

## **Rail Straightness Control in Service**

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### **Abstract**

Rail manufacturing, even with the most advanced technologies, leads to bars which inevitably have a residual deviation from the perfectly straight shape. These deviations, that should not be confused with the phenomenon of corrugation that happens in service mainly in tight curves, have wavelengths longer than 1 m and can result in high groundborne vibrations, ballast settlement due to excessive superstructure vibrations, excessive stresses in the bogies, booming noise at rather low frequency. Straightness can be controlled only in service, with the rails installed in the track, and track deflections induced by measuring cars can hide the original shape. The paper aims at describing a methodology that allows, by the simple use of a portable trolley, to check for rail straightness of rails in service identifying, if any, periodicities in the rail shape. Results from different measuring campaigns are critically compared.

**Keywords:** railway, rail, straightness, quality control, noise, vibrations, ballast.

## **1 Introduction**

Rails are produced by hot rolling followed by cooling (either natural or artificially accelerated) and a final straightening with a set of rollers. Straightening, which induces noticeable residual stresses, is requested because differential cooling between the rail head, the rail web and the rail foot inevitably leads to distortions that can not be compensated during track lay down.

Checking the straightness during the straightening process is not easy, as long as the rail must be checked “on the fly” while passing through the rollers and the rail surface is contaminated by iron oxides (calamine). As a matter of fact, current international standards in force (EN 13674-1) define the maximum allowed deviations from a straight line but without any reference to possible periodicities (or “waviness”) of the rail.

It was found in a previous research that long wavelengths may have adverse effects on several parameters linked to normal service, especially at higher speeds. In this situation, in fact, a wavy rail may induce high vibrations in the ground that can be felt at long distances from the track, may displace the ballast below the track and, possibly, may even disturb riding quality of rolling stock and passengers comfort. Measuring the waviness of rails in service is even harder, as measuring cars induce a global track vertical displacement (in the order of 1 mm) that is normally much larger than the original geometrical defect of the rail (in the order of 0.2÷0.5 mm). This paper illustrates the result of several measuring campaigns held by sampling rail irregularity of different high speed lines with a portable trolley. An original signal processing procedure allowed to precisely identify the various components of waviness. It will be shown that residual waviness after straightening depends on each rolling plant.

## **2 Rail longitudinal irregularities**

### **2.1 Basics on rail rolling and straightening**

Rail manufacturing is normally made starting from a reheating furnace where slabs of the desired steel quality are introduced. Due the large volumes produced, these furnaces are normally part of an integral cycle steel making plant which includes a blast furnace and all the following plants to convert cast iron into steel (converter, LF, degassing plant) and a continuous caster. The technology of slab manufacturing will not be described further as after the reheating furnace all the previous structure of the steel is lost.

There are several approaches to the choice of the rail rolling mill, but in most cases it includes a break mill, some (typically 2) reversible stands and a finishing stand. After the last stand, rails which are untreated (not subjected to artificial cooling) lay down on a cooling bed which brings the steel back to room temperature.

After cooling, the macroscopic appearance of the rails is the one shown in Figure 1 [1], which is obviously incompatible with their direct use. The final rail longitudinal and lateral profile can be considered as a superposition of the short wavelength inevitable errors in the rolling mills (typically due to uneven wear of the finishing stand) and long wavelength irregularities due to the different cooling rates of the head and of the foot of the rail.

Rails are therefore straightened by using a “roller straightener” which is a set of hydraulically actuated rollers which impose a set of reversed plastic strains resulting in a rail whose straightness is acceptable (Figure 2). Due to the rollers pitch and different rolling and cooling story of each rail, each plant gives different final results which, moreover, may vary depending on the steel composition (being the forces related to the elastic-plastic behaviour of the material). The simulation of a rail straightening process, being intrinsically non linear, is quite complex and, as it lies outside the scope of this paper, the reader is referred to the specific literature on the

subject (e.g. [2]). As a result of the straightening process rails are delivered with residual stresses which may affect their fatigue and failure behaviour [3].

As a result of the process, the residual irregularity is presumed to exhibit a regular pattern at least far from the ends where the process can be considered as stationary.



Figure 1: Rail rolling plant (left) and cooling bed (right).

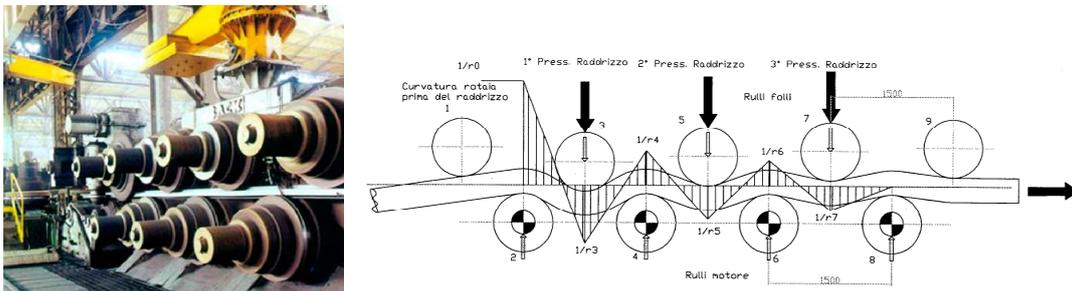


Figure 2: View (left) and scheme (right) of a hydraulic rail straightener. Residual rail curvatures under rollers are shown (right), where lower rollers are motorized and upper rollers are trailed [1].

## 2.2 Acceptable straightness during manufacturing

Rails are produced according to several standards throughout Europe. In this paper, only the current European Standard [4] will be considered, as it includes also all the provisions stated by the former standard from UIC [5].

The standard [4] identifies the criteria for rail straightness as shown in Figure 3. It is interesting to see that the same physical quantity, i.e. the deviation from the nominally straight profile, is defined as “flatness” for the rail body and “straightness” for rail ends and consists of mainly two values for rails of class A, i.e. the most precise class, suitable for high speed lines:

- vertical flatness  $d \leq 0.3$  for  $l=3$  m and  $d \leq 0.2$  for  $l=1$  m for rail body;

- vertical straightness  $d \leq 0.4$  for  $l=2$  m and  $e \leq 0.2$  for rail ends.

No indications are given about the shape (or wavelength content, which is approximately the same to some extent) of the longitudinal deviations, i.e. it is not indicated if they can appear as isolated defects or with a more precise and repetitive patterns. For clarity reasons, only the term straightness will be used in this paper from now on.

Table 9 — Straightness, surface flatness and twist tolerances

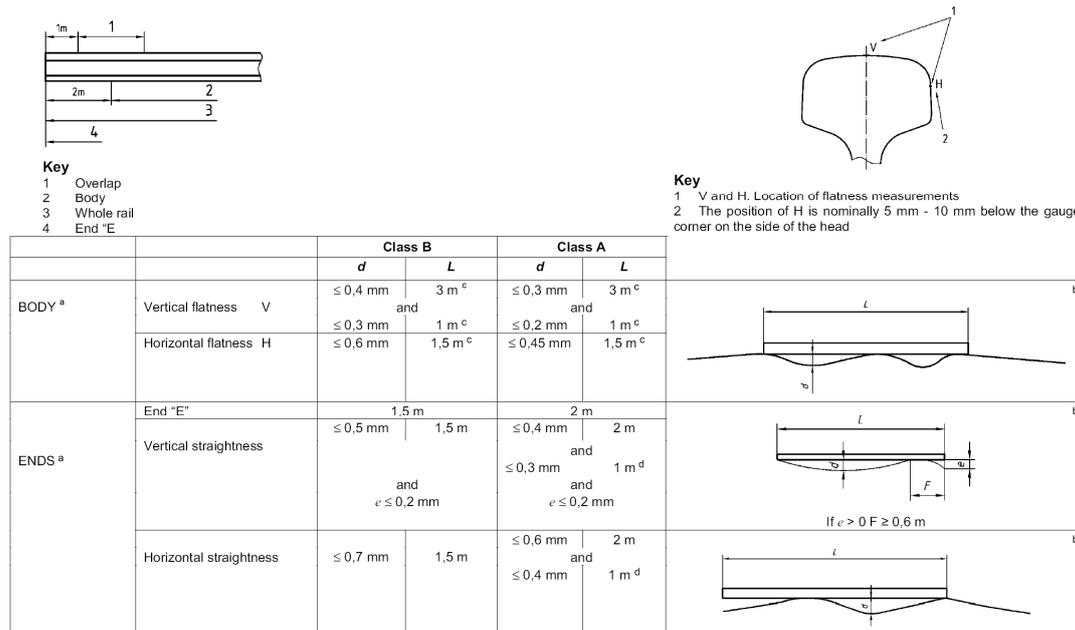


Figure 3: Straightness and flatness rail tolerances [4].

Measurement of rail straightness can be done effectively only with contactless systems due to rail speed during the straightening process and the inevitably long nature of the bar. As known, there are nowadays available on the market plant which produce rail 120 m long, and this prevents the use of manual checks of any of the rail dimensions.

As long as quite small dimensions are to be checked (peak to peak irregularity of 0.3 mm), it is important to say that oxides present on the rail may adversely affect the measurement. On the other side, opaque surfaces after rolling are perfect for contactless measurements with lasers and cameras triangulation systems. As the measurement is made "on the fly", also the dynamics of the rail during straightness check is important.

### 2.3 Railhead and track irregularities in the current standards

Wheel-rail interaction is responsible for noise and vibration generation. Current standards on noise type testing of vehicles include the measurement of rail vertical

irregularity (“roughness”) [6] in a rather short wavelength range, whose upper limit is defined by both the field of interest and the available measuring technologies. The technical specification [7] for high speed rolling stock requires that “the wavelength bandwidth shall be at least [0,003; 0,10] meter”. Quite recently, the technical specification [8] for conventional rail noise confirms the same range and spectrum. A specific standard [9] was developed to evaluate the reliability of the measurements of longer wavelengths. Depending on the bandwidth range of interest, the samples shall total a length of at least 15 m for each rail, if the bandwidth range involved does not exceed the 0,25 m one-third octave band or 7,2 m for each rail, if the bandwidth range involved does not exceed the 0,1 m one-third octave band.

Although at the moment no regulations impose the measurement of waves longer than the 100 mm one-third octave band, it is interesting to observe that both [7] and [8] use the limit spectrum shown in Figure 4, where the longest one-third octave wavelength is centred at 400 mm.

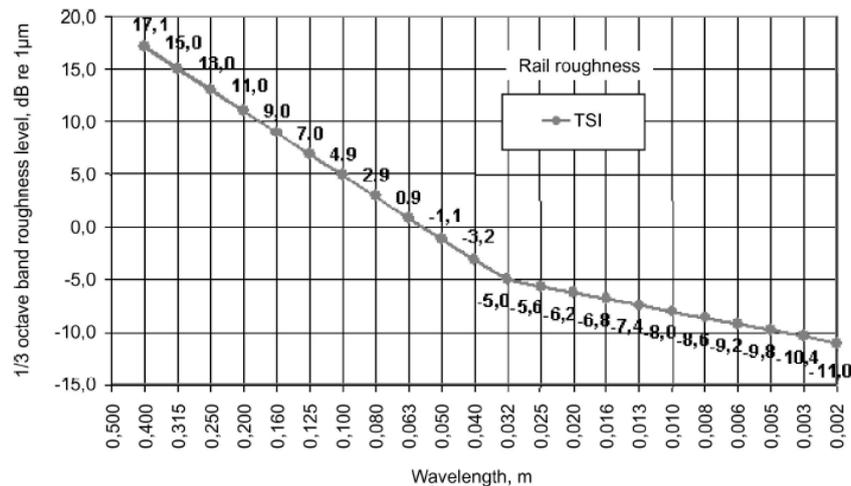


Figure 4: Limit roughness spectrum for test track to be used during noise emission type tests for interoperable high speed and conventional trains.

To limit unwanted irregular train dynamics, track geometry must be kept under control. Vertical geometry of the track, known as “longitudinal level”, must be managed by track maintenance machines. Track irregularities are nowadays checked normally by measuring trains, which implies that track irregularities are measured with the track (and the rails) loaded. The European Standard [10] defines three fields of wavelengths, named D1 ( $3 < \lambda \leq 25$  m), D2 ( $25 < \lambda \leq 70$  m) and D3 ( $70 < \lambda \leq 150$  m), where the last should be used for measuring long wavelength defects for line speeds greater than 250 km/h.

Similarly [11], track defect spectra in a broader (longer) wavelength domain confirm the same tendency, i.e. the RMS amplitude of track vertical (longitudinal level) defect increases more or less steadily at longer wavelengths up to around 100 m. By looking at the details of Figure 5, it can be observed that the figures are obtained by

superimposing two main different sets of data, i.e. typical “rail roughness” measurements (up to 0.4 m at most) and “longitudinal level” measurements (down to 1 m). The comparison of the two diagrams is not straightforward as the left diagram is expressed in terms of Power Spectral Density (PSD,  $\text{mm}^2/(1/\text{m})$ ) while the right one is expressed in terms of energy (RMS, dB ref.  $1 \mu\text{m}$ ).

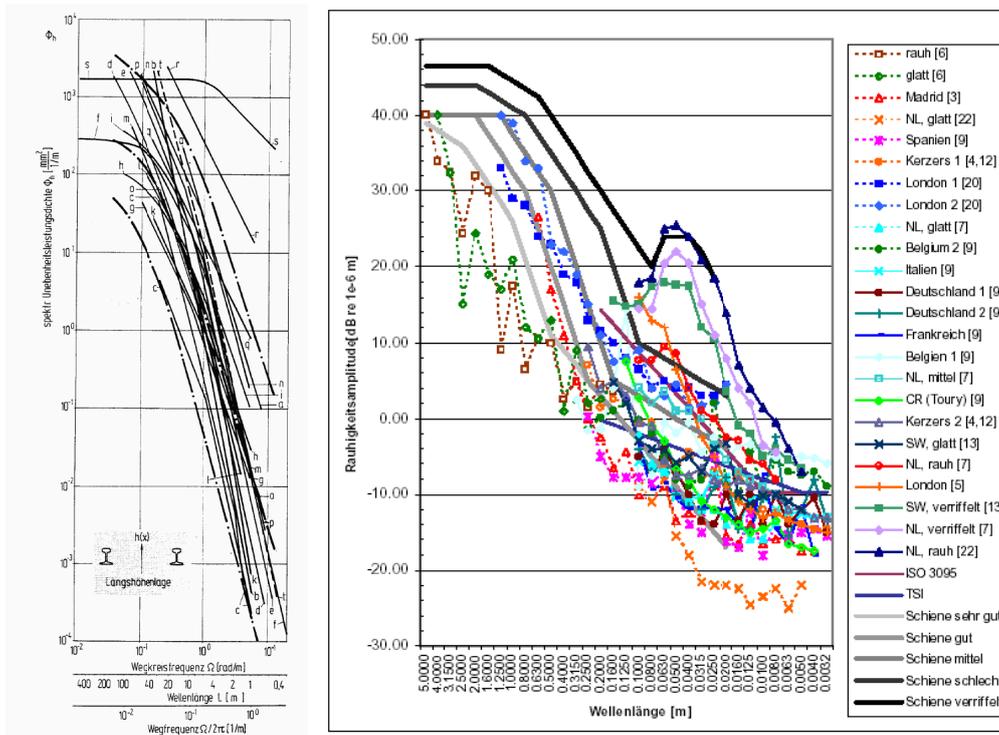


Figure 5. Track longitudinal level defects up to around 200 m long wavelength (from [11]).

It results that there is a “hole” in the standards in terms of wavelengths, as the  $0.25 \div 3$  m is not covered. The main reason for this lack is that shorter wavelength defects can be corrected by rail grinding while longer wavelength defects can be corrected by track tamping, but measures to correct defects in the intermediate wavelength range are not available.

## 2.4 Measurement of straightness in service

Whatever the rail straightness tolerance which is accepted in the manufacturing plant, the result of the application of a rail can be deduced only from the behaviour measured during actual service.

In a previously published paper [12], one of the authors successfully assessed the possibility of a very lightweight (around 3 kg) pushed trolley to measure the longitudinal vertical irregularity of a railhead up to the 3 m one-third octave band. The main advantage of the use of such equipment is that it can measure the actual

profile of the rail on an *unloaded* track, thereby resulting in the shape of the rail undisturbed by the load of any measuring train. As an example of the results obtained by that activity a one-third band spectrum, calculated over a 200-metres central portion of a much longer record by using the “perfect filtering algorithm”, is shown in Figure 6. Limit curves from TSIs and EN ISO 3095 are linearly extrapolated (in a log-log domain) beyond their domain of definition. The extension of curves in [6, 7 and 8] to longer wavelengths, which is somewhat arbitrary, is confirmed by a number of measurements and, therefore, it can be retained as empirically valid.

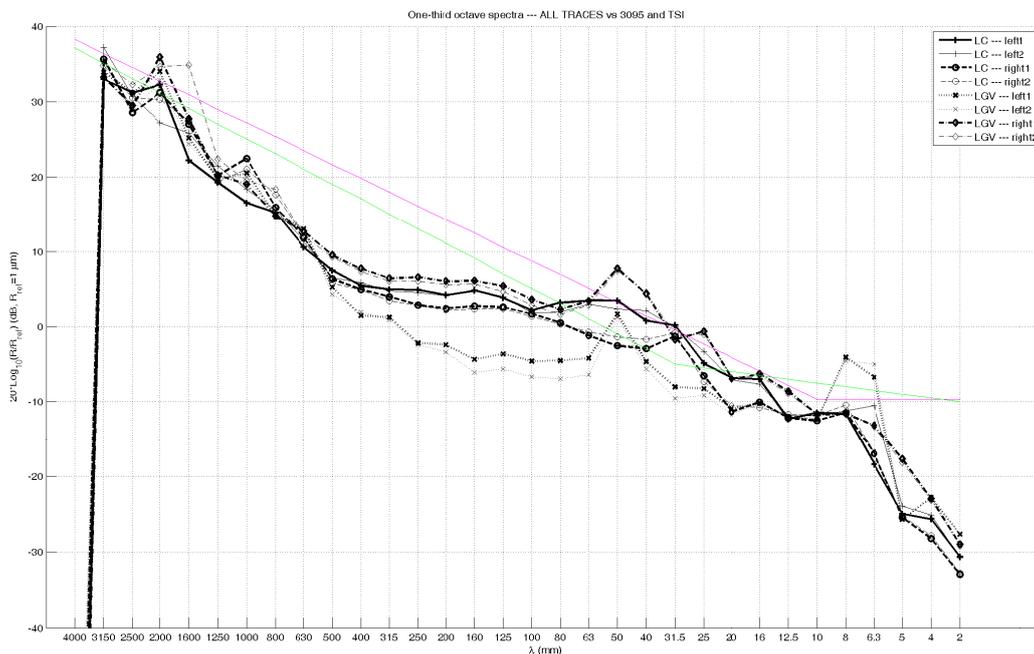


Figure 6. Example of a rail irregularity spectrum (from [12]).

### 3 Rail straightness periodicities detection

#### 3.1 Rail irregularity as a random process

Wide-band statistical processes, as rail irregularity measurements indisputably is, exhibit interesting properties which are defined and analysed in textbooks and scientific literature [13]. A special signal, called *white noise*, results from a Gaussian random process and has special properties, such as a flat spectrum in the frequency domain (same amplitude at all frequencies) and an autocorrelation which is identically zero except for a time shift  $t=0$  (i.e. when the signal is superimposed to itself). This signal gets its name from the fact that white light is made of all wavelengths of the same amplitude.

To further complicate the situation, the shape of a spectrum depends in its representation in the frequency domain (i.e. either with the “narrow band” representation resulting from the application of the Fourier transform or with the “constant percentage band” (CPB) representation resulting from the application of digital or analogue  $1/n$  octave-band filters) and in the amplitude domain (which may be expressed in terms of energy, power, energy spectral density or power spectral density).

From Figure 4 and Figure 6 it can be easily observed that rail straightness is a phenomenon which is quite far from a white noise. Amplitude in octave bands at lower frequencies (long wavelengths), expressed in “power” (i.e.  $\mu\text{m}^2$  or in  $20\log_{10}$  scale in dB) is much greater than that at higher frequencies (shorter wavelengths), which is exactly the opposite of what results from a white noise, where the power amplitude in octave-band representation increases with centre frequency.

The slope of the spectral representation can be expressed with the so-called  $1/f^n$  behaviour. For white noise  $n=0$ , as the spectrum is flat; other notable cases are those of *pink noise*, for which  $n=1$  (the name comes from the fact that the light with such spectrum is pink), and *Brown noise*, for which  $n=2$  (the name comes from Robert Brown, who first described the motion of particles or “random walk noise”).

While a future paper will be devoted to the analysis of the spectral properties of the rail irregularity signals, in this work only the practical implications of a specific algorithm for regular pattern detection will be described.

### 3.2 The detection algorithm

Apparently, the easiest way to obtain the spectral content of a signal is to perform a Fourier transform. This anyway contrasts with the resolution in the case of a narrow band representation (too many spectral lines are obtained, hiding the contribution of the most important components) or with the fact that precise components can be hard to individuate if CPB representation is chosen (as long as CBP sums up all the components in each  $1/n$  octave band).

The noise rejection problem can be overcome by calculating the spectral properties of the autocorrelation function. For what said before, any *noise* signal at time  $t+\tau$  is by definition unpredictable by observing the signal at time  $t$ , whatever the delay  $\tau$  is considered. The autocorrelation function of an infinitely long sine signal is therefore a sine again while the autocorrelation of any noise is a peak at  $t=0$ . This allows to “concentrate” the noise of all kinds (=of any wavelength) at the single line  $t=0$ , reducing all noises to an equivalent white noise.

To illustrate the main advantages of the processing principle, Figure 7 shows the signal from a 200 m long record. The upper figures are the original signal (filtered in order to keep only 4 m and shorter wavelengths), its Fourier transform (FFT) and the power spectral density (PSD) estimation as computed with the Matlab<sup>®</sup> command

pwelch. The lower figures are the autocorrelation of the signal and, again, its FFT and PSD. It is evident how the noise is much reduced with the second approach, while the relative importance of the various components of the signal are well highlighted in the PSD of the autocorrelation.

It is worth to underline that this method does not allow an exact *quantification* of the amplitudes involved in the reconstruction of the original signal (this is possible only from its FFT) but gives a quite straightforward picture of the main components which constitute the rail straightness error.

The advantage of the method is particularly evident by comparing the PSDs at the longer wavelengths, where the signal is “corrupted” by the normal increase in the energy content which is intrinsic in this kind of signals. The PSD of the autocorrelation is capable to resolve the content from sine components from the overall signal due also to “noise” in the signals.

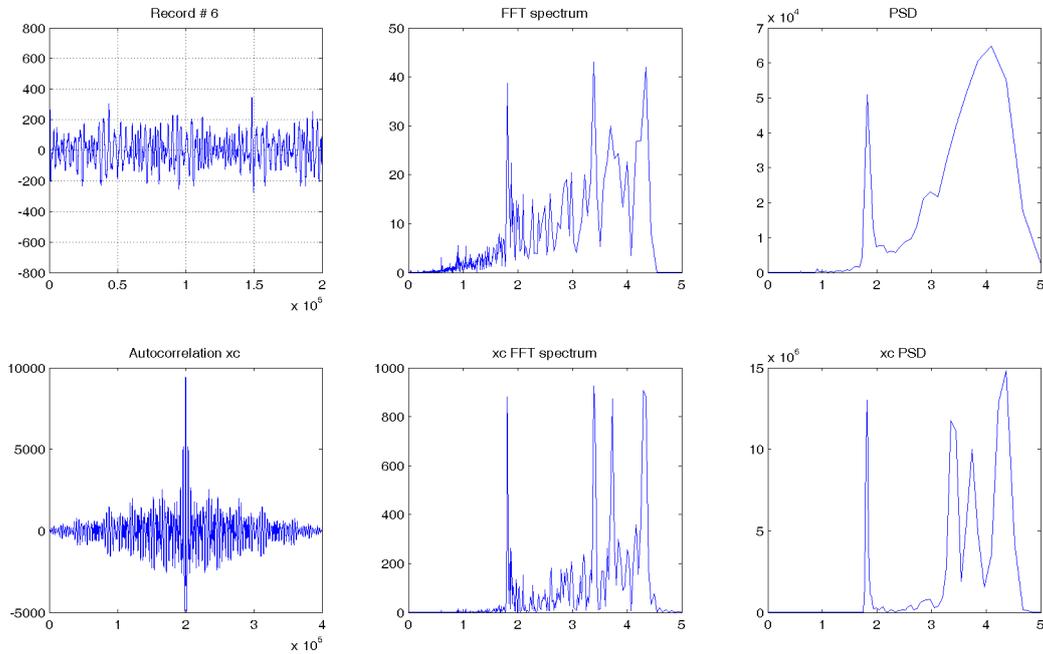


Figure 7. Example of a rail straightness periodic irregularities detection. From left to right, from top to bottom: rail straightness signal ( $\mu\text{m}$  vs. samples,  $ds=1$  mm) + FFT and PSD (vs. distance in m), autocorrelation ( $\mu\text{m}^2$  vs. samples,  $ds=1$  mm) + FFT and PSD (vs. distance in m). Data from manufacturer A (year unknown), see below.

## 4 Results and discussion

### 4.1 Measuring campaigns

The results from several measuring campaigns are compared in the following. It must be stated in advance that some data are taken from measuring campaigns made for other purposes and that in those occasions the rail manufacturing plant and year

were not recorded; nevertheless, the geographic location of those measurements throughout Europe allows to hypothesize at least the manufacturer.

In order to make the comparison anonym, the results were randomised and letter A, B, C, D were assigned to the manufacturers. With the exception of one case described below, all the records were longer than 240 m, reaching a maximum of 600 m. The equipment settings were modified in order to measure at the best of its possibilities the wavelengths up to 4 m; the results are absolutely consistent and allow to suppose that the trolley behaviour is more than satisfactory up this one-third octave band wavelength centre.

## 4.2 Results

Figure 8 shows the result of the analysis of different measuring campaigns were the reader can observe the main feature of each case. The outcomes of such quite large variety of cases allows to identify the most important periodical irregularities affecting rail straightness in service.

It is interesting to observe that the same manufacturer, depending on the year of manufacturing, has produced rails with different residual straightness; at the same time the dominant residual periodic irregularity goes from 1.8 m to more than 4 meters, suggesting that the details of the rolling mill and straightener may heavily affect the final geometric quality of the rails.

The results of the one-third octave spectra, non reported here for reasons of space, looks consistent with the spectra indicated in [7], [8] and [11].

## 5 Conclusions

The developed method consists of two main phases: the collection of reliable data and their analysis. If the first step proved to be quite hard in the past, sufficient confidence was reached at the end to ensure that the quality of the acquired data is good enough to perform the following analysis. The second step is instead quite simple, as signal processing techniques described in this paper are simple and well established.

Results obtained are consistent and appear to be immediately usable in quality control, especially at those long wavelengths that are so hard to be controlled.

Further developments of the analysis of the data will be done considering statistical properties of the signals and their representation. The main aim of this following work will be focused on the quantification of the defects exceeding the “normal” distribution of rail irregularity in service.

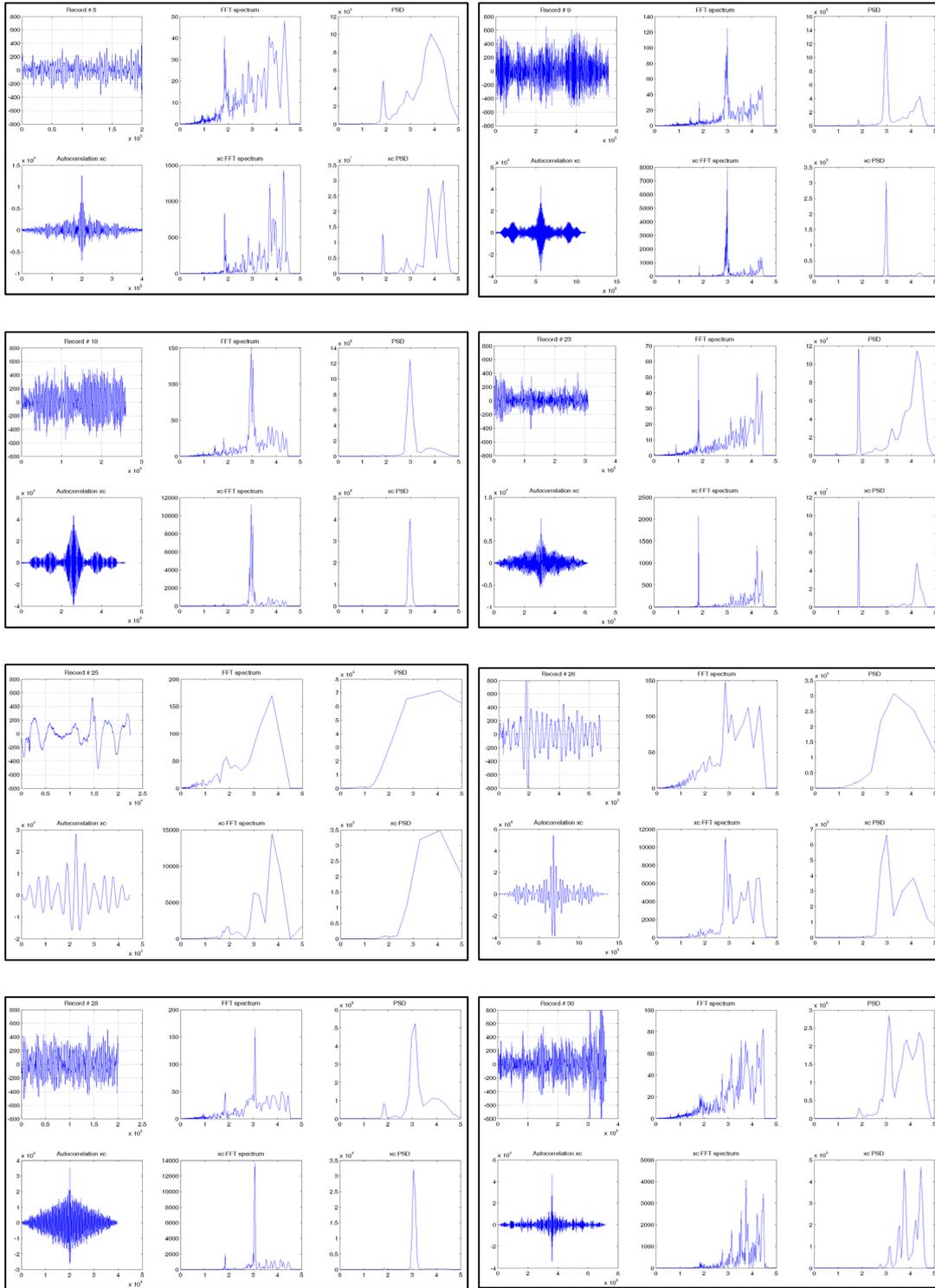


Figure 8. Rail straightness from manufacturer A (year unknown) and B (2010) (first row); manufacturer B (2010) and C (2001) (second row); manufacturer D (2010) and B (2006) (third row); manufacturer B (2010) and B (1991) (fourth row).

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