VIBRA-1-2-3: A software package for ground borne vibration and noise prediction

1 Introduction

The basic principle of train induced vibrations is schematically shown in Fig. 1: Vibrations created by passing trains are transmitted through the soil to the foundations of the buildings nearby and from there through the walls to the rooms. In the rooms these excitations can be felt as annoying vibrations or as ground borne noise.

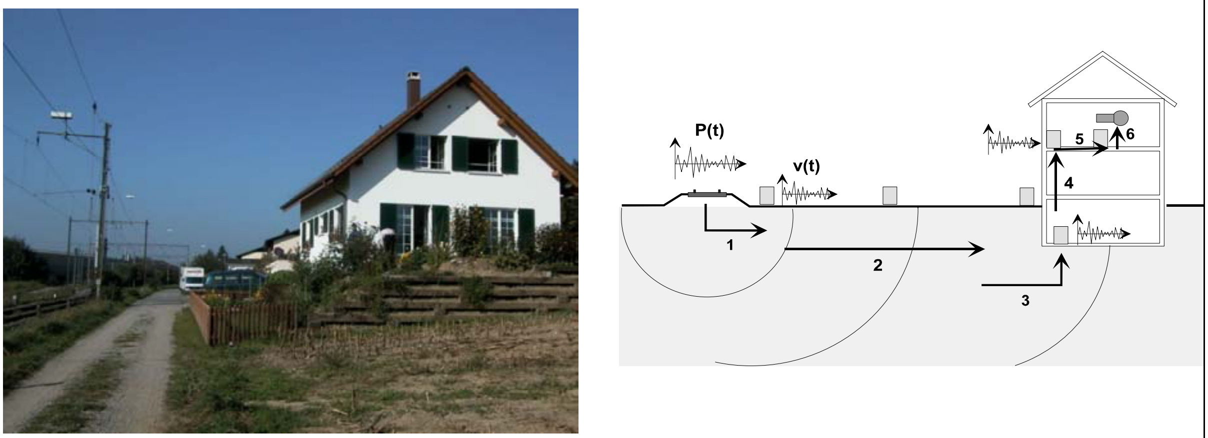


Fig 1.1 Propagation of railway induced vibrations and ground borne noise

The source of vibration is the time varying forcing function produced by the train, shown in Fig. 1.1 as P(t). The propagation of the vibration can be divided into six domains:

1. Rail - Track
2. Track – Free field
3. Free field - Foundation
4. Foundation - Walls
5. Walls - Floors
6. Floors – Ground borne noise

In each of these domains a specific propagation phenomenon prevails; if we succeed in describing these phenomena with a suitable model, we will come up with a reliable prediction of vibrations in buildings near railway tracks.

With VIBRA-1-2-3 a software package has been developed by ZIEGLER CONSULTANTS and SBB (Swiss Rail) in order to offer a convenient tool for the prediction of ground borne vibration and noise. VIBRA-1 is a easy to use empirical prediction model suitable for analysing the impact of new or modified railway lines on a large number of buildings. VIBRA-2 is an empirical model as well, but it is based on 1/3-octave source and transfer spectra, allowing thus a more detailed analysis. VIBRA-3 eventually is the data base program that serves as a container for storing the measurement data in a systematic way and provides a convenient engine for statistical evaluations. The results of these statistical evaluations can and should be used to improve the models used in VIBRA-1 and VIBRA-2.

2 VIBRA-1: A simplified empirical model

VIBRA-1 is a computer program for the approximate analysis of train induced vibrations and ground borne noise. Using readily available data on train traffic, track type, track subsoil and building structure, the ground borne vibration and noise are computed. The analysis is based on an empirical model that is based on a large number of measurements.

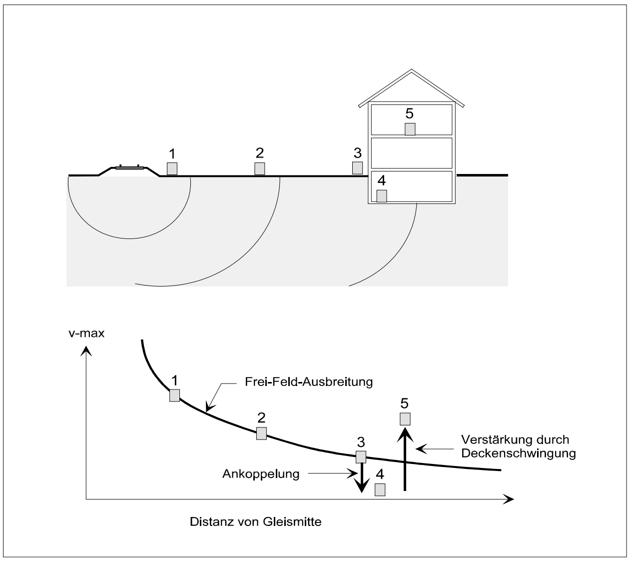


Fig. 2.1 Basic principles of train induced vibrations

Vibrations created by passing trains are – as shown in Fig. 2.1 –propagated through the soil to the building foundation. From there they travel through the walls up to the floors and ceilings in the entire building. On its path from the track to the building foundation the vibrations are attenuated in the soil due to geometric and material damping. While passing from the soil to the building foundation the vibrations are considerably attenuated due to the so called "coupling effect". The vibrations reach the higher storeys through the walls without much modification. In the floors the vibrations are generally amplified by a large amount due to resonance phenomena. As a last step the vibrations of the floor and walls may create an annoying low frequency noise called "secondary radiated sound".

2.1 Vibration propagation

The attenuation behaviour shown in Fig. 2.1 can be expressed by Eq. (1) as follows:

$$v = v_0 \cdot F_z \left(\frac{G}{G_0} \right)^h F_s \left(\frac{r_0}{r} \right)^m F_a \cdot F_e \qquad (1)$$

with:
- v = RMS-value (over train passage time) of the vibration velocity in the middle of the floor
- v_0 = Reference value of vibration. This value corresponds to the vibration in a distance r_0
- F_z = Weighting factor for train type.
- G = Average velocity of a train type.
- G_0 = Reference train velocity
- h = Exponent for scaling train velocity
- F_s = Track factor for switches and other track irregularities
- r_0 = Reference distance
- r = Distance between building and track centre line
- m = Exponent for geometric and material damping in the soil
- F_a = Coupling factor between building and soil
- F_e = Factor for vibration amplification in floor

2.2 Ground borne noise

Ground borne noise is created by the vibration of floor and ceiling and to a lesser extent by the vibration of walls. The correlation between vibration amplitude in a room and ground borne noise (or more accurately: secondary radiated sound) is very complex. For an infinite rigid plate the conditions are still comparatively straightforward. The theoretical correlation between radiated sound and vibration of the rigid plate is given by Eq. (2):

$$L_p = L_v + 20 \cdot \log \sigma \qquad (2)$$

with: L_p = RMS-value of radiated sound in dB ($p_{ref} = 2 * 10^{-5}$ Pa)
L_v = RMS-value of vibration of rigid plate in dB($v_{ref} = 5 * 10^{-5}$ mm/s)
σ = Radiation efficiency

This means that – with the reference values specified above – the sound pressure in dB is numerically equal to the vibration of the rigid plate plus a term representing the radiation efficiency of the plate. For an infinite rigid plate σ = 1 and thus the last term in Eq. (2) is zero. In a room however this term is not zero. Due to the reflections and due to the vibrations of the ceiling and the walls this term can reach values as high as 20 dB.

Evaluations of a large number of measurements show that the radiation efficiency varies usually between 5 and 15 dB. In VIBRA-1 the calculation of ground borne noise is carried out with the following equation:

$$L_{Aeq} = L_v - A + \sigma \qquad (3)$$

with L_{Aeq} = A-weighted equivalent sound pressure level of a passing train in the middle of the room
L_v = RMS value of v over the train passage time for the frequency range between 50 and 125 Hz, converted into dB (with $v_{ref} = 5 * 10^{-5}$ mm/s). v is calculated with Eq. (1) but with the parameters for ground borne noise.
A = A-weighting: A value of 26 dB is used, which corresponds to the A-weighting of the 63-Hz band.
σ = Factor taking in account the transition from vibration to secondary radiated sound.

In addition to calculating the ground borne noise with *radiation efficiency* – as described above – VIBRA-1 offers also the possibility to calculate ground borne noise with the empirical equation (4) according to Grütz:

$$L_{Aeq} = L_{vA} \;\; C1 + C2 \qquad (4)$$

with L_{vA} = A-weighted vibration velocity of floor
$C1$ = Empirical constant
$C2$ = Empirical constant

(Literatur for the method Grütz: Deutsche Bahn AG München; Körperschall- und Erschütterungsschutz; Leitfaden für den Planer.)

2.3 Modelling parameters

Fig. 2.2 shows the standard parameters in VIBRA-1 for the immision calculation. It should be noted that this set of parameters is not intended as a generally applicable set of parameters. For each individual case it should be checked, whether the parameters are applicable. Possibly specific measurements have to be carried out.

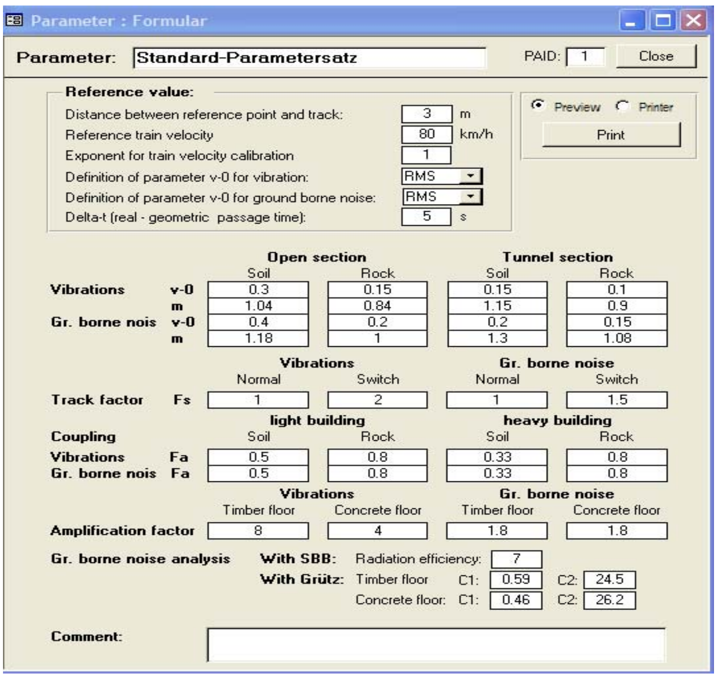


Fig. 2.2 Standard-Parameters in VIBRA-1

3 VIBRA-2: An empirical model based on 1/3 octave spectra

As opposed to VIBRA-1 which determines the vibrations using a comparatively simple model and only a few data about subsoil and building structure, VIBRA-2 is based on a more elaborate model that includes all important aspects of vibration propagation near railway lines.

While developing the computational model in VIBRA-2 the following principles have been followed:

- The model should include all relevant aspects. It should be able to calculate the vibrations from the track to the vibrations in the buildings including the effects of ground borne noise.
- The model should have an open structure, thus giving the user the possibility to control and influence all steps in the computation.
- The model should be flexible. It should be easy to incorporate new information. Above all it should be easy to incorporate results of vibrations measurements.
- The model should have an adequate degree of detailing. The degree of detailing cannot go as far as in FE models, but it should be possible to include for instance the effects of an isolating layer or the eigenfrequency of a floor.

Based on these ideas a model has been developed that belongs to the group of empirical frequency dependant models. As starting point of the computation a so called “source spectrum” is used. This corresponds to a 1/3 octave spectrum of a specified train type running at a specified velocity on a specified track type on a specified subsoil (or tunnel) measured at a specified distance from the track.

Starting from this source spectrum the vibration spectrum for different locations is computed – as shown in Fig. 3.1 – by multiplying the source spectrum successively with corresponding transfer spectra.

Based on the source spectrum the track spectrum that we would measure at a reference distance from the track is obtained by multiplying the source spectrum with transfer spectra for track type, track condition, local track feature (switch), track isolation and the transfer spectrum for the subsoil.

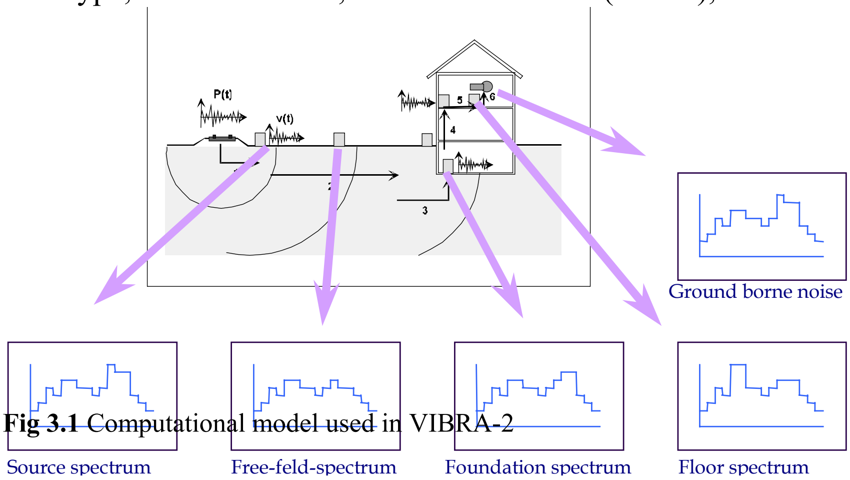


Fig 3.1 Computational model used in VIBRA-2

From the track spectrum we obtain the free-field spectrum by multiplying the track spectrum with the transfer spectrum for track position (tunnel, embankment, cutting) and the transfer spectrum for geometrical and material damping. This is the spectrum we would measure at a measuring point in the free field at the specified distance from the track. If required a transfer spectrum for special free field features (e.g. isolating barriers) could be introduced.

The following equation is used for frequency dependent attenuation:

$$v = v_0 \left(\frac{r_0}{r} \right)^{n(f)} e^{\left(-\frac{2\pi f D}{v_B}(r - r_0) \right)}$$

with:

v	=	Vibration velocity in a distance r from the track
v_0	=	Vibration velocity in a distance r_0 from the track
r_0	=	Usually 8 m
r	=	Distance from the track
n	=	Exponent for geometrical damping
f	=	Frequency
D	=	Material damping
v_B	=	Velocity of surface waves

If we set the parameter D to zero we obtain the simpler equation:

$$v = v_0 \left(\frac{r_0}{r} \right)^{n(f)}$$

with the well known linear attenuation in the double logarithmic representation (as used in VIBRA-1).

Multiplying the free field spectrum with the transfer spectrum for coupling we obtain the foundation spectrum. Multiplying the foundation spectrum with the transfer spectrum for the floor we obtain the floor spectrum. If required a transfer spectrum for special building features can be introduced.

From the floor spectrum we calculate the spectrum for ground borne noise using the method “SBB” or the method “Grütz”. With “Grütz” frequency independent factors are used, while the method “SBB” continues using transfer spectra.

Thus this procedure of successive multiplication of the source spectrum with various transfer spectra brings us finally to the vibration in the room and to the ground borne noise. Fig 3.2 and 3.3 show an example of a source spectrum and of a transfer spectrum.

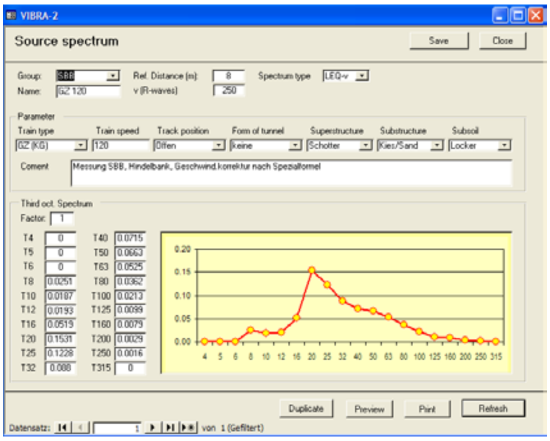


Fig 3.2 Sample of source spectrum

Fig. 3.3 Sample of a transfer spectrum

The results are displayed graphically for the individual train types (Fig.3.4) or summed up for all trains (Fig.3.5).

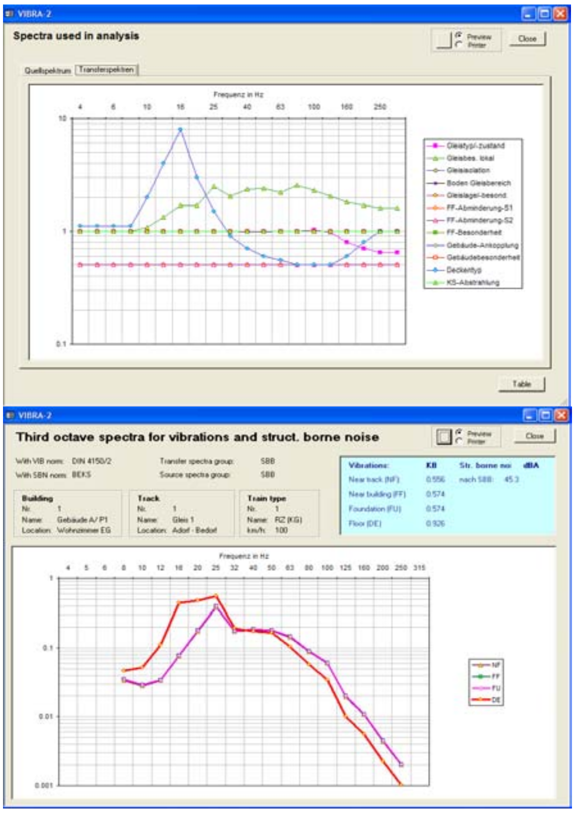


Fig 3.4 Results for one train type

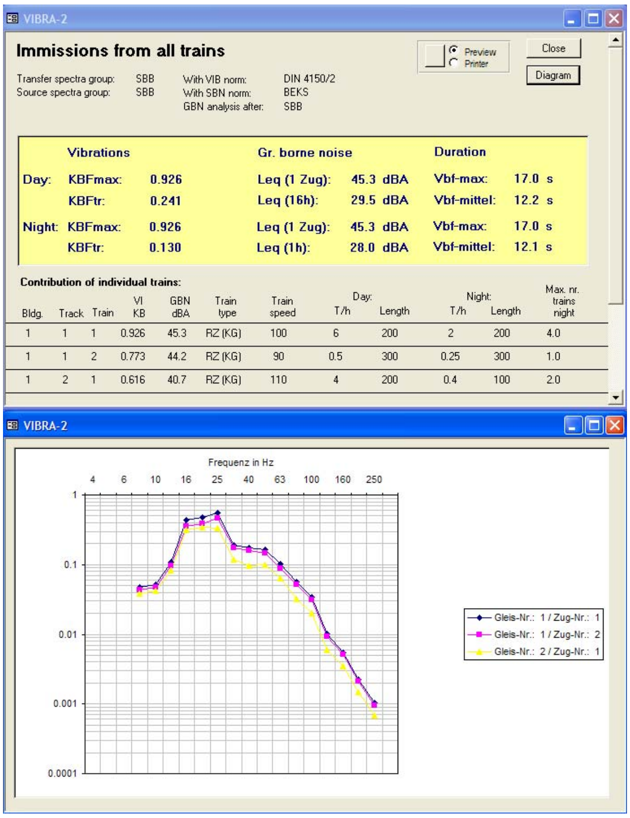


Fig. 3.5 Results for all trains

4 VIBRA-3: A data base for railway induced vibrations

The data base in VIBRA-3 assumes that the measurements for ground borne vibration and noise are carried out according to the scheme shown in Fig. 4.1. The basic lay out is a measurement array with several sensors arranged along a line perpendicular to the railway track. The sensors can be of the type velocity, acceleration or sound pressure. The signals recorded by the sensors are not stored as such in the data base. They have to be evaluated first. VIBRA-3 stores only the characteristic values of the signals (peak values, effective values etc.) and the 1/3 octave values. The data entry form in Fig. 4.2 shows at a glance all relevant information of a measurement array.

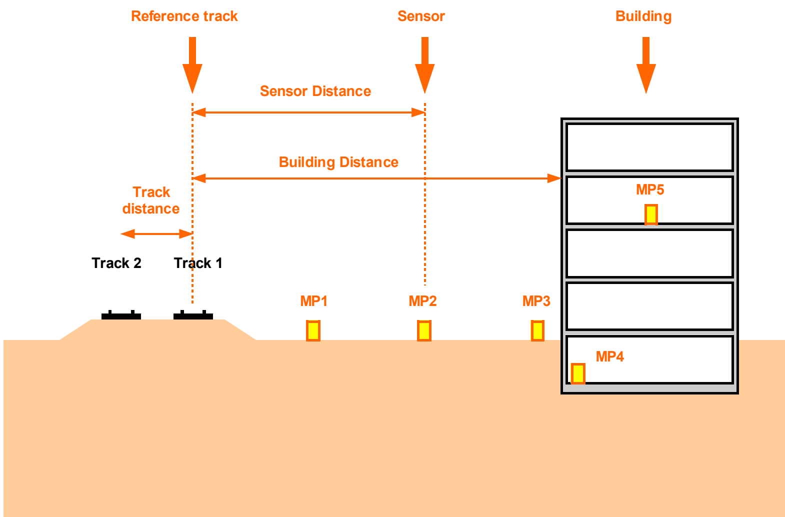


Fig 4.1 Schematic representation of measurement array

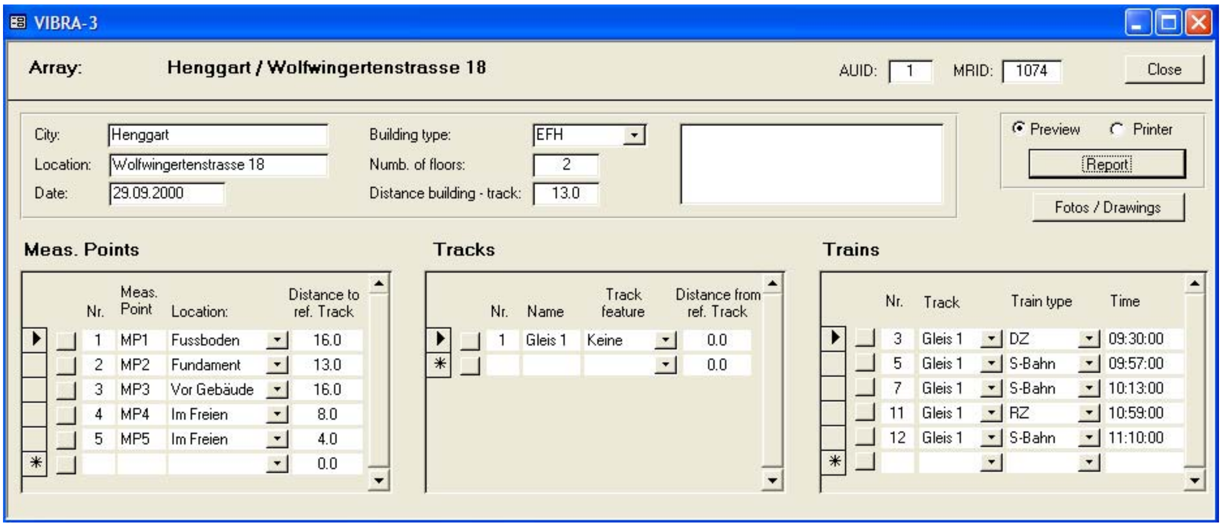


Fig. 4.2 Data entry form in VIBRA-1

For each measurement the following data can be entered:

Peak	Peak value
RMS-F	Maximum RMS value with 1/8 s time window
RMS-S	Maximum RMS value with 1 s time window
RMS-L	RMS value over the entire train passage time
KBFT	KB_{FT}-value according to DIN 4150/2
LAeq	A-weighted sound pressure level over the entire train passage time
Lam-s	Maximum A-weighted sound pressure level with 1 s - time window
Lam-f	Maximum A-weighted sound pressure level with 1/8 s - time window
TB-Typ	Type of 1/3 octave band spectrum
TB4 – TB320	Values of 1/3 octave band spectrum from 4 Hz to 320 Hz

A statistical evaluation program allows extensiv statistical evaluation and most importantly of all parameters that are used in VIBRA-1 and VIBRA-2. Fig. 4.3 shows a sample of such an evaluation.

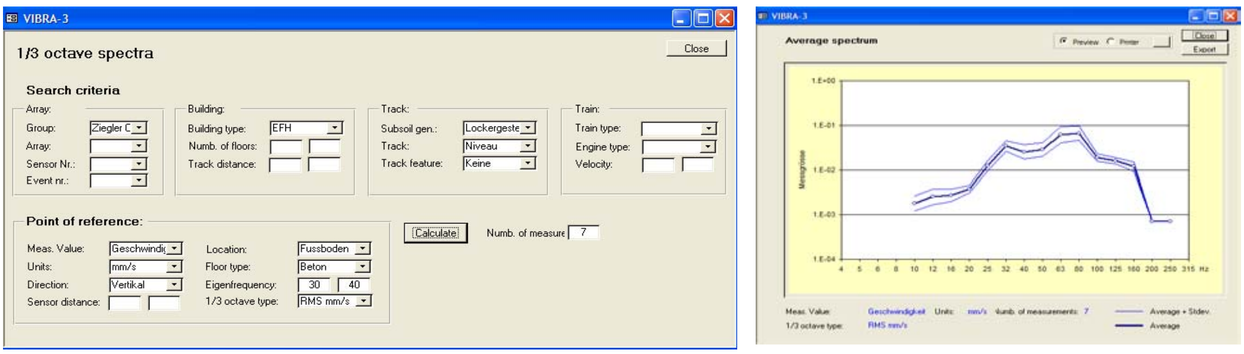


Fig 4.3 Screen "1/3 octave spectra search criteria"

In developing the data base VIBRA-3 great care has been taken to include only the information that is really needed. Unnecessary data fields would make data entry cumbersome and time consuming. With the limitation to the most important data VIBRA-3 has become a very efficient tool to store systematically data from vibration measurements. Furthermore VIBRA-3 has a built-in “data exchange file” which simplifies data exchange between users.

5 Reliability of vibration predictions

5.1 Functions of random variables

We have seen, that the train induced vibration in a room can be calculated by the empirical equation (1):

$$v = v_0 \cdot F_z \left(\frac{G}{G_0} \right)^h F_s \left(\frac{r_0}{r} \right)^m F_a \cdot F_e \qquad (1)$$

Assuming that the train velocity is determined and that no switches exist, omitting also the factor F_z for train type, Eq. (1) reduces to:

$$v = v_0 \left(\frac{r_0}{r} \right)^m F_a \cdot F_e \qquad (5)$$

Thus the vibration in a room can be represented as a product of four random variables as shown in Eq. (6):

$$V = Q \cdot R \cdot A \cdot E \qquad (6)$$

where we assume that all four variables have a log-normal distribution. The expected value of such a function is calculated by:

$$\mu_V = e^{(\lambda_V + \frac{1}{2}\varsigma_V^2)} \qquad (7)$$

with

$$\lambda_V = \lambda_Q + \lambda_R + \lambda_A + \lambda_E \qquad (8)$$

$$\varsigma_V = \sqrt{\varsigma_Q^2 + \varsigma_R^2 + \varsigma_A^2 + \varsigma_E^2} \qquad (9)$$

For random variables with log-normal distribution the following holds:

$$\lambda_Q = \mu(\ln Q) \qquad (10)$$

$$\varsigma_Q = \sqrt{Var(\ln Q)} \qquad (11)$$

with:

$$\mu(x) = \frac{1}{n} \sum_{i=1}^{n} x_i \qquad (12)$$

$$Var(x) = \frac{1}{n} \sum_{i=1}^{n} (x_i - \mu_x)^2 \qquad (13)$$

$$\sigma_x = \sqrt{Var(x)} \qquad (14)$$

$$COV = \frac{\sigma_x}{\mu_x} \qquad (15)$$

With this excursion into probability theory the reliability of a prediction of train induced vibration can be obtained quite easily.

5.2 Mean value and variation

To illustrate the uncertainty in vibration prediction we are using the case of a single dwelling house with concrete floors in 16 m distance from the track. Train traffic is a typical suburban mixture with occasional freight trains.

The vibration V and the ground borne noise P can be calculated with the functions:

$$V = Q \cdot R \cdot A \cdot E \qquad (16)$$

$$P = V_{63-100} \cdot K \qquad (17)$$

In table 5.1 the mean values, the coefficient of variation and the corresponding values for log-normal distribution are listed. They are taken from the report "Zuverlässigkeit von Erschütterungs- und Körperschallprognosen bei Eisenbahnlinien" of the Symposium 2003.

Table 5.1 Statistical values for the required random variables

Parameter	Variable	μ	σ	COV	λ	ξ
Vibration in a distance of 8 m from the track (in KB)	Q	0.324	0.123	0.379	-1.198	0.388
Attenuation factor for R = 16 m	R	0.546	0.264	0.483	-0.751	0.590
Coupling factor	A	0.462	0.206	0.447	-0.867	0.441
Amplification throug floor	E	3.113	2.122	0.682	0.936	0.626
Conversion into radiated sound	K	1.250	0.653	0.522	0.122	0.432

With Eq. (7) and (8) and the values of table 5.1 we obtain:

V = 0.263 KB

with a coefficient of variation of:

COV = 1.04

In the same way we obtain for ground borne noise a mean value of:

P = 0.074 Pa

with a coefficient of variation of:

COV = 1.13

Converted into decibel we obtain for ground borne noise:

Leq_{KS} = 45.4 dBA +/- 6.5 dB

5.3 Discussion of results

The calculation in the previous section, which has been carried out with data from statistical evaluations (assuming that no measurements are available), yield the following results:

- The predicted mean value of vibration in a room has an uncertainty factor of 2. The coefficient of variation assumes a value of 1.04, which means that the limits for standard deviation is mean * 2.04 and mean / 2.04.

- The predicted mean value of ground borne noise in a room has an uncertainty of +/- 6.5 dB. The coefficient of variation assumes a value of 1.13. With this value we obtain the limits for standard deviation of +/- 6.5 dB.

In Fig. 5.1 the contributions of the individual factors are depicted. We recognize that the amplification factor of the floor and the attenuation factor in the free field have the highest contribution. But also the other three factors have a considerable contribution.

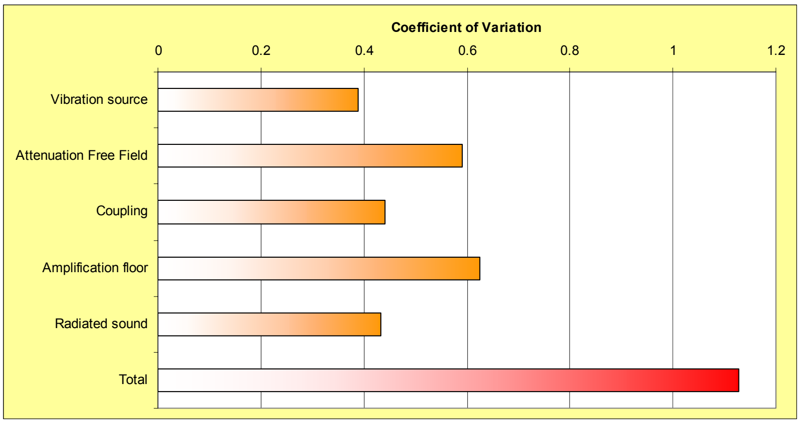


Bild 5.1 Variationskoeffizienten der einzelnen Einflussfaktoren

In spite of this disappointing result not every prediction of ground borne vibration or noise has this high degree of uncertainty. By carrying out all the measurements that can be done at the planning stage the uncertainties can be reduced considerably.

6 Testing the VIBRA model

VIBRA-1-2-3 has been in use for almost 10 years. A large amount of programming, vibration measurement and data evaluation has gone into it. The parameters in VIBRA-1 and the source and transfer spectra in VIBRA-2 are the results of statistical evaluation of a large amount of data. Still we are never quite sure how well these averaged data are applicable for a specific case. For this reason we have carried out specific measurements in order to test the applicability of the VIBRA programs in standard situations.

In the following we are presenting the results of two measurements: the attenuation measurement in the free field and the measurement of the influence of a switch. Fig 6.1 shows the section with the attenuation measurement, Fig. 6.2 the switch. The position of the arrays is shown in Fig. 6.3.

Fig. 6.1 Section for attenuation measurement

Fig. 6.2 Section with switch

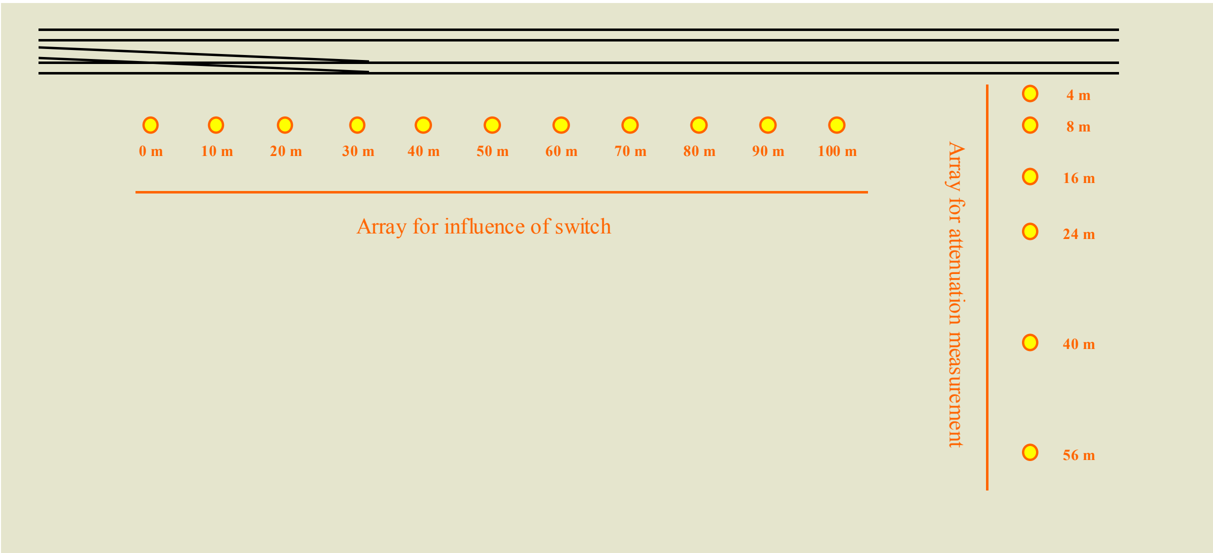
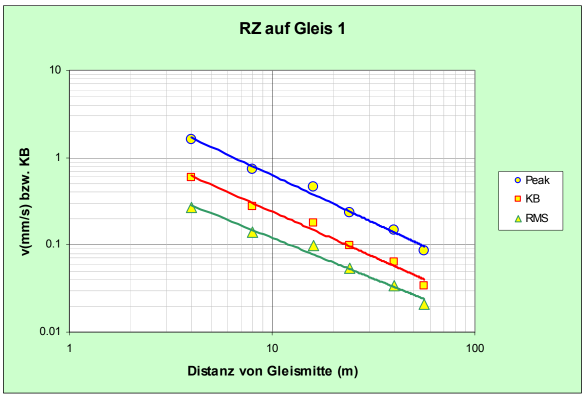


Fig.6.3 Position of measurement arrays.

6.1 Free-field attenuation

Fig. 6.4a and b show the evaluation of the attenuation array. On the left side the attenuation for passenger trains and on the right side the attenuation for freight trains is displayed. The attenuation follows very closely a straight line in the double-log-plot as assumed in the equation $v = v_0\,(r_0/r)^m$ used in VIBRA-1. The exponent m derived from the KB-data equals 1.03 for passenger trains and 1.20 for freight trains. This is obviously quite close to the value of m = 1.04 used in the standard parameter set in VIBRA-1 (see Fig. 2.2). The three lines in Fig. 6.4a and b are more or less parallel, which shows that there is a constant ratio between the three parameters Peak, KB and RMS.



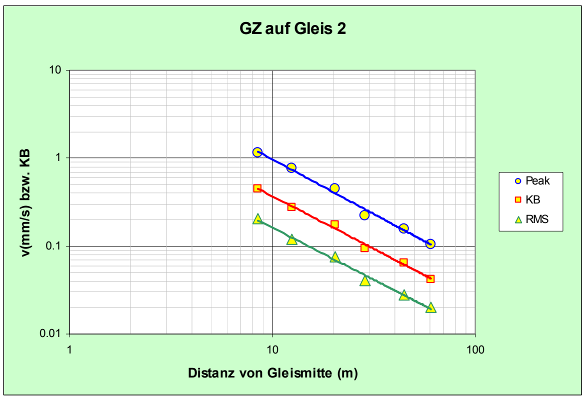


Fig. 6.4a Attenuation for passenger trains

Fig. 6.4b Attenuation for freight trains

6.2 Influence of a switch

It has been assumed so far that switches provoke roughly a doubling of the vibration level. Fig. 6.5 confirms that this assumption is not far from the truth. The peak values in the part without switch are in the range of 0.6 to 1.0 mm/s while the switch creates values in the range of 0.8 to 1.65 mm/s. Surprisingly the highest values have not been measured close to the centre piece of the switch but at a distance of 50 m. Certainly switches deserve additional measurements.

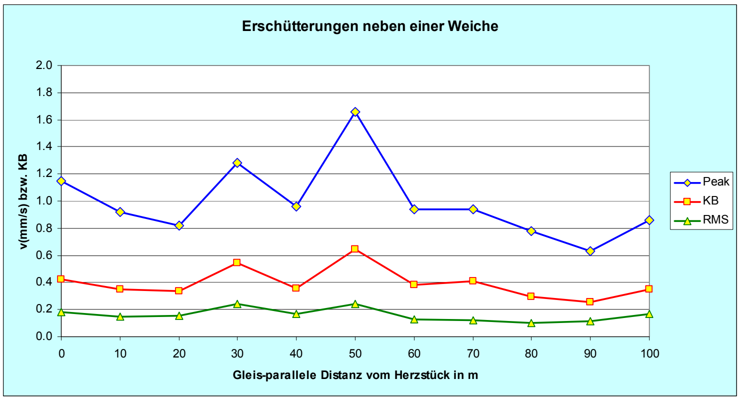


Fig.6.5 Switch measurement array along the track.

6.3 Spectral evaluation

The data obtained from the attenuation array has also been used for comparison with the spectra included in VIBRA-2. Fig. 6.6 shows the source spectrum from SBB for passenger trains at 120 km/h compared with the source spectrum obtained from the measurements at Schönenwerd for passenger trains with 110 to 120 km/h. Both spectra are for a distance of 8 m from the track. The difference in amplitude and spectral distribution is obviously quite large. This result confirms again, that when using VIBRA-2 the user should not rely only on the spectra included in the program VIBRA-2 but should create his own spectra based on measurements carried out by himself.

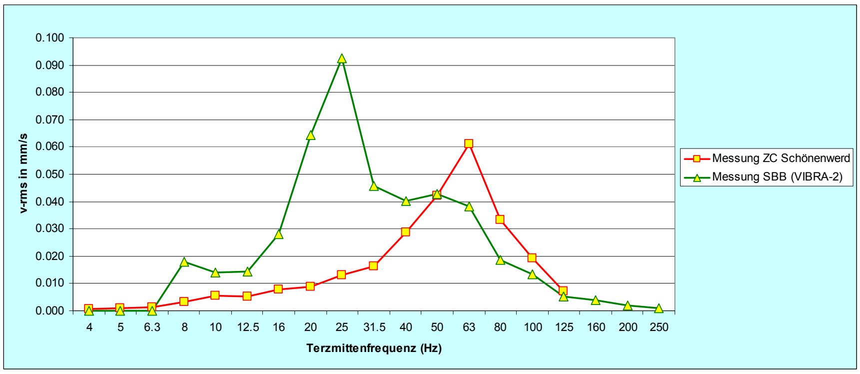


Fig. 6.6 Comparison of source spectrum from SBB with spectrum measured by ZC at Schönenwerd

Similarly the spectral free-field attenuation model – included in VIBRA-2 as exponent m(f) – should be used with adequate caution. Fig. 6.7a shows the spectral attenuation obtained at the array “Schönenwerd” and 6.7b the spectral attenuation used in VIBRA-2 as “DB-Model”. The DB-Model has been taken from: “Deutsche Bahn AG München; Körperschall- und Erschütterungsschutz; Leitfaden für den Planer“. In this paper these curves are suggested for approximate evaluations. Again the difference is quite considerable and it is always good practice to confirm source and transfer spectra in VIBRA-2 by measurements carried out at the location of interest itself.

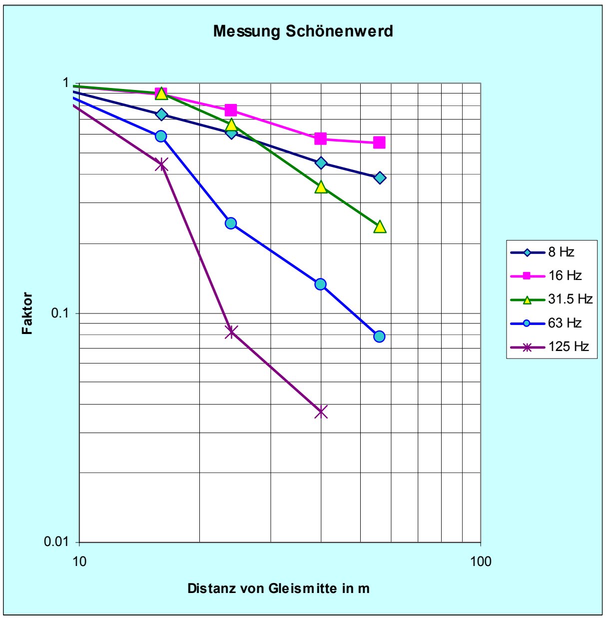


Fig. 6.7a Spectral attenuation from Schönenwerd

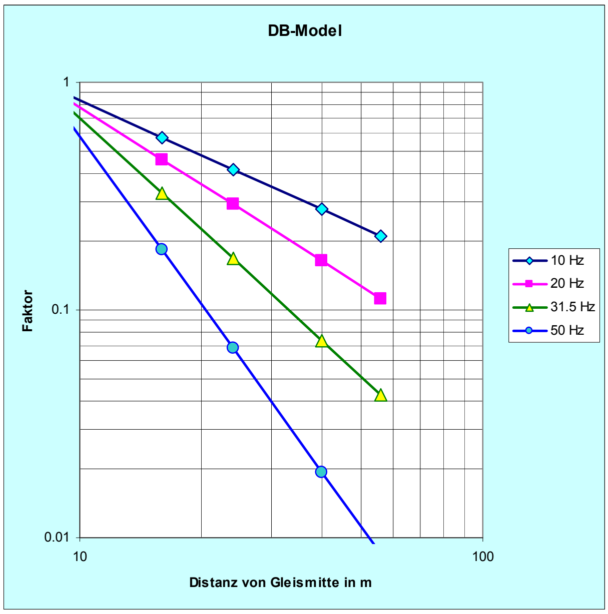


Fig. 6.7b Spectral attenuation in DB-Model (included in VIBRA-2)

7 Concluding remarks

The computational models used in VIBRA-1-2-3 have been presented in some detail. It is obvious that the task of predicting ground borne vibration and noise from rail traffic is not an easy one and requires a lot of experience. A major point of concern is the large amount of uncertainty in the prediction. A probabilistic analysis treating the ground borne vibration and noise as a function of five random variables yields the following results:

- In a vibration prediction without measurements an uncertainty factor of approximately 2 has to be reckoned with. For ground borne noise predictions the uncertainty is in the order of 6.5 dB. Increasing the database for the determination of the analysis parameters will not substantially decrease the uncertainty factor.

- To enhance the reliability of a vibration prediction all influencing factors, that can be measured somehow, have to be measured. In eliminating two or three of the five random variables the uncertainty in the prediction can be reduced substantially.

- The use of complex models for a prediction does not automatically reduce the uncertainty. Complex models will reduce the uncertainty only when the required input data are available. To get these input data measurements are required.