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The determination of railway vibrations levels in practice

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ABSTRACT

Noise and vibration caused by railway lines are often experienced as a nuisance by inhabitants in the vicinity. The most effective method for audible noise control at railway lines are noise barriers. However, shielding does not have a reducing effect on vibrations. It can even give opposite results in relation to annoyance. Vibrations through the soil are perceptible to humans as motion of the floor, rattling cups on a cupboard or as low-frequency structure-borne noise. On locations with sensitive equipment vibrations can even cause malfunction to the equipment.

Determining the strength of vibrations and also the strength of the accompanied low-frequency noise is particularly complex. This is caused by variations in train types (various passenger trains and freight trains), running speed, differences in railway constructions and, of course, the different conditions of coil structures. Measurements inside or nearby dwellings are difficult. Disturbances from other vibration sources, such as trucks and the activities of the resident's themselves, are difficult to differentiate.

This paper provides practical experience of performing measurements nearby railway lines and describes a method that can be used in order to obtain reliable results with a statistical approach.

Keywords: Train Vibration Measurements, Transmission
I-INCE Classification of Subjects Number(s): 72.2, 13.4

1. INTRODUCTION

Vibration nuisance caused by railway lines is a recognized problem in the Netherlands today. Construction projects, maintenance and a higher frequent timetable will cause more nuisance by noise and vibration radiation for inhabitants near railway lines.

Especially the vibration throughout the 24 hours is fairly intensive, but also the low-frequency noise produced by vibrations will affect their living. This low-frequency noise and vibration is, in contrary to air borne noise propagated through the air, more difficult and unclear to observe and a phenomenon difficult to understand. It is known that vibrations can cause discomfort, complaints, absenteeism and health damage. The influence of the visual appearance of damage to their buildings and knowing there is a possibility of a higher frequent timetable contributes to an even higher discomfort level for inhabitants.

Technical measures to reduce the vibration radiance are limited. The effectiveness of these measures are not always certain and thereby the realization might be expensive (but not always). It is internationally recognized, that calculating or measuring the radiation of vibrations caused by railway lines is difficult. A newly introduced method based on a statistical approach provides new opportunities.

2. EXCITATION AND PROPAGATION OF VIBRATION OF TRAINS

The predominant vibration (and noise) source for rail-bound vehicles is the dynamic energy caused by the interaction between rail and wheel. This is the result of the steel on steel contact. The vibration-generation principal is given in figure 1. The other possible noise and vibration sources, such as compressors, ventilation systems and rail interruptions are not of importance. Modern noise and vibration control engineering will solve the problems of these possible sources.

Thus, the most relevant vibration source is the energy produced at the wheel, and at the rail. The strength of the source is dependent of the impedance of the wheel in combination with the bogie and the loaded carriage, the impedance of the rail in combination with the sleepers or the complete track construction and the structural condition of the soil. The source can be differentiated in: rolling noise, impulse noise and curve squeal noise.

Especially for low frequency vibration (lower than approximately 8 Hz) an energy source is decisive, depending on the variation of the impedances of the track. Most of the time, this variation is caused by the differences in movement in the wheel at an above the sleeper position and between the sleeper position. For very low frequencies you have the semi-static displacement of a mass.

The diagram in figure 1 shows that for noise at the wayside, by propagation in open air, four vibration sources are important. The most important excitation mechanism is roughness. This means the roughness of the wheel and that of the rail. The interaction between the wheel and the rail affects the distribution of energy between wheel and rail. Moreover, it is clear that airborne noise outside, along the track, noise inside a carriage, vibration through the soil and structure-borne noise are directly related to each other and are all based on the wheel and rail interaction.

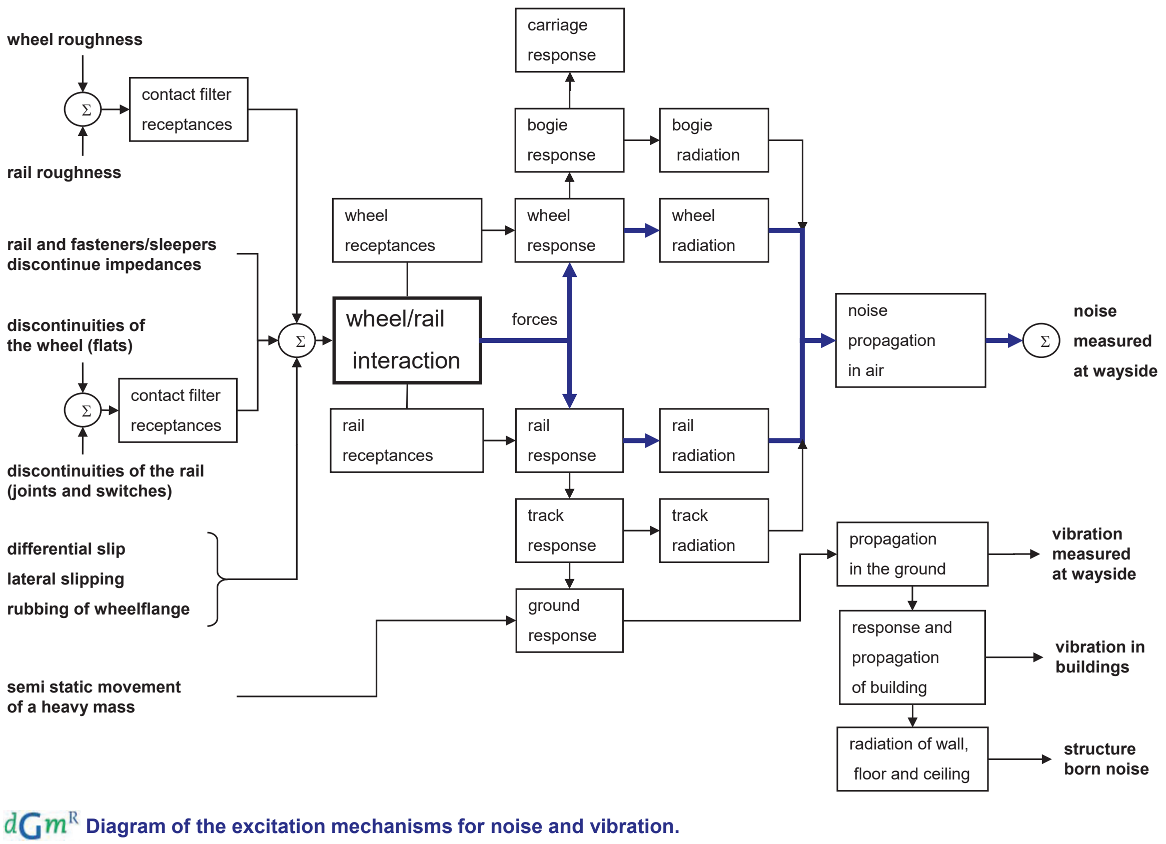


Figure 1. Diagram of the excitation mechanisms for noise and vibration.

There are two special aspects that deal with vibration propagation. Vibrations inside buildings and low frequency structure-borne noise. Those are the results of vibrations from the track, the ground response, the propagation of vibration energy in the ground and the response and propagation inside buildings. For structure-borne noise the radiation of walls, floor and ceiling within a room are also important factors.

3. EFFECTS IN HUMANS AND ON SENSITIVE EQUIPMENT

As mentioned, soil vibrations are noticeable or perceptible as feasible vibrations to human beings and audible as low-frequency noise. Perceptible vibration is related to the vibration level of the floor where you are sitting on, standing on, or where your bed is located. The quantity is the velocity of the vibration in mm/s or the velocity level in dB reference 1 nm/s. The perception level of just nearly feasible vibration lies around 0.1 mm/s of the floor where you are standing on. Vibrations in the magnitude of 0.01 to 0.03 mm/s (velocity levels of 80 - 90 dB) lie just below our perception level. Vibrations are noticeable around 0.3 - 1 mm/s (velocity levels of 110 - 120 dB) for most humans. Very strong noticeable vibrations for most humans have a level of about 1 - 10 mm/s (velocity levels of 120 - 140 dB). The frequency range is from 1 Hz to about 80 Hz, but also below 1 Hz humans are sensitive to vibrations because this can cause seasickness.

Special equipment such as medical microscopes, electronic microscopes, organic spectrum analyzers and Magnetic Resonance Imaging's (MRI's) can be very sensitive to vibrations. There are specifications known of permissible vibrations around 40 to 60 dB below the perception border of humans. Vibration levels of 40 to 60 dB ref 1 nm/s or velocity levels of about 0.1 to 1 μm/s.

Audible noise has a theoretical frequency range starting from 10 or 20 Hz. There are people who claim that they can hear even lower frequencies. For these situations you might discuss whether this is hearing or feeling. Between the range of 30 Hz and 80 Hz you can have the discussion whether you hear noise or feel vibrations. This is shown in figure 2. You can see that there is an overlap in which an average human is more sensitive to audible noise than to perceptible vibrations.

The figure also points out that audible noise is noticeable or annoying at a frequency above 80 Hz. In most of the cases of annoyance, the audible noise is between 80 and 250 Hz.

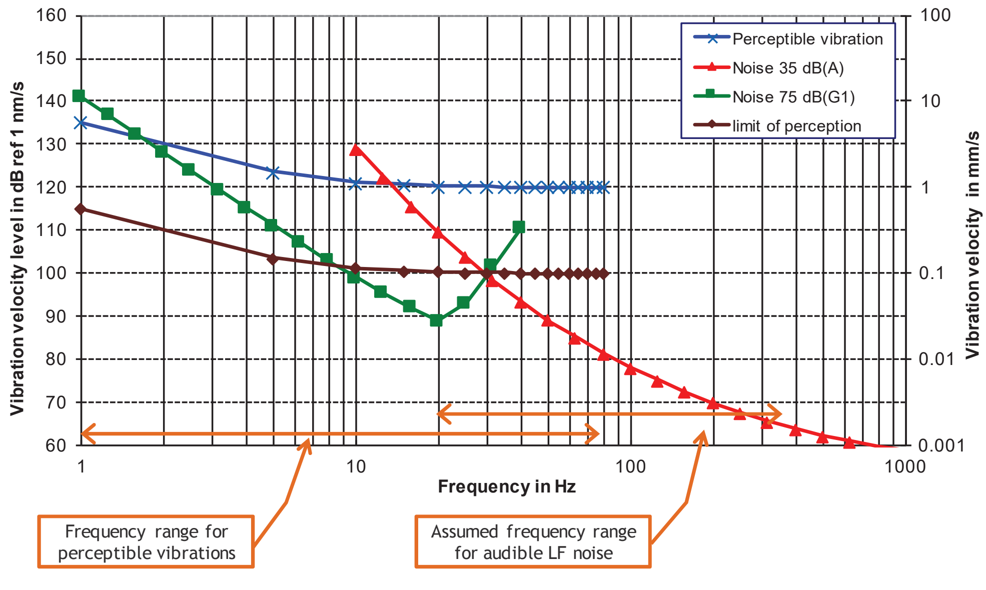


Figure 2. Graph with the sensitivity curves for humans on vibrations of floors of a dwelling and on low frequency structure-borne noise.

Low frequency structure-borne noise is produced in rooms by the radiation of walls, the floor and the ceiling of this room. Subsequently, this means that the quantity of the radiating surface is important but also the radiation coefficient of these surfaces. In general, a concrete wall has a high radiating coefficient and wood or plasterboard has a low coefficient.

Very generally speaking, the following statement is roughly applicable. In most of the cases there is more nuisance by perceptible vibrations when there is a soft soil. In situations where there is a solid soil or very dense sand layers or when you have a concrete structure between the railway line and the dwelling you have more nuisance by low frequency structure-borne noise.

4. MEASUREMENT PROCEDURES AND REQUIREMENTS

In the Netherlands there are some measurements procedures or guidelines on how to determine the vibration levels in houses and apartment buildings. These guidelines are described in [1] and [2]. The guidelines are supplemented with [3] to determine the vibration levels on a more statistically representative and reproducible way.

You have to measure the velocity level of some of the floors of a dwelling. You have to estimate which floor of the various rooms of a dwelling have the highest vibration level. This estimation will be based on the characteristics of the construction and the experience of the researcher. The measurement has to take at least a whole week to have some statistical average of the trains. Problems when preforming these measurements are the disturbances by activities of people living in this building, other road traffic, and the minimum measurement time of at least a whole week. It is also important that during your measurement you have measured some passing freight trains. And you always have the question on the most worst train producing the highest vibration level. The measurement must be performed in the three directions of the vibrations (x, y and z).

An alternative procedure is that you measure at least for a week at a point on the foundation, complemented with some simultaneous measurements on the foundation and on various floors of the dwelling during a shorter time period. This time period is described as at least more than 24 hours.

The vibration levels of the foundation of all the measured trains should have a factor (or should add a decibel value) for the prediction of a vibration value at a certain floor. The difference between the foundation point and chosen measurement point in the dwelling is called $H_{building}$ [3]. This is the transmission factor of a building from the foundation to a certain room. This $H_{building}$ has the quantity "factor" with no units or in the unit dB.

The vibration levels of the floor must be compared to the maximum allowable vibration limits. The procedure also describes some proceedings on how to come to a review framework to verify that your measurements are reproducible. This procedure is described as measurement type number 2 in the guideline [3].

The measurement of low-frequency noise can be straightforward. Some measurement procedures use microphones. One of the largest problems is that the low frequency vibrations are in relation to the room's own resonance frequencies. Common dimensions for a living or bedroom are 2.7 meter height (63 /126/189 Hz), 3 meter width (57/113/170 Hz) and 5 meter length (34/68/102 Hz). Moreover, the effects of acoustical absorption and reverberation times are important. This means that performing these low frequency measurements are quite complicated and not as accurate as desired. It is also possible to calculate the low-frequency noise levels directly from the vibration levels of the walls, floor en ceiling.

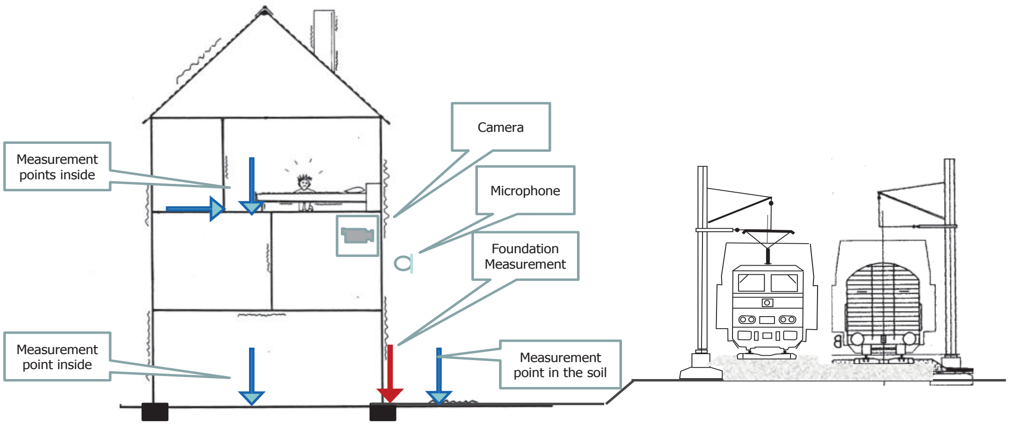
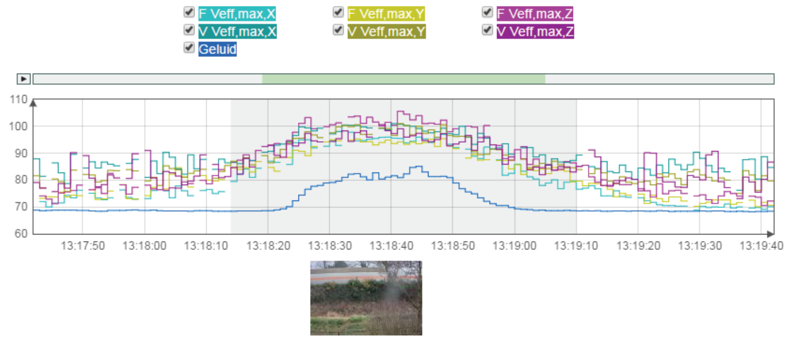


Figure 3 the measurement set-up in practice to determine the vibration of trains.

In the figure above you will find how these measurements work out in practice. The main measurement point is on the foundation of the dwelling for at least a week. Measurement points inside the dwelling determine the $H_{building}$ transmission factors during a 24 hour measurement. To validate if the measured vibrations are indeed the result of passing trains, a digital camera and a microphone are also a component of the installed set-up. Using the Sensornet data acquisition system [4] you can gather your data by automatically defining the events of passing trains with additional data, for example the running speed, the train type or even the train identification. Figure 4 gives an example of results of a data acquisition system.



Show 100 entries

Tijdstip piek	Duur	V km/u	Fn veff,max	Fn DomO event	Fn DomXYZ event	Vl veff,max gemeten	Vl veff,max berekend	Vl DomO event	Vl DomXYZ event	Type	Fn Verstoring
2015-03-17 00:02:36	57		111.1	O8 = -2.3dB	z	-	108.8	-	-	Trein	
2015-03-18 23:42:01	46		109.4	O8 = -2.3dB	z	106.3	107.1	O8	z	Trein	
2015-03-26 04:07:52	72		107.9	O8 = -2.3dB	z	-	105.6	-	-	Trein	
2015-03-19 04:51:01	56		107.3	O8 = -2.3dB	z	104.1	105.0	O8	z	Trein	
2015-03-23 13:51:02	67		106.9	O8 = -2.3dB	z	-	104.6	-	-	Trein	2 treinen
2015-03-17 21:23:09	39		105.9	O8 = -2.3dB	z	102.4	103.6	O8	z	Trein	
2015-03-20 13:18:42	56		105.6	O8 = -2.3dB	z	-	103.3	-	-	Trein	
2015-03-24 23:11:51	14		105.5	O8 = -2.3dB	z	-	103.2	-	-	Trein	
2015-03-17 13:13:43	50		105.1	O8 = -2.3dB	z	104.4	102.8	O8	z	Trein	2 trein
2015-03-22 20:30:57	14		105.1	O8 = -2.3dB	z	-	102.8	-	-	Trein	

Showing 1 to 100 of 3,443 entries   Previous 1 2 3 4 5 … 35 Next

Figure 4 Example of the database of all the events. Data collected by Sensornet.

5. ONE MEASUREMENT POINT FOR ONE DWELLING?

Measurements on the foundations are much more practical and will give a good completion to the large spread in vibration levels in the soil. Due to the large variation of vibration propagation in the soil, it is very complicated to come to an accurate calculation model to predict vibration levels. Difficulties of defining source positions and the large differences in the structural soil condition are other factors that make predictions less accurate (figure 5).

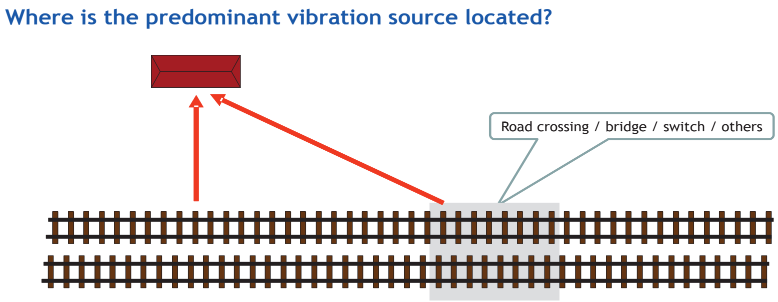


Figure 5 A schematic example of a possible vibration source along a railroad

Based on all the possibilities, it is advisable to determine the vibration level of different dwellings instead of performing multiple measurements in one dwelling. Through collecting data such as the condition of the soil structure, distance between railroad and dwelling and the characteristics of the building, we will gain more insight in the transmission factor.

6. A REALISTIC $H_{building}$ TRANSMISSION FACTOR

The measurements of the vibration levels of the foundation in combination with a measurement point at a certain floor in the dwelling, gives some information about the propagation of the vibration energy in the building. The difference between the foundation point and a random measurement point in the dwelling is called $H_{building.}$ When using a more realistic and practical approach, we need an estimation of the propagation of the vibration energy from the foundation to an arbitrary floor of a room in the dwelling. As mentioned, this must be by definition the only floor of a room with the highest vibration level of all passing trains. And for this we have to realize that theoretically every arbitrary train can give another vibration spectra. In practice, it is known that, for example a passing passenger train can give other predominant vibration frequencies compared to the vibration frequencies of a freight train.

The figures 6-9 give the transfer factors in dB between foundation and a point in the middle of a floor. In figure 6 the results of some measurements are displayed. The plotted transfer factor for each 1/3 octave band is used as input for $H_{building}$ of Wijnia [5]. This $H_{building}$ was based on continuous vibration sources and for a massive building structures. The graph also presents the highest measured transfer factor (the solid purple line). Figure 7 displays measurement results of [5] for the continuous vibration sources and also an estimation for non-continuous vibration sources, like passing trains. After all, for non-continuous vibration sources or more pulse-shaped signals we do not come to a complete effect of resonant rise.

As shown in the figures below, there is no difference in the vibration levels in the lower frequencies (< 8 Hz). We might expect that an average building is more or less rigid in this frequency range. It can also state that if there are any differences, we might have a, more or less, instable building or some extreme sagging and bending of the floor in this building.

Based on the graphs we can state that the frequency range between 10 Hz and 50 Hz is dominant, and that for non-continuous vibrations a 3 to 10 dB higher transfer factor is a conservative assumption for vibrations of passing trains.

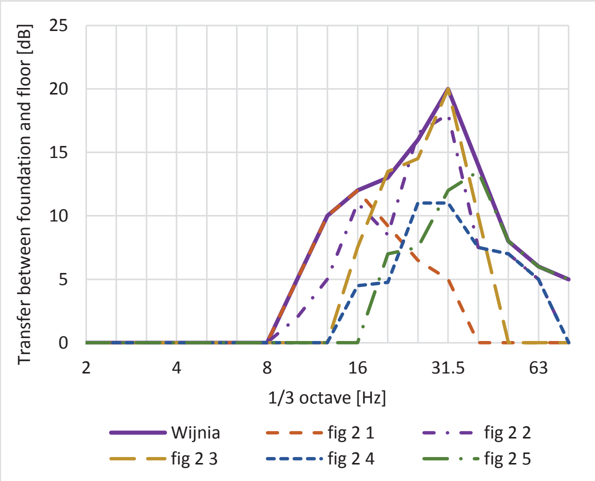


Figure 6 Measured transmission factors for massive building structure by [5]

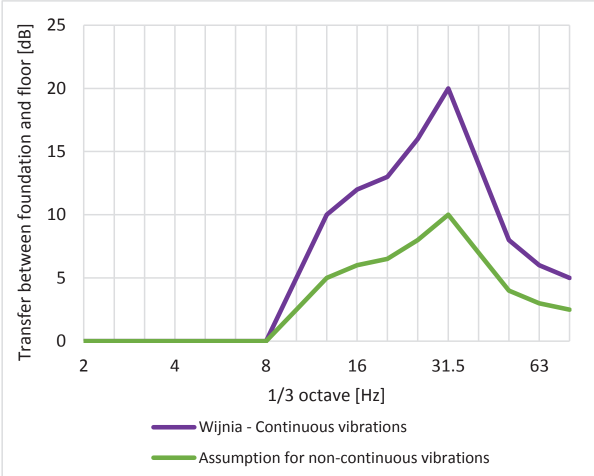


Figure 7 Measurement results of continuous vibration [5] and of non- vibrations

Figure 8 shows some measurement results of various projects in the Netherlands. The measured $H_{building}$ is in octaves as the guideline prescribed. The measured values are divided into two groups; a group containing only dwellings consisting of a massive building structure like masonry and concrete (blue lines), and a group consisting of only light structural dwellings with floors of wood (orange lines). The thin lines are individual samples of measured results. The thicker lines are the highest measured transfer factors per group for each frequency. Figure 9 displays a rough proposal for a realistic $H_{building}$ value for different dwellings. The given $H_{building}$-values are based on literature [5] and recent performed measurements (figure 9).

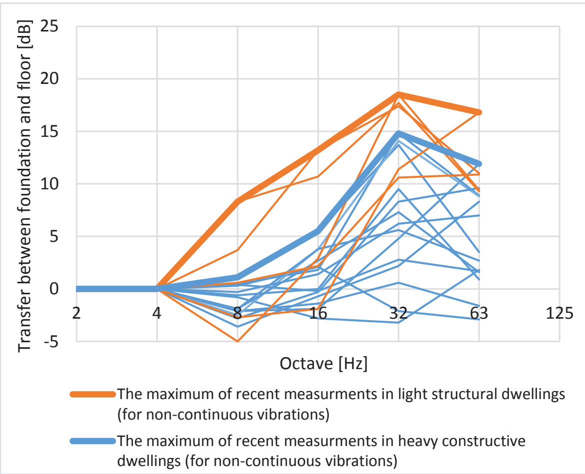


Figure 8 Measurement results according [3] divided into two groups, a group containing only dwellings with a massive building structure (blue) and a group consisting of only light structural dwellings (orange)

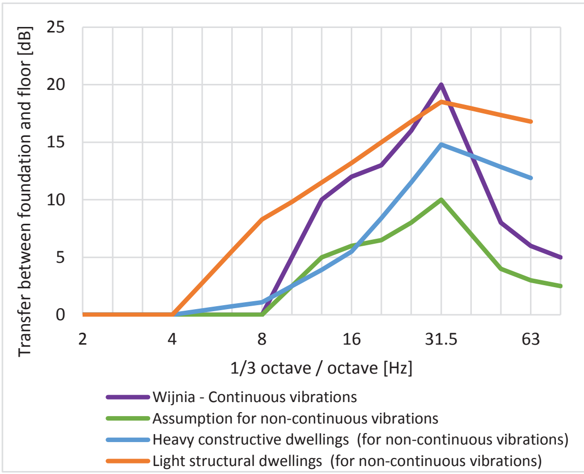


Figure 9 An overview of all the $H_{building}$ values. (The recent measurements are only in octaves as the guideline prescribed)

Especially the measurements on carpet, parquet and other floor coverings require special attention. After all, it is not like you can “just remove" this carpet, during the execution of the measurements. The distorting effects of the floor coverings is extremely important. Moreover, the measurements are often done on a bare floor while at least one human (the mass) must be on the site. This extra mass will result into a more correct determination of the vibration level. The static loading in the floor will give another vibration response, mostly lower resonance frequencies and higher impedance, due to the extra mass.

7. FURTHER INVESTIGATION

Determining the strength of vibrations and the strength of low-frequency noise is particularly complex. A realistic $H_{building}$ transmission factor is essential for determining a practical value for the strength of vibrations inside dwellings, apartments, offices and other buildings. This $H_{building}$ is essential when performing measurements according to the principles on BTS option 2 [3].

To come to a more representative and more reproducible determination of the vibration strength in dwellings/buildings (and also of the structure-born low frequency noise) a proposal for further investigation is defined by the following aspects;

1. An analysis of existing $H_{buiding}$-measurements. And indeed, if the dispersion of the measurements is too large, you might split up results for a more final determination.
2. Carry out extensive measurements on each floor for dwellings/buildings during ongoing projects or in special designated dwellings/buildings. During these measurements we need to observe the current situations and to what extent the $H_{building}$ is determined by the floor points against a representative value of the absolute vibration. DGMR's approach is to measure the ground floor in a living room and the floor in a bedroom upstairs. For this a floor with a large span near the rail side is preferred. But we also know that if there are two or more floors (or an inhabited attic), you should actually have more measurement positions in this dwelling/building.
3. Analysis of the quantity of the $H_{building}$ values. This includes an analysis of the $H_{buiding}$ values based on a theoretical approach, $H_{buiding}$-measurements and determination of the $H_{buiding}$ will be assessed. The readings will be compared with measurement reports from other measurement institutes and, in practice, common spreads in $H_{building}$ will be imaged.

A theoretical exercise is needed to determine if the assumptions for $H_{buidling}$ are reliable for different types of dwellings. For example:

a) Piled buildings with concrete floors;
b) Piled buildings with wooden floors;
c) Non piled buildings with wooden floors;
d) Multilayer apartments and offices.

Of course, this investigation will be reported to come to a better determination of the vibration strength and structure-born low frequency noise level.

8. CONCLUSIONS

Vibration nuisance caused by railways can be divided into feasible vibrations for a human being and low-frequency noise produced by vibrations. Both contribute to a higher level of discomfort for inhabitants. The frequency range for feasible vibrations is from about 1 Hz to 80 Hz, and the audible noise has a theoretical frequency range starting at 10 or 20 Hz up to the higher frequencies. There is an overlap in which an average human is more sensitive to audible noise than to perceptible vibrations.

According to the guideline [3] you have to measure the velocity level of some of the floors of a dwelling. Problems are disturbances by activities of people living in this building, other road traffic, and the minimum measurement time of at least a whole week. An alternative procedure is that you measure at least for a week at a point on the foundation of the building.

However, determining the strength of the vibrations and the strength of the accompanied low-frequency noise somewhere in the building is particularly complex. The strength of the vibration for feasible vibrations and for structure-borne low-frequency noise can be measured on the foundation of the building and by using a predetermined realistic $H_{building}$ transmission factor, practical values for the strength of vibrations and low-frequency noise will be determined.

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