shows for a rather extreme example.

In this example vibration amplification happens already on the way from the track to the building foundations due to very unfavourable underground geodynamics (Figure 9, top). The residential building itself reacts extremely vulnerable to vibrations with roughly 40 dB_v vibration amplification in the frequency band 1-50 Hz as well in the vertical as in the horizontal directions (Figure 9, center). Altogether this results in a pronounced amplification from the future track to the residential floors in the low and medium frequency range (Figure 9, bottom). It is evident that this building will require special abatement measures far beyond a regular ballast mat.

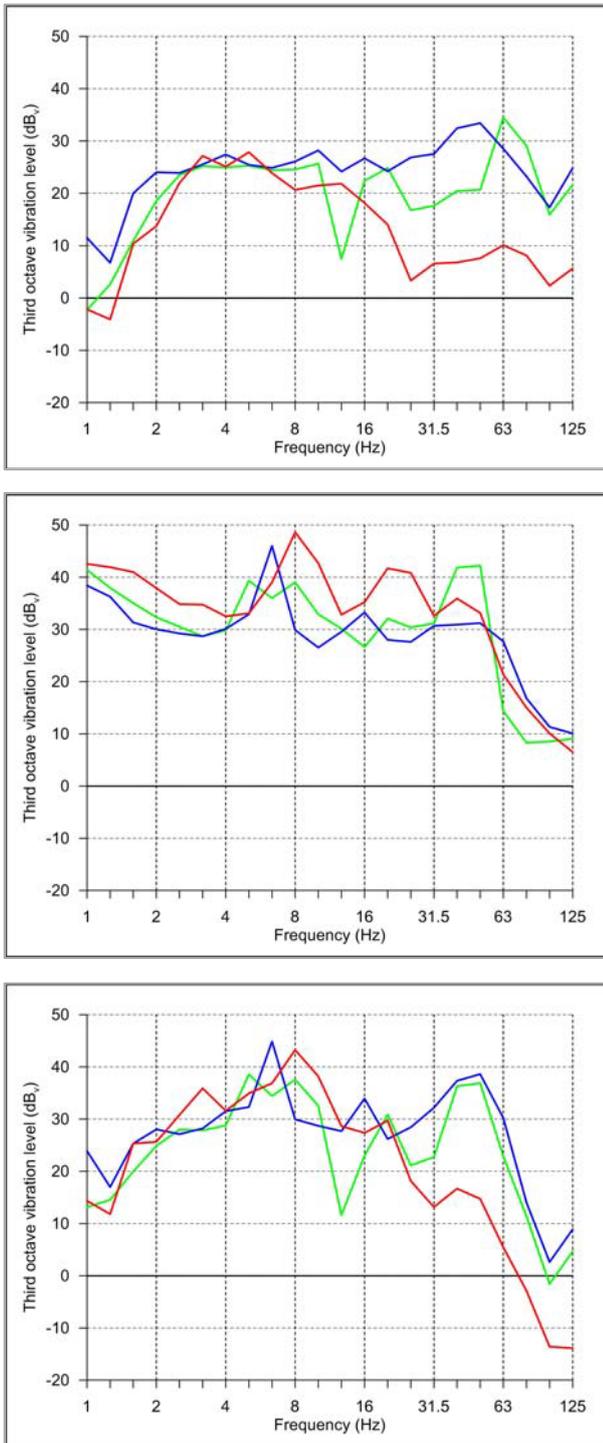


Figure 9. VibroScan vibration transfer function (green: longitudinal-component; blue: transverse-component; red: vertical-component)
 top: from VibroScan position to building foundation
 center: from building foundation to upper floor
 bottom: from VibroScan position to upper floor.

Another example for VibroScan results are mobility investigations. Mobility represents the frequency response function formed by the ratio of the particle velocity response to the excitation force.

Also the mobility spectra of tunnels own great variability (Figure 10). Maximum mobility can occur at low frequencies (6 Hz) as well as at high frequencies

(160 Hz) depending on the tunnel design and the feedback with the geodynamics of surrounding bedrock.

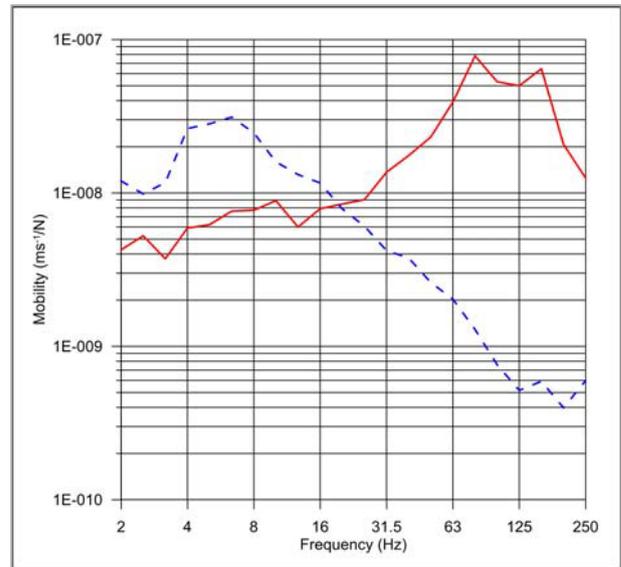


Figure 10. Mobility of different tunnels in tubing segment design (red) and NATM design (blue)

Constructive imperfections like “vibration bridges” or connections, which ease the way for vibrations from the source to the receiver, can also be identified by VibroScan experiments, as they are performed within the already built tunnel. For instance, cement grouting during tunnel driving can create a connection to nearby building foundations. This force-locked connection amplifies immissions strongly and broadens the transferred frequency spectra considerably. Being once detected such defects can be taken into account in the insertion loss calculations and thus repaired in due time.

Finally the accuracy of the VibroScan forecasts can be illustrated by the comparison of the forecasted insertion loss with measured results after completion for Römerbergtunnel, Schwanenstadt/Upper Austria, and Zammer Tunnel, Zams/Tyrol (Figure 11).

VibroScan investigations have been successfully undertaken for numerous railway and Metro lines in Austria, Germany, Greece, Italy, Spain and Switzerland.

The probably most spectacular project was the Viennese Metro line tunnel built in 2 m distance to the foundations of the so-called Musikverein building. Because of the unbeatable acoustics of the golden Musikverein auditorium “any perceptible modification of the sound situation” was prohibited. The VibroScan measurements resulted in the design of a floating-slab system, which successfully overcomes all relevant natural frequencies. The extreme request of the Musikverein is fulfilled without any deduction.

A similar challenge formed the vibration protection for the Sagrada Familia basilica in Barcelona, where the high-speed tracks of the AVE-tunnel are only a few meters sideways from the foundations as well.

Recently the Lainzer Tunnel in Vienna was put into operation, which crosses in extremely shallow depths below densely populated residential areas inhabited by several tens of thousands inhabitants.

Acceptance measurements as well as the fact, that not one single complaint was made, prove the success of the floating slab design according to the VibroScan investigations.

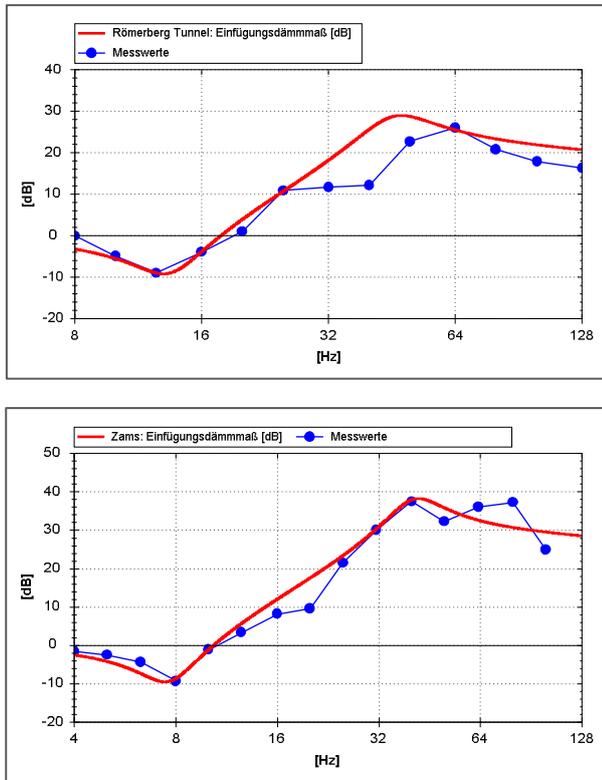


Figure 11. Insertion loss comparison at Römerbergtunnel (top) and Zammer Tunnel (bottom); red: insertion loss forecast made with VibroScan; blue: measured insertion loss after tunnel completion

5. Conclusions

Due to the limited knowledge of the geodynamic behaviour of the local underground and the broad scatter of building dynamic properties vibration experiments are indispensable for reliable vibration prediction and abatement. The advantages can be summarized as follows:

- Emission frequencies of trains depend not only on the characteristics from trains, track and tunnel design but also on the feedback with the underground. Emissions have to be investigated for each project individually.
- The underground is at least stratified into inhomogeneous horizons thus forming a complex elastic system only perceptible by in-situ investigations.
- Sufficient model-depth domains are required to receive realistic geodynamic models which cover also the lower part of the vibration transfer spectra.
- Building dynamic attributes, like the natural frequencies of rising structures and ceilings own a considerable scatter and require individual measurements.

- Synthesizing vibrations by a VibroScan vibrator enable the determination of the vibration transfer functions from a future source to neighbourhood 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 when 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 taken into account in insertion loss calculations.

References

- [1] P. Steinhauser, ETR, 62, 12 (2013)
- [2] J. Studer, J. Laue, M. Koller, Bodendynamik, Springer (2007)
- [3] F. Krüger et al., Schall- und Erschütterungsschutz im Schienenverkehr (Expert Verlag, 2006)
- [4] P. Steinhauser, W. Steinhauser, 10. Symposium Bauwerksdynamik, EMPA (2007)
- [5] IVI, Datasheet minivib, Tulsa (2005)
- [6] R. Flesch, Symposium: Erdbebensicherheit in Österreich, AIT (2014)
- [7] A. Egger, 4. VDI-Fachtagung Baudynamik, VDI-Bericht 2160 (2012)