Vibrations induced by trains

Case Study: Extension of track platform of *Gare do Oriente*

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Summary

This work describes a set of research studies that were made with the intent of studying vibrations created by the circulation of trains.

In the last decades, the development of high-speed trains emphasized the need to closely monitor this phenomenon.

The purpose of this study is to provide a state-of-the-art about data acquisition process. It also presents a new experience, including important concepts in certain areas such as analysis of signals, seismic geotechnical engineering and track engineering.

A field study with the purpose of measuring vibrations induced by train circulation was carried out in July of 2009 and took place at *Gare do Oriente* (train station located in Lisbon). The next step was to develop a whole set of analysis tools in Matlab, meticulously incorporating digital filters for signal processing.

1. Introduction

Human beings are constantly exposed to mechanical vibrations that affect their well-being, sometimes causing discomfort or even worse, injuries. Vibrations are undesirable and dangerous, but can be present at work, in transportation and even at home.

In this document's case study, vibrations are related with the interaction between the vibrating machine (train) and the structure (rail track).

These vibrations produced during contact, can excite the system's resonant frequency (rail track or vehicle components), causing important vibration sources, as well as noise.

Due to harmful effects they have in humans, sensitive equipment and structures, there is a need to put effort into developing both the instrumentation technique and equipment. This way, we can carry out monitoring according to certain parameters, in order to assess risks and, therefore, control these effects.

This subject became relevant with the appearance of high speed trains, since with the increasing speed, there is also an increase of vibration magnitude.

In Portugal, the use of high speed railways is still being discussed while project studies move forward. In this context, came the need to monitor vibrations in the field, in order to acquire the data needed to develop computational analysis.

Making use of analyses tools in Matlab and by using theories necessary to study this subject, the signal analyses was performed.

Filter design and application of the baseline correction of the signal are crucial aspects to reach the correct results.

The railway sector's constant development should be supported by a strong scientific research, always seeking an optimization of resources while keeping environmental damages low. For this reason, this thesis tries to demonstrate the status of this subject's investigation, giving information and providing a new field experiment.

2. Vibrations induced by trains

The vibration phenomenon caused by train traffic can be described as wave propagation through structures and the ground. For example, the energy created can cause discomfort to people and interference in sensitive machinery.

Train movement on certain locations causes a response from the surrounding environment. This response depends on the quality of the rail track, type of foundations and type of vehicle. These factors determine the vibration level. In the following tables can be found a detailed description of vibration-related factors:

Table 1 - Factors Related to Vibration Source. Adapted from Harris Miller Miller & Hanson Inc (2005).

Factors	Influence
Vehicle suspension	If the suspension is stiff in the vertical direction, the effective vibration forces will be higher. On transit cars, only the primary suspension affects the vibration levels, the secondary suspension that supports the car body has no apparent effect.
Wheels condition	Wheel roughness and flat spots are the major cause of vibration from steel-wheel/steel-rail train systems.
Track surface	Rough track is often the cause of vibration problems. Maintaining a smooth track surface will reduce vibration levels.
Track Support System	On rail systems, the track support system is one of the major components in determining the levels of ground-borne vibration. The highest vibration levels are created by track that is rigidly attached to a concrete trackbed. The vibration levels are much lower when special vibration control track systems such as resilient fasteners, ballast mats, and floating slabs are used.
Speed	As intuitively expected, higher speeds result in higher vibration levels.
Track Structure	The general rule -of-thumb is that the heavier the track structure, the lower the vibration levels.
Depth of vibration source	There are significant differences in the vibration characteristics when the source is underground compared to at the ground surface.

Table 2 - Factors Related to Vibration Path. Adapted from Harris Miller Miller & Hanson Inc (2005).

Factors	Influence
Soil type	It is generally expected that vibration levels will be higher in stiff clay type soils than in loose sandy soils.
Rock layers	Vibration levels often seem to be high near at-grade track when the depth to bedrock is 30 feet or less. Tunnels founded in rock will result in lower vibration amplitudes close to the tunnel. Because of efficient propagation, the vibration level does not attenuate as rapidly in rock as it does in soil.
Soil Layering	Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics.
Depth to water table	The presence of the water table is often expected to have a significant effect on ground-borne vibration, but evidence to date cannot be expressed with a definite relationship.
Frost depth	There is some indication that vibration propagation is less efficient when the ground is frozen.

It is important to add some additional information concerning some factors. Vibrations in soft soils originated the concept of critical speed, because each type of soil has their own wave velocity propagation. With the increase of train traffic speed, that speed is either equaled or exceeded, originating the amplification of the vibration phenomenon.

Another important factor is the way loads are transmitted to the infrastructure. Nowadays, the way railway vehicles are designed to allow discrimination between suspension loads and non-suspension loads. However, it is important to keep in mind that despite having non-suspension loads significantly smaller than suspension loads, the tests that were carried out confirm that the vibration results precisely from non-suspension loads of the train.

In cases like this, the vibration source can be caused by many system components. However, each part of the system has a natural frequency. One of this study's key-points is the study of the phenomenon in the frequency domain. Nevertheless, the range of relevant frequencies is not yet well established.

According to Auersh (2004) the concerned frequency gap in the vibration induced by trains is between 0 and 150Hz, while according to Hildbrand (2001) a relevancy decline occurs while the frequencies increase, having 200-250Hz as the limit of relevancy value. Degrande et al. (2001) used a lowpass filter at 500Hz for measurements in the track and 250Hz cutoff frequency for the free field.

The inventory of this kind of work field is not the only purpose of this investigation, but also to help in the evaluation of mitigation measures. Use of jet-grouting for treating soft soils, new elastic components on the track and scheduling maintenance are some examples.

The fact that there are regulations regarding train traffic vibrations allows the comparison with limit values concerning building damage, human perception and machinery interference. The purpose is to evaluate the situation according to legal mechanisms and get a better perception of the in situ conditions.

3. Field work

The field work developed in July 2009, defined an instrumental alignment in the proximity of Oriente Station (figure 1). This study was made in cooperation between LNEC and RAVE in order to prepare elements for the *Relatório de Conformidade Ambiental do Projecto de Execução (RECAPE)* for extension of the train station.

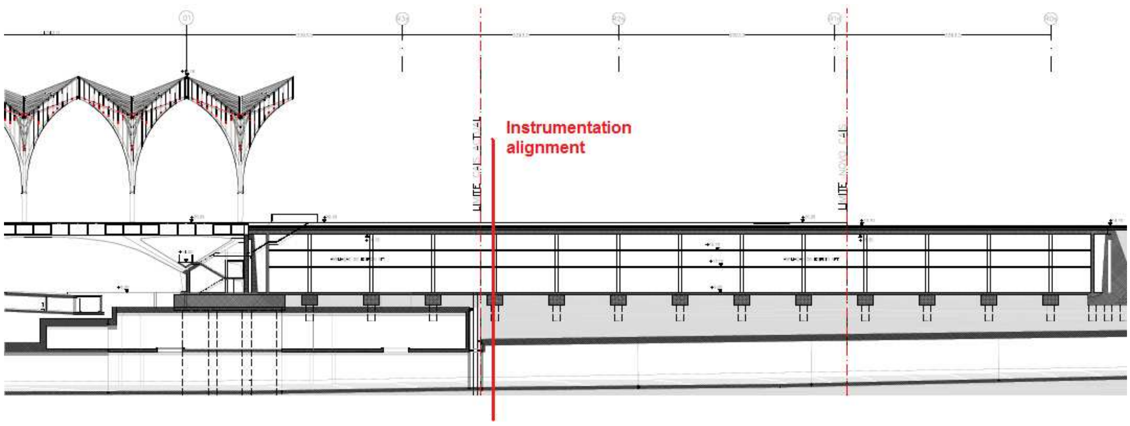

Figure 1 – *Gare do Oriente* structure

Besides acquiring signs of three kind of trains (CPA – Tilt Train, UTE - Triple Electric Unit trains and LOC – Cars plus locomotive train), environmental records were also performed.

This kind of investigation has improved a lot during this last decade. Some published case studies made a study optimization possible, while also verifying situations to improve in future studies.

In order to obtain quality data it is important to pay careful attention to the selection of instrumentation and fixation conditions, because the site have several types of foundation for this case study.

The structure of Oriente Station vibrates as a whole, very differently from the vibrating response in the free field. The zone's geology features recent deposits and alluvium for the upper stratums. Underneath them, lower stratums feature a good response to compression resistance, composed of *Braço de Prata* Areolas and *Marvila* lime stone.

The instrumentation setup consists in a transverse alignment to the rail track, with 11 measuring points. Location in the free field was determined by applying a constant distance between the points. However, in the proximity of the track, local conditions (Centieira Street) lead to a change of plans.

The following schematic shows the instrumentation setup:

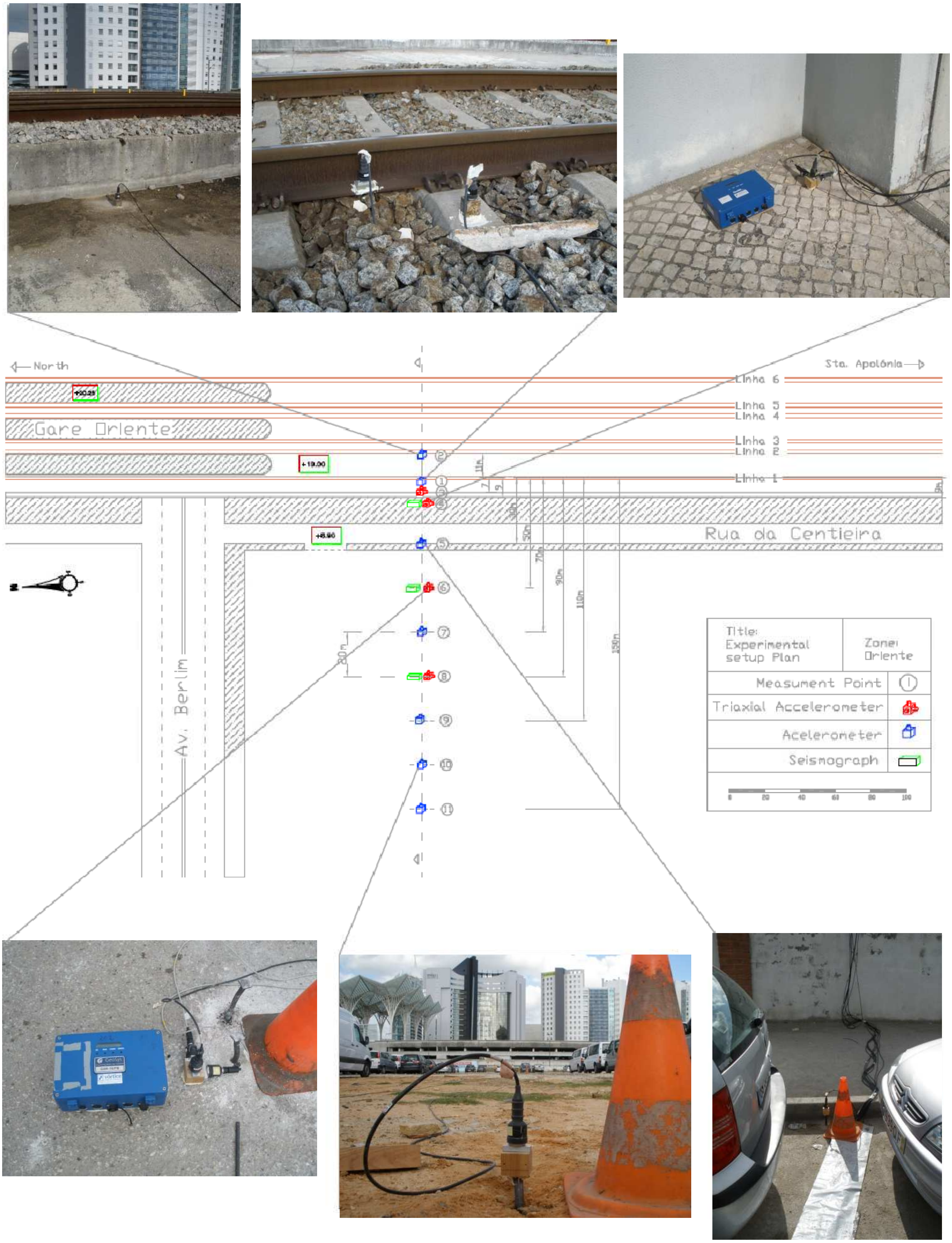

Figure 2 - Instrumentation setup plan

4. Signal analysis

Signal analysis is an important step in the study of vibrations. So, several computer codes were developed to get the results, with the help of the Matlab program.

Given the large quantity of collected data signals, it was necessary to do some sampling choices. The representative value of the event, measurement of a train passage, was determined with 65536 points, corresponding to 32,768 seconds of the signal.

Baseline correction using the moving average of the signal was the first step. This procedure sets the signal to the base axis and performs filtering for low frequencies. The main filter that was applied was a 4-degree Butterworth-type, whose design is given special attention on this work. The effect of the global filter in the magnitude of maximum Fourier amplitude is shown in the image below.

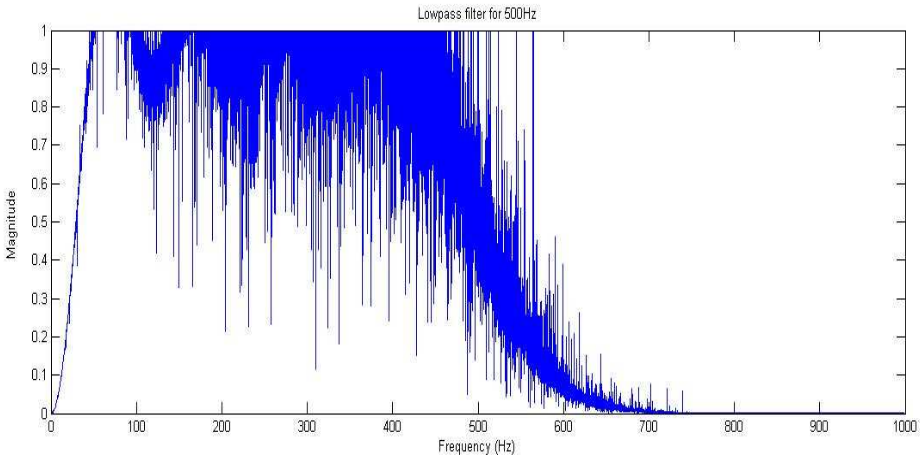

Figure 3 - Filter magnitude reduction for Fourier amplitude

Butterworth was the chosen option for filtering the signal, but another option was tested. Truncation of the signal in the cutoff frequency is another way for treating the signal.

Descriptors of peak values and RMS (root mean square) values, for time, frequency and special domain are usually used for characterization of the vibration. The results are presented with acceleration, velocity and displacement descriptors.

To obtain different descriptors, signal integration was made by using the Newmark algorithm, fast Fourier transform (FFT) and computation of the event’s duration.

5. Results

Only four measuring points (1, 4, 5 e 8) were taken for the work field measurement analysis of results. Having in mind the purpose of the study, this choice was made carefully and necessary due to the number of data points recorded for each train passage.

The results for different vibration descriptors according to the distance are shown in figure 4:

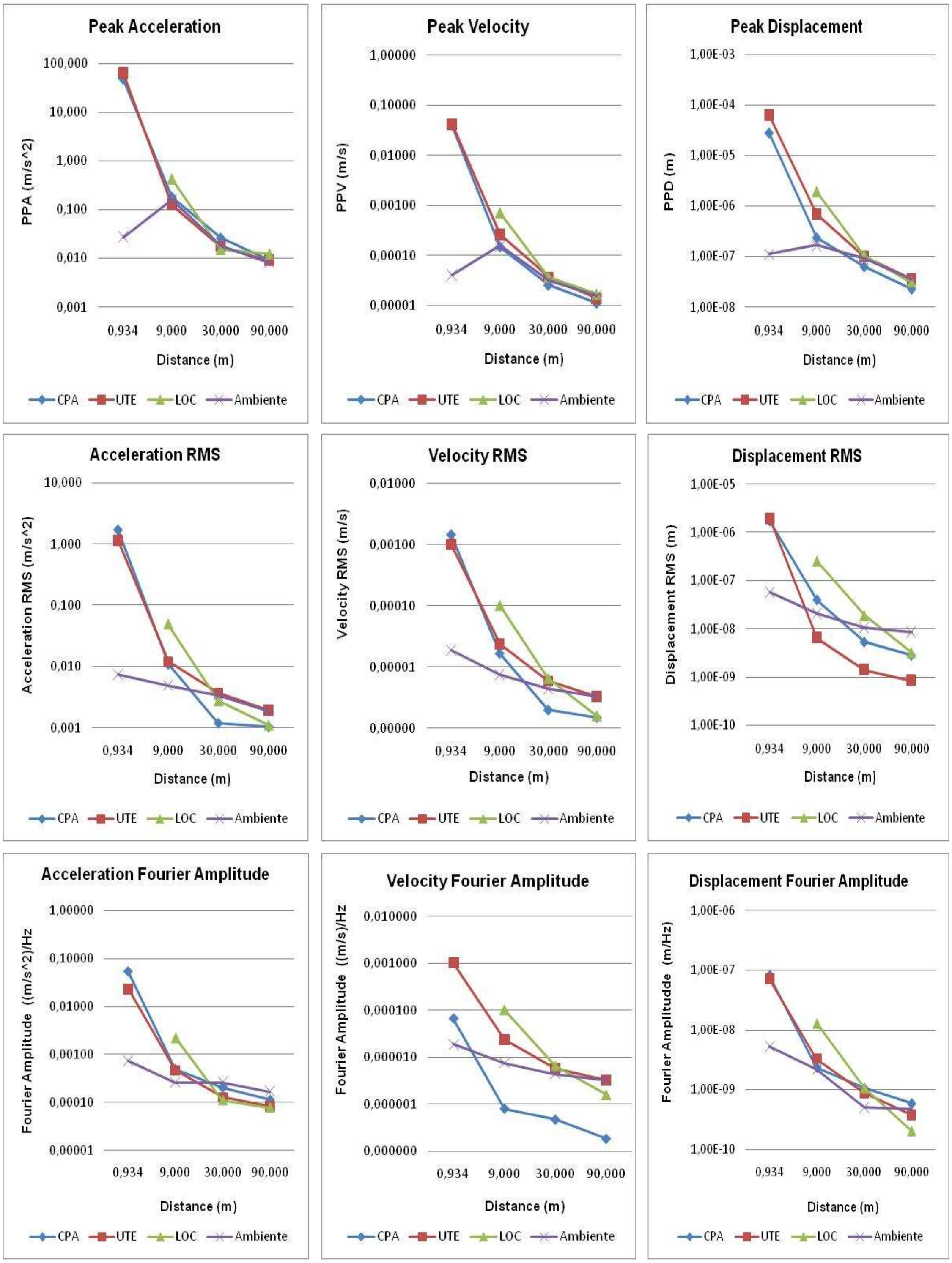

Figure 4 - Comparative results between signals on points 1, 4, 5 and 8.

The general tendency of the graphs shows a damping of magnitude vibrations with the increase of the distance to the line's center. It is possible to divide the values recorded into 2 groups, those under the station's structure and those in the free field site. This categorization is perfectly noticeable with interpretative help of environmental data. For a distance to the line's center of 9 meters (point 4) it is verified that the recorded signals for trains and environment begin to approach. In the next point of measure, the correspondence between the values is evident.

To do the comparison between different trains it is necessary to consider the vehicle mass, since it is one of the main influence factors for the created level of vibrations. The trains with greater mass are LOC trains, followed by CPA trains and lastly UTE trains. In fact, for 9 meters of distance to the line's center, the LOC train presents the highest level results.

For signals recorded in perfect conditions near the line it is possible to identify the number of train cars. The figure 5 shows the discrimination of the six parts of the Alfa Pendular train.

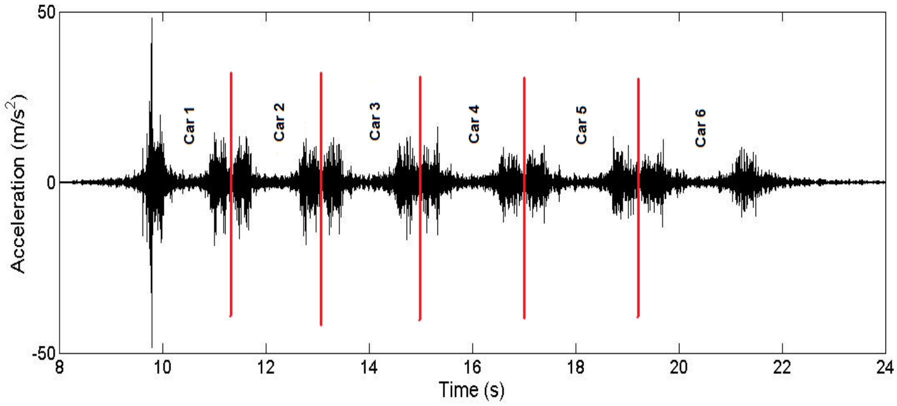

Figure 5 - Sleeper signal for CPA train

This signal analysis was used to estimate the speed of the train at the place of the work field.

Making use of the graphic results characteristics on the sleeper and known train geometry, it was computed 50 km/h on the measurement site, where the train is in deceleration due to station stop.

In the subject of range frequency associated with this kind of phenomenon, it was concluded the following. For sites away from the line's center it is important to study the vibration until the cutoff frequency of 250Hz is reached. However, this work has shown the need of a lowpass 500Hz cutoff frequency for sites near a rail track or placed in the grid track structure.

By analyses of Fourier amplitude maximum, figure 6 shows a decreasing value of the frequency for the maximum Fourier amplitude with the increase of the rail track distance.

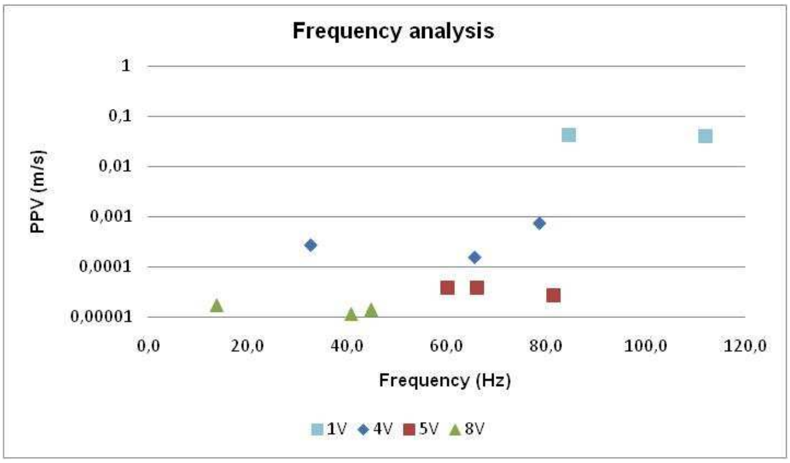

Figure 6 - Frequency value of the maximum Fourier amplitude

Figure 7 show the influence of the distance in the vibration level can be explained with the duration of the event:

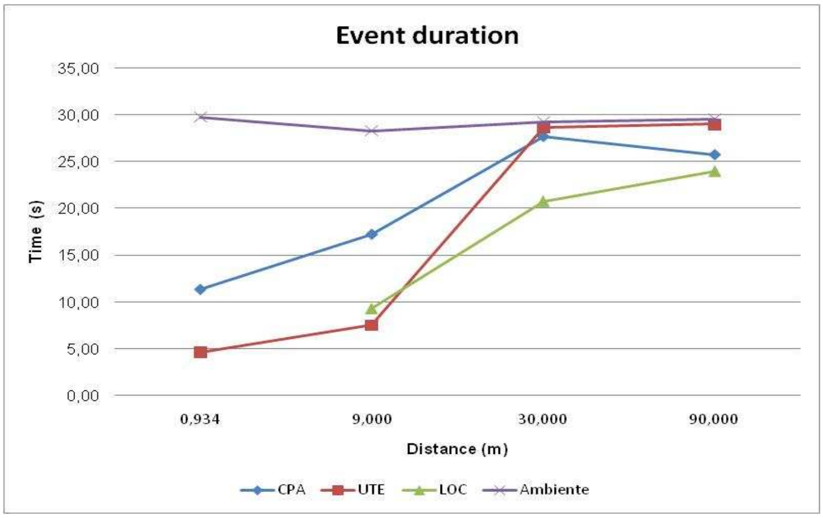

Figure 7 - Influence of the distance on the event duration

The environmental data approaches the duration of the sampling window (32,768 seconds), but for the signals of the trains, the duration begins to reach the environmental value at 30 meters (point 5) from the line's center.

For different kinds of European trains, in figure 8 are shown measurement results:

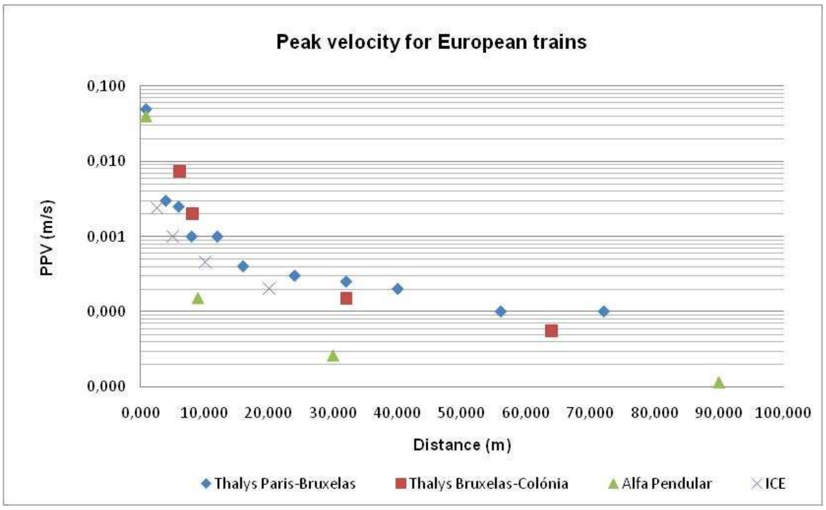

Figure 8 – Work filed results from European train.

It is necessary have in mind that for the work field of this paper, the speed of Alfa Pendular train was smaller than Thallys and ICE trains, and this factor have influence for vibrations level. However, the graph indicates smaller effect for this work.

6. Conclusion

In Portugal, the research on vibrations induced by train traffic is still underdeveloped. This work is intended to provide a solution to change this situation.

The field experiment was very important to understand how the measurements are made and know the ambient conditions on the site, allowing a more careful discussion of results.

It can be concluded that damage inflicted by vibrations phenomena is usually related to discomfort caused to people who live or work in offices near a rail track. In buildings, vibration levels don't have enough energy to cause structural damage, only cosmetic.

Field work developed with LNEC had two goals, the first was to obtain the know-how for future measuring campaigns and the second one was to characterize the current vibrations in the location.

With the aid of computational analysis, the whole signal evaluation process was carried out. Filter design was one of the most interesting parts of the investigation, as it is the tool which can provide data selection and eliminate existing noise.

The result levels obtained for descriptors fit with magnitude levels of other studies presented on this work.

It was also confirmed the vibration range indicated by different authors, so it is important to study the phenomenon up to 250Hz in the free field. In places closer to the track, where higher energy levels were recorded, it is necessary to adopt the cutoff frequency of 500Hz, which is the reason why we should carry out an extend frequencies spectrum analysis.

In places further from the track's center, vibrations of a passing train come closer to the ambient record.

This work try to demonstrate the current status of today's investigation in vibrations induced by trains and provide a new approach. Results obtained from the field work were quite satisfactory. However, railway engineering can advance further with these types of studies in an attempt to mitigate problems resulting from train circulation.

References

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