PERFORMING RAILWAY TRAFFIC VIBRATION FORECAST USING IN SITU VIBRATION MEASUREMENTS

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Abstract

As international normalized methods for performing railway traffic vibration prediction are not available yet, the authors of this paper will analyze the feasibility and applicability of an *in situ* vibration measurement method in accordance with the guidelines establish in ISO 14837-1.

The authors will present the achieved results of several vibration measurements, performed near the railways and the related transfer functions that will allow predicting the vibrations near different receiver locations.

Keywords: Vibration Forecast; Vibration Measurements; Railway Traffic Vibrations.

1   Introduction

In this paper the vibration is characterized by each second RMS (Root Mean Square) value of vibration velocity and the maximum value associated with the event is used.
Such methodology follows reference [1] and reference [2].
The unit used is mm/s, in line with the LNEC (Portuguese National Laboratory of Civil Engineering) Criteria explained in reference [1].
Since the effect of vibrations can occur at 4 levels:
1.   Human disturbance due to vibration sensation.
2.   Human disturbance due to noise produced by the structural vibration.
3.   Damage to buildings.
4.   Interference with the operation of equipment.

And since in accordance with the requirements of ISO 14837-1 [3], the typical frequencies of interest for each of these effects are as follows:
1.   1Hz to 80 Hz.
2.   16Hz to 250 Hz.
3.   1Hz to 500 Hz.
4.   1Hz to 200 Hz

The determination of the total value of vibration associated with a particular event should only use the above frequency range of interest.

This study directs to the human disturbance due to vibration sensation and to human disturbance due to structural noise produced by vibration, so that will be analyzed, for each event, the frequency ranges 1 Hz to 80 Hz and 16Hz to 250Hz.

This constraint justifies the characterization of RMS values, more suitable for human disturbance [2] [4], instead of characterization of peak values, more suitable for the disruption of structures [5].

To determine the global value (v_G) for the ranges 1 Hz to 80 Hz and 16 Hz to 250 Hz, there are used the following equations, where v_f corresponds to the vibration velocity of each frequency band:

$$v_{G,1-80Hz} = \sqrt{\sum_{f=1}^{80} v_f^2} \tag{1}$$

$$v_{G,16-250Hz} = \sqrt{\sum_{f=16}^{250} v_f^2} \tag{2}$$

2 Objectives

It is intended to evaluate the feasibility and applicability of a forecast method, based on the use of vibration attenuation factors, determined from *in situ* vibration measurements.

3 Method

To determine the vibration attenuation factors, the method uses:
1. A mass, which is driven into the ground, to generate an impulse of vibration (Figure 1).
2. 2 vibrometers (Figure 2), with capacity for registration RMS values at every second, in the 1/3 octave bands between 1 Hz and 250 Hz, and able to detect values sufficiently small (ideally less than 0,001 mm/s), for simultaneous registration of the impulse of vibration at 2 points.

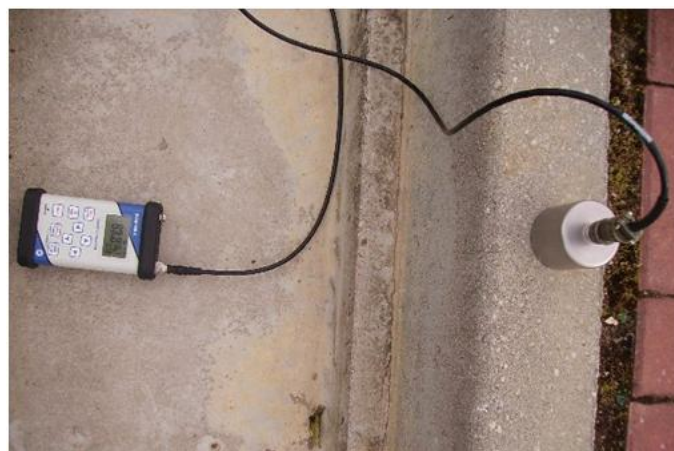Figure 1 – Example of using mass to generate an impulse of vibration

Figure 2 – Example of a vibrometer consisting of an accelerometer and a signal analyzer

When the impulse occurs, it is measured for each second the RMS value of vibration velocity, on the 1/3 octave bands between 1 Hz and 250 Hz (v_f) simultaneously at two points (P_1 and P_2) at known distances (d_1 and d_2), and is found the maximum values ($v_{max,f}$) associated with the impulse.

Assuming the following theoretical relationship between the vibration velocity in P_1 and P_2 [3] [6]:

$$v_{\max,f,P2} = v_{\max,f,P1} \times \left(\frac{d_2}{d_1} \right)^{k_f}$$

(3)

One can determine the attenuation factors k_f based on the following equation (applied to each frequency band):

$$k_f = \frac{\log\left(\dfrac{v_{\max,f,P2}}{v_{\max,f,P1}} \right)}{\log\left(\dfrac{d_2}{d_1} \right)}$$

(4)

3

The place of the impulse must coincide, or be as close as possible, to the place where the new railway line is expected to be installed, P_1 must coincide, or be as close as possible, to the reference distances where the future vibration can be known, and P_2 must coincide, or be as close as possible, to where one wants to predict the vibration.

The test should be repeated at least 3 times and should be used, for security reasons, the maximum values of k_f ($k_{max,f}$).

As these values correspond to attenuation factors for a point source, it is necessary to transform them into attenuation factors for linear sources ($K_{line,f}$) using the following equation (applied to each frequency band):

$$K_{linear,f} = \frac{\log\left(\dfrac{\displaystyle\int_{l=0}^{l} v_{max,f,P2} \times \left(\dfrac{d_2 + x}{d_2}\right)^{k_{max,f}} dx}{\displaystyle\int_{l=0}^{l} v_{max,f,P1} \times \left(\dfrac{d_1 + x}{d_1}\right)^{k_{max,f}} dx}\right)}{\log\left(\dfrac{d_2}{d_1}\right)} \tag{5}$$

Using a table of integrals [7], it appears that, in a generic way:

$$\int (ax+b)^n \, dx = \frac{(ax+b)^{n+1}}{(n+1)a} \text{ for } n \neq -1 \tag{6}$$

Using this general equation and considering $l = \infty$, we can demonstrate the following important relation:

$$K_{linear,f} \cong k_{max,f} + 0.5 \tag{7}$$

4 Tests performed

The tests were carried out along the Railway Line in Algarve (Portugal) at the following 2 sites:

- Site 1:
  Next to the *Teatro das Figuras* in Faro, corresponding to a paved area where trains have lower velocity, given the proximity of the station (Figure 3).
- Site 2:
  In rural area, not paved, where trains have a higher velocity (Figure 4).

Thus, Measurements belonged to two kinds of vibration sources:

- Impulse induced: 1 mass of 13 kg (Figure 1).
- Different trains running on the line.

Were used the following equipment:

- 1 vibrometer including an IMI 626A04 accelerometer and a signal analyzer Svantek 958.
- 1 vibrometer including a PCB 393B31 accelerometer and a signal analyzer Svantek 946A.

Figure 3 – Photo illustration for Site 1

Figure 4 – Photo illustration for Site 2

4.1 Impulse induced

The results obtained for the vibration attenuation factors k_{max} are presented in Table 1. It is noted that the mass and distances used only allow the vibrometers to distinguish the occurrence of the impulse for frequency bands greater than or equal to 8 Hz. However, such limitation is not a problem for the frequency range associated with normal passage of trains, as will be demonstrated on the next chapter.

Table 1 – Speeds and vibration attenuation factors obtained *in situ* (impulse).

Frequency Band [Hz]	$v_{max,f}$ [mm/s]				$k_{max,f}$	
	Site 1		Site 2		Site 1	Site 2
	P_1	P_2	P_1	P_2		
8	0,0005	0,0004	0,00030	0,00019	-0,16	-0,19
10	0,0007	0,0005	0,00053	0,00036	-0,34	-0,17
12,5	0,0008	0,0005	0,00106	0,00037	-0,38	-0,46
16	0,0014	0,0006	0,00140	0,00033	-0,67	-0,64
20	0,0032	0,0009	0,00189	0,00026	-1,01	-0,87
25	0,0061	0,0020	0,00285	0,00022	-0,89	-1,12
31,5	0,0125	0,0033	0,00420	0,00037	-1,09	-1,06
40	0,0251	0,0035	0,00824	0,00039	-1,60	-1,32
50	0,0253	0,0038	0,01238	0,00029	-1,55	-1,63
63	0,0054	0,0010	0,01688	0,00034	-1,40	-1,70
80	0,0075	0,0005	0,03302	0,00024	-2,22	-2,15
100	0,0083	0,0005	0,03772	0,00015	-2,33	-2,40
125	0,0048	0,0003	0,01096	0,00012	-2,27	-1,97
160	0,0047	0,0001	0,00614	0,00012	-3,57	-1,72
200	0,0015	0,00002	0,00302	0,00006	-3,34	-1,72
250	0,0005	0,00002	0,00093	0,00003	-2,61	-1,47
8-80Hz	**0,0395**	**0,0067**	**0,0404**	**0,0010**	**-1,45**	**-1,59**
16-250Hz	**0,0409**	**0,0067**	**0,0567**	**0,0009**	**-1,48**	**-1,80**

4.2 Trains

In Table 2 and Table 3 are presented the measured values in P_1 due to passing trains, the forecasted values in P_2, based on attenuation factors determined by the method and presented in Table 1 (corrected for linear attenuation factors), and the values actually measured in P_2 due to passing of trains, for Site 1 and Site 2.

Table 4 shows the differences between predictions and measurements.

In the graphs of Figure 5 and Figure 6 are shown the spectrum of vibration velocity of the trains, at P_1, for Site 1 and 2, being visible the irrelevance of the values associated with the frequency bands below 8 Hz.

Table 2 – Comparison of measurements and forecasts (Trains, Site 1).

Frequency Band [Hz]	Maximum value measured in P_1 [mm/s]				Maximum value expected in P_2 [mm/s]				Maximum value measured in P_2 [mm/s]			
	Type of train											
	1	2	3	4	1	2	3	4	1	2	3	4
1	0,0077	0,0009	0,0011	0,0012	-	-	-	-	0,0019	0,0037	0,0017	0,0009
1,3	0,0008	0,002	0,0025	0,0013	-	-	-	-	0,0009	0,0016	0,0015	0,002
1,6	0,0005	0,0006	0,0005	0,0004	-	-	-	-	0,0008	0,0013	0,0006	0,0005
2	0,001	0,001	0,0004	0,0004	-	-	-	-	0,0008	0,0023	0,0004	0,0006
2,5	0,0007	0,0004	0,0007	0,0004	-	-	-	-	0,0004	0,0023	0,0004	0,0004
3,1	0,0003	0,0006	0,0005	0,0003	-	-	-	-	0,0003	0,0014	0,0004	0,0004
4	0,0006	0,0008	0,0002	0,0001	-	-	-	-	0,0007	0,0006	0,0005	0,0005
5	0,0005	0,001	0,0005	0,0002	-	-	-	-	0,0007	0,0011	0,0002	0,0012
6,3	0,0006	0,0011	0,0006	0,0004	-	-	-	-	0,0004	0,0005	0,0004	0,0022
8	0,0008	0,0007	0,0008	0,0003	0,0011	0,0006	0,0007	0,0003	0,0006	0,001	0,0002	0,0016
10	0,0012	0,0024	0,001	0,0005	0,0014	0,0028	0,0012	0,0006	0,0006	0,0021	0,0007	0,0009
12,5	0,0018	0,003	0,0013	0,0028	0,002	0,0034	0,0015	0,0031	0,0009	0,0041	0,0044	0,0036
16	0,0035	0,005	0,0093	0,0019	0,003	0,0042	0,0079	0,0016	0,0015	0,007	0,0029	0,0067
20	0,0123	0,0154	0,0089	0,0144	0,0075	0,0094	0,0054	0,0087	0,0062	0,0069	0,0098	0,0154
25	0,0298	0,0668	0,0961	0,0552	0,0203	0,0456	0,0656	0,0377	0,0139	0,0216	0,0265	0,0319
31,5	0,0748	0,0985	0,1213	0,0825	0,042	0,0553	0,0681	0,0463	0,0239	0,0531	0,0362	0,0334
40	0,0724	0,119	0,1301	0,0666	0,0247	0,0406	0,0444	0,0227	0,0133	0,0257	0,0275	0,0073
50	0,0446	0,0847	0,0608	0,0365	0,016	0,0303	0,0218	0,0131	0,0187	0,0104	0,0256	0,005
63	0,0419	0,072	0,0591	0,0571	0,0174	0,0298	0,0245	0,0237	0,0094	0,0037	0,0104	0,0013
80	0,0247	0,0931	0,1255	0,0688	0,0046	0,0173	0,0233	0,0128	0,0017	0,0021	0,0059	0,0013
100	0,0145	0,0641	0,0971	0,0377	0,0024	0,0107	0,0162	0,0063	0,0013	0,0019	0,004	0,0008
125	0,005	0,0108	0,0192	0,0068	0,0009	0,0019	0,0034	0,0012	0,0006	0,0012	0,0012	0,0002
160	0,0048	0,0059	0,0126	0,0051	0,0002	0,0003	0,0006	0,0003	0,0005	0,001	0,0005	0,0001
200	0,0025	0,0047	0,0095	0,0052	0,0002	0,0003	0,0006	0,0003	0,0002	0,0007	0,0002	0,0001
250	0,0007	0,0015	0,0054	0,0048	0,0001	0,0002	0,0007	0,0006	0,0001	0,0002	0,0002	0,0001
$v_{G,1-80Hz}$	0,1277	0,2228	0,253	0,1544	0,0586	0,095	0,1124	0,0712	0,0378	0,065	0,0608	0,0503
$v_{G,16-250Hz}$	0,1285	0,2322	0,2721	0,1593	0,0586	0,0955	0,1136	0,0714	0,0378	0,0646	0,0607	0,05

Type of train: 1: Alfa, 2: Intercity, 3: Regional; 4: Freight.

Table 3 – Comparison of measurements and forecasts (Trains, Site 2).

Frequency Band [Hz]	Maximum value measured in P_1 [mm/s]				Maximum value expected in P_2 [mm/s]				Maximum value measured in P_2 [mm/s]			
	Type of train											
	1	2	3	4	1	2	3	4	1	2	3	4
1	0,0132	0,0007	0,0002	0,0012	-	-	-	-	0,0009	0,0009	0,0014	0,0011
1,3	0,0015	0,0015	0,0002	0,0016	-	-	-	-	0,0015	0,0016	0,0008	0,0009
1,6	0,0028	0,0003	0,0069	0,0003	-	-	-	-	0,0011	0,0005	0,0005	0,002
2	0,0018	0,0007	0,0062	0,0008	-	-	-	-	0,0004	0,0007	0,0004	0,0005
2,5	0,0011	0,0001	0,0017	0,0015	-	-	-	-	0,0008	0,0007	0,0004	0,0004
3,1	0,0012	0,0012	0,0095	0,0011	-	-	-	-	0,0005	0,0007	0,0003	0,0008
4	0,0035	0,0011	0,0028	0,0013	-	-	-	-	0,0011	0,0017	0,0003	0,0004
5	0,0088	0,0018	0,0034	0,0017	-	-	-	-	0,0017	0,0014	0,0006	0,002
6,3	0,0109	0,0152	0,0041	0,009	-	-	-	-	0,0072	0,004	0,003	0,0069
8	0,006	0,0134	0,0058	0,0156	0,0102	0,0227	0,0098	0,0264	0,0016	0,0156	0,0057	0,006
10	0,0197	0,0132	0,0097	0,0167	0,0345	0,0231	0,017	0,0293	0,0053	0,0154	0,0042	0,0136
12,5	0,014	0,0257	0,0155	0,013	0,015	0,0275	0,0166	0,0139	0,0041	0,0074	0,0045	0,0207
16	0,0206	0,0094	0,0061	0,0087	0,0162	0,0074	0,0048	0,0069	0,0104	0,0065	0,0022	0,0092
20	0,0134	0,0176	0,0099	0,0172	0,0071	0,0094	0,0053	0,0092	0,0042	0,0111	0,0083	0,0063
25	0,0265	0,0257	0,0206	0,0237	0,0092	0,009	0,0072	0,0083	0,0088	0,0112	0,0049	0,008
31,5	0,0374	0,0319	0,0233	0,0379	0,0144	0,0123	0,009	0,0146	0,012	0,016	0,0116	0,0097
40	0,0557	0,0625	0,0398	0,0525	0,0138	0,0155	0,0099	0,013	0,0199	0,0251	0,0138	0,0287
50	0,0573	0,2177	0,0866	0,0888	0,0084	0,0318	0,0127	0,013	0,0112	0,0208	0,0088	0,018
63	0,1129	0,2226	0,0781	0,165	0,0147	0,0289	0,0101	0,0214	0,0098	0,0092	0,0042	0,0138
80	0,3004	0,2208	0,1733	0,1492	0,0181	0,0133	0,0105	0,009	0,0039	0,0047	0,002	0,0034
100	0,3772	0,1555	0,1402	0,0656	0,0149	0,0061	0,0055	0,0026	0,0037	0,0047	0,0014	0,0017
125	0,0795	0,0495	0,0281	0,0264	0,0065	0,0041	0,0023	0,0022	0,0017	0,0025	0,001	0,0017
160	0,0236	0,041	0,0268	0,014	0,003	0,0051	0,0034	0,0018	0,0016	0,0034	0,0008	0,0011
200	0,0084	0,0296	0,0155	0,0071	0,0011	0,0037	0,0019	0,0009	0,0023	0,0016	0,0007	0,0011
250	0,003	0,0171	0,0106	0,0048	0,0006	0,0033	0,002	0,0009	0,0019	0,0008	0,0005	0,0008
$v_{G,1\text{-}80Hz}$	0,3363	0,3911	0,2166	0,2516	0,0541	0,0667	0,0363	0,0551	0,033	0,0477	0,0246	0,0484
$v_{G,16\text{-}250Hz}$	0,5112	0,4256	0,2605	0,2603	0,041	0,0524	0,0267	0,0362	0,0317	0,0419	0,0229	0,0405

Type of train: 1: Alfa, 2: Intercity, 3: Regional; 4: Freight.

Table 4 – Differences between predictions and measurements (global values).

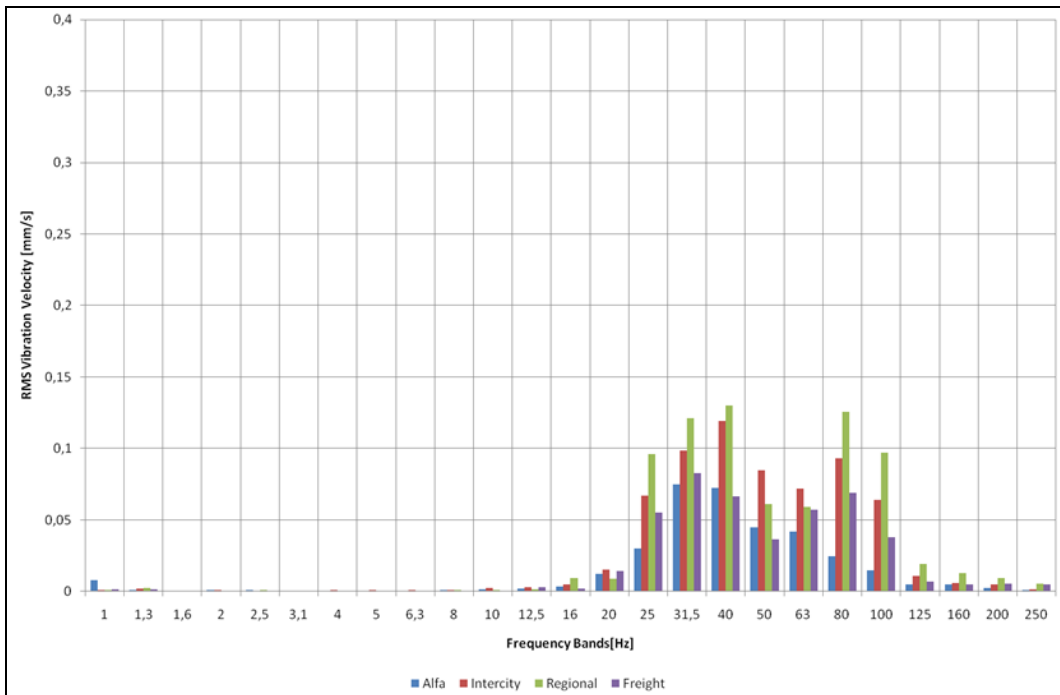| Site	$(v_{Gexpected} - v_{Gmeasured})/v_{Gmeasured}$							
	Alfa Pendular		Intercity		Regional		Freight	
	1-80Hz	16-250Hz	1-80Hz	16-250Hz	1-80Hz	16-250Hz	1-80Hz	16-250Hz
1	55%	55%	46%	48%	85%	87%	42%	43%
2	64%	29%	40%	25%	48%	17%	14%	-11%

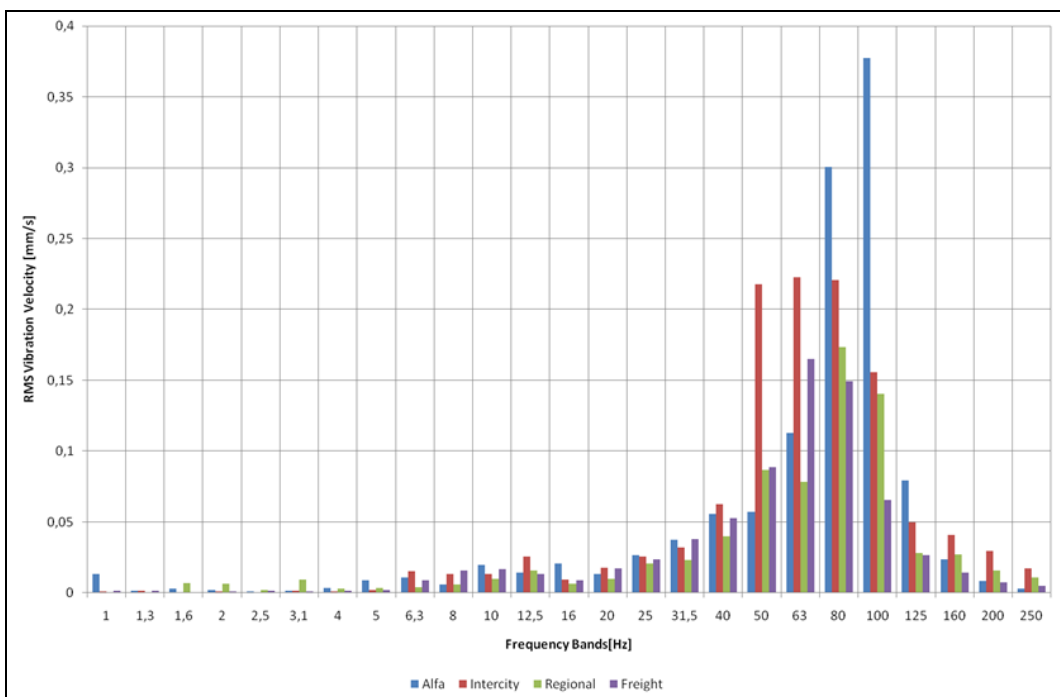Figure 5 – Spectrum of vibration velocity of trains in P_1 (Site 1)

Figure 6 – Spectrum of vibration velocity of trains in P1 (Site 2)

9

5 Conclusions

The analysis of the previous tables shows that, overall, the estimates are mostly higher than the measurements, which put us in a position of safety.
The deviations found in terms of significant global values range between -11% and 87%.
These deviations may seem high, but are of the order of magnitude of the deviations found when using the calculation of attenuation factors corresponding to the passage of a particular train - without the correction of linear source - to predict the values corresponding to the passage of other trains, which demonstrates the suitability of the method and the difficulty of obtaining more precise methods.

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