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Procedia - Social and Behavioral Sciences 53 (2012) 245 – 255

Procedia
Social and Behavioral Sciences

SIIV - 5th International Congress - Sustainability of Road Infrastructures

Vibration induced by rail traffic: evaluation of attenuation properties in a bituminous sub-ballast layer

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Abstract

The attenuation properties of a Hot-Mix Asphalt track bed containing crumb rubber (particle size 2-5 mm) are evaluated. A large number of vibration measurements have been carried out in a test section of a railway interconnection (Turin-Milan HS Railway) where two solutions of 12 cm of sub-ballast layer have been realized (with and without rubber). The vibrations were measured using a set of piezoelectric accelerometers positioned at various distances from the track to measure their generation and propagation. The results show that the new hot mix asphalt layer can influence the train vibration transmission.

Keywords: Rail vibration; sub-ballast; hot mix asphalt; accelerometer; attenuation properties.

1. Properties of hot mix asphalt with rubber

The reduction of vibrations transmitted by railway, without increasing too much the construction cost, is going to be a very important issue to deal with. The most effective construction techniques used until now are based on very complex and expensive solutions (such as floating slabs) and on the use of special and once again expensive materials (such as elastomeric mats).

In this research a possible innovative technique has been tested, based on the use of hot mix asphalt in which a part of the traditional aggregates is substituted with rubber granulates (2 – 4 mm) produced from waste tires [1].

Before put in site the new material, a wide integrated research was carried–out by Rete Ferroviaria Italiana SPA and the University of Rome "La Sapienza" to assess its suitability, as sub-ballast layer in railway track beds [2],[3].

In laboratory four mixes were prepared with different kind and content of rubber granulate using the dry process and traditional hot mix asphalt, too. Two kind of rubber were involved with different process

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 doi:10.1016/j.sbspro.2012.09.877

productions. The former was obtained by cryogenic pre-freezing: when a temperature of about -100 °C is achieved, waste tires become so rigid that they could be reduced in small pieces with a system of hammers and sieves. The latter was obtained only by mechanical shredding of tires in the desired size.

Both mechanical and damping properties of all asphalt mixes were evaluated in laboratory by a dynamic machine. It appears that the rubber granulate put into asphalt concrete enhances its propensity to dissipate energy. As a matter of the fact, loss factor values rise with the increase of rubber content.

The use of rubber granulate slightly increases the bitumen demand by asphalt mixtures and largely affects asphalt concrete mechanical performance. Laboratory evaluation clearly showed the decay of both stability and stiffness modulus referred to the traditional sub-ballast asphalt.

The type of rubber granulate seems to be involved, somehow, in the decay of the mechanical properties as the rubber granulate coming from cryogenic treatment caused more critical behaviour than the one obtained just by mechanical shredding of waste tires. The laboratory outcomes encouraged an experimental research in real field. Then, the new material was laid down over a double track interconnection named Novara West, including in the HS railway Turin-Milan.

2. In-situ vibration measurement of track

2.1. Field equipment

Measurements of ground vibration induced by different type of excitation of the railway system were performed. The vibrations were measured using piezoelectric accelerometers with electronics incorporated and powered by a signal conditioner. For measurements near the rail, where higher accelerations were expected, accelerometers with sensitivity of 100 mV/g, measurement range ±50g and maximum non-linearity ±1% were used, while for measurement on the points away from the track, accelerometers with sensibility of 1000 mV/g, measurement range ±5g and non-linearity <1% were used.

Each accelerometer was connected to a battery powered conditioner, with 3 cables twisted and shielded from the conditioner to the sensor and shielded coaxial cables from conditioner to the acquisition system, realized by two "Spider8" 8 channels, 16-bit resolution and measuring range ±10V, maximum frequency 0.5 kHz, sampling set to 1200 S/s and anti-aliasing filters. The acquisition of measurement signal was made with the software CatMan, installed on two laptops connected to both "Spider8". The data recording was performed on PC hard drives.

In total were used seven accelerometers of 50g and 11 accelerometers of 5g differently combined in sections of measurement and the various stages of relief, 18 conditioners, 2 Spider8 and 2 laptops.

On each section were placed 4 templates in metal to permit the positioning of the measuring sensors. The first template was positioned direct on rail. The second template was positioned at the embankment, below the sub-ballast conglomerate through a small excavation in which was placed a concrete prism to drown the template.

The third and fourth ones were positioned with similar methodology in correspondence of the ditch at the bottom of embankment. Over the template, steel cubes with threaded holes were fixed prepared for mounting accelerometers (one for each free face). In tests as 1 and 3 accelerometer per point were used.

In sections 2, 4, 5, 8 and 9 a metal plate was installed over the traverse, to stimulate in an impulsive way the system, but in such way to avoid the concentration point of pressure impact.

2.2. Accelerometers configuration

The accelerometers were placed at four positions respectively named A (near the track), B (on footpath), C (at the end of the bank) and D (into the ditch). In A and C positions the acceleration signal were measured on three direction x, y, z when the x direction is perpendicular to the railway track, the y direction is parallel to the railway track and the z direction is the vertical direction on the ground. In B and D positions only the z acceleration were measured.

The accelerometer position and the distance between them are presented schematically in Fig. 1.

Section	AB (m)	BC (m)	CD (m)	AD (m)
2	3.07	3.32	6.42	12.81
3	3.06	3.33	6.49	12.88
4	3.05	3.31	6.53	12.89
5	3.07	3.28	6.52	12.87
8	3.05	3.29	6.36	12.70
9	3.06	3.24	6.56	12.85

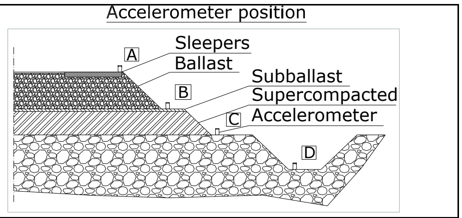

Fig. 1. Distances and accelerometer positions in each measurement section

2.3. Measurement sections

The experiments were performed in two seasons, on June and on February. In the Fig. 2 the distribution of the instrumented sections are presented. From section 1 to 6, in south rail, the sub-ballast layer with rubber granules was placed. The internal ones (2, 3, 4, 5) were equipped with accelerometers.

The sections from 7 to 9 were built with traditional sub-ballast and stations 8 and 9, placed at a suitable distance from the transition zone between the two different materials, were equipped.

The construction with the ballast and railway infrastructure installations has been completed adopting the identical executive procedures throughout the whole observation area. Materials used for construction of railway track were essentially identical. Therefore, the sections may differ only by the characteristics of the sub-ballast, unless otherwise unwanted non-uniformity caused by any unexpected non-homogeneity of materials or construction processes, which really might exist.

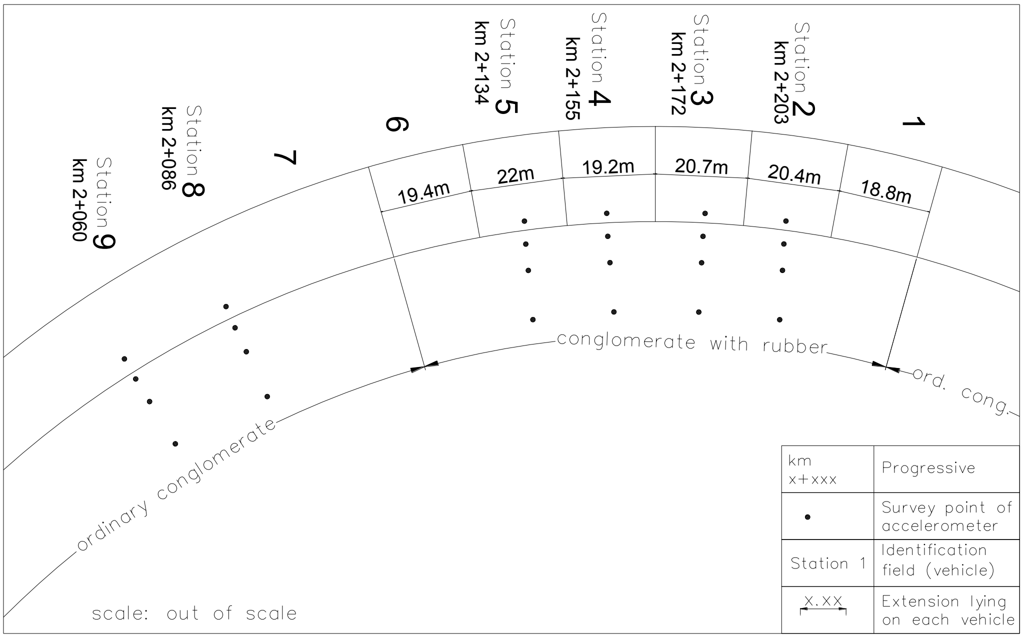

Fig. 2. Sections of measurements at interconnection

2.4. Type of excitations and accelerometer measurements

In order to evaluate the vibration behaviour of new sub-ballast layer, numerous tests were carried out by measuring the acceleration signals in various positions and for different types of excitation (Fig. 3) as follows:

- impact hammer excitation: 21 measurements;
- maintenance vehicle passages: 42 measurements;
- high speed train passages: 14 measurements.

The measures realized by impact hammer excitation are studied separately as an experimental case.

The measurements were realized at four sections with rubber (number 2, 3, 4 and 5) and two sections without rubber (number 8 and 9).

Fig. 3. Type of excitation: impact hammer, maintenance vehicle and high speed train

For each passage series, the speed of vehicles doesn't vary so significantly from one measure to another and from section with rubber to other section without rubber, making so negligible its influence [4], [5] as the aim of this study is the comparison of attenuation properties between two kinds of material.

3. Analysis of accelerometer measurements

3.1. Choice of signal length

The comparison between results of all the instrumented sections is easier if the signals have the same length. The acceleration signals, for the same type of excitation (high speed train, maintenance vehicle and impact hammer excitation) and for both sections (with and without rubber) were registered with different length. Therefore it would be found a solution to take the same length of signal for the same type of excitation, making so possible the comparison between both sections. For this reason two alternatives were compared; choose a segment centred between the maximum values or take the whole part where is the signal.

The first alternative was rejected because truncating the useful length of signal causes the "Leakage error" [6] on the power spectral density, making difficult the calculation of the weighted acceleration in real value, while at the transfer function is not influenced so much. The second alternative was chosen to continue this study, taking the useful part of signal.

In Fig. 4 is presented the length of signal chosen (20 seconds) as the measure of high speed train passed at section with rubber (event named measure TAV-01, section 4) and at section without rubber (event named measure TAV-08, section 9).

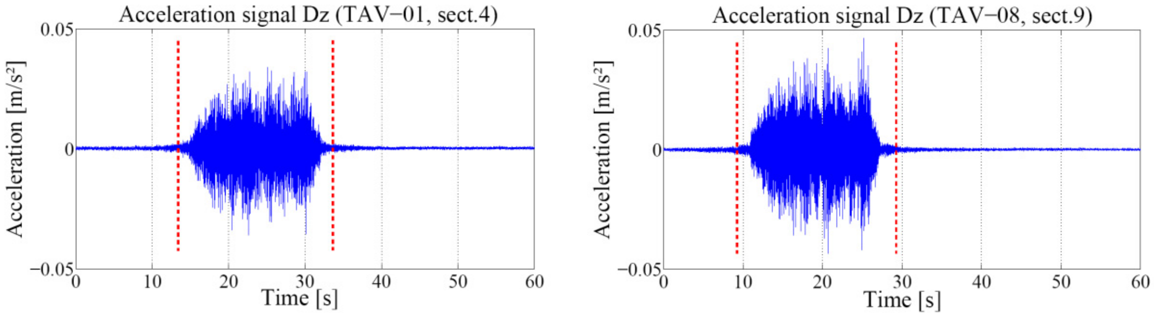

Fig. 4. Acceleration time histories for HS train measures at section with rubber (TAV_01) and without rubber (TAV_08)

3.2. Filtering process

A Butterworth low pass filter with cut-off frequency of 150 Hz was applied at the measurements to eliminate the noise. The signals taken from accelerometer were in volt and divided by the accelerometer sensitivity they were taken in terms of acceleration of gravity (V/V/g = g).

So the acceleration signals were obtained and then the acceleration spectrum, the transfer function, the peak component particle velocity were constructed and the weighted accelerations were calculated helping on confrontation process between section with and without rubber, to evaluate which performs better from vibrations (attenuates more or give minimal values of peak component particle velocities or weighted accelerations).

The measurements of accelerometers have an undesired phenomenon called "*drift associated*" [7] caused by a small direct current DC bias on acceleration signal. The presence of drift can lead to large integration errors, so before the integration of acceleration signal a Butterworth high pass filter with cut-off frequency 0.5 Hz was used to centralize the signal because the vibration occurs on a fixed point and has a zero mean over time. The Butterworth is the ideal filter for the pass band as can be seen on the figure below, with zero decibel attenuation (Fig. 5).

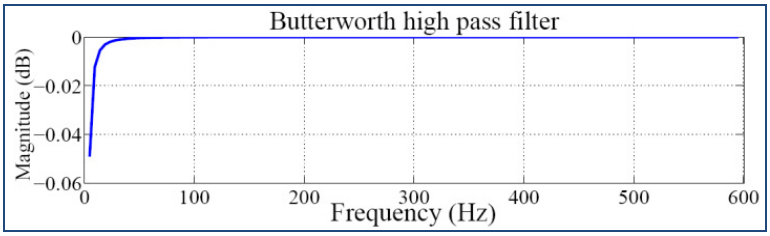

Fig. 5. Butterworth high pass filter

3.3. Construction of acceleration and velocity spectrum

The power spectral density describes how the power (or variance) of a time series is distributed with frequency [8]. Mathematically, it is defined as the Fourier Transform of the autocorrelation sequence of the time series. The Fourier transform (1) helps to decompose the signal f(t) into a sum of sine and cosine series of different frequencies [9].

$$f(t) = a_0 + \sum_{n=1}^{\infty} [a_n \sin(2\pi nt) + b_n \cos(2\pi nt)] \tag{1}$$

The Fast Fourier Transform has become such a commonplace algorithm which is built into MATLAB program where a Fourier transform of signal in the frequency range [0, fmax] with discrete step, depends on the length of the signal.

The velocity spectrum, taken from integration of acceleration signal, was obtained with the same procedure as acceleration spectrum.

3.4. Power spectral density in third octave band

Using the standard ISO/DIS 8608 to smooth the power spectral density curve [10], the spectrum in third octave band was obtained. The smoothing process consists on application of an algorithm starting to power spectral density in harmonics. At the same way the velocity spectrums were calculated performing previously integration of the acceleration and the filtering process as above mentioned.

The acceleration spectrums in decibel are calculated, for each frequency band, referred to the Eq. (2) [11]:

$$L = 10\log\frac{a^2}{a_0^2} \tag{2}$$

where: a is the root means square of acceleration in m/s^2 and a_0 is the reference value of acceleration 10^{-6} m/s^2.

For each third octave bands i the term a^2 may be calculated by product between PSD and its relative band width (BW) as follows with the Eq. (3).

$$a_i^2 = PSD^a \cdot BW \tag{3}$$

3.5. Evaluation of vibration

The evaluation of vibrations for both sections with and without rubber consists in:

- construction of the transfer function, to evaluate the global attenuation properties;
- calculation of the weighted acceleration referred to the ISO 2631/2, that's a reference for the effects of vibration on people [12];
- construction of the peak component particle velocity referred to the UNI 9916:2004, that's a reference to evaluate the effects of vibration on building [13].

A brief description of the three phases follows.

The transfer function

The transfer functions were calculated as the square root of the ratio between the values of power spectral density in accelerometer position D and A (see Fig. 6) through the Eq. (4) as below:

$$TF = \sqrt{\frac{PSD^a_{(D)}}{PSD^a_{(A)}}} \tag{4}$$

where: $PSD^a_{(D)}$ and $PSD^a_{(A)}$ are the acceleration power spectral density in m²/s³, respectively at accelerometer position D and A.

Using the power spectral density in decibel the transfer function is defined as the difference between the values of acceleration spectrum respectively at accelerometer position A and D.

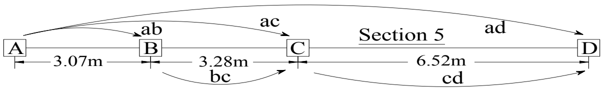

Fig. 6. Distances between accelerometers in section 5

The weighted acceleration

The weighted acceleration in frequency a_W is calculated with Eq. (5) referred to [12] and [14] to evaluate the human exposure to whole-body vibration as:

$$a_W = \sqrt{\sum_i (W_i \cdot a_i)^2} \qquad (5)$$

where: a_i is the root means square of acceleration for the *i-th* of third octave band center frequency, W_i is the weighted factor for the *i-th* of third octave band.

The peak component particle velocity

The peak component particle velocity (6) is calculated from velocity spectrum (PSD^v) in third octave band referred to UNI 9916:2004) and ISO 2631/2 to evaluate the effects of vibration on building as:

$$v_i = \sqrt{PSD_i^v \cdot BW_i} \qquad (6)$$

where: v_i is the root means square of velocity for the *i-th* of third octave band center frequency, BWi is the bandwidth for the *i-th* of third octave band center frequency.

For each i third octave band center frequency the peak of velocity Vi (7) is calculated by:

$$V_i = v_i \sqrt{2} \qquad (7)$$

The limit values of weighted accelerations in frequency (ISO 2631) and peak component particle velocity (UNI 9616) are used as reference in this study since the measurements were carried out on open field, without buildings.

4. Results and discussions

At Fig. 7 the acceleration spectrum for some high speed train passages are presented.

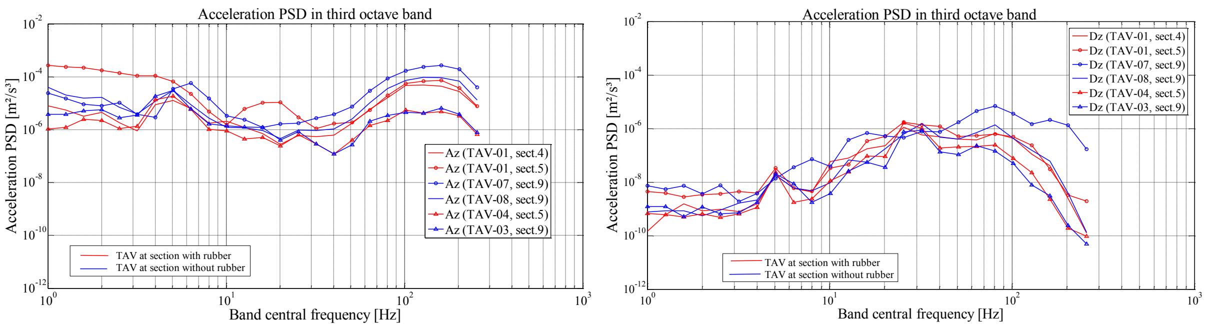

Fig. 7. Power spectral density for high speed train at accelerometer position A (left) and D (right) for sections with rubber (red line) and without rubber (blue line)

As expected the power spectral density at accelerometer position D is less than at accelerometer position A because is farther to the railway. Looking at the spectral accelerations it's difficult to give an immediate answer to the question: which section, with or without rubber, performs better from vibrations?. This is more evident on graphics of Fig. 8 where the acceleration spectrum and velocity spectrum are presented for one train passed at section with rubber (TAV_04, section 5) and at section without rubber (TAV_03, section 9). As it can be seen from graphics, the spectrum of two types of sections alternated.

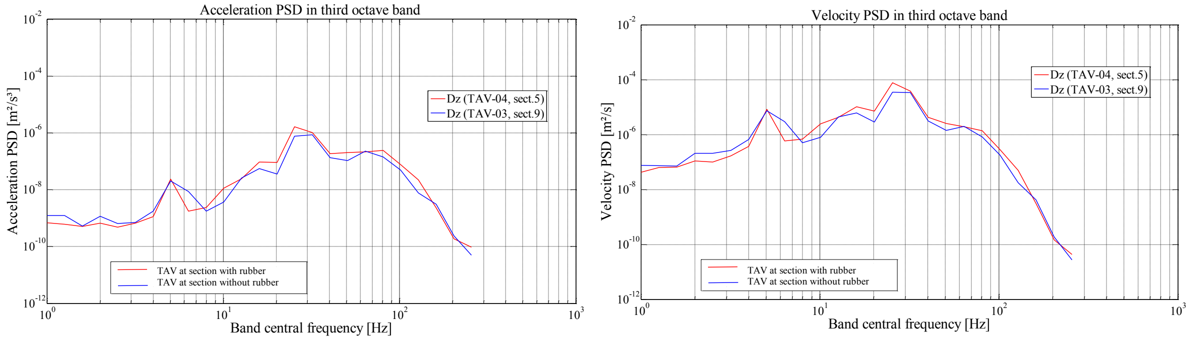

Fig. 8. Acceleration and velocity spectrums in third octave band for sections with rubber (red line) and without rubber (blue line)

In Fig. 9 the transfer functions for two measures of maintenance vehicle passages are presented, calculated using the acceleration spectrum in third octave band in decibel.

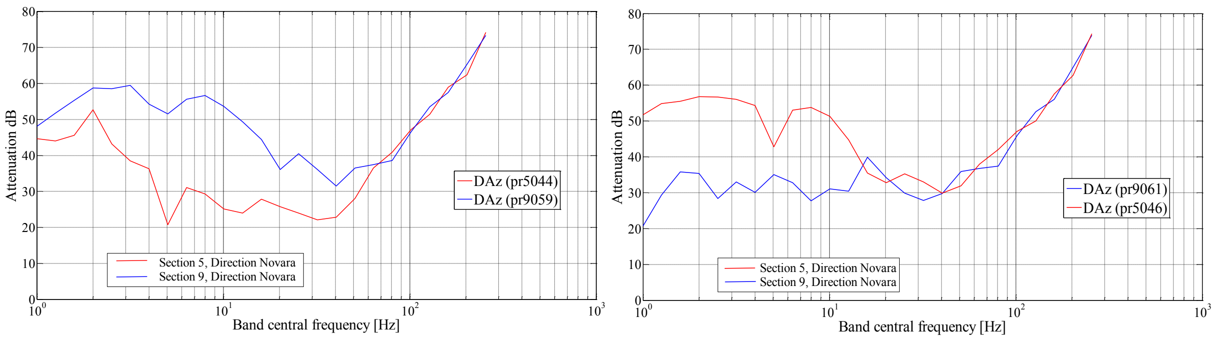

Fig. 9. Transfer function (maintenance vehicles) for measures in sections with rubber (red line) and without rubber (blue line)

Some measures show that the transfer function results in favour of section without rubber (diagram on the left) and others measures show that the transfer function results in favour of section with rubber (diagram on the right).

In Fig. 10 the results are presented in terms of spectrum of peak component particle velocity for measures of high speed train passed at section with rubber (TAV_04 and TAV_01, section 5) and at section without rubber (TAV_03 and TAV_07, section 9). The graphic at the left correspond to the same high speed train which passed at the section with rubber (TAV_04, section 5) and immediately after at the section without rubber (TAV_03, section 9) while the graphic at the right correspond the other measure of another high speed train passed respectively in the above mentioned sections.

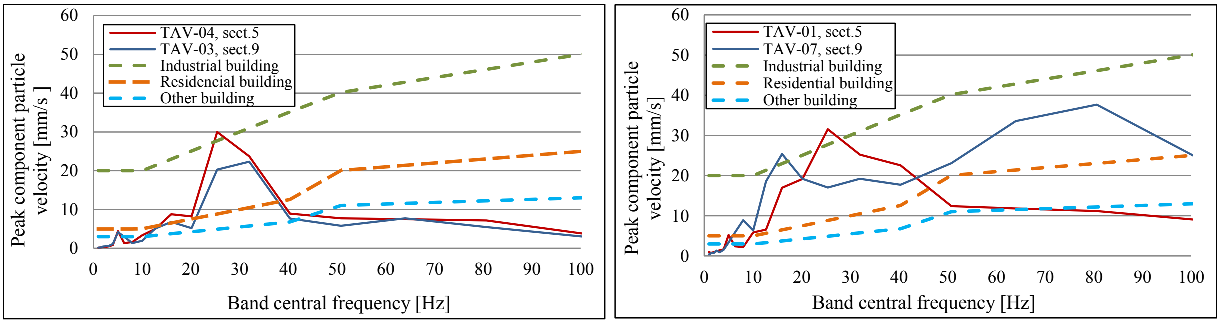

Fig. 10. Peak component particle velocity of high speed train passages at section with rubber (red line) and at section without rubber (blue line). The dashed line correspond the reference value taken from standard UNI 9916:2004

Looking at others results in term of spectrum of peak component particle velocity it can be seen the variability of the frequency ranges where one solution has a better or worse behaviour in respect to the other solution.

So, nor the peak component particle velocity nor the transfer functions give an immediate response about which material performs better, that means which one of those sections has lower peak component particle velocity or attenuates more. However the peak component particle velocity, excluding low frequency band, show a more clear structure in which the intervals of frequency evidences in favour of one section.

In Fig. 11 for instance, the parenthesis show the frequency ranges where the chosen vibration index, for the asphalt with rubber results better than the index for asphalt without rubber, and vice versa.

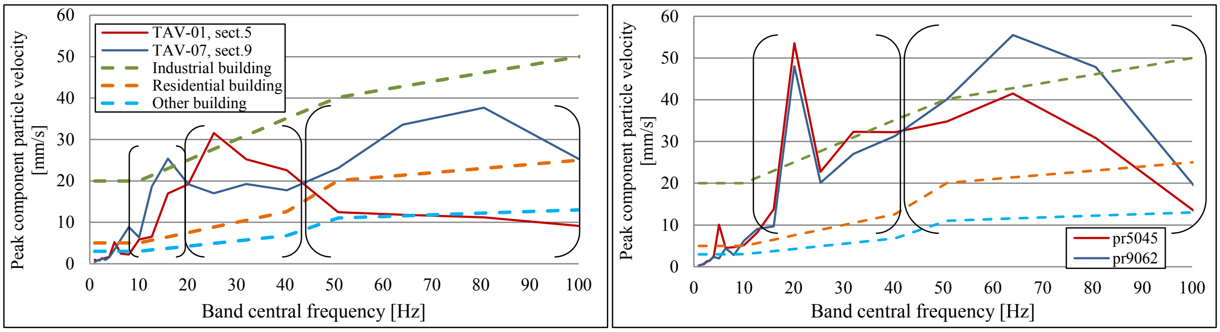

Fig. 11. Peak component particle velocity of high speed train and maintenance vehicle for section with rubber (red line) and without rubber (blue line). The dashed lines are limits of UNI 9916:2004

Frequency range from 1 to 10 Hz, when graphics alternate, can't be considered. According to this observation we used those intervals of frequency as synthetic indices to compare and associate the multiplicity of available graphics.

Referring to passages shown in Fig. 11 the schematic diagram of Fig. 12 can explain the chosen procedure: in 50-100 Hz range, both the measures are clearly in favour of rubberized section that gains two lines up. In 20-40 Hz range the no-rubber section gains two lines. In the 10-20 Hz range, each section gains 1 line, because there is a constant prevalence of one over the other in the first graphic, but a prevalence of the other over the one in the second graphic. When the graphics alternate also into the same graphic, as occurs in 1-10 Hz range, no material gains lines.

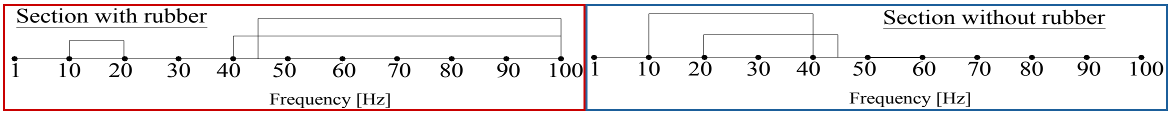

Fig. 12. Intervals of frequency in favour for each material, based on the two cases showed in Fig. 11.

In Fig. 13 there is the sum of cases (lines gained) in favour to rubber section (positive) and without rubber section (negative), and the sum of weighted differences, to take in account the major differences observed in some frequency ranges.

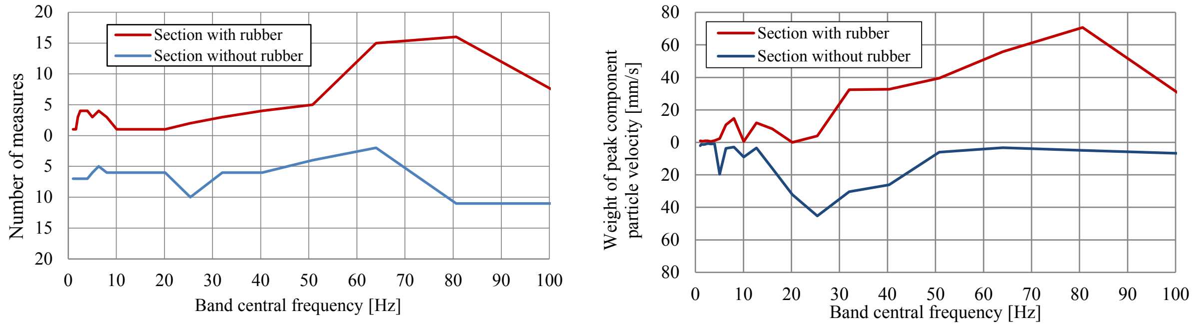

Fig. 13. Comparison between results showing the measures in favour (left - number of case; right – weighted differences)

Synthetic indices used suggest that the section without rubber performs better at frequency range from 10 Hz to 30Hz while section with rubber at frequency range from 50Hz to 100Hz (referred to the peak component particle velocity graphics). This result comes from the whole survey on high speed train and maintenance vehicle measurements.

The analysis of the transfer functions provides enough information to affirm that in the higher frequencies range, over 100Hz, the asphalt without rubber performs lightly better (attenuates a little bit more). Fig.14 shows that the transfer functions for some maintenance vehicle at section without rubber (blue and cyan line) are above those of rubber section (red and green line).

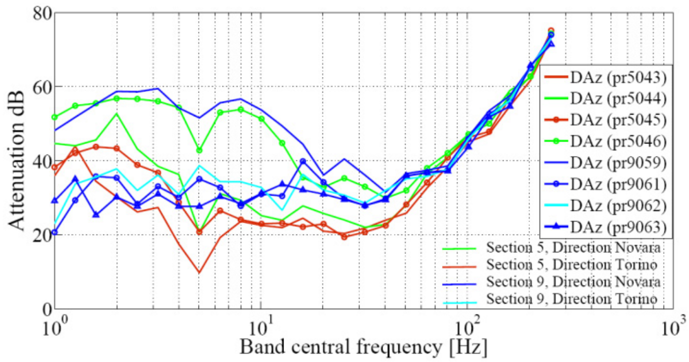

Fig. 14. Transfer function for some maintenance vehicle with rubber (red and green line) and without rubber (blue and turquoise line)

The measures realized with hammer (manual excitation) are studied as a separate case. For that excitation method, in the frequency range from 1 Hz to 30 Hz the sections without rubber perform better that the sections with rubber, while for frequency range from 30Hz to 100 Hz the contrary happens.

5. Conclusions

The large measurement survey carried out on the Novara West interconnection of the new High Speed Railway gave a relevant plenty of results that are not as coherent as wished at the beginning of the research.

A comparative analysis has been conducted by separating the different zones of the peak component particle velocity graphs and transfer functions.

A very simplified method were used to obtain some suggestion to answer the question if the rubber added asphalt could be more efficient than the traditional one in reducing train transit vibration transmitted to the environment close to the railway.

In the majority of high speed train and maintenance vehicle passages, the rubber gives benefit in the range 50-100 Hz, while it has a worse behaviour in the range 10-30 Hz. The absolute values of peak component particle velocity achieved in the lower range of frequency are nearer to the limit proposed in common standards than those achieved in the higher range of the previous two. So, the rubber adding method tested in this research might produce some negative effects more important than the positive ones attainable for frequencies range more tolerable by the man or by the buildings.

Acknowledgements

The research is supported by RFI (Rete Ferroviaria Italiana). The authors thank Dr. Alessandro Buonanno, Dr. Giuseppe Pennucci, Dr. Roberto Oliverio and Prof. Giuseppe Cantisani for their support in the research, in vibration measurements and in processing of the data.

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