Attenuation of rail vibration:
Analysis of experimental data

A. Bracciali, F. Piccioli

Dipartimento di Meccanica e Tecnologie Industriali – Università di Firenze
v. Santa Marta, 3 – 50139 Firenze
e-mail: bracciali@ing.unifi.it

Keywords: rail, vibration, noise, damping, testing

Abstract:

Vibration and noise emission are not locate directly under the wheel during train pass-by, instead waves propagate along the rail away from the rail/wheel contact point. In this work data from several experimental campaign are analysed to understand the way in which vibration decay along track. Data are analysed through complex frequency and energy analyses. Analysis mostly deal whit data recorded during train pass-by, in this way some effects, that are impossible to take into account with analysis done with impact hammer, can be shown.

Introduction

During trains pass-by track acoustic emission is not exactly located under wheels, but depending on the transmissibility along the rails, sections adjacent to the wheels can substantially contribute to the global emission.
Should be pointed out that track vibrations can't be traced to rail modal shapes. Having the rail infinite length, its motion consists in propagating waves that carry vibrations away from excitation point located, obviously, in the wheel rail contact point.
Normally vibrations decade logarithmically with distance. With propagating waves, the loss in transmission or the decay or the attenuation is usual given in term of dB/m, in case, obviously, that characteristics of the medium are enough constant.
The attenuation can be measured by exiting the track in a suitable way and then regarding the level of the response at different distances from the excitation point. In similar manner, is possible to measure the response in the same location moving the excitation away along the rail. The first working method is suitable when using a shaker, instead the other is preferred when using an impact hammer (the use of an impact hammer is preferred for measurement during normal rail traffic because is easier to use during trains intervals).
Anyway should be point out that:

- It is impossible to carry out measurements for characterisation of the track in term of decay with a static (or quasi static) load corresponding of train axeload.
- Measurement can't take into account that effects coming from adjacent sections subsequently excited by the moving wheel are superimposing.
- Although waves propagation speed in the rail is about 5 km/s, superficial ground waves or superimposition of reflections in the rail (that in frequency range of interest have to be consider a three-dimensional solid) can affect the *in situ* behaviour of the track, so train speed can have a non negligible influence.

For the reasons listed above in this paper we mostly deal with the behaviour of the rail during the pass-by of trains. Particularly the signal of a vertical accelerometer placed under the railhead is considered and the behaviour during the approach of the first axle and the going away of the last axle is analysed. Analysis of data, recorded in two measurement campaign is done taking into account the global level and the power spectrum density of vibration.

Recorded data

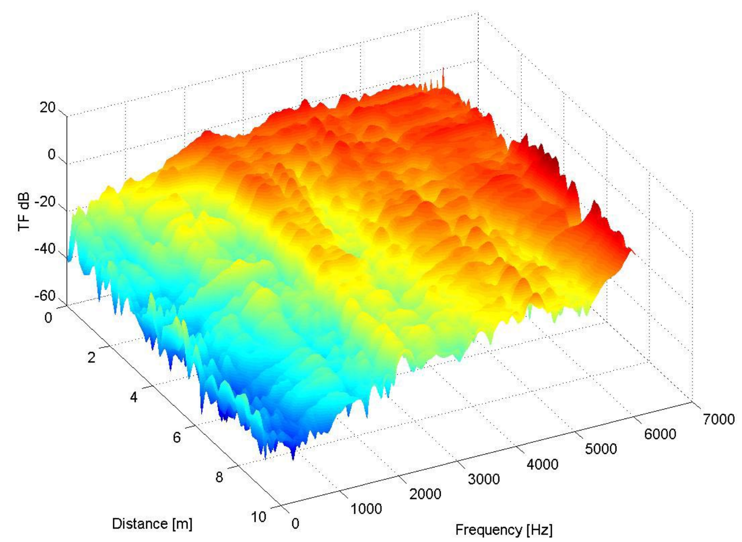
The analysed parameter is the vertical acceleration of the rail.
Data were recorded in two different measurement campaign can be divided:

1. Measurement at Nozzano (1998 Lucca Viareggio line), shuttle test train with heavy damaged wheels (wheel flat).
2. Measurement at Renacci (2000 high-speed line Firenze Roma), ETR 500 plt test train speed up to 300 km/h.
3. Measurement at Renacci (2000) mixed traffic in commercial service.

Nozzano test train was made of one electric loco class E646 (110 ton Bò Bò Bò) with undamaged wheels, three MDVC coach with damaged wheels and a npbd driving coach for push-pull operation with undamaged wheels.
Renacci test train was a ETR 500 plt trainset in eight car formation (eight coach between two locos), some wheels were treated for low noise emission, anyway in this work we deal only with the first and the last wheel in the train that were standard.
Signals of excitation and response to impact (hammer) were available in both locations to calculate response functions in the measurement section to excitation in different point along the rail (up to 10m away from accelerometer with steps of 150 mm.
During Renacci measurement, signal of some train in commercial service were recorded, these trains were of different types (high speed trains, tilting train, loco hauled passenger or freight train).
The rail was UIC 60 on concrete sleepers with ballast, railpads were present, the surface of the rail was in good conditions, fastener were different with FS type at Nozzano and Pandrol at Renacci. There weren't any switch or joint close of the measurement section.
In both location was present a treadle that recorded the passing of each wheel, this signal is useful in the analysis to evaluate distance from measurement section.
During Nozzano campaign the accelerometer was mounted on the rail body.
The sampling frequency was in both cases 12800 Hz.

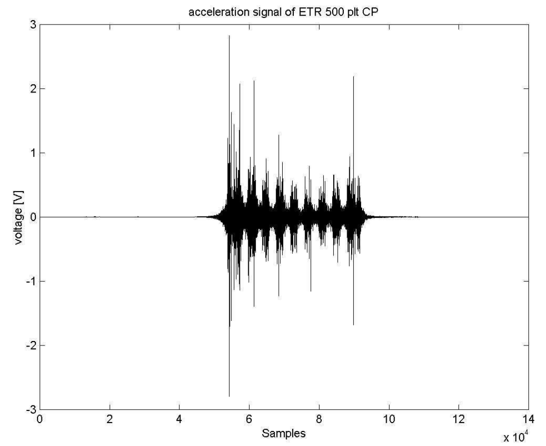
Transfer function estimation

Using signals of the excitation from impact hammer in different point along the rail and response in the measurement section, transfer function is estimated at different distances. Transfer function is estimated using TFE algorithm of MATLAB®, five impacts and relative responses are used for each calculation, the frequency resolution is 50 Hz.
Results are plotted in a 3D graph with colour shade as shown in the subsequent figure.

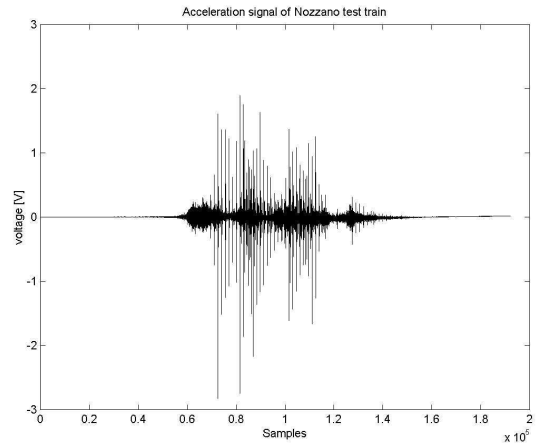


TFE Vs distance Renacci

Global vibration level analysis



Renacci acceleration signal

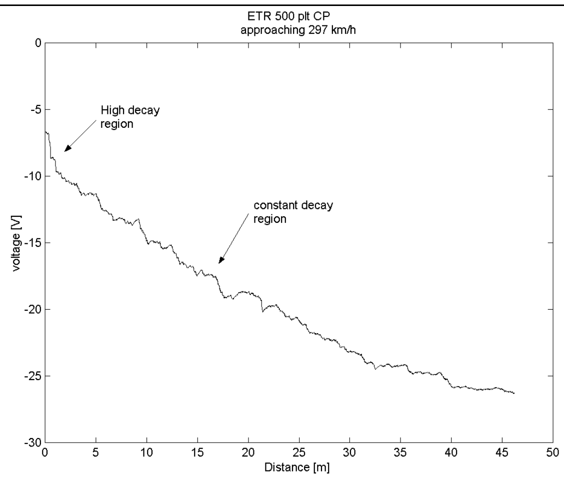


Nozzano acceleration signal

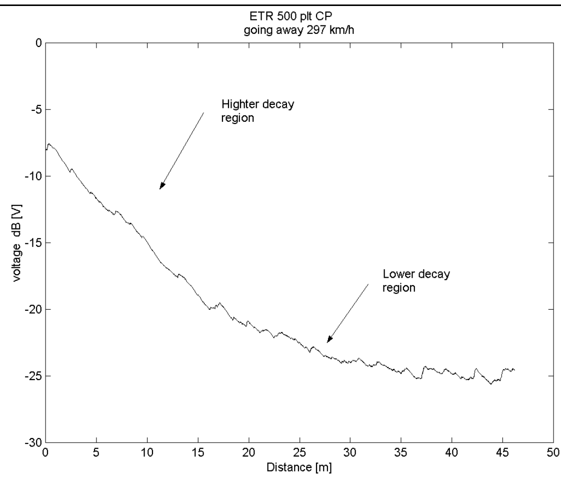
In figures typical signals recorded in Renacci (undamaged wheels) and in Nozzano (damaged wheels) are illustrated, should be point out that in the second case the signal is mostly affected from wheels flats impacts, actually in the portion corresponding to the coach wheels aren't easily recognisable. In both graph values in the y-axis are reported in volts (used accelerometers have a nominal sensitivity of 10 mV/g).
In order to evaluate the global level decay rate subsequent operation are done on signals:

- Identification of a suitable distance from the measurement section where the noise to signal ratio isn't too high.
- Exponential weighting of the signal with a very fast constant (1/64)
- Identification of the position of the first end last axle in the train signal using the treadle signal. Being the leading or the trailing axle considered the main source of the excitation.
- Identification of two portions of signal corresponding to the approach, from the above mentioned distance to the measurement section, of the first axle and the going away, from the measurement section to the above mentioned distance, of the last axle.

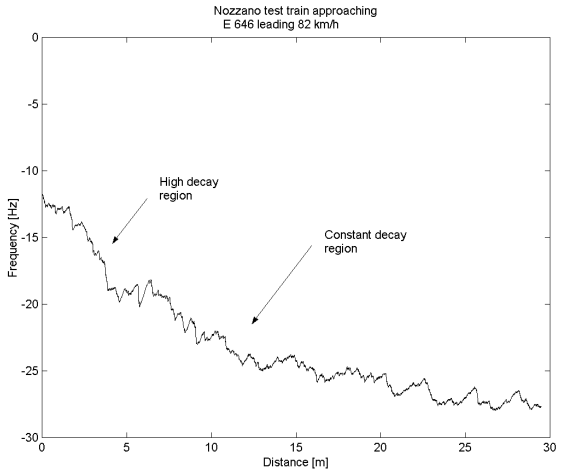
Exponential weighting is done in order to highlight the main decaying behaviour of the signal, actually the weighting eliminate faster fluctuations of the signal. Exponential weighting has been chosen among other methods to be that which produces best results without introducing great numerical errors.
Examples of obtained result in different cases are shown in subsequent figures, on the x axis a linear scale is used for the distance from measurement section, on the y axis voltage corresponding to the vibration level is shown in dB, thus is easy to evaluate the decay in dB/m.



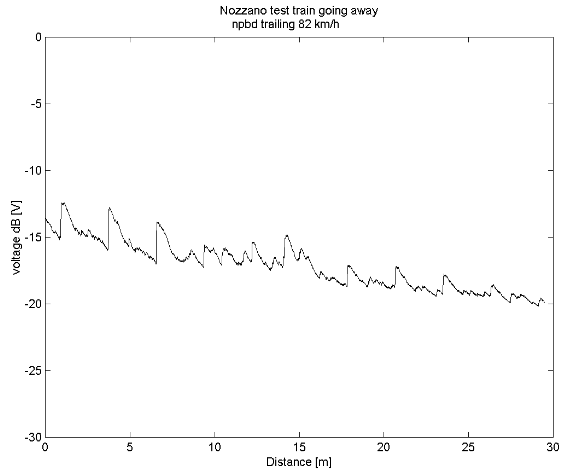
Renacci approach decay



Renacci going away decay



Nozzano approach decay

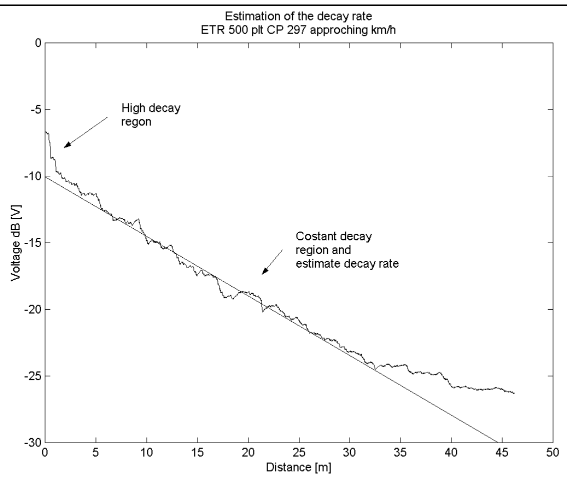


Nozzano going away decay

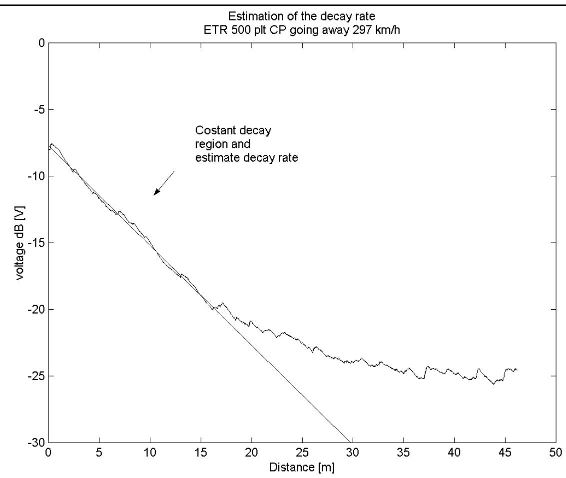
Should be point out that:

- With the Nozzano test train, with damaged wheels, there is a remarkable difference between behaviour of the loco and that of the driving coach. The behaviour of the loco is similar to that of trains with undamaged wheels, the one of the driving coach instead is heavily affected by the presence of impacts. Should be reminded that neither the loco nor the driving coach had their own wheels damaged.
- With symmetric trains (ETR 500) there is a remarkable difference between the behaviour of the leading axle end that of the trailing one. In the first case a high decay region (less than 2 meter long) is followed by a region with a nearly constant decay rate (dB/m); in the second case there is a region (about 20 m) whit a constant decay rate (greater of that previous mentioned) is followed by a region with very low decay rate.

In the case of approaching axle forced vibration can be assumed to be the main cause of behaviour in the high decay region, instead the behaviour in the lower and more constant decay region can be explained with propagating waves. In the case of trailing vehicle the two regions mentioned above seem to be less recognisable.
In the portion of the signal in which the decay rate is more constant, a decay rate in dB/m is estimated using a least square interpolation.



Estimation of decay rate



Estimation of decay rate

Results can be summarised:

Renacci

Approach between 5 and 30 m and going away between 1 and 20 m from measurement section

Train[1]	Number of trains[2]	.dB/m approach	.dB/m going away	Average trains speed[3] [km/h]
ETR 500 plt CP	6	0.38 ±0.033	0.60 ±0.045	182.5
ETR 500 plt CP	2	0.45 ±0.021	0.76 ±0.012	293.5
ETR 500 3kV	2	0.37 ± 0.004	0.66 ±0.038	194.5
E 402 A	2	0.39 ± 0.009	/	192.5
E 402 B	2	0.33 ± 0.018	/	190
ETR 480 ETR 460	2	0.49 ± 0.044	0.82 ±0.028	208.5

1 type of train. 2 number of that type of train at similar speed. 3 average speed of trains.
(CP means "corsa prova" = test run)

Should be point out that ETR 500 plt CP is always the same train, other type are actually of the same type but are different member of the respective class or type.
There are difference in decay rate between train whit different axleload (ETR 480/460 are tilting unit with light axleload), a difference between decay rate can be seen at different speed for the ETR 500 plt CP.
For the four trains hauled by class E402 loco the decay for the last axle (trailing coach) can be estimated:

Renacci

Going away between 1 and 20 m from measurement section

Trailing vehicle	dB/m going away	Train speed [km/h]
UIC Z[1]	0.75	185
GC[2]	0.85	197
UIC Z	0.75	190
GC	0.83	195

1 lighter whit disk brakes. 2 heavier whit mixed disk/block brakes

For the Nozzano test train only run with leading loco are analysed, being the signal from the trailing or leading (depending on train direction) driving coach mostly effected by impacts of adjacent damaged wheels.
In the case of the driving coach the leading axle can't be considered the only, or at least the main, source of the excitation.

Nozzano

approach 8 e 20 m from measurement section

Train	Leading vehicle	dB/m approach	Train speed [km/h]
Test train	E 646	0.35	103
Test train	E 646	0.34	82
Test train	E 646	0.25	62
Test train	E 646	0.27	41

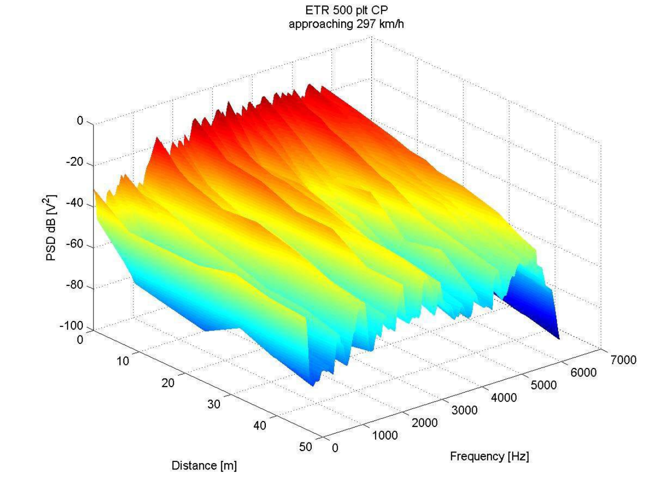
Frequency analysis

The global level analysis, like that previously conducted, can't deal with the contribution to the total transmissibility of single frequencies. Statistical properties of approaching and going away signals are analysed with the following procedure:

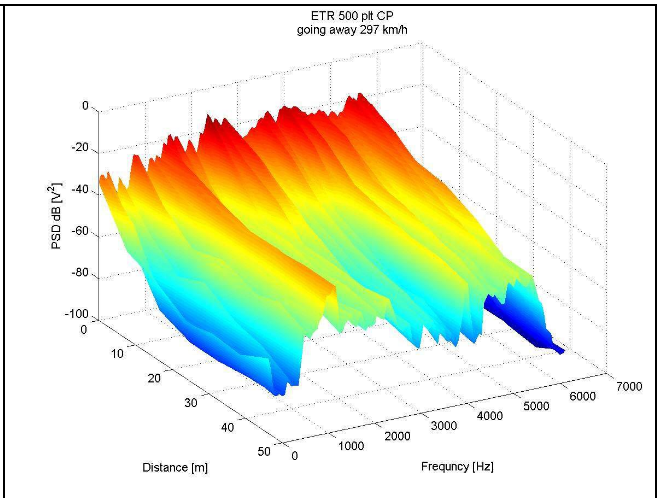
- Approaching and going away signals are divided in segment of 1024 samples.
- For every segment of 1024 samples Power Spectral Density is calculated with MATLAB® PSD algorithm, 256 point FFT is used giving a frequency resolution of 50 Hz.
- Results of every segment are plotted on a 3D graph with colour shade.

Obviously, with this procedure, for train with different speed a different number of segments of 1024 are taken into account.

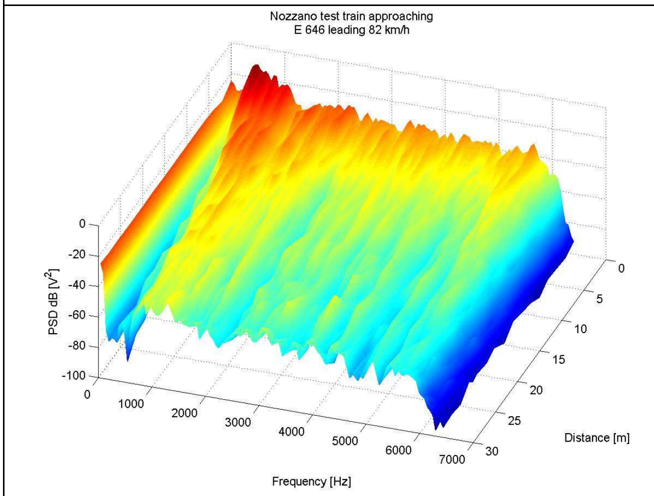
Observing 3D graph we can see that certain frequency decay with a lower rate, these frequency are obviously those that more contribute to the vibration propagation in the rail.



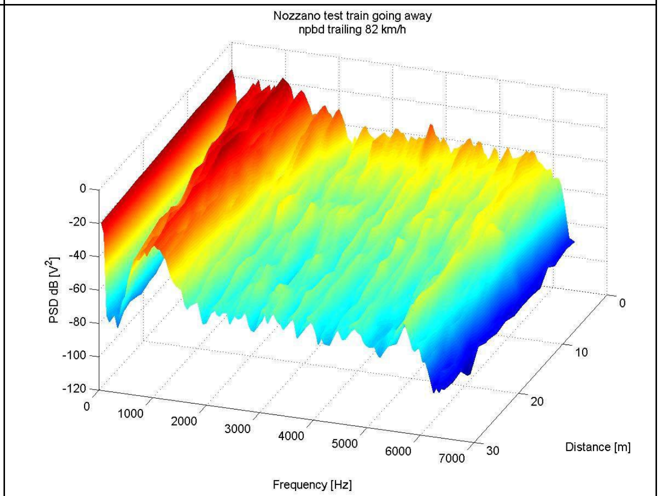
PSD Vs distance



PSD Vs distance

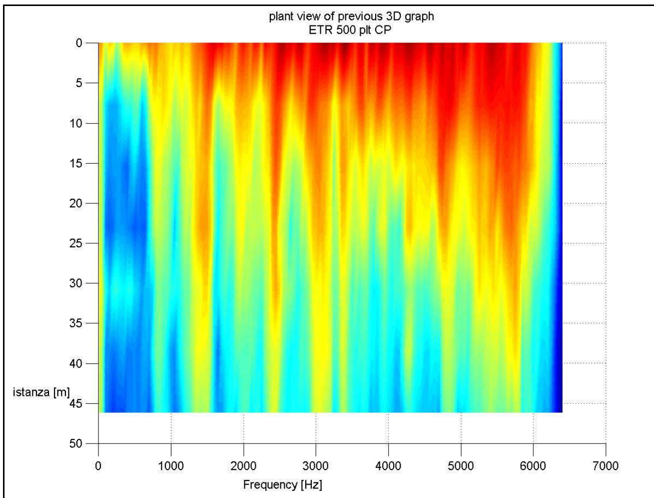


PSD Vs distance

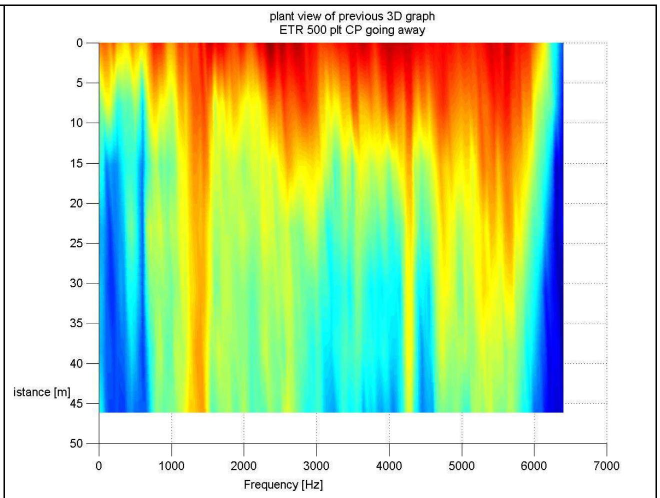


PSD Vs distance

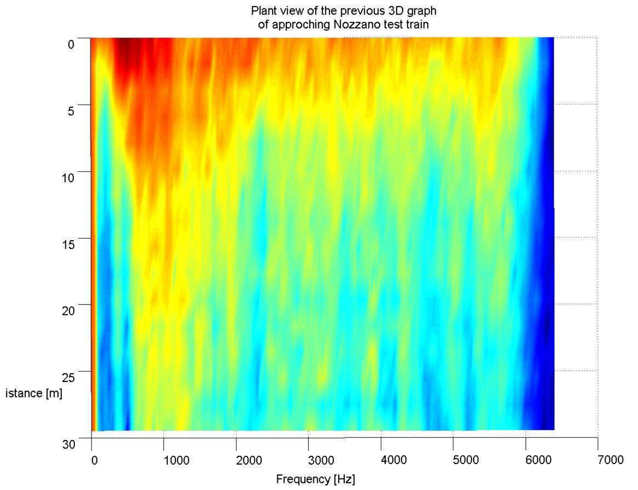
In all cases a low decay region can be seen near the frequency of 1000 Hz, in graphs relative to Renacci approaching trains other low decay region can be seen near 2500 and 3000 Hz.



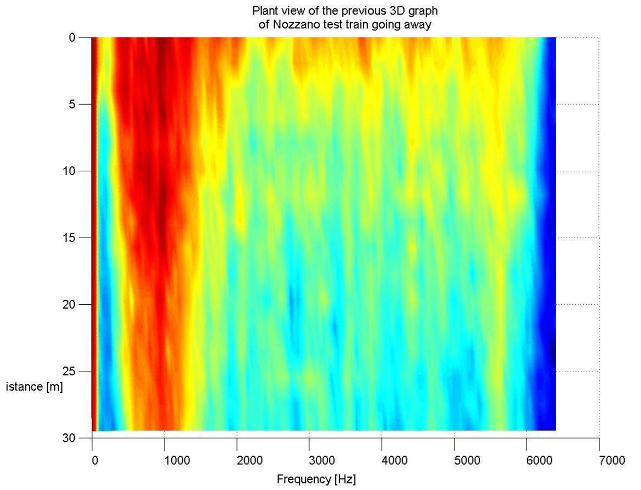
Plant view of PSD Vs distance



Plant view of PSD Vs distance

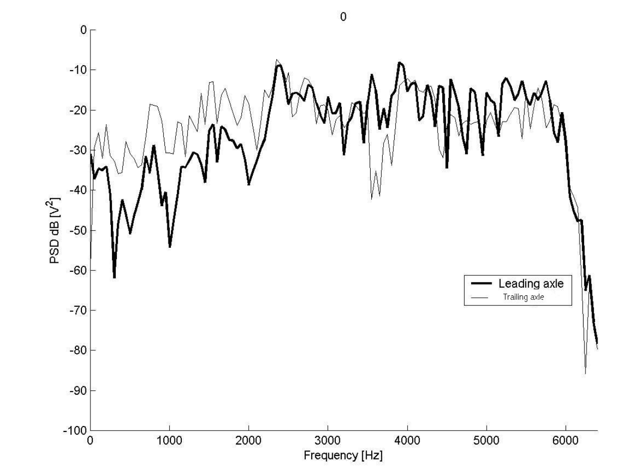


Plant view of PSD Vs distance

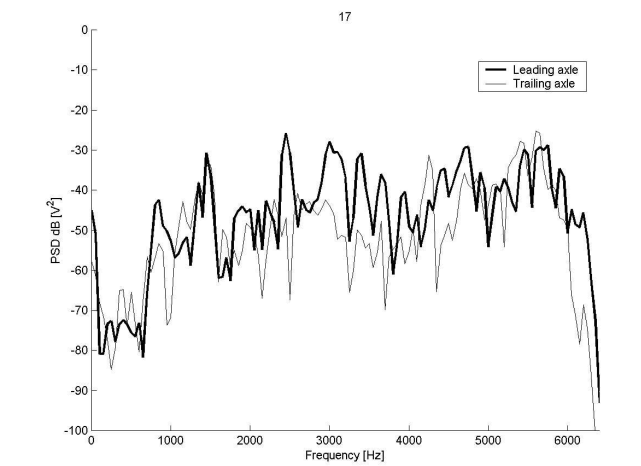


Plant view of PSD Vs distance

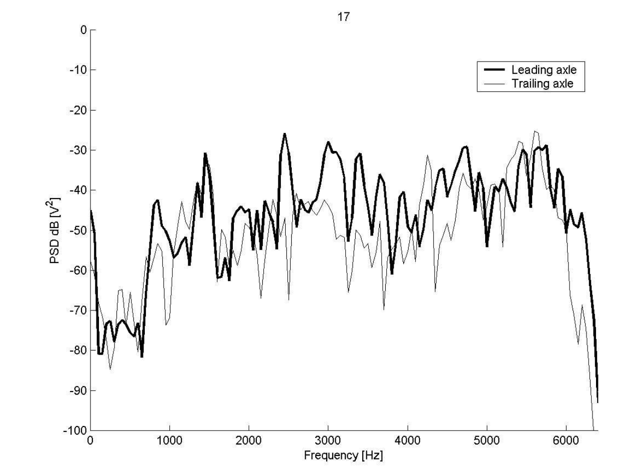
Should be pointed out that colour shade is relevant only for a single graph so no absolute comparison should be made.
In an other representation the way in which the PSD change at different distance from the measurement section can be observed, in this way PSD of the approaching axle and of the going away axle can be compared.
In this representation is more clear that, with a constant length of the segment of 1024 samples, the PSD is calculated for fast trains in few point (in the space) than for slower trains. The approaching or going away section of the signal can be divided in a fixed number of segments without taking into account the train speed, in this way the PSD of different trains at different speeds can be compared, should be pointed out that obviously for fast trains the PSD is calculated using a short part of the signal (in the time).



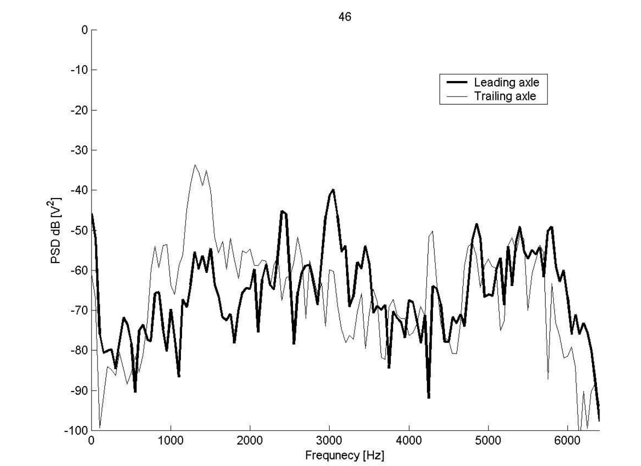
PSD over measurement section



PSD about 32 m away



PSD about 17m away



PSD about 47 m away

PSDs in figures are calculated with the latter method.
Observing above figures can be seen that in approaching axle PSD there are peaks near 2500 and 3000 Hz that in the going away PSD are not present.

Conclusions

From the analysis conducted emerges that even the attenuation capability should be a characteristic of the rail and track construction (rail, pads, ballast), in practice the way in which the level of vibration decrease can be influenced by some of the characteristics of the excitation source.
Difference in attenuation can be seen depending on approaching or going away from the point of interest, on the axleload, on the braking system and on the speed of the train.
In the case of damaged wheels can be seen that an heavy vehicle can stops excitation coming from adjacent wheels, instead a light vehicle let excitation of damaged wheels passes.
Research can be continued investigating deeper causes of different phenomena observed, finding this can lead to an effective way to reduce vibration propagation in railway track.

Bibliography

[1] D. J. Thompson: Experimental analysis of wave propagation in railway tracks. Journal of sound and vibration 203(5) 1997.