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Vibrations in Signalling Equipment: Limitations and Improvements of Current Standards

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Abstract

Signalling equipment mounted on rails are subjected to harsh environmental conditions in electrical, thermal and mechanical terms. The presence of nearby local features in the track (such as void sleepers, joints, local railhead defects, bad geometry welds) or highly defective passing-by wheel treads (polygonization, wheel flats) give rise to exceptionally high mechanical stresses that are not properly accounted for in the current standards for signalling equipment acceptance. The paper describes the results of a measuring programme held in a location where wheel treadles suffer abnormal failures. A critical analysis of current standards is shown, together with the proposal of new indicators to better characterize the vibration environment that can be encountered in practice on a real track.

Keywords: signalling equipment, vibrations, shocks, testing, signal processing, railway standards.

1 Introduction

Signalling equipment includes a large variety of objects that work in different contexts. International standards [1] define four classes of signalling equipment:

- on rail
- on sleeper
- on ballast
- outside the track (from 1 to 3 m from the rail)

In this paper we will deal only with shock and vibrations of equipment falling in the first category, for which the standard indicates the RMS acceleration in the mutually orthogonal directions (280 m/s² vertical, 140 m/s² transversal, 50 m/s² longitudinal) and the corresponding spectrum PSD. Shocks are considered as a combination of both mean value/duration and peak/duration; on the rail, these values are 420 m/s² for 6 ms and 2500 m/s² for 1 ms. These values are derived from a UIC report [2].

Italian standard IS402:2000 [3] defines instead 5 categories of environments for signalling equipment:

- category 1V: environment not subject to vibration (station buildings);
- category 2V: environment protected by noticeable vibrations, with equipment installed at more than 1 m from the rail;
- category 3V: environment subject to not high levels of shocks and vibrations, with equipment installed at less than 1 m from the rail but not mounted on the rails or on its support;
- category 4V: environment subject to high levels of shocks and vibrations with products mounted on the rail support (sleeper on concrete platform);
- category 5V: environment subject to extremely high levels of shocks and vibrations with products mounted on the rail.

Category 5V, in which the object described in this paper falls, must be tested with random vibrations with total values of 27 g_{RMS} , 13 g_{RMS} and 5 g_{RMS} respectively in the vertical, transversal and longitudinal direction. This values, although a little lower, are comparable with those indicated in [1]. General information on random vibration tests can be found in [4], although both [1] and [3] give all the information needed to perform the tests.

About vibration spectra, Figure 1 compares [1] and [3] showing that the standards are more or less equivalent in terms of amplitudes and frequencies.



Figure 1. Comparison of power spectral densities for random testing (excerpt from [1] and [3])

About shocks, [3] specifies that the acceptance tests must be done with 18 shocks (6 in each direction, 3 in the positive and 3 in the negative direction). The shape of the pulses in clearly taken from [5], and the values are 50 g for 6 ms in the vertical direction and 10 g for 11 ms in the other directions.

2 Experimental activities

An electromagnetic wheel detector (WD or treadle) rail mounted suffered repeated failures when installed in a site located in a conventional line in the North-East of Italy (rails UIC 60 manufactured in 1988, concrete sleepers manufactured in 1986). An experimental campaign to measure the vibration environment was planned as there were some concerns about ballast tamping and vibration isolation.

Figure 2 shows the details of the site which resulted critical for the treadles for several reasons. First of all, the function of the treadle is to count the axles in an axle counter signalling application, where track circuits are normally used to interact with signals, and in fact the classic installation of insulated rail joints (IRJ) is visible. In Italy, IRJs are prepared in the workshop with rail crops of different length that are therefore welded on the field with the aluminothermic welding process. This environment is potentially harmful for the WD as impacts with the welds and the IRJ may lead to abnormal stresses.

The situation is complicated by the specific relative positioning of the WD on the left and the right rail. In order to be able to determine not only the pass-by of an axle but also the running direction, the treadles must be separated by a certain distance which, for ultra-low floor wagons that run in that line since a few months, forced the infrastructure owner to further separate the sleepers where the WD are mounted. This resulted in an abnormally wide sleeper bay and in a possible lack of tamping. Rubber sleeper pad where also missing or displaced as a result of trackworks to get this particular arrangement.



Figure 2. Track under test general view (left, 1=insulated rail joint, 2=aluminothermic weld, 3=treadle) and close-up on the treadles (right)

The measuring chain included displacement and acceleration transducers, according to the following scheme (see Figure 3):

- sleeper acceleration and vertical deflections were measured near the WDs, welds and IRJs;
- accelerometers were measured under the rail foot at WD, welds and IRJ locations;
- accelerometers were mounted also directly on the WDs;
- further measurements were performed at about 20 m from the treadle (so-called "standard track").

The sampling frequency was selected to 10 kHz in order to consider also short phenomena (shocks), while the end-of-scale for the transducers was ± 500 g for accelerometers and 10 mm for displacement transducers (mounted with an approximate preload of 5 mm, resulting in a useful range of ± 5 mm).



Figure 3. Overview of the sensors in the area of one WD (left) and detail on a LVDT displacement sensor mounted on a sleeper

As the layout of the track was peculiar, it was decided to measure the vertical track decay rate (TDR), that is the estimation in 1/3 octave bands of the attenuation of vibrations (expressed in dB/m) along the track when excited in the vertical direction.

TDR is an important indicator in external noise evaluation as the contribution of the noise emitted by the rail can be important in case the decay is insufficient. In this work the concept is extended to understand how impacts can reach the WDs. Data acquisition and processing to estimate TDR are detailed in [6], to which the reader is referred for more information. Figure 4 describes the rationale of the test.

Another source of important knowledge is the railhead surface status. Once again, international standards on noise help to define "rail roughness" in a wavelength range that can heavily affect rail vibrations (and therefore emitted noise). Measurements of rail roughness were done according to [7] and to [8]. Figure 5 shows the equipment used during the tests, a trolley that was used by one of the authors to perform numerous activities [9].



Figure 4. To estimate TDR, track is excited vertically in a number of locations (left) by using a roving instrumented hammer (right) and an accelerometer mounted under measuring point 0 (not shown)



Figure 5. The trolley (CAT, <u>www.railmeasurement.com</u>) used to perform roughness measurements. The trolley proved to be incompatible with the regular functioning of the treadle, as it is counted as a passing by wheel

3 Collected data

The maximum speed allowed on the line is 150 km/h and the traffic is mixed. Being the measuring section in the vicinity of a station, pass-by speeds varied from 30 km/h to the maximum speed, with long distance and regional passenger trains, freight trains and EMUs of different kind. A good mixture of disc braked and block braked wheels was recorded, and this is quite important because, roughly speaking, tread braked trains are around 8 dB(A) noisier than disc braked trains. This difference, which reflects also on rail vibrations and therefore on the excitation of the WDs, is due to the different tread roughness resulting from the action (or the absence of the action) of brake blocks ("shoes") on the wheel tread.

Around 90 trains were recorded during the measuring campaign and, due to the local nature of some traffic, exactly the same rolling stock was observed during the three days of measurements, allowing also some repeatability check of the measured data.

4 Data analysis

In a previous paper [10], the authors performed a similar test campaign on a insleeper point machine. In that occasion, data where "segmented" to capture the features of the point machine under the action of each passing bogie, implicitly taking the assumption that there were no disturbances or other phenomena *between* the bogies.

The present case is completely different as, as it will be shown hereinafter, disturbances coming from nearby welds and IRJ are of the same order of magnitude of those given by the wheel (or the bogie) passing over the WD.

Another difference from the previous work is that the focus was that case on the dynamic behaviour of the point machine and of its vibration isolation system, while in the present case the attention is on the accumulation of damage that makes the WD fail, and to such a goal *all the signal* is important, not only that in the vicinity of the bogies.

For these reasons it was decided not to segment the acceleration signals but to analyse them fully, according to a more conventional data analysis approach.

Three types of calculation were performed on acceleration data:

- Moving Root Mean Square (RMS)
- Moving Kurtosis
- RMS and Kurtosis counting

The first calculation was performed in order to evaluate the RMS of acceleration present on the measured element. This was made on slices of 1000 samples (=0.1 s) shifted by 100 samples (=0.01 s), resulting in an overlap of 90%. This first analysis was unable to fully explain the failures observed in the WDs, in particular because the RMS level on rail where the WDs are installed proved to be not much higher than that of the "standard track".

For this reason a further analysis was performed using the kurtosis statistical indicator, with the aim of highlighting the presence of possible peaks in the signals. The presence of short acceleration peaks due to shocks during the passage of a train can in fact be negligible at energy level (RMS indicator), but, nevertheless, can heavily affect the life of a mechanical and/or electronic device as the WD.

The kurtosis parameter emphasizes the presence of such shocks. It is defined as the fourth statistical moment of a given signal and it is widely used in machinery diagnostics, particularly for the condition monitoring of rolling element bearings (see for example [11]). Because the fourth power is involved, the value of kurtosis is weighted towards the values in the tails of the probability density distribution – i.e. it

is related to the spread in the distribution. The value of kurtosis for a Gaussian distribution is 3, and a higher kurtosis value indicates that there is a larger spread of higher signal values that would generally be the case for a Gaussian distribution.

It can be observed that the contribution to the RMS value of short peak of high amplitude (with a durations of let's say 1/500 of the slice duration, i.e. 0.2 ms) is almost negligible while the same peak is instead well emphasized in the kurtosis. This becomes evident when looking at the definition of the RMS and kurtosis functions:

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \alpha(i)^{2}} \quad Kurtosis = \frac{\frac{1}{N} \sum_{i=1}^{N} (\alpha(i) - \bar{\alpha})^{4}}{\left(\frac{1}{N} \sum_{i=1}^{N} (\alpha(i) - \bar{\alpha})^{2}\right)^{2}}$$
(1)

Some examples of combination of the RMS and kurtosis indicator are now described to highlight the outcomes of this "blind" analysis method, where no distinctions or attempts to isolate single phenomena along the trains are made and the whole train is analysed instead. In all figures of these examples, the traces are, from top to bottom, wheel detectors, welds, joints and rails + standard track rails.

For <u>train t902</u>, a freight train with tread braked wheels running at 106 km/h, the difference in terms of RMS between all the elements of the track, and in particular between rails feet under WDs and rail foot under the "standard track", are quite small (Figure 6). Energy levels are quite high due to the speed and the high roughness of the wheel treads. The difference between the same elements in terms of kurtosis is instead quite large, indicating that even if the vibration energy is almost the same, the number and the relevance of the shocks is very different. The presence of a high number of shocks near the WDs area is due to the presence of welds and joints, while the absence of high kurtosis levels on the "standard track" suggests that no wheel flats are present.

For <u>train t928</u>, a regional train with disc braked wheelsets running at 129 km/h, the difference in RMS level is just a bit larger between the rails, but differences in the kurtosis indicator are much smaller than in the previous case (Figure 7).

This behaviour is believed to be related to presence of wheel flats. In this case shocks are present in all rail sections (also in the "standard track" rail) resulting in a relatively small difference in the kurtosis indicator. Nevertheless in the WDs area both wheels flats, welds and joint peaks are present, partially explaining the difference in energy.

<u>Train t947</u>, a regional train with rolling stock similar to the previous example and running at 120 km/h regional train, shows a non negligible difference in RMS levels together with evident differences in the values of kurtosis. In case rolling stock was probably not affected by wheel flats and the shocks are evident only in the WDs area due to the presence of welds and joints. (Figure 8).



Figure 6. RMS (upper) and kurtosis (lower) for train t902 (freight at 106 km/h)



Figure 7. RMS (upper) and kurtosis (lower) for train t928 (regional at 129 km/h).



Figure 8. RMS (upper) and kurtosis (lower) for train t947 (120 km/h). Traces represent for each case, from top to bottom: WDs, welds, joints, rails + standard track rail

4.4 Investigation on the presence of wheel flats

The last two examples, related to apparently quite similar trains, were further investigated in order to also highlight the differences and, possibly, confirm the hypotheses made on the presence or on the absence of wheel flats.

Time histories show (Figure 9) substantial differences between the two trains signals that can be summarised as follows:

train t928 shows high peaks (amplitude up to 700 m/s²) in the "standard track" area, while train t947 shows instead much lower accelerations (up to 250 m/s²);

- peaks in the "standard track" area are not synchronized with wheels (red lines) for train t928, indicating the presence of wheels flats, while higher acceleration levels in the "standard track" for train t947 are instead synchronized with wheels, indicating this levels as the result of the normal rolling of a disc braked wheel;
- looking at the acceleration recorded on right rail foot under the WD, train t928 shows further peaks not synchronized with wheels, that are due the combination of the impacts given by interaction of the wheel with IRJs, welds and the presence of wheel flats, while for train t947 less non-synchronized peaks appear (as there are no wheel flats) that are related only to the interaction of the wheel with IRJs and welds.

This confirms that the "blind" analysis made by observing the results of the RMS and kurtosis indicator is able to detect also the presence of wheel flats and the differences in excitation given by rough tread braked wheels or by smooth disc braked wheels.



Figure 9. Time history (upper) and zoom (mid) of the acceleration recorded on "standard track" for train t928 (left) and train t947 (right). Portion of the acceleration recorded on right rail foot under WD (lower) for the same trains

4.5 Statistical analysis of peak levels

Although examples may be interesting, any conclusions drawn from them must be confirmed by the analysis performed on a statistically relevant fleet of passing by trains.

Each train data set was then subjected to both RMS and kurtosis statistical analysis of peaks. In each signal peaks were first automatically identified by a specific procedure (an example is shown in Figure 10), then peaks for each channel were classified and a frequency distribution of values was obtained.



Figure 10. Peaks extraction procedure example: kurtosis values calculated for the accelerations recorded on the right IRJ for train t908

Cumulative distributions were calculated by means of numerical integration of the distribution histograms. Figure 11 shows the RMS and kurtosis cumulative curves for all trains measured during the measuring campaign, where the bigger differences between track elements are visible in the kurtosis curves, while the behaviour of RMS curves is less "definite" especially in the case of joints, welds and WDs.

The physical interpretation of this curves is that the difference in stress for the different track elements is not related to energy (vibrations) but instead in term of influence of the peaks (shocks) on the signal.



Figure 11. RMS (upper, in g units) and kurtosis (lower) cumulative curve of occurrences for all trains

4.6 Pass-by vertical track deflections

The analysis of deflection data was limited to the observation of typical recorded values during train pass by in order to compare the behaviour of the track near the WDs and at different distances from it. It was observed that the deflection of the sleepers near the WDs during train pass by was larger than that "standard track", although values are not extremely high. The ratio of the deflection near the WDs and that on the "standard track" is normally around two.

An investigation on the behaviour of different types of vehicles was performed and it was found that generally lighter vehicles, like passenger coaches, show a greater ratio deflections in the WDs area / deflection of the "standard track"; locomotives have instead smaller ratio. This can be explained as a possible non linearity of the track: heavier vehicles may saturate the gap possibly present under the sleepers due to poor tamping.

In any case, it was believed that track deflections are quite normal and can not be considered responsible for the WD high failure rate observed in the measuring site.

4.7 Vertical track decay rate

The estimated vertical TDR is shown in Figure 12 together with the TDR measured in two other sites and the following main differences can be observed:

- slab track is much more damped (high decay rate) than ballasted track in all the frequency range;
- the comparison ballasted track is more damped than present campaign track from around 500 Hz to around 1100 Hz (both track generally exhibit lower damping than the slab track);
- the present track has a particularly low damping (around 0.6 dB/m) in a quite wide frequency (800 to 1200 Hz approximately).

Even considering all the limits of this particular application of the TDR procedure, it is quite evident that the low damping of the present track leads to a much easier vibration propagation along the rails. As an example, to reduce of 50% (=-6 dB) the vibration at around 1 kHz it is necessary to move by approximately 10 m from the excitation position.



Figure 12. Vertical track decay rate for three different tracks: present ballasted track (blue trace), comparison ballasted track (red trace), slab track (magenta line). Green thick line is the lower limit in TSI HS RS for noise type tests purposes[12]

4.8 Rail roughness

The measurements, longer than 60 m, included all the irregularities (welded and insulated rail joints) and were filtered in the 30÷100 mm wavelength range that is particularly meaningful, being the typical range were rail corrugation is mostly likely to happen. It resulted that the railhead surface is in good longitudinal conditions (Figure 13). It can be concluded that the excitation due to the wheel-rail contact far from local defects.



Figure 13. Roughness measured in the 30÷100 mm wavelength range for left (upper) and lower (right) rails. Peaks due to rail welds and insulated rail joints are clearly visible

4.9 Shocks counting

In order to possibly identify the number of impacts affecting the various measured sections of the track, a specific algorithm was set up and tested. It is important to underline that the algorithm represents an attempt to identify the optimal counting method. The results shown in the following should be considered only as an indication, but nevertheless can be useful to start a discussion on the relative importance of shocks and vibrations.

The algorithm is, briefly, as follows:

- the signals were considered in slices of 1024 samples;
- slices were overlapped by 922 samples (90%);
- for each slice both the maximum acceleration (in absolute value) and the kurtosis were computed, resulting in two signals per channel;
- within the kurtosis signal, the peaks (local maxima) were located by using the findpeaks Matlab function;
- a neighbourhood of 10 samples ([-5,+5]) was then considered in the corresponding signal of the maxima and the maximum value was then found.

As a result, maxima and kurtosis signals are synchronised as they are derived from the same time base.

All the channels were subjected to such procedure. As some representative example, Figure 14 and Figure 15 show the number of peaks for all trains on the "standard track", in correspondence of an IRJ and directly on the WD.

Although the number of samples is too low to draw firm conclusions, is evident that the number of events of high amplitude is not negligible, especially where their presence is logical (e.g. on insulated rail joints). The WD is subjected, even for such a short measuring campaign, to a quite high number of spikes bigger than 2500 m/s².



Figure 14. Number of peaks in 50 m/s² bins for the standard track and IRJ02 measuring points



Figure 15. Number of peaks in 50 m/s² bins for WD01 measuring point

5 Conclusions

Several measurements were done in a measuring site (rail vibrations, track vertical deflection measurements, vertical track decay rate estimation, rail roughness) showing the greatest importance of peaks (impacts or shocks) in the accelerations to which the wheel detectors (treadles) are subjected to.

While vibrations in the "standard" track were rather low due to the good surface quality of the rails, the stresses of the wheel detectors installed in proximity of aluminothermic welds and insulated joints are dominated by a series of shocks also for rolling stock with "round" wheels (no wheel flats or other defects detectable).

A quite classical indicator in condition monitoring, the kurtosis function, was used to identify the peaks within the signals of passing by trains. The indications given by this parameter proved to be more stable and reliable than those given by the average energy (RMS) signal.

About track vertical deflection and rail corrugation the track looks in average conditions for a conventional line, requiring neither tamping nor grinding, while the estimated vertical rack decay rate showed poor track damping properties. In the author's opinion, this is one of the fundamental parameters to identify, in the future, the minimum distance of signalling equipment from a weld or a joint, as a lower TDR results in higher acceleration values far from local discontinuities. High rail vibrations and shocks, together with the high transmissibility of vibrations along the rail, are the possible reasons for the failures observed on the wheel detectors measured in the present work.

As a conclusion from the activity, it can be said that the standards for type tests should reflect more tightly the conditions found in service (more shocks) while assessing the quality of welds (geometry) and track properties (vertical decay rate and roughness) to define the minimum distance from welds and insulated rail joints.

An attempt was made to count the number of shocks starting from the simultaneous use of RMS and kurtosis data, nevertheless the proposed algorithm needs to be validated by further work.

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