IDENTIFICATION AND MONITORING OF OUT-OF-ROUNDNESS OF A METRO VEHICLE BY MEANS OF ACOUSTIC MEASUREMENTS

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KEYWORDS: Wheel defect, Out-of-Roundness, Noise, Diagnostics, Monitoring

ABSTRACT
Wheel wear and damage issues can be particularly serious in metro vehicles. Whatever their origin, Out-of-Roundness (OOR) wheel tread irregularities are responsible for high wheel-rail contact forces, originating abnormal levels of noise and vibration in most of the vehicle and track components. In this paper a methodology based on acoustic detection of abnormal noise level within the passenger compartment is shown. Results are discussed with advantages and limitations compared to a number of other techniques.

INTRODUCTION

Metro vehicles are subjected to particularly stressing load cycles due to high acceleration and deceleration, steep gradient and narrow curves.

Wheel circumferential geometry defects, called out-of-roundness (or OOR), are pretty common in metro systems where traction effort is typically high compared to normal force (i.e. the adhesion is highly exploited). Their origin is exacerbated by some architecture typical of older metro vehicles, like single motor bogies or very stiff components of the running gear.

It is important to highlight that high values on longitudinal creepage are due to low curve radius and can not be avoided for normal (passive steering) vehicles. The OOR generation and growth follows to some extent the rules of rail corrugation, although the “loop” mechanisms may be quite different.

The consequences of OOR are high level of noise, an unacceptable increase in groundborne vibration levels, unexpected failures in rolling stock and/or track components.

As the instrumentation of an entire fleet proves to be a normally too expensive task to be accomplished, the measurement of the geometric quality of wheels is made normally by means of trackside measurement of noise and/or vibration emitted during pass-bys. This requires a stationary equipment to be installed in a suitable location along the line with all the complications related to a fixed installation.

As occasional checks may be necessary and/or the deterioration rate in not high enough to justify the investment of a complex measuring station, the authors developed a simplified methodology based on acoustic measurements. The application of this technique proved to be useful in the frame of a dispute, being capable to identify the requested OOR feature.

RATIONALE OF THE PROBLEM

Out-of-Roundness is a pretty common defect in rolling stock wheels. A literature survey conducted in 2000 [1] classifies wheel tread irregularities and the possible origin of the different phenomena is proposed. The following categories are then defined:

- Eccentricity
- Discrete defect

- Periodic non-roundness
- Non periodic (stochastic) non-roundness
- Corrugation
- Roughness
- Flats
- Spalling
- Shelling

Authors were approached by a metro administration to analyse and quantify as much as possible the origin of an apparent malfunctioning of some metro vehicles. As the complaints were followed by a debate between the supplier of the wheels and the metro operating company, results will be shown here anonymously. We will focus on the identification of the signal processing methodology and on the results.

Vehicles considered in this paper are conventional metro cars, permanently coupled as EMU units of two different kinds, that will be called in the following Type A (two vehicles with two bogies with full traction with only one electric motor per bogie --- wheel arrangement BB-BB) comprising a driver's cab and a very similar Type B without driver's cab. The typical trainset arrangement are a 6-vehicle train with three EMU (Type A – Type B – Type A) or a 4-vehicle train with two EMU (Type A – Type A), the latter being used only in off-peak hours.

Drivers reported an abnormal noise level in the driver's cab after a short mileage after reprofiling / wheel tyre change. As there are only two driver's cabs compared to 12 bogies, it is clear that the abnormality required some check before affirming that the problem was endemic. Attempts to make a subjective judgement gave contradictory results, the line being in service since many decades with rails and, generally speaking, infrastructure of different age and kind; in particular, the tunnel portion of the line are characterized by different tunnel shape and size and the noise is, clearly, much less uniform than in the external part of the line.

DEFINITION OF THE IDENTIFICATION AND MEASUREMENT STRATEGIES

Whatever the cause of the supposed damage to wheel tread, several hypotheses were evaluated before performing any experimental activity. The authors proposed therefore a list of possibilities using the most common measuring techniques (Table 1) (the measuring "comb" will be discussed in the last chapter of the paper).

After extensive discussion with the parties involved, it was decided to use the acoustic check, although it were the more risky approach, being acoustic measurements potentially disturbed by additional sources (passengers, public announcement system inside the vehicle, air compressors, horn, etc.). Note that vehicle windows can be partly opened (this being the normal condition during hot season as HVAC system is not present on such vehicles). End doors of each vehicle are closed (there is no possibility to pass from one carbody to the other during passenger service).

The activity was then defined with the following goals:

- noise measurements must be possible in normal service without requiring any particular conditioning of the vehicle prior the measurement (only windows need to be closed before taking the measurements);
- time domain signals must be recorded and made available to all the parties to compare calculations made with different systems;
- measurements need to be possible on the entire fleet (with different types of wheels / bogies) without limitations.

Table 1: possible measuring strategy to assess OOR

Type of check	**Transducer and measurement details**	**Advantages**	**Disadvantages**
Acoustic	Microphone on board	• Low cost • Simple • Objective quantification of complaints	• Limited information (no precise correlation with speed) • Attribution of responsibility (wheels? axleboxes?) impossible
Vibrational	Axlebox acceleration	• Objective • Measurement quantities are certainly responsible for reported disturbances	• Impossible to be applied to all vehicles (very high costs!) • Limited information but possible identification of periodic OOR (polygonization)
Geometric simple	OOR measurement with 0.01 mm dial gauge	• Simple • Low measurement cost • Accurate (but limited to visual inspection)	• Vehicles must be available at underfloor lathe (one motor per bogie!) • Difficult quantification of OOR (profile not recorded) • Attribution of responsibility (wheels? Axleboxes?) impossible
Geometric advanced	OOR measurement with 0.05 mm measuring "comb"	• Simple • Automatic quantification of OOR (multiple profiles recorded) • Accurate (visual inspection)	• Higher costs • Vehicles must be available at underfloor lathe (one motor per bogie!) • Requires specific measuring jigs

The analysis of time histories was then discussed and the minimum requirements were defined:

- calculation of time histories of A-weighted sound pressure level with time constant FAST (L_{pAF});
- where L_{pAF} will result reasonably constant, narrow band and constant percentage (1/3 octave and 1/12 octave) band properties will be derived;
- main / characteristic features of noise will be identified;
- identification, if possible, of warning / alert / alarm levels of wheels OOR.

At the end of the activity, raw data, results and all the procedures developed had to be delivered to the parties.

MEASURING CHAIN

Time schedule requirements and limitations to budget forced to use a low cost option while keeping as much as possible high the quality of the measurements. As no legal aspects had to be covered it was decided not to use certified noise measuring systems following classical IEC 651 standard but to use a non-certified measuring chain calibrated before and after the measurement with a reference sound source.

The measuring chain was therefore made of:

- a Bruel&Kjaer condenser microphone type 4189;
- an IEPE microphone preamplifier Bruel&Kjaer type 2671;
- input module National Instruments type NI USB-9233 (up to 4 inputs, 24 bit ADC, 50 kS/s per channel with simultaneous acquisition, IEPE power supply) with USB interface;
- National Instruments LabVIEW Signal Express ver. 2.5.0 acquisition software;
- Laptops with Windows XP Pro or Windows Vista operating system;

- microphone calibrator Larson Davis type CAL200/079A04.

The measuring chain is powered by the USB port of the laptop; thanks to this feature, it was possible to “hop on – hop off” the vehicles at the stops during normal passenger service.

Train speed was measured by using a Bushnell Radar Speed Gun placed shallow to the window with the minimum angle φ. The “cosine effect”, i.e. the fact the measured speed v_m and the actual speed v are linked by the equation $v=v_m/\cos(\varphi)$ was evaluated during test runs in the driver’s cab and found to be less than 3% (i.e. speed displayed by the Speed Gun was only slightly less than the real speed). No correction was therefore applied to displayed speeds. Some views of the instrumentations are shown in Figure 1.

Figure 1: Radar Speed Gun used for speed measurement (left); the authors on the platform waiting for the next metro (centre), during measurements in normal service (right).

ON-BOARD MEASUREMENTS

The line serviced by the vehicles has five stations (four sections) outside tunnels. Measurements were taken on almost all vehicles of the fleet (60 EMU units, for a total of 120 vehicles) in three days of measurements. At one of the stations the office for travelling personnel was used a recharging station for laptop batteries, ensuring an almost continuous measuring time from 9.00 to 23.00. Rush hours (6.30-9.00, 12.30-14.00, 17.00-19.00) were discarded as the high number of passengers could lead to an abnormally high sound attenuation inside the vehicle. Measurements were taken during winter, therefore keeping all the windows closed was not a problem.

The measurements proved to be exceptionally easy thanks to the active participation of passengers that remained particularly quiet during the test having noted the presence of technicians with microphones!

SIGNAL PROCESSING

<u>General considerations</u>

Although drivers reported a high level of low frequency noise, during the test a relatively high sampling frequency (f_s=25 kHz) was used. Although not sufficient to cover the whole audible spectrum, such a sampling frequency allows to identify a number of phenomena that would have been missed by using a lower one.

Attending all of the measurements allowed to take note of all the singularities possibly contaminating the measurements like:

- horn blow;
- braking noise;
- rail joints, switches & crossings and other track irregularities;
- all noise coming from passengers.

Sound Pressure Level and Spectral Distribution

After having identified and removed all “defective” sections, the signal was decimated with a factor 10 (resulting sampling frequency f_s=2500 Hz), reducing therefore the useful frequency range theoretically to 1250 Hz. In order to take into account the anti-aliasing filter applied to following analyses, all the results shown in the following will include the 1/12 octave spectra up to the centre frequency of 1000 Hz.

The post-processing analysis was applied to raw signals as follows (the figures are relative to the results of the analysis procedure applied to noise recorded on-board a vehicle whose driver’s cab was reported to be particularly noisy):

- the A-weighted sound pressure level (with FAST time constant) ref. 20 μPa of the decimated signal (Figure 2). The use of A-weighting allows to reach numerical results that are more related to the physiological sensation of noise perceived on board, while the selection of the 1/12 octave resolution, much finer than the usual 1/3 octave, allowed to avoid in the following analysis the inclusion of bands with high resonances that were believed not to be due to the phenomenon under investigations;

- in black in Figure 2, the 5 s time history where it is believed that the noise conditions are sufficiently stationary and suitable to accept the measurement (constant speed, no audible background noise). This selection was done by listening at both the raw and decimated signals;

- the 1/12 octave band RMS spectrum in dB ref. 20 μPa of the selected 5 s section (Figure 3).The use of the energy (Root Mean Square, RMS) indicator for the spectral properties of the signal allows to calculate the power of a given frequency range by simply summing up the energy of the considered bands, as will be shown hereinafter.

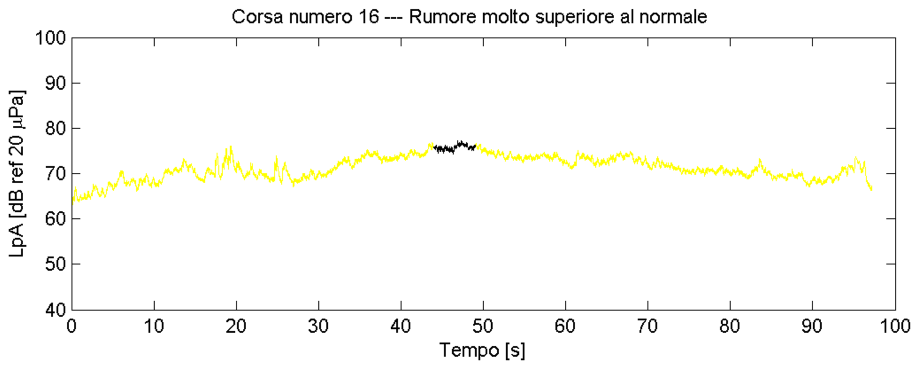

Figure 2: Sound pressure level in the 0-1250 Hz range (A-weighted, FAST time constant) vs. time with indication of a 5 s constant conditions slice Data are relative to a vehicle reported to be “much noisier than normal”.

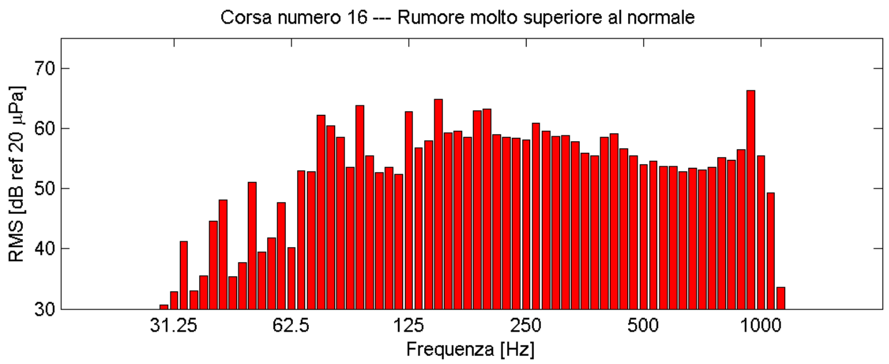

Figure 3: One-twelfth octave band RMS spectrum vs. frequency of the selected slice. Data are relative to a vehicle reported to be “much noisier than normal”..

Trains were classified depending on noise levels in four categories on the basis of the reports issued by drivers as:

- driver's cab *normal noise*;
- driver's cab *slightly noisier* than the normal, but still acceptable without great discomfort;
- driver's cab *noisier* than the normal, with a noticeable degree of discomfort;
- driver's cab *much noisier* than the normal, with a non acceptable degree of discomfort.

Obviously this classification has a meaning only for vehicles with driver's cab (i.e. the front end of Type A traction units). The average noise properties of these four categories can be seen in Figure 4, where their average spectrum is shown per each category.

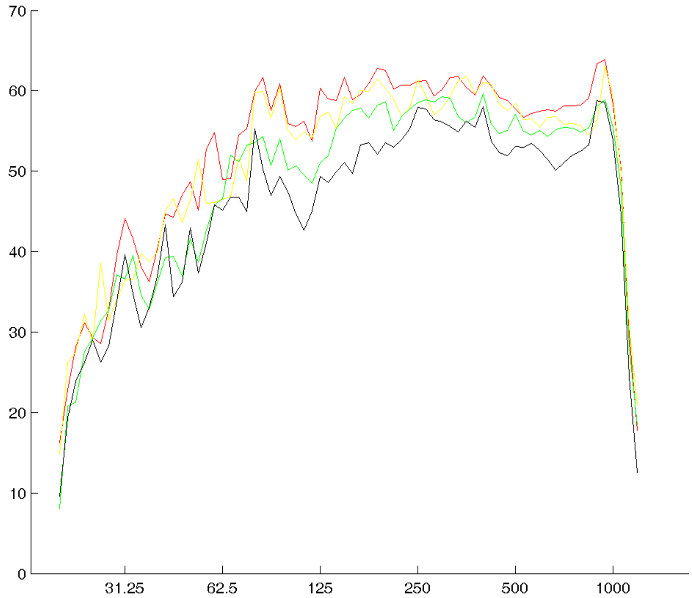

Figure 4: RMS average spectra [dB ref 20 µPa] divided for noise category: black=*normal noise*, green=*slightly noisier*, yellow=*noisier*, red=*much noisier*.

Definition of the indicator for the identification of OOR

The average spectra shown in Figure 4 exhibit a certain degree of regularity in the considered frequency range with some exceptions, typically below 80 Hz and above 250 Hz, where the curves seem not to follow the behaviour described by train drivers.

After a deep analysis it was chosen to select for the identification the total energy falling *only* between and including the 1/12 octave centre bands of 83 Hz and 198 Hz. Figure 5 shows the results of this procedure applied to the first batch of 32 measured vehicles; using this criterion the RMS value shows that the four categories correspond to the following levels:

- *Normal noise*: 59.9 dB (=0)
- *Slightly noisier:* 67.5 dB (=+7.6 dB)
- *Noisier*: 70.1 dB (=+10.2 dB)
- *Much noisier:* 71.6 dB (=+11.7 dB)

These values were evaluated as sufficiently distinguishing the four proposed categories and the indicator was accepted. The entire procedure (acquisition, filtering, energy calculation, etc.) was finalized and made available as a simple and user friendly tool that allowed the metro company to perform further measurements autonomously without the need of the assistance of the authors.

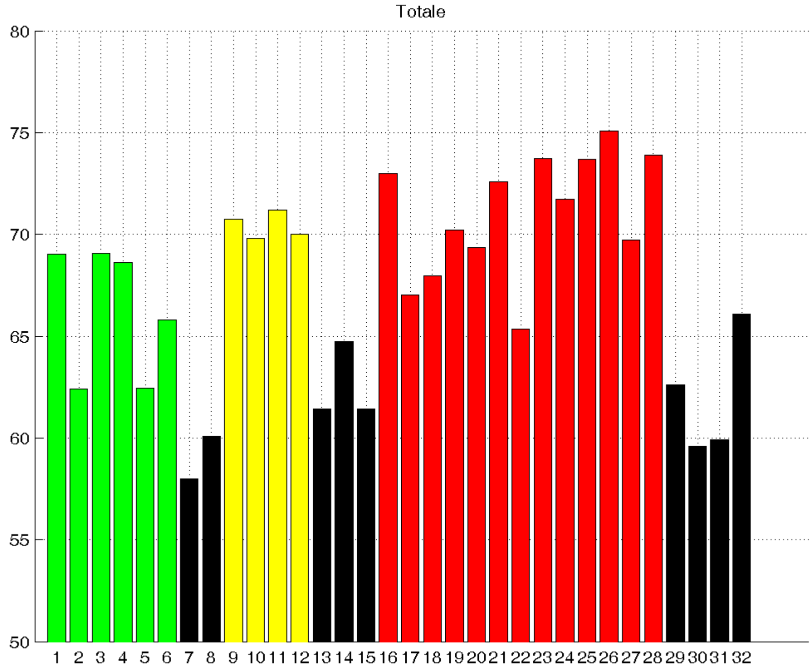

Figure 5: Total RMS values [dB ref 20 μPa] (in the 83÷198 Hz frequency range) for a sample of 32 vehicles divided by noise category: black=*normal noise*, green=*slightly noisier*, yellow=*noisier*, red=*much noisier*.

OOR MEASUREMENT AND CLASSIFICATION

After noise measurements, wheels belonging to vehicles that were recognized to be *much noisier* than the normal were measured with the vehicle resting on the underfloor lathe available in the maintenance workshop. The method used is the classical one comprising a 0.01 mm dial gauge mounted on a magnetic base. The measurement of the trend of OOR (wheel radius) is recorded taken notes on paper by the operator (Figure 6).

Figure 6: OOR measurement with 0.01 mm dial gauge.

From these measurements is came out that the defect is of stochastic type. From the paper by Nielsen, “this type of OOR may be caused by unbalances in the wheelset or by inhomogeneous material properties of the wheel… it can be concluded that the stochastic shape contains several different harmonics”. This explains why no defined frequencies were found in the spectra recorded on board.

OOR MEASUREMENT IMPROVEMENT

As information recorded with conventional measuring equipment are limited (one circumference, no data recording), the use of a tool developed by the authors consisting of a set of steel leaf springs equipped with strain gauges was suggested (Figure 7). By its shape, it was named “comb”.

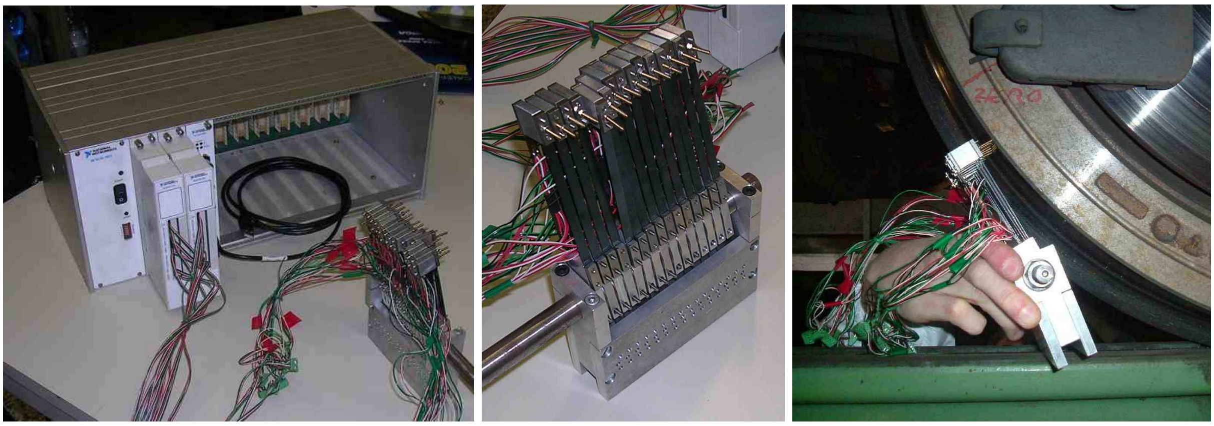

Figure 7:Measuring “comb” with SCXI chassis (top right), detail of the “comb” (bottom left) and a snapshot taken during jig preparation (bottom right).

Although the resolution of the equipment is lower than the classical dial gauge (0.05 mm instead of 0.01 mm), the potential of the instrument are evident. The typical output of this measuring tool is shown in Figure 8, Figure 9 and Figure 10.

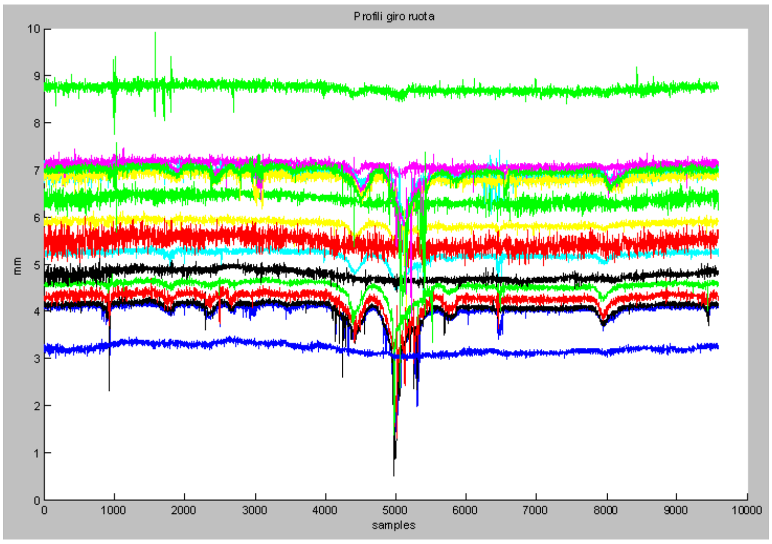

Figure 8: Output of the different blades of the “comb” measured during wheel rotation at constant angular speed.

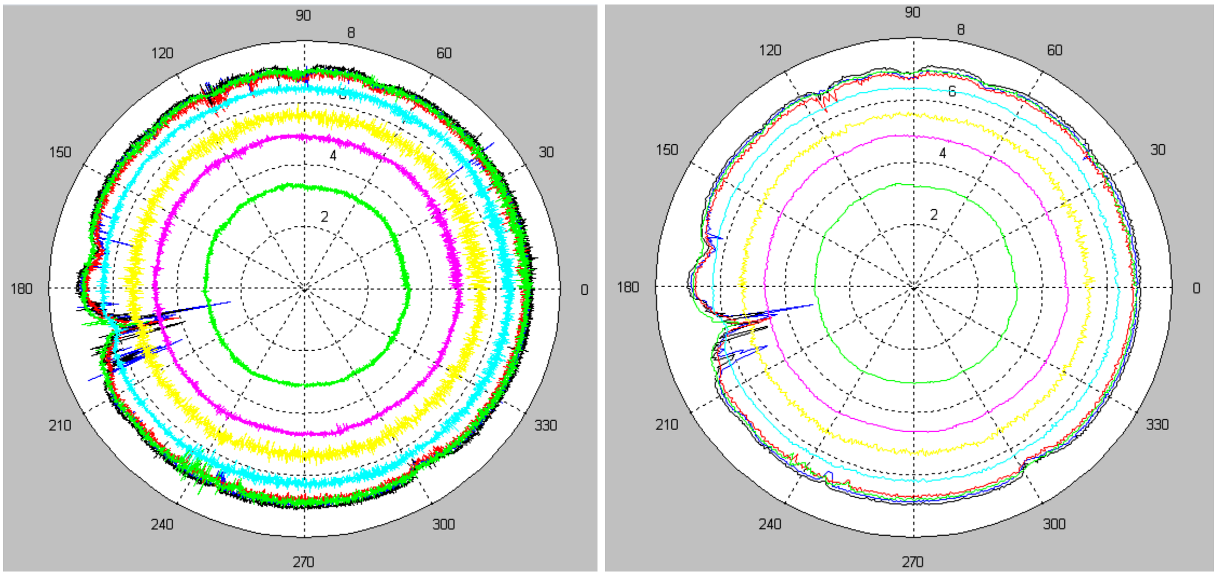

Figure 9: Representation in polar coordinates of the output of the different blades of the “comb”. Left: raw data, right: filtered data.

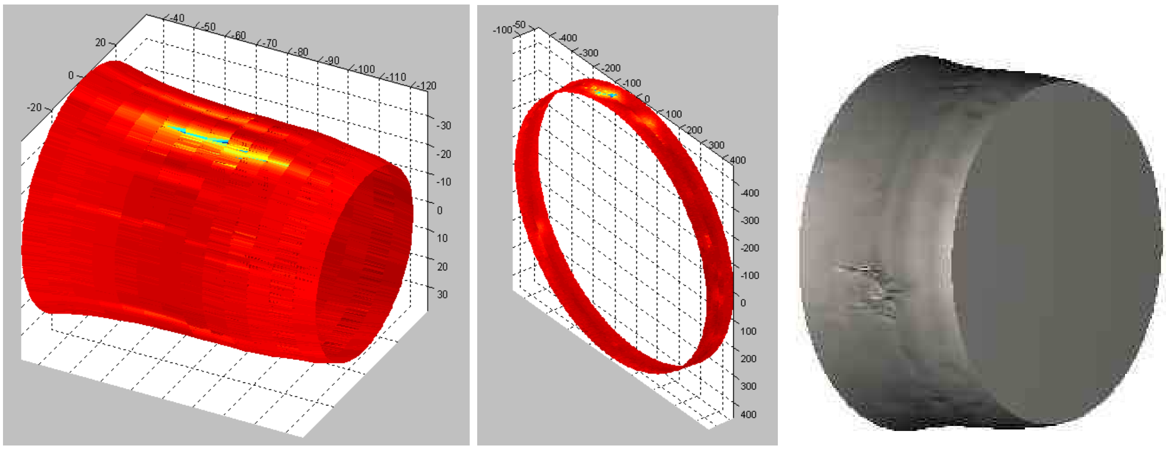

Figure 10: Three different graphical reconstruction of the measurements made with the “comb” on a wheel with a shelling defect on the tread.

CONCLUSIONS

In this paper a simple and effective procedure was defined and verified on the field, with the goal of identifying with a single-figure indicator the geometrical condition of the tread of a metro vehicle wheel. The definition of a simple measuring chain, of a robust procedure and of a fast processing techniques allowed the final user to have a reliable tool to assess in real time the status of any vehicle of the fleet. Identified out-of-roundness, of stochastic type, could be better defined by the use of a simple and powerful tool developed by the authors that will hopefully be used in the continuation of this work.

ACKNOWLEDGMENTS

Prof. Renzo Ciuffi input is gratefully acknowledged in the development of the measuring “comb”.

REFERENCES

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