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RAIL CORRUGATION GROWTH IN A METRO CURVE

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ABSTRACT

The metro network in Naples, Italy, is characterized by slopes up to 5.5% and tight curves with radius down to 208 m. Full traction vehicles are employed to reach the desired performances in terms of acceleration also on the steepest sections. The combination of high traction effort, line characteristics, vehicle suspension properties and operation conditions leads to extensive rail corrugation phenomena on the low rail in almost all the curves of the network. This corrugation is responsible for high noise levels, failures of vehicle components and, in some sections, of high groundborne noise and vibrations.
One of these curves was selected to investigate corrugation growth. This paper reports on a study based on extensive rail corrugation measurements held on a long, polycentric curve with a slope continuously varying from 0 to 5.2%. Special grinding techniques and the application of friction modifiers were evaluated to possibly increase maintenance intervals, also in view of tests on head hardened rails.

1 FOREWORD

The metro network in Naples, Italy, is managed by Metronapoli SpA, a public company owned by the Municipality and by the local public transportation company ANM (Azienda Napoletana Mobilità). Currently one 14 km-long double track line is in service, while other sections are under construction. The most important step will be the closing of the ring passing through the airport and the main railway station that will link the city centre and the north suburban area with the docks and the Municipality buildings.

The line currently in service was opened in different times starting in 1992. The line is underground for approximately 70% and it characterized by a remarkably high slope (up to 5.5%) which required the use of full-traction vehicles. Trains have normally six cars, which electrically are made of pairs of vehicles (traction units).

Track formation is quite variable along the line, with four different types of superstructure, all of them exhibiting corrugation problems. Some tunnel sections have direct rail fixation on concrete slab, while others have floating mass-spring systems and booted sleepers; open air track is ballasted with monobloc concrete sleepers. All tracks, both in tunnels and in open sections, suffer from corrugation, despite the fact that external line runs through particularly humid and wooded area where the expected average friction coefficient is much lower than in tunnels.

This paper reports on the activities performed on a single track section in a tunnel, i.e. the curve approximately 1.1 km long between the stations of Cilea/Quattro Giornate and Vanvitelli, where the trains climb up on a slope up to 5.2%.

The scope of the work is to investigate rail corrugation growth in order to better plan track maintenance, to reduce passengers annoyance and to reduce groundborne vibrations problems (in other line sections). Curative rail grinding is used since line opening mainly to reduce noise, as vehicles have no air conditioning systems and the high temperatures typical of South Italy force to keep windows open. Noise levels in the passenger area often pass 100 dB(A), which makes travel particularly uncomfortable.

As corrugation recurrence is particularly fast (in some cases it was believed that 2 months are sufficient to restore the situation before grinding), the investigation on the selected curve may give an insight on the development in time of the phenomenon.

The potential advantages of *offset grinding*, a high productivity grinding finishing technique, were also investigated. Although it is unable to reshape the rail transverse profile, final quality of the railhead surface seems particularly good and possibly able to retard the reappearance of corrugation.

Metronapoli is currently evaluating the use of friction modifiers (FM) in order to reduce the corrugation growth rate. It was desired to define a good practice protocol for the installation of FM dispensers, for example defining the minimum curve radius for the application of these units, by comparing historical records and data from the present work.

The use of head hardened rails is another acknowledged remedy to reduce to a minimum rail corrugation growth. Premium rails are going to be laid down in the next months and another goal of this work was to define the best section where a trial site could be located.

2 TRACK FORMATION AND GEOMETRY

The considered track section is uniform along its length. It is made of UIC60 rails (steel grade 900A) with inclination 1:20, continuously welded, mounted via Nabla fastenings on booted sleeper inserted in 3 m-long pre-stressed concrete blocks. Track gauge is 1435 mm, without any gauge widening also in tighter curve.

The mass-spring floating slab track formation proved to be effective to eliminate in practice all vibration transmission problems. Other sections with direct rail fixation to the slab are instead strongly affected by this problem.

Track geometry is quite complex as it was designed under the assumption that an Automatic Train Operation (ATO) service would be employed. Radius and cant vary along the track, which contains an initial short tangent section, constant curvature and variable curvature (clothoid transitions) sections. In practice the service is operated with an Automatic Train Protection safety system, both Continuous and Discontinuous, leading to variable and rather unpredictable discrepancy with planned speed that often results in non-zero cant deficiency. Nominal train acceleration and deceleration is 1.0 m/s^2.

For handling reasons, during the construction it was possible to use only 18-m long rails welded either with flash butt or aluminothermic processes. Welds are extremely helpful to identify as precisely as possible local geometry features of the track. In the selected section 62 welds were found, giving the possibility to define a corresponding limited number of rails where track and traffic characteristics can be reasonably considered constant and where is it possible to evaluate local corrugation growth.

A reference system was set up, positive in the train direction, with its origin at the end of the curve which is coincident with the beginning of the Vanvitelli station platform,. Kilometric Progressives (PK) resulted therefore negative.

Figure 1 shows the track during corrugation measurements and a close-up of the rail. Figure 2 shows a sketch of the curve, where some specific locations that will be referenced to throughout the paper are indicated (see also Table 1). Table 2 shows the position of part of the low rail welds, the PK of rail centre and the (average) track geometric properties for each rail.

Figure 1. Metronapoli Cilea-Vanvitelli track (left) and an example of heavily corrugated low rail (right).

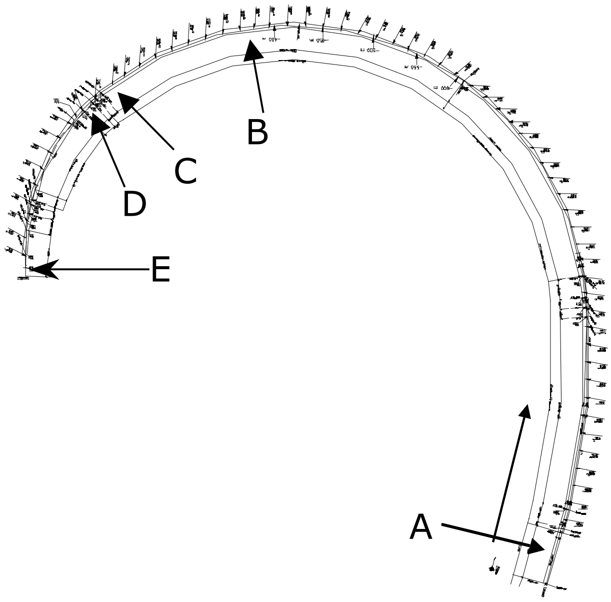

Figure 2. Plan of the Cilea-Vanvitelli line (“odd” track, trains running from A to E)

Table 1. Reference points in selected track section

Pt.	Description	Relative PK [m]	Rail #
A	Mounting location of FM dispenser between 21.9.2004 and 4.7.2005	-1093.029	62
B	Offset grinding start	-363.672	21
C	Offset grinding end	-208.672	12
D	Mounting location of FM dispenser after 29.8.2005	-169.688	10
E	Beginning of the Vanvitelli station platform	0.000	1

Table 2. Geometric properties for each rail (excerpt) with examples of constant radius curve, vertical and horizontal transitions.

Weld and Rail #	Rail lenght measured with tape	PK rail centre	Curve radius [m]	Slope [‰]	Cant [mm]
63					
62	18.01		625.000	2.000	0.000
61	17.990	-1077.535	625.000	2.000	0.772
60	17.99	-1059.545	625.000	2.000	2.585
59	17.840	-1041.630	625.000	2.000	4.391
58	17.990	-1023.715	625.000	2.000	6.196
57	18.010	-1005.715	625.000	2.000	8.011
56	18.000	-987.710	625.000	2.000	9.825
55	17.990	-969.715	625.000	2.000	11.639
54	18.000	-951.720	625.000	2.000	13.452
53	17.860	-933.790	625.000	2.000	15.259
52	17.990	-915.865	625.000	2.000	17.066
51	18.000	-897.870	625.000	2.000	18.879
50	18.010	-879.865	625.000	2.000	20.000
49	18.000	-861.860	552.924	2.000	20.000
48	18.020	-843.850	300.000	2.227	20.000
47	17.990	-825.845	300.000	5.981	23.185
46	15.730	-808.985	300.000	9.496	25.997
45	17.980	-792.130	300.000	13.011	28.808
44	18.010	-774.135	300.000	16.763	31.810
43	18.020	-756.120	300.000	20.519	34.815
42	18.010	-738.105	300.000	24.275	37.820
41	17.990	-720.105	300.000	28.028	40.822
40	18.000	-702.110	300.000	31.780	43.824
39	18.010	-684.105	300.000	35.534	46.827
38	15.690	-667.255	300.000	39.047	49.637
37	17.980	-650.420	300.000	42.557	52.446
36	18.020	-632.420	300.000	46.310	55.448
35	18.000	-614.410	300.000	50.065	58.452
34	18.000	-596.410	300.000	52.000	60.000
33	17.980	-578.420	300.000	52.000	60.000
32	17.980	-560.440	300.000	52.000	60.000
31	18.000	-542.450	300.000	52.000	60.000
30	15.870	-525.515	300.000	52.000	60.000

3 CORRUGATION INDICATORS AND MEASUREMENT METHODOLOGY

3.1 Measuring equipment description

In 2004 Metronapoli bought a trolley (CAT - *Corrugation Analysis Trolley*, supplied by Dr. Stuart Grassie) that the user pushes along the track. It consists of a suspended servo accelerometer which contacts the rail via a hard steel ball. Data acquisition is made with an A/D card connected to a PC via USB interface. Asynchronous sampling is driven by an odometer made of a small wheel with a rubber O-ring mounted on the shaft of an optical encoder that rolls longitudinally along the railhead. The user can select the sampling distance, which was fixed at 1 mm for this work. A detailed description of the equipment can be found in [1], although the latest version is improved in many practical aspects.

A two stage integration, the first analog in the trolley hardware and the second digital within the software after the A/D conversion, provides directly the displacement signal vs. distance. This signal can be filtered in all the wavelength ranges described in [2] with the trolley software, namely in the range 10-30 mm, 30-100 mm, 100-300 mm, 300-1000 mm, plus 1000-3000 mm, 30-300 mm and 300-3000 m.

3.2 Wavelength range for corrugation analysis

It was observed that the corrugation phenomenon is quite "erratic", changing the position and the wavelength of the corrugation pitch. It was evident since the beginning that the use of the wavelength range described in the previous paragraph would have led to a significant loss of information in certain wavelength ranges. It should not be forgotten, however, that the scope of [2] is the acceptance of grinding works and *not* the definition of corrugation limits in service or the analysis of corrugation growth.

An alternative is offered by the recently published International Standards on railway noise [3, 4], where a wavelength range of 10-80 mm is specified. These standards are relative to the measurement of noise emitted by train, which is exactly the field of interest here.

Several filters were tested to identify the best wavelength range to be considered, namely 10-30 mm, 30-100 mm, 10-100 mm and 10-80 mm. Instead of defining a new wavelength range, it was preferred to use one already present in the standards.

Digital IIR filters implemented in the trolley software are extremely fast but inevitably introduce phase distortion. As the trolley software does not give the possibility to define arbitrary filters, all the raw acquired data were exported in text format and filtered in the 10-80 mm one-third octave wavelength bands according to [3, 4]. To preserve local features of the measured signals, it was preferred to perform a slower *perfect filtering* [5] with zero phase distortion between the stop bands (8.91-89.8 mm) of the selected wavelength range.

3.3 Choice of an indicator of corrugation level

The long length of the selected track required the definition of a concise parameter to define the corrugation level of a certain section. Some preliminary trials were conducted by dividing the track in uniform length sections (10, 50 and 100 m), but it was soon realized that the results would have been of low usefulness for the purpose of this work.

Several attempts were done, including exceedence and kurtosis analyses, but at the end it was decided to use the following indicators:

- a so called "block RMS" analysis, a feature already present in the trolley software, where the entire measurement is considered for 1 m-long blocks (1000 samples) and the RMS value is calculated, resulting in approximately 1100 values. The block RMS plot gives an immediate pictorial feeling of the corrugation level of the whole track, regardless from the single rail length and/or track characteristics;
- an RMS calculation for each rail as previously identified, resulting in 62 values. It is supposed that a single parameter for each rail may be sufficient to give an estimation of its corrugation level;
- for each rail, a one-third octave band wavelength spectrum, obtained from raw (unfiltered) data. These spectra can be used to identify, where present, their maximum (dominant corrugation wavelength) and to relate it to specific track and traffic characteristics.

Energy analysis of filtered data is shown in par. 6.3 while spectral analysis of raw data is shown in par. 6.4.

3.4 Rail identification problems

The comparison of measurements made during a long time period may be critical if distances are not *exactly* the same.

Distances estimated by the trolley with the method described in 3.1 can be affected by small errors due to temperature changes, high corrugation levels and so on. To compensate for this (accumulating) error, an offset table was defined by means of a specific measurement run with adhesive tape stripes stuck across the railhead in correspondence of welds. As welds are clearly visible in all measurements, with or without tapes, the offset table proved to be effective in relating *all* corrugation measurements *exactly* to the same rail sections.

This error has little effect on the wavelengths as it was always below 1%. This discrepancy (10 m/km) is relevant in this work but it is absolutely negligible during the normal use of the instrument, i.e. the daily check of railhead corrugation level.

4 AVAILABLE PRELIMINARY DATA

It is evident that any research on corrugation should start with rails freshly ground. Nevertheless, the existing track was in initially partly known conditions and this justified a limited analysis of it.

Metronapoli records say that the track was ground during the night 28-29.05.2004. In the rest of the paper this operation will be called *previous grinding*.

After 115 days, on 21.9.2004, a dispenser *PIV* supplied by Kelsan using the water-based *KELTRACK*® friction modifier was installed in position A (see Figure 2), although it is reported that it worked discontinuously and that it stopped working approximately in December 2004.

Only a couple of measurements were taken as soon as the trolley was available (12.01.2005, 228 days after previous grinding) and on 5.7.2005 (402 days after previous grinding). This limited activity is due to the extensive use of the trolley in all the rest of the network and by the fact that low rail conditions were really desperate. Transverse profile was absolutely incorrect (almost flat) and large rolling contact fatigue damages were present on the rail gauge face, including extensive gauge corner cracking, head checks and spalling phenomena. A grinding is not deferrable and was scheduled for August 2005.

A large increase in rail corrugation was anyway observed in the entire curve through a rough analysis (Figure 3). The central portion of the section showed large increase in corrugation levels, especially in the –0.400 m to –0.200 m part of the curve, where some sections passed from a block RMS value of 2 μm to a value of 11 μm.

The last 150 m of the curve almost doubled the level of corrugation in most of the 10 m-long sections considered and exhibited the highest levels of corrugation.

These results were not considered conclusive as two points are certainly not sufficient to identify a trend. It can only be said that corrugation increased from 7 months to 13 months after previous grinding, and that this was somewhat unexpected given the already very high levels recorded during the first measurements.

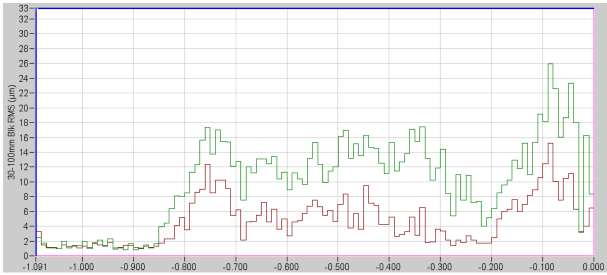

Figure 3. *Block RMS* of data filtered in the 30-100 mm wavelength range for 10 m-long non-overlapping sections measured 402 days (upper) and 228 days (lower) after previous grinding.

5 GRINDING OPERATIONS

5.1 Conventional grinding

Grinding operations were performed on the selected track section during the night shifts of 23-24 and 24-25 August 2005 (referred to in the following as *last grinding*).

During the first shift a conventional grinding (tangential grinding stones) was performed along the entire curve, with two goals:

- to restore a very good transverse profile, at the same trying to minimize future gauge corner damages;
- to remove the almost 250 μm peak-to-peak corrugation, especially in the last section of the curve.

Grinding works acceptance tightly followed the methodology described in [2]. A quite demanding Technical Specification was written to restore the original transverse profile within Class Q, group C, while longitudinal profile was corrected to Class 1 (moving average RMS criterion).

It is worth to note that the high slope of almost all the line and the relatively high distance from the depot were significant constraints to grinding productivity.

5.2 Offset grinding

A short section of the constant curvature track (points B to C, approximately 150 m long, R=300 m, rails 21 to

12) where train speed is constant was ground during the second shift with a technique called *offset grinding* [6] to evaluate the potential advantage of this technique in order to reduce rail corrugation growth.

This type of grinding is unable to restore the transverse profile and can be therefore used only where it is already satisfactory. Conventional grinding (reprofiling) has a productivity the largely depends on the number of passes required by the actual worn shape of the transverse railhead profile; it is typically in the order of 200-250 m/h of finished track. Offset grinding has a noticeably higher productivity (approximately 1000 m/h of finished track) and an extra grinding pass can be justified in special cases with limited extra costs.

Offset grinding does not leave grinding stones mark in the typical corrugation wavelength range. Residual roughness should therefore not activate the corrugation process prematurely.

It is worth to mention that although the visual appearance of the finished surface is particularly smooth, some small metal chips can be felt by scraping a fingertip on the railhead. This feeling is confirmed by trolley measurements, thanks to its extremely high sensitivity that allows to measure even the tiniest rail irregularities. These irregularities disappear just after one day of traffic on the narrow, bright strip (*running band*) left by trains pass-by (Figure 4); it is therefore recommended to perform longitudinal profile measurements *after some traffic*, in contrast with [2] where it is stated that “it is preferable for measurements to be made immediately after reprofiling”. It is not possible here to give indications on the time needed to remove these small irregularities, possibly depending it from tonnage and local creep conditions.

The centre of the running band was corresponding to the 43 mm lateral position of the trolley probe, and this was selected as the standard position for the all the remaining measurements considered in this paper. No similar running band was found on the high rail.

The exceedence and spectral analyses performed on 5 m-long sections on conventional and offset ground rails are shown in Figure 5. Both sections have the same distribution of samples in terms of amplitude (note that more than 95% of the samples are within ±2 µm). The one-third octave spectra show that while conventional grinding has a peak at around 20 mm, the energy of the offset ground rail is well below the limits in the 1-8 cm range required by the standards on noise [3, 4], concentrating most of the energy in the 8.0 mm and 6.3 mm bands. It should be noted that this range is believed to be less important for noise generation as these wavelengths are filtered out by the contact patch area. In any case both the grinding works would have been accepted for noise type tests, as some minor exceedences of the limit curve are allowed.

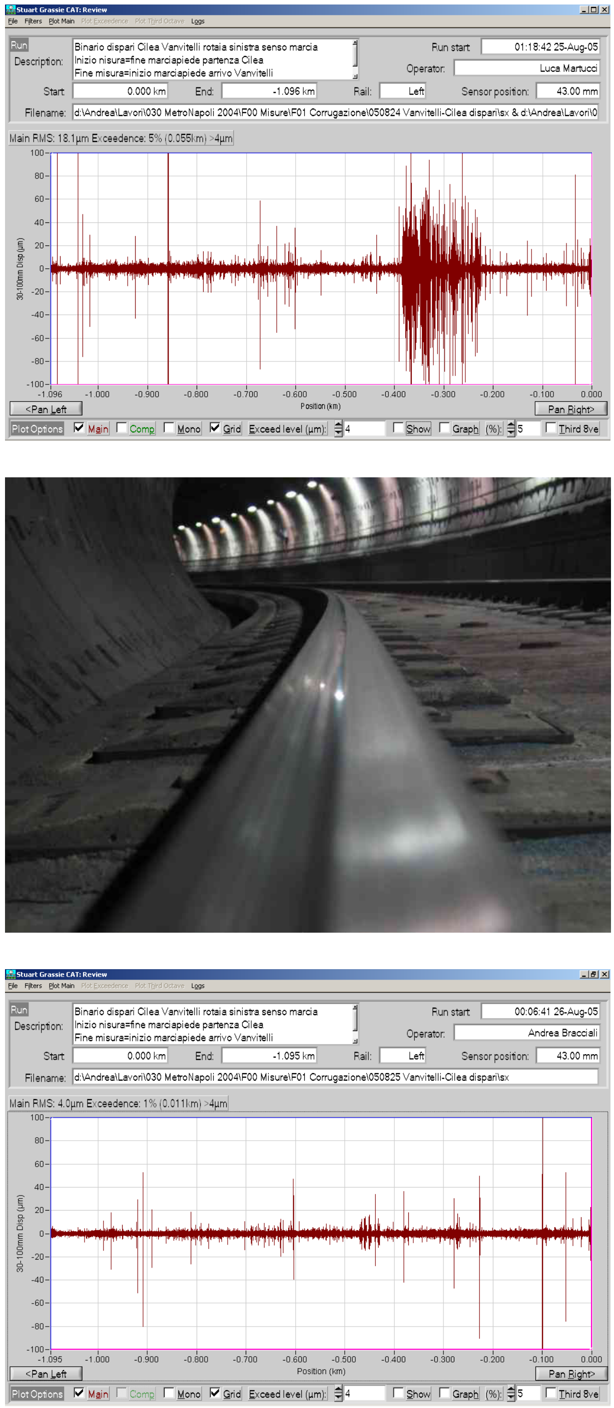

Figure 4. Corrugation in the 30-100 mm wavelength range immediately after last grinding (top). Running band appearance after one day (mid) and relative corrugation (bottom).

5.3 Friction modifier dispenser location

Instead of simply leaving the FM dispenser not operating in its original position (A) in order to evaluate the roughness growth without FM, it was reactivated and moved to position (D) to evaluate its effect on the smallest radius section and to test installations in canted track.

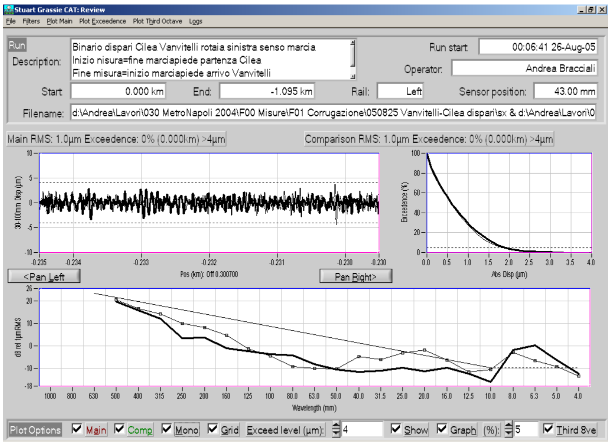

Figure 5. Comparison of low rail residual roughness of 5 m-long sections after conventional (thin line) and offset (solid line) grinding.

Although the manufacturer recommends to use the wiping bars in tangent track being the FM a liquid with very low viscosity, it can be sometimes a problem to find out a location quite close to the point to be protected were that condition is verified. In this case point (D) is approximately 925 m far from the last tangent track and the efficacy of FM had to be investigated for such a long distance. With some minor adjustments and with the help of the manufacturer, the installation was successful also in presence of a 80 mm cant.

6 CORRUGATION GROWTH ANALYSIS

6.1 Measurements planning

A tight measurement programme was set up to observe at the best the evolution of the low rail corrugation in time.

Measurements started immediately after grinding and time intervals were particularly short at the beginning, trying to identify if and when corrugation has a "trigger" time. The presence of the FM dispenser in rail number 10 forced to "skip" it due to the wiping bars that can not be traversed with the trolley. Results from this rail are strongly affected and are not included in the following analyses. A simple procedure allowed to take care of the missing distance.

The schedule shown in During the entire measurement campaign traffic conditions were regular. It must be noted that a problem to one of the treadles of the FM dispenser led to a stop in the operation of the unit somewhere between the last two measurements.

Table 3 is based on increasing time intervals. Some measurements were made on only part of the curve for other reasons, but that conclusions reached are not affected by this limitation. An additional measurement performed on day 70 after last grinding (02.11.2005) is not included as adhesive tape was used to identify welds.

During the entire measurement campaign traffic conditions were regular. It must be noted that a problem to one of the treadles of the FM dispenser led to a stop in the operation of the unit somewhere between the last two measurements.

Table 3. Corrugation measurement programme. Meas #1 (at –224 days) and meas #2 (at –50 days from last grinding) are not listed (see par. 4). Meas #12 is affected by adhesive tape stripes on welds.

Day	Days After last grinding	Days from previous meas.	Note
23/08/2005			First shift
24/08/2005	0		Second shift Meas #3
25/08/2005	1	1	Meas # 4
29/08/2005	5	4	Meas # 5
01/09/2005	8	3	Meas # 6
05/09/2005	12	4	Meas # 7
19/09/2005	26	14	Meas # 8
26/09/2005	33	7	Meas # 9
10/10/2005	47	14	Meas # 10
27/10/2005	64	17	Meas #11
02/11/2005	*70*	---	*Meas # 12*
16/11/2005	84	20	Meas # 13
15/12/2005	113	29	Meas # 14
23/01/2006	152	39	Meas # 15

6.2 Corrugation data filtering and synchronization

As already mentioned, data were filtered in the 10-80 mm wavelength range and were synchronized by using an offset table that took into account the trolley odometer small deviations.

The typical result from this process is a set of figures, one per each rail, showing the trend of corrugation behaviour in time. In order to prevent the influence of weld peaks at the end of measurement, two different approaches were followed:

- only the central part of the rail was selected, originating a "complete" and a "reduced" rail signal (named RxxC and RxxR, where xx is the rail under analysis);
- a 1 m-long Tukey window applied to the "tails" of the signal was introduced in the perfect filtering process.

As the second approach proved to be more effective and conservative of local features, only data relative to "complete" rails are shown here.

As an example, the evolution of corrugation on two rails is shown in Figure 6 and in Figure 7, where it is possible also to compare corrugation levels with those *before* last grinding (at –50 and –224 days). Record at 70 days after last grinding (meas #2, affected by adhesive tape) is the reference for rail lengths.

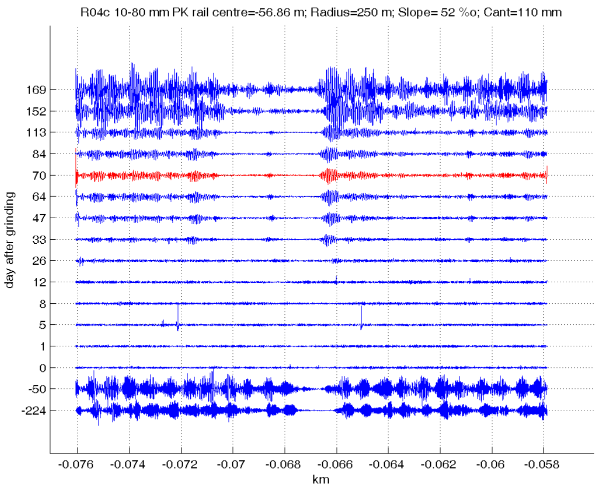

Figure 6. Evolution of corrugation for rail 4. Note the sudden increase of corrugation levels after day 113.

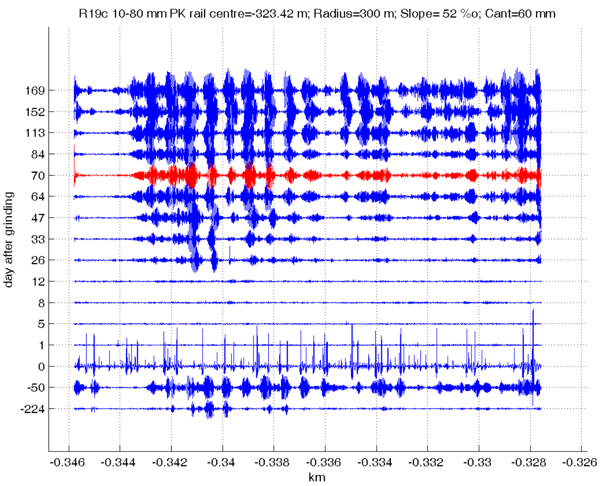

Figure 7. Evolution of corrugation for rail 19. Note the spikes after offset grinding (day 0).

6.3 RMS rail corrugation values

A pictorial view is certainly not sufficient to evaluate the trend of low rail corrugation growth. RMS was calculated for each "complete" rail, resulting in a matrix where the RMS value is a function of the considered rail and the measurement date. Meas #3 (day 0), affected by spikes in the offset ground section, and meas #12 (day 70), affected by spikes due to tape, are not included in this analysis (Figure 8). Numerical information can be found in 2-D plots (Figure 9 and Figure 10). A comparison with the data collected after *previous* and after *last* grinding works is shown in Figure 11.

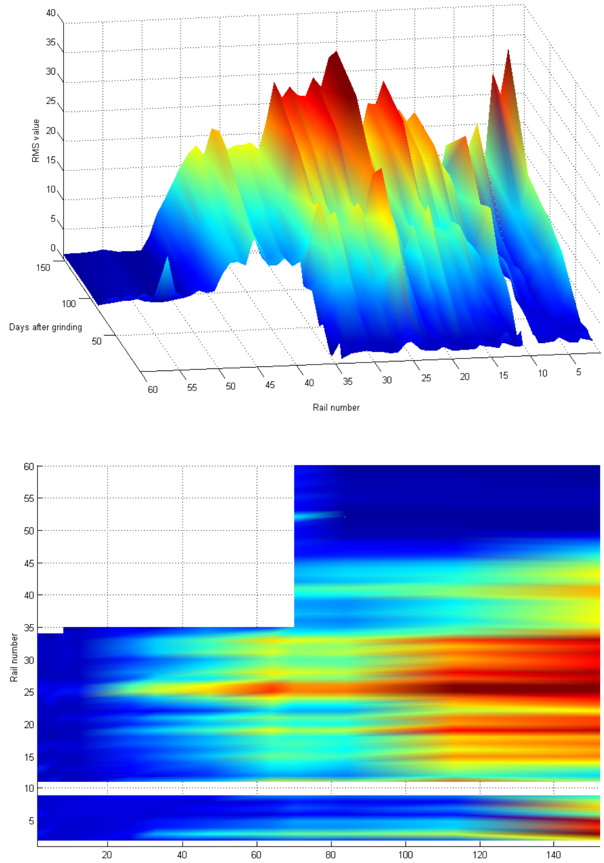

Figure 8. RMS value for all rails and all measurements. White areas are relative to short measurements and to rail number 10 (see text).

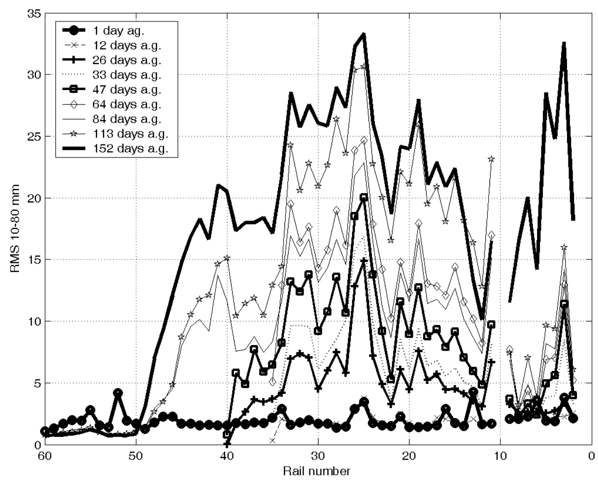

Figure 9. Corrugation RMS value for each rail after *last* grinding.

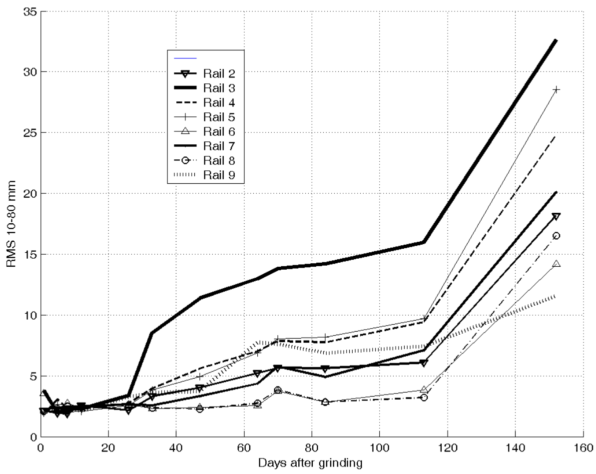

Figure 10. Corrugation RMS value for rails 2-9 (after FM dispenser).

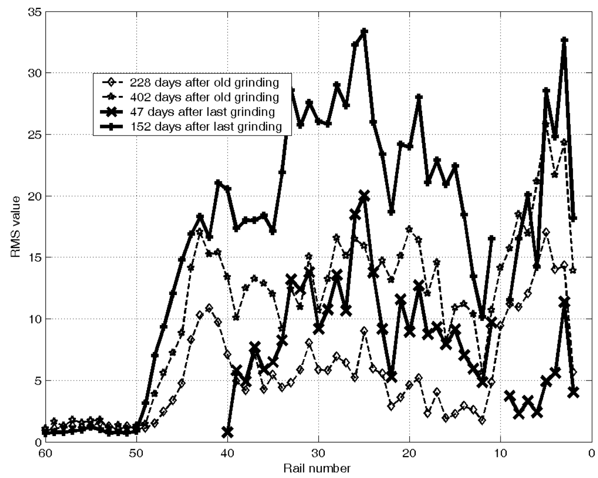

Figure 11. Comparison between rail corrugation after *previous* (or *old*) grinding and selected measurements after *last* grinding.

The following conclusions can be drawn after *last* grinding:

- levels remain low until 12 days after last grinding. Levels abruptly start to grow up after 26 days and don't seem to reduce the growth rate until 152 days;
- rails 62-50 (R=625 m, slope=0.2 %, cant= from 0 to 20 mm) don't exhibit any corrugation after 5 months. Trains reach the maximum speed of 60 km/h approximately after 120 m (rail 57) and travel therefore at constant speed;
- corrugation of rails 49-45 (transition from R=625 m to R=300 m, slope= 0.2 % to 1.3 %, cant=20 mm to 28 mm) increases with distance and with time, ending with values that are comparable with the rest of the curve;
- constant radius rails 44-22 (R=300 m, slope=1.6 % to 5.2 %, cant=31 mm to 80 mm) have the maximum corrugation around rail 25;
- rails 21-12 (R=300 m, slope=5.2 %, cant=60 mm), offset ground, have levels similar to the rest of the curve, except for rails 12 and 13 where trains start to slow down approaching the smallest radius curve;
- rail 11 (R=300 m, slope=5.2 %, cant=60 mm), conventionally ground, has corrugation values greater than the apparently identical previous rail 12;
- rails 9 to 2 after FM dispenser (R=300 m to 204 m to 462 m, slope=5.2 % to 3.5 %, cant=80 mm to 110 mm to 74 mm) have much lower value until the dispenser worked. After it halted for a treadle failure, corrugation started to grow up fast and reached values similar to the rest of the curve.

Comparing measurements after *previous* grinding and after *last* grinding the following can be concluded:

- corrugation after 228 days after the previous grinding is lower than that observed only 47 days after the last grinding, for all rails before the new FM dispenser location;
- after last grinding, rails after FM dispenser were protected and showed very limited corrugation until day 113; the malfunctioning of the treadle caused the sudden increase on corrugation that reached and passed the values measured at day 402 after previous grinding. This incidentally shows that the previous FM dispenser location (A) was very far but nevertheless useful to protect also the final portion of the curve;
- the long 300 m-radius curve is affected by heavy corrugation for all its length. Corrugation levels reached 152 days after last grinding without the application of FM are approximately twice as the values reached after 402 days from previous grinding, when, although not monitored, the FM dispenser was at least partly operating.

6.4 One-third octave band rail corrugation spectra

It was observed that corrugation is erratic, as somewhere it is bigger *between* the sleepers and somewhere else it is bigger *on* the sleepers. It is therefore almost impossible to find a continuous and repetitive wave wear pattern. Roughly speaking, a one-third octave band spectrum can be calculated for each rail although it was observed that corrugation pitch may vary several times within, for example, 1 m of rail.

Wavelength spectral distribution of the corrugation for each rail can be observed in 3-D and colour plots for the last measurement in Figure 12.

The 40 mm-wavelength centre band is clearly dominant from rail 48 to rail 14; rails 13 to 11 have a peak at 31.5 mm. The rails after the FM dispenser show a maximum at 63-80 mm. It is not possible to formulate hypotheses on the mechanism that leads to different corrugation wavelengths, also because the FM dispenser worked for some time before stopping and this possibly initiated the corrugation differently.

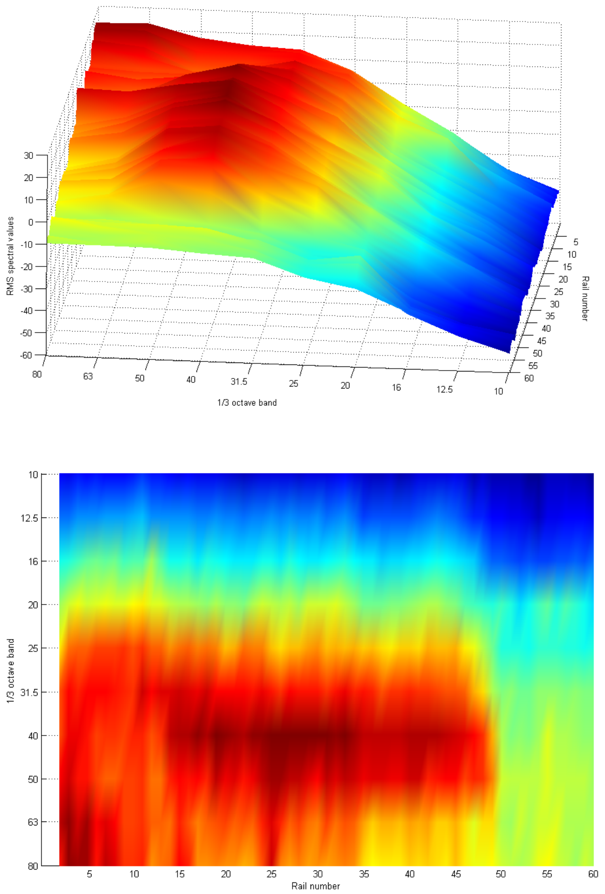

Figure 12. One-third octave wavelength band spectra for all rails (data from last measurement, 23 Jan 2006).

6 CONCLUSIONS AND DEVELOPMENTS

Corrugation growth on the low rail in a complex curve with high gradient and cant was analysed investigating the influence of track parameters, the use of friction modifiers and offset grinding.

About track parameters, corrugation seems driven by curve radius, as no corrugation is evident in tangent track. Corrugation always appears for R≤300 m. This condition inevitably triggers corrugation formation.

As traffic parameters (traction, braking, speed) are not constant for all trains (ATO not active) no firm conclusion can be drawn from measured data. Anyway, the behaviour of some rails (11, 22) with inexplicably lower corrugation can possibly be related to mentioned parameters. This would require further investigation.

Corrugation reappears with very high levels already after one month (rails 24 and 25). Grinding costs can be extremely high if no countermeasures are taken.

Spectral analysis showed a peak in the 40 mm wavelength for rails from the beginning to the tight curve to the section where friction modifier dispenser is installed. After it the peak shifts to 80 mm, which incidentally is the upper limit of the analysis conducted here. This may be due to a different initiation of corrugation during the period of efficiency of that equipment. The possible presence of longer wavelengths would require further investigations.

The use of friction modifiers seems unavoidable for this combination of rolling stock and track layout. It appears evident that when friction dispensers work correctly the corrugation remains under control for a much longer time than without them.

Undesired problems helped to highlight that even a short absence of friction modifier is sufficient to produce very high corrugation levels which are hardly removed without grinding. Maintenance practice should therefore focus on tank refilling. Remote check of the functionality of the friction modifier dispenser could prove extremely useful.

The efficacy of friction modifier is evident also for distances up to 1 km. This can reduce the number of units (cost) and can help to find out a tangent track or a track with limited cant for installation.

There is no final evidence of the advantage of using offset grinding to slow down corrugation growth. Traffic and track parameters seem by far much more important.

Head hardened rails can be placed in almost all the locations after rail 48. Corrugation growth without friction modifier is so fast that 4 to 6 months should be more than sufficient to evidence their behaviour, shortening trials. To limit installation costs and complications, care should be taken to avoid the installation on rails where track circuits equipment is installed.

After the results from this study, line was ground again in April 2006 and the FM dispenser was reinstalled on rail 50 to protect all the curve. Data collection is in progress.

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