Frequency characteristics in railway traffic induced ground vibrations
Caractéristiques des fréquences des vibrations du sol induites par le traffic ferroviaire

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ABSTRACT: By knowing the speed and the axle distance distribution of a train, the frequency characteristics of the induced ground vibrations can be determined. This has been concluded after analyses of both numerical (2-dimenesional finite element analyses) and actual measurements. In the numerical studies, no amplification of frequencies due to resonance of the soil could be determined. In the actual measurements, however, amplifications were obtained at frequencies that could be caused by resonance of the soil deposit.

RESUME: Connaissant la vitesse et la distribution de la distance à l'axe d'un train, les caractéristiques de la fréquence des vibrations du sol induites peuvent être déterminées. C'est la conclusion de l'analyse de résultats numériques (analyse aux éléments dinis à 2-dimensions) et de mesures actuelles. Dans l'étude numérique, aucure amplification des fréquences due à une resonance du sol a pu être détermineé. Par contre, dans les mesures actuelles, des amplifications des fréquences pouvant être causées par résonance du sol ont été obtenues.

1. INTRODUCTION

The environmental concern of noise and vibrations has become important in recent years because of the possible detrimental effects upon both structures and people. The interest to drive trains at higher speeds and carry heavier loads on the railway tracks has also increased. This, together with the environmental aspect, has created a growing interest in the problem of railway traffic induced ground vibrations. A doctoral project has commenced at the Royal Institute of Technology to increase the knowledge about this problem by simulating railway traffic induced ground vibrations in numerical models and comparing the results with actual measurements.

The purpose of the research presented in this paper was to analyze whether the load frequency and/or the natural frequencies of the soil (eigenfrequencies) could be seen in the Fourier spectra of the results from numerical calculations and actual measurements. The numerical models of the problem have been created in the three-dimensional dynamic finite element program ABAQUS, but only 2-dimensional finite element analyses have been performed so far. During these analyses of results from numerical calculations and actual measurements, it was found that by just knowing the speed and the axle distances of the train, the dominating frequencies of the induced vibrations could be determined. It was also investigated whether any amplifications around the soils natural frequencies could be seen. In the analyses, amplification at frequencies was found in the actual measurements, but not in the results from the numerical models.

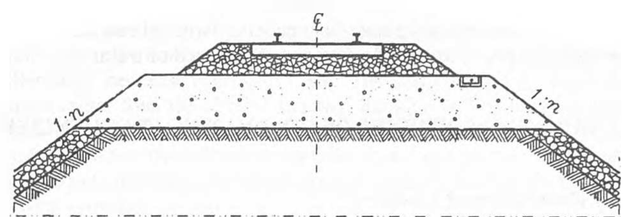


Figure 2.1 Section of a typical Swedish railway embankment (Sahlin & Sundquist, 1995)

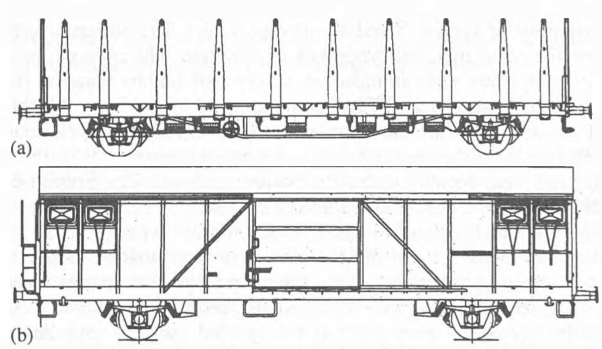


Figure 2.2 Example of two typical Swedish freight wagons (a) Kbps-wagon (b) Gbs-wagon. (SJ Produktionsstab, 1991)

2. TRAINS AND SOIL CONDITIONS IN SWEDEN

2.1 Damping characteristics of vibrations

When the vibrations are propagating from a source as a wave motion, the intensity decreases with distance due to both material and geometrical damping. The geometrical damping occurs because the vibration energy is spreading over a larger area as the wave front is moving from the source. The material damping is caused by friction in the transmitting medium. The wave energy is then transformed into heat energy. The material damping is less in clay than sand, because clay has an almost elastic stress-strain behavior. Vibrations can cause settlements in sand, while clay is almost not affected. The magnitude of vibrations in sand also decreases rapidly relative to distance, while in clay the vibrations can spread to long distances. The major problems with railway traffic induced ground vibrations exist where railways and nearby buildings are founded on clay. Here, the resulting building vibrations can be very disturbing for people's comfort and have detrimental effects on structures and equipment. This is specially the case in Scandinavia where soft clay is a very common soil type.

2.2 Railway embankments

Swedish railway embankments can be considered as a layered system of different materials. The upper part of the embankment consists of railway track, sleepers and ballast. Under the ballast follows a fill material to varying depths depending on geotechnical conditions and topography. Nowadays, the sleepers are mainly made of concrete. The ballast consists of an upper and a lower section. The upper ballast is very stiff and is made to retain large forces in all directions and to be elastic. The material should be poorly graded in order to create more voids. The particle shape should also be angular and cubical in order to create as much friction as possible. The underlying ballast is designed to spread the weight from the train as much as possible, and to drain and protect the embankment against erosion. The underlying ballast should be well graded, and not consist of too many large particles and have good compression characteristics. The fill must have good stability and bearing capacity and it should consist of a material that is not frost sensitive. A typical Swedish railway embankment is shown in Figure 2.1.

2.3 Trains

It is known that freight trains induce larger vibrations than passenger trains. The cause of this is believed to be the greater weight that freight trains are transporting (Hannelius, 1978). The passenger trains usually consist of one locomotive, followed by 4-5 wagons. Larger vibrations are induced by the locomotive, which is considerably heavier than the other wagons. It has also been observed that higher speeds create larger vibrations. The freight trains are usually several hundred meters long carrying up to 2000 tons. According to Hannelius (1978) resonance phenomena often occur in nearby 2-3 story wood buildings on homogenous clay layers, especially when the freight trains consist of wagons with equally spaced axles. Hannelius (1978) also observed that heavy freight trains with a varying axle spacing caused less resonance phenomena than freight trains with equal axle distances. Typical Swedish freight wagons are shown in Figure 2.2. According to Hannelius the primary parameters causing large vibrations are the weight, length of train, axle distances and speed of train.

3. NUMERICAL STUDIES OF DOMINATING FREQUENCIES

3.1 Finite Element Modeling

An attempt was made to simulate the conditions of an actual railway track with an embankment on a soft clay layer. The railway track was simulated by beam elements with the same dimensions as typical Swedish railway tracks. The sleepers were given the same material properties as concrete. The railway track and the sleepers were founded on a very stiff ballast material (0-0.35 m) followed by a stiff ballast material (0.35-1.75 m). All this was made to simulate the actual conditions and to get a good load spreading from the moving loads. An approximately 19 m thick clay layer was located under the ballast material. The properties of the different material in the model are listed in Table 3.1.

The total dimension of the finite-element mesh was 80x20.65 m^2 with 2115 elements and 4085 nodes. 5 m long infinite elements were located at both sides of the model and the bottom was fixed in all directions in order to simulate bedrock (Figure 3.1.a). Smaller elements were used at the ground surface, and larger elements further away. The smallest element had a dimension of 0.175x0.175 m^2 and smallest node distance was 0.0875 m. The largest finite element had a dimension of 2.8x2.8 m^2. The element's size and node distance were chosen so that the spacing of the sleepers would be 0.7 m (Figure 3.1.c). The nodes at the ground surface were subjected to moving loads as shown in Figure 3.2. The load step was chosen as the node distance divided by the velocity of the train and the time step as the load step divided by 4.

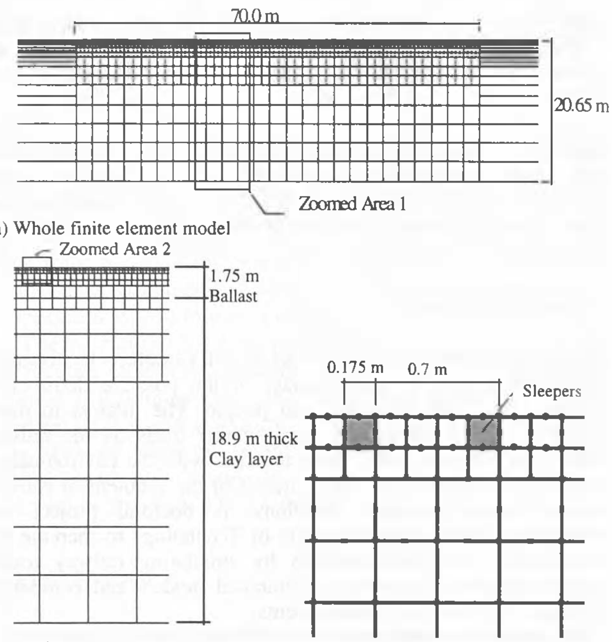
3.2 Natural frequencies of the soil deposit

The purpose of these finite element analyses was to investigate whether the load frequency and/or the natural frequencies of the soil (eigenfrequencies) could be seen in the Fourier spectra. It was generally known that vibrations induced from railway traffic were more prominent around certain frequencies. The cause of this was, however, not fully understood (Zachrisson et al., 1996). The general impression from the people involved in measuring vibrations from railway traffic, was that loading conditions such as spacing of axles and speed of train affect the frequency characteristics more than soil conditions do.

Table 3.1 Material properties used in the FE-model.

Element type	Depth (m)	Elasticity modulus (MPa)	Poisson's ratio	Density (kg/m3)	Rayleigh damping
Beam elements	0	200.0E+3	0.3	7800	
Concrete elements	0 - 0.175	30.0E+3	0.15	2400	α=0.09, β=0.009
Ballast elements: upper layers	0- 0.35	300.0	0.3	2200	α=0.09, β=0.009
Ballast elements: lower layers	0.35 - 1.75	150.0	0.3	2000	α=0.09, β=0.009
Clay elements	1.75 - 20.65	15.0	0.495	1600	α=0.075, β=0.005

Where α and β are mass and stiffness proportional damping, respectivly.



(a) Whole finite element model

(b) Zoomed Area 1 (c) Zoomed Area 2

Figure 3.1 Finite element model.

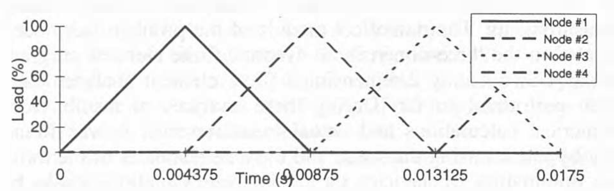


Figure 3.2 Moving load at a speed of 20 m/s. The spacing between the nodes is 0.0875 m.

The natural frequencies of the soil are frequencies where the soil response can be amplified. If the frequency of the dynamic load from the train tunes in with one or more of soil deposit's natural frequencies, the response of the vibrations for these frequencies will be magnified. The nth natural frequency is given by the following formula:

$$f_n = \frac{(2n+1)c_s}{4H} \tag{3.1}$$

where, n = 0,1,2..., H = thickness of deposit and c_s = shear wave velocity. Thus, the characteristic site frequencies depend only on thickness and the shear wave velocity of the soil. The peak amplification decreases, however, with increasing natural frequency (Kramer, 1996). The greatest amplification occurs, therefore, at the lowest natural frequency (n=0), also known as the fundamental frequency. According to Chouw, Le & Schmid (1991) the natural frequencies also depend on the direction of the vibrations. When the excitation is horizontal, the nth natural frequency is given by the above equation. In vertical excitation, the compression wave velocity should be used instead of the shear wave velocity. The natural frequencies for the finite element model are given as follows: Horizontal excitation: $f_{n,h}$=0.74, 2.22, 3.70, 5.18, 6.67, 8.15, 9.63, 11.11, 12.59, 14.07, 15.55, 17.04 (Hz); Vertical excitation: $f_{n,v}$= 7.44, 22.33 (Hz)

3.3 Loading frequencies

In the first analyzed cases, only one single axle distance was examined. The results from the moving loads were obtained by measuring the response at different depths in the middle of the FE-model. All the finite element calculations were made by direct time integration calculations. A frequency analysis was performed on the measured response by calculating the power spectrum, defined as:

$$S_{xx} = \frac{[F\{\mathbf{X}\}]^2}{n^2} \qquad (3.2)$$

where, n = number samples, [F{**X**}] = Fourier transform of the signal (X).

In the case of equally spaced axle distances, it was assumed that the loading frequency was the speed of the train divided by the axle distance (the distance between the loads). This was also shown to agree with obtained power spectrum from the measured responses. In the second analysis, unequally spaced axle distances were examined. A new approach was required to determine the loading frequency. This was made by creating a time signal of the axle distances and performing a frequency analysis. The agreement between power spectra of the load distribution and the power spectra of measured responses of two axle distances was very good. The finite element analyses were then continued by analyzing a simulated real train. Good agreement was also obtained here for the power spectra of the load distribution and the measured response. Finally, frequency analyses were performed on actual measurements from passing trains with known axle distances. Good agreement was obtained again between the power spectra of the load distribution and the power spectra of the measurements. A detailed description of these cases will be discussed in the following paragraph.

3.4 Calculated cases

In all the following finite element analyses, 17 loads were moving over the FE-model, except for the analysis of a simulated train, where more moving loads were used. All the moving loads moved at a certain speed and with a certain spacing (axle distance) between the loads. All the moving loads were loaded with a vertical load of 20 kN in a manner as discussed earlier in the chapter (Figure 3.2). The response of the particle acceleration was measured in the middle of the finite element model at six different depths (0.0, 1.05, 3.15, 5.25, 9.45 and 17.85 m) in both the horizontal and the vertical directions. The responses of the particle displacement and velocity were also measured in the simulated train. A frequency analysis was then performed on the measured response and compared with the loading frequencies as described in the preceding paragraph.

In the results it was seen that higher frequencies decreased at greater depth further away from the source. This may be caused by natural phenomena such as geometrical and material damping. The material damping was included in the finite element model by the Rayleigh damping model (Table 3.1). However, there is also an involuntary damping in the finite element method. In order for the finite element model to catch the vibration waves satisfactorily, a certain amount of finite elements is needed. As a rule of thumb, the smallest expected wave length should be 5 times larger than the element sizes. Using this rule, the largest allowable frequencies were calculated for the finite element model as shown in Table 3.2. However, in the finite element model, frequencies were measured around 16 Hz, where the largest allowed frequency is 4 Hz. This rule of thumb may be too conservative, but caution should be taken when interpreting the result for frequencies above the allowable frequency.

Table 3.2 Largest allowable frequencies in the FE-model.

Depth (m)	Element size (m)	Shear Wave Velocity (m/s)	Largest allowable frequency (Hz)
0	0.0875	3140.4	7178.0
0 - 0.175	0.175	2331.3	2664.3
0 - 0.35	0.175	229.0	261.7
0.35 - 1.05	0.35	169.8	97.1
1.05 - 1.75	0.7	169.8	48.5
1.75 - 2.45	0.7	56.0	16.0
2.45 - 6.65	1.4	56.0	8.0
6.65- 20.65	2.8	56.0	4.0

3.4.1 Equally spaced axle distances

The analysis consisted of 17 moving loads equally spaced. The power spectrum of the vertical acceleration for moving loads with a spacing of 5 m and a speed of 10 m/s is shown in Figure 3.3. As seen in the figure, the measured frequencies coincide with the load characteristics. Five peaks at frequencies 2, 4, 6, 8 and 10 Hz are predominant. The peaks at higher frequencies decrease a lot faster at greater depths, and the lower frequencies 2 and 4 Hz becomes more prominent. The same case, but for the measurement in the horizontal direction (Figure 3.4), shows a different behavior. At depths 0.0 and 1.05 m two peaks at frequencies 4 and 14 Hz are predominant. At greater depths the peaks at 2, 4 and 6 Hz are prominent, with the 2 Hz peak as the largest.

3.4.2 Unequally spaced axle distances

In the analyses of unequally spaced axle distances, two different axle spacings were used. The spacing separating the loads was alternated between short and long. The longer spacing was 1.5 times larger than the shorter spacing. As seen in Figure 3.5.a, the load characteristics in the frequency domain are much more complex when two different axle distances are used as compared to one axle distance. The load characteristics have, however, still a very symmetrical behavior.

The power spectra when the axle distances are 5 and 7.5 m and the speed of the loads were 10 m/s are shown in Figures 3.5 and 3.6 for the vertical respectively to horizontal acceleration. They all have the same frequencies as the load characteristics. In the vertical response, 4 Hz seems to be more prominent, and in the horizontal response the 1.6 Hz frequency is predominant.

3.4.3 Real train simulation

In this analysis a train consisting of a Rc-locomotive, followed by 16 Gbs-Wagons and another Rc-locomotive, is simulated. In total, 39 moving loads were used, with 5 different spacings varying between 2.7 to 8.0 m. The loads moved at a speed of 70 km/h. The responses of acceleration, velocity and displacement were measured. Only the vertical responses are reported here.

For the vertical acceleration at the ground surface (Figure 3.7b), all the frequencies among 0-17 Hz are seen as in the load characteristics. Higher frequencies are not so prominent at greater depths. The 2.8 Hz frequency predominates at all depths (Figure 3.7b-e). The particle velocity (Figure 3.7.f) has a behavior similar to the acceleration, with the prominent frequency at 2.8 Hz. For the particle displacement (Figure 3.7.g), however, only frequencies below 1 Hz are prominent in the power spectra. The fact that the displacement in the frequency domain mainly shows low frequency motion, is due to the fact that the displacement is the 2[nd] integrate of the acceleration. The integration procedure has a smoothing and filtering effect [in the frequency domain, $\hat{u}(\omega)=\hat{v}(\omega)/\omega=\hat{a}(\omega)/\omega^2$]. Thus, the acceleration shows a significantly higher proportion of higher frequencies as compared to both velocity and the displacement.

3.4.4 A non-periodic load distribution

In order to get a load characteristic that does not have a specific frequency, 17 loads moving at a speed of 20 m/s were randomly chosen with a spacing between 1 and 10 m. The load characteristics, shown in Figure 3.8.a, indicate that one specific frequency peak is obtained at 20 Hz. In other words, the fundamental load frequency was obtained for the least common axle distance. From the measured response of the vertical

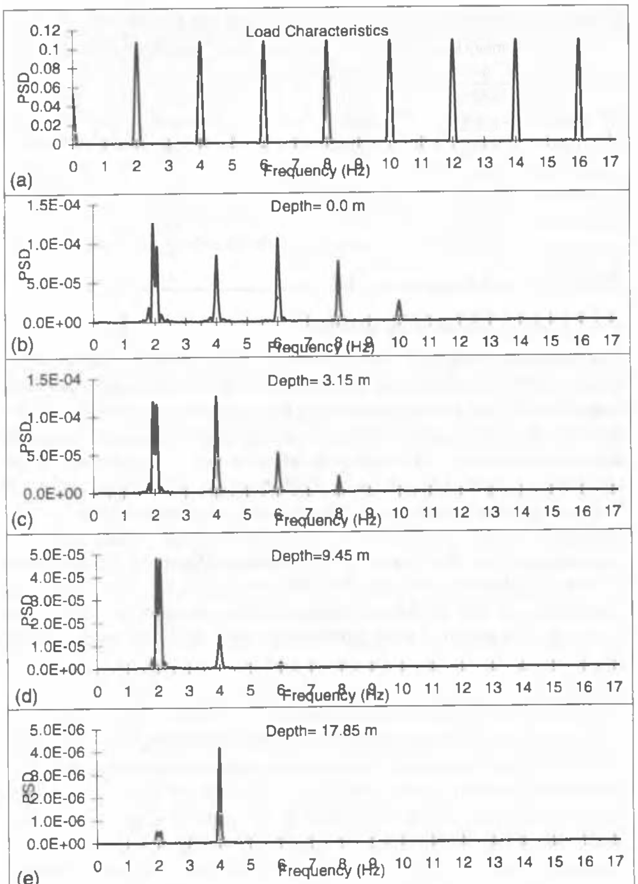


Figure 3.3 Power spectrum of the vertical acceleration for moving loads with axle spacing of 5 m and a speed of 10 m/s.

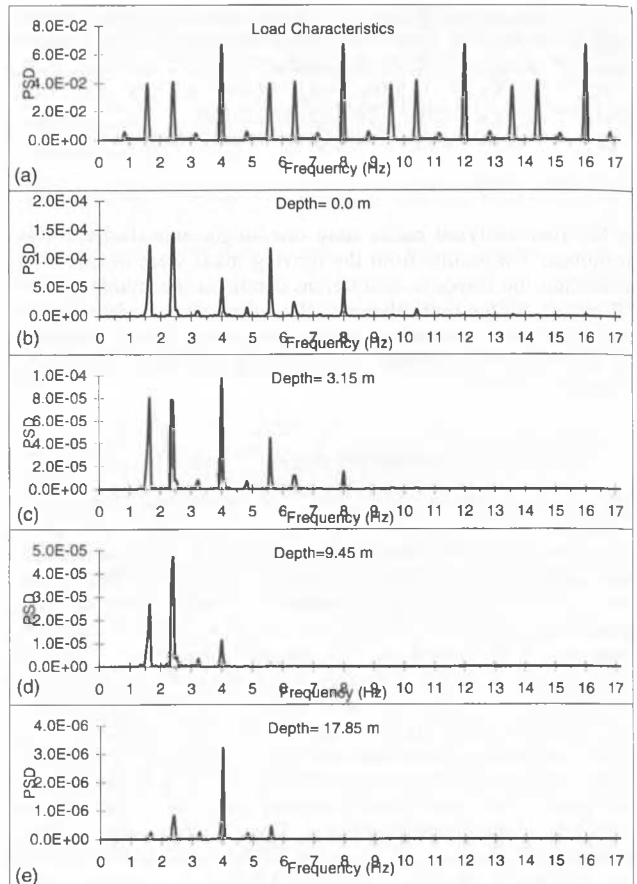


Figure 3.5 Power spectrum of the vertical acceleration for moving loads with axle spacing of 5, 7.5 m and a speed of 10 m/s.

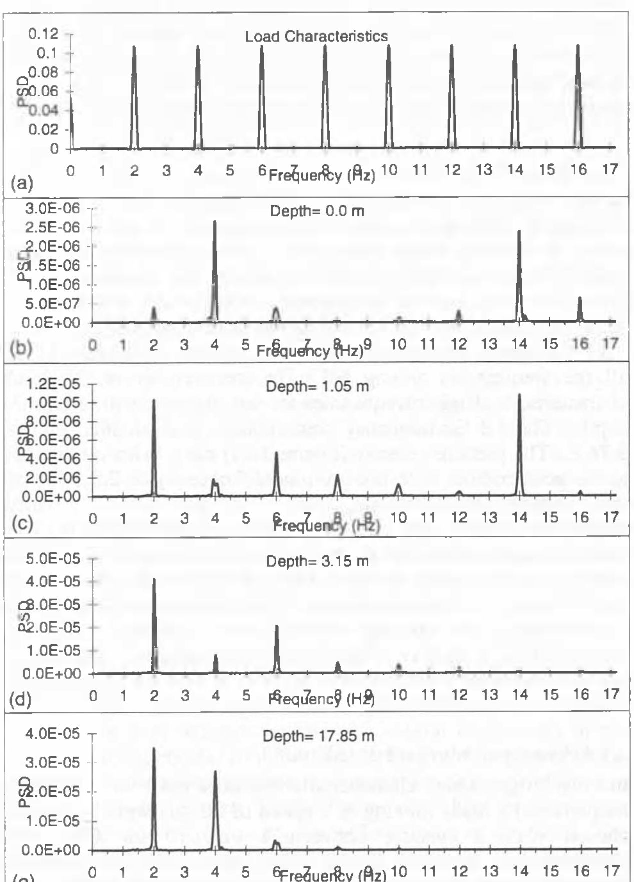


Figure 3.4 Power spectrum of the horizontal acceleration for moving loads with axle spacing of 5 m and a speed of 10 m/s.

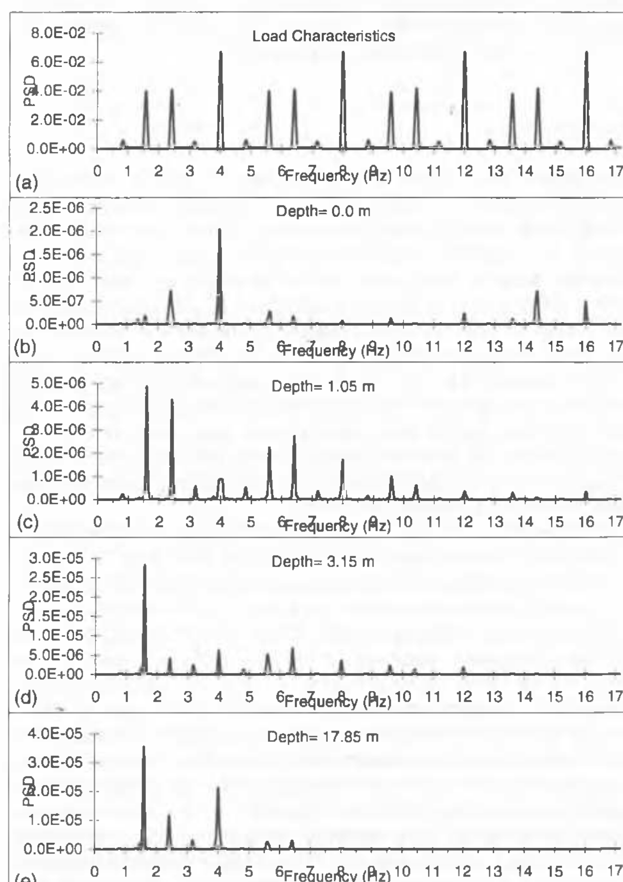


Figure 3.6 Power spectrum of the horizontal acceleration for moving loads with axle spacing of 5, 7.5 m and a speed of 10 m/s

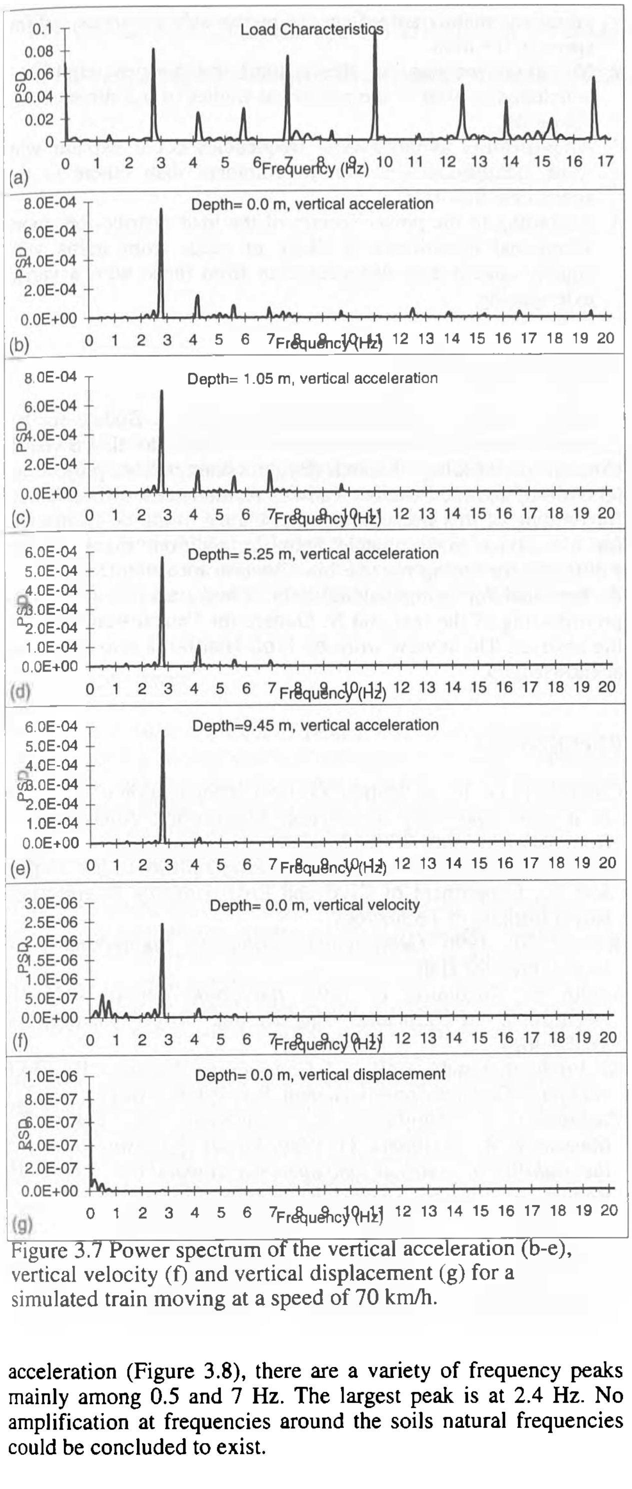


Figure 3.7 Power spectrum of the vertical acceleration (b-e), vertical velocity (f) and vertical displacement (g) for a simulated train moving at a speed of 70 km/h.

acceleration (Figure 3.8), there are a variety of frequency peaks mainly among 0.5 and 7 Hz. The largest peak is at 2.4 Hz. No amplification at frequencies around the soils natural frequencies could be concluded to exist.

4. ANALYSIS OF DOMINATING FREQUENCIES IN ACTUAL MEASUREMENTS

In order to verify the theory that axle distances are the main influence on the predominant frequencies in railway traffic induced ground vibrations, analyses of actual measurements are necessary. Two case histories performed by the Swedish Railway Administration were analyzed. The measurements were recorded by accelerometers of type Brüel & Kjær 8306 having a frequency range of 0.4-400 Hz. The measurements were sampled digitally with a sampling frequency of 1024 measurements per second. Frequency analyses were performed in the same manner as in the numerical studies. From the known axle distances of the trains, the loading distribution was obtained, and the load characteristics in the frequency domain could be determined.

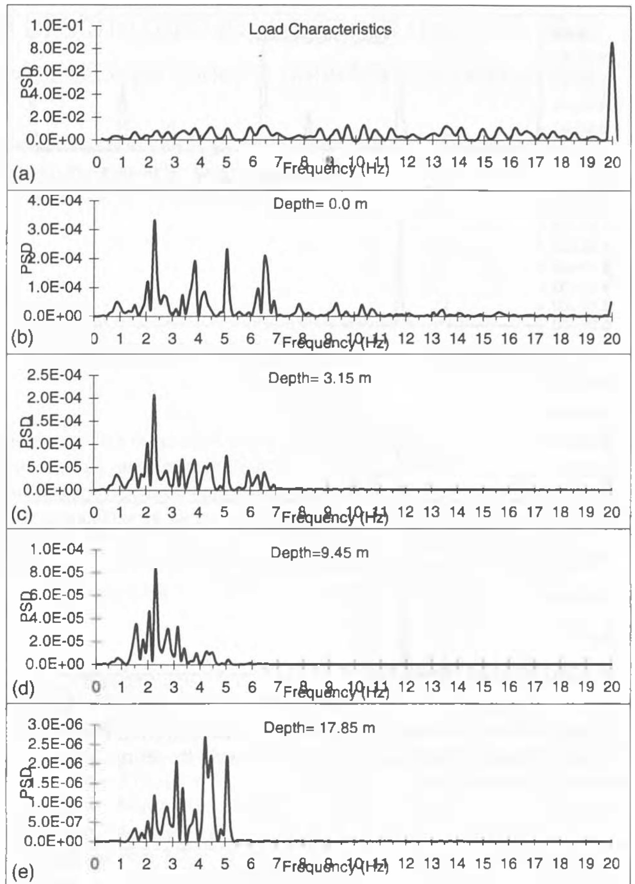


Figure 3.8 Power spectrum of the vertical acceleration for moving loads with random axle spacing and a speed of 20 m/s.

4.1 Alvhem

Alvhem is located about 40 km north of Gothenburg, Sweden. The soil conditions at the site consist of a very deep soft and homogeneous clay layer. The clay layer is about 40 m deep and has an average shear wave velocity of 50 m/s, giving the following natural frequencies: $f_{n,h}$= 0.3, 0.9, 1.6, 2.2, 2.8, 3.4, 4.1, 4.7, 5.3, 5.9, 6.6, 7.2, 7.8, 8.5, 9.1, 9.7, 10.3 (Hz); $f_{n,v}$= 3.1, 9.4 (Hz)

The passing train consisted of a M-locomotive, followed by a maneuvering wagon and ten QBX-wagons loaded with macadam. The train traveled at a speed of 92 km/h. The load characteristic is shown in Figure 3.9.a. Vibration measurements were performed at 5, 15 and 25 m from the railway track, both in the vertical and at the horizontal directions parallel to the railway track. Only the power spectrum of the vertical acceleration is reported here. As seen in Figure 3.9, good agreement is obtained with the load characteristics. At 5 m from the railway track, the frequency at 5.4 Hz is the most predominant one. Further away, the frequency at 7.2 Hz is more prominent. The prominence of these frequencies could be explained by resonance of the soil deposit. However, no certain conclusions about amplification at these frequencies can be made.

4.2 Hynboholm

In Hynboholm, outside Kristenhamn, Sweden, the soil consists of a relatively soft clay layer (c_s= 55 m/s) about 9 m deep. Due to complaints of vibration disturbances in residential buildings located nearby the railway track, vibration measurements have been performed. The measurements were performed on a train consisting of a Rc-locomotive followed by 21 Kbps-wagons loaded with timber. The train was driving at a speed of 87 km/h. Vertical acceleration measurements were performed at distances

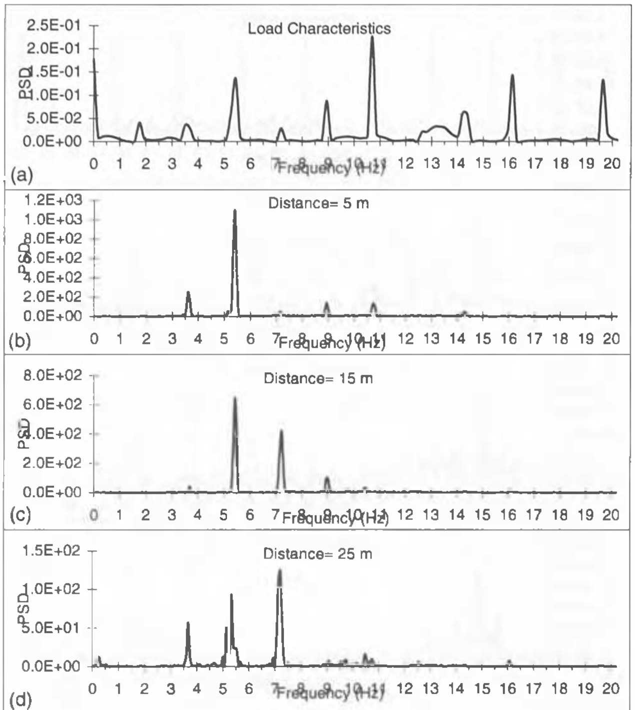


Figure 3.9 Power spectrum of the vertical acceleration from vibration measurements at Alvhem for a train traveling at a speed of 92 km/h.

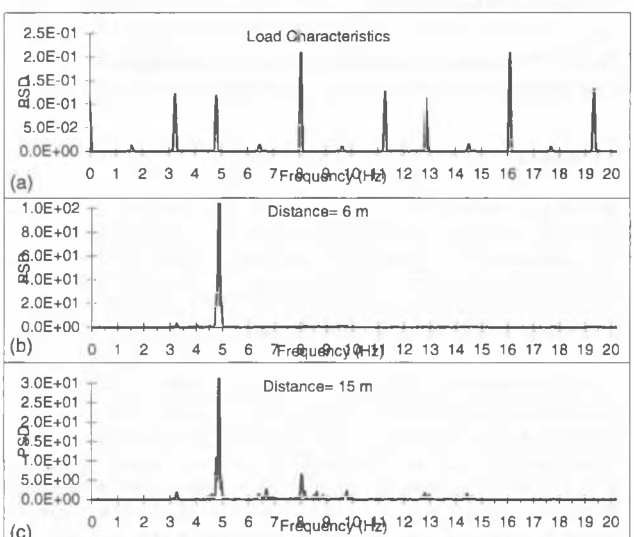


Figure 3.10 Power spectrum of the vertical acceleration from vibration measurements at Hynboholm for a train traveling at a speed of 87 km/h.

of 6 and 15 m from the railway track. The frequency analysis indicates a strong amplification at the 4.8 Hz frequency (Figure 3.10). However, the obtained frequency peaks show good agreement with the load characteristics. The reason why the 4.8 frequency is so predominant might be explained by amplification of a natural frequency. The natural frequencies are listed as follows: $f_{n,h}$= 1.5, 4.6, 7.7, 10.7, 13.8, 16.8 (Hz); $f_{o,v}$= 15.4 Hz

5. CONCLUSIONS

The following conclusions can be made based on the studies:

1. According to the studies, both the actual measurements and results from numerical calculations showed that the predominating frequencies in railway traffic induced ground vibrations mainly are influenced by the axle distances and the speed of the train.
2. No amplifications at the natural frequencies could be concluded to exist in the numerical studies of a 2-dimensional FE-model.
3. Amplification at the natural frequencies could explain why some frequencies were more prominent than others in the actual case histories.
4. According to the power spectra of the load distribution, more vibrational disturbance is likely to occur from trains with equally spaced axle distances than from those with a varied axle spacing.

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