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Severity and growth evaluation of rail corrugations on sharp curves using wheel/rail interaction

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Abstract

A railway network generally spans over a large distance so the structural health monitoring of such a rail infrastructure system is one of the critical challenges in rail industry practice. Especially in an underground/subway or elevated system, the facilities, resources and time period permitted for critical infrastructure inspection and maintenance is considerably limited. As a result, the automated inspection system of railway is in very high demand. Rail corrugation defect is the periodic, undulated or wave-like vertical alignment of rail surface. The wavelength and severity of rail corrugations is dependant to track structure, track geometry, traction system, rail vehicle behaviours, and wheel-rail interaction. The rail corrugations are the source of rapid track degradation, poor ride comfort, and nuisance noise. Often such rail irregularities are observed on the low rail of small-radius or very sharp curves. This paper presents the utilization of an inspection train vehicle to evaluate and monitor rail corrugation growth on sharp curved tracks. As a case study, a set of rail surface data of a very sharp curve was chosen for demonstration. This study shows the severity and growth evaluation of rail corrugation by integrating numerical train/track simulations, axle box acceleration data obtained from the calibrated track inspection vehicle "AK Car", and spectral data analytics.

Keywords: railway, inspection train, axle box acceleration, growth monitoring, rail corrugation

1. Introduction

Social and economic growth of a city, region or country is inevitably underpinned by rail mass transit. Stimulating sustainable productivity, an urban rail infrastructure is often built either underground or on the surface surrounded by agglomerate buildings and public communities. Its network generally spans over a large distance. Ongoing operation and maintenance of rail infrastructure systems are critical to public safety in addition to managing business risks and reliability. With a dramatic demand from the public to run faster and more frequent train services, structural health monitoring of such rail infrastructure system is one of the challenges in practice. Especially in underground train or subway systems, the tunnel facilities, resources and time windows permitted for railway staff to carry out the critical infrastructure inspection and maintenance is extremely limited. Any tiny period of train-free duration in a late night discourages on-track activities by the railway staff. As a result, the utilisation and application of an inspection train vehicle has been more demanding than ever [1-3].

Rail corrugations are an irregularity on rail running surface, inducing large dynamic loads and vibrations onto adjacent railway track components as well as rolling stocks. Such a defect is a periodic, undulated or wave-like vertical alignment of the rail surface. The rail corrugations are typically caused by uneven wears due to the variations of wheel-rail contact stresses. The wavelength and severity of corrugations is dependant to track structure, track geometry, traction system, rail vehicle behaviours, and wheel-rail interaction. The corrugations are the source of rapid track degradation, poor ride comfort, and noticeably nuisance noise. Often such irregularities are observed on the low rail of small-radius curves. A large number of research studies have been devoted into the fundamental causes and mitigation techniques [4-7]. Effect of rail corrugation wavelengths on noise generations has been the main focus. It is noted that $v = f\lambda$ (v is the train speed, f is the frequency, and λ is the wavelength). '*Contact patch filter*' was found to be a mechanism that attenuates very high frequency effect above 2,000 Hz. Table 1 shows the frequency ranges associated with railway noises. To meet appropriate requirement, maintenance and control of rail roughness at

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E-mail addresses: s.kaewunruen@bham.ac.uk; sakdirat@hotmail.com various wavelengths are generally carried out by rail grinding and lubrication [4, 8, 9]. In Australia, an urban rail network seems to suffer from rail corrugations on the low rail in curves. In addition to noise issues, the defect incurs costly track and train maintenance [5, 10-12]. It could also be a source causing other types of rail defects, e.g. rail squats, shelling, etc. [13-14]. On this ground, monitoring and control of rail corrugations is mandatorily required [15-17].

Table 1 Wavelength ranges associated with railway noises [4, 5, 7].

Railway noise	Frequency ranges	Wavelength (at 40 km/h)
Audible ground-bourne	25-250 Hz	40-400 mm
Structure-bourne	100-2000 Hz	5-100 mm
Wheel-rail rolling noise	100-5000 Hz	2-100 mm
Range of greatest human sensitivity	2,000-5,000 hz	1-5 mm

The inspection or patrol train vehicle is generally equipped with sensors (i.e. accelerometers, gyroscope, ground penetrating radar, etc.) and high-speed cameras to supplement track inspection activities. This paper presents the utilization of an inspection train vehicle to evaluate and monitor rail corrugation growth on curved tracks. It demonstrates the integration of numerical train/track simulations, axle box acceleration data obtained from the calibrated track inspection vehicle “AK Car”, and data analytics in order to assess and monitor rail corrugation growth on curves. The case study demonstrates such a technique to monitor the rail corrugation defect on a sharp curve, where short-pitch rail corrugation on the low rail prevails [18-21], in an Australian underground rail track system.

2. Track Inspection Vehicle

Track recording data is the track geometry data obtained from an inspection vehicle. The accuracy, repeatability and quality of the data depend largely on measurement method, sensor and instrumentation, train speed, and location identification [22]. In this case study, the track inspection vehicle has been installed with axle-box accelerometers. The inertia data is then computed to provide track maintenance engineers with geometry data. The geometry data, which had been recorded using ‘AK Car’ Geometry Recording Vehicle, illustrates fundamental dynamic track parameters (top, line, gauge, cross level and twist) in each stage of rail track’s life cycle.

2.1 Gauge

Track gauge is defined as the distance between the gauge points on the face of each rail. The default gauge point is 16 mm from the azimuth (maximum y point) on the rail surface. AK car recognises the known distance between laser cameras instrumented on its bogie, so that the resulting gauge measurement is the difference between the optimal gauge (1435mm) and the measured gauge [22].

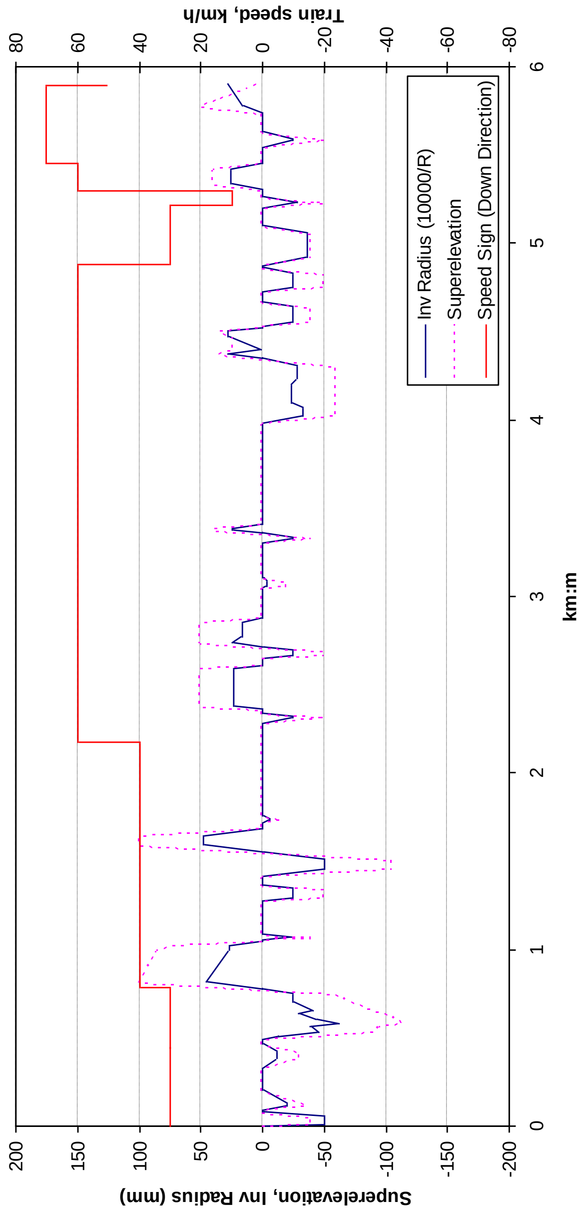

Fig. 1 Track speed and geometry

2.2 Superelevation

Superelevation (or so-called crosslevel) is defined as the height of one rail above the other. The superelevation is calculated from all four of the inertial measurement package components installed on the AK Car body, consisting of two single-axis fibre optic rate gyroscopes (measuring roll and yaw in terms of turning angles); two accelerometers (measuring vertical and lateral accelerations); and a signal conditioning board [22].

2.3 Top

Track surface is defined as the evenness or uniformity of track in short distances measured along the top of the rails.

Under load of AK Car body, top surface of rails and vertical alignments can be measured by either a mid-chord offset or by a space curve method. The AK Car uses the former method (calculating a versine at 1.8m) by adopting 10m chords [22].

Fig. 2 A typical curved track where a high-pitch corrugation on low rail tends to occur

Fig. 3 AK Car, a track inspection train

2.4 Line

Line or horizontal alignment is defined as the local variation in curvature of each rail of track. It should be zero on the tangent or straight track so that the AK Car 'measured line data' represents the deviation from zero. In a curve, the deviation will be from the uniform alignment over a specified distance, in this case, of 10m chords [22].

Corrugation roughness data can also be obtained by double integration of axle box acceleration with respect to train/track receptances and signal filtering, similar to *Top* data. Calibration and repeatability test were previously carried out to meet rail authority requirements [22-24]. This roughness data represents the combined vertical rail surface quality for all wavelengths.

3. Growth and Severity: A Case Study

Rail corrugations have been a problem especially in curved tracks. A pilot study was carried out on an urban rail network. The geometry and speed of the uni-directional track are shown in Fig. 1. From Fig. 1, the section from km0.400 to km0.800 tends to undergo 'unbalanced' speed that usually causes 'short-pitch' low rail corrugation, compared with the adjacent section (km0.750 to km1.055). The track structure consists of 60kg rail, fastening system, and timber sleepers embedded into concrete slab, as shown in Fig. 2. Track inspections are often carried out in practice by using a Track Inspection Vehicle, i.e. 'AK Car' as shown in Fig. 3.

To evaluate and monitor the rail corrugation growth on curves, the axle box acceleration and corrugation data were collected from AK Car archive for the runs between July 2010 and August 2013. It is noted that the data sampling rate is 10,000 Hz, resulting in a good quality data for frequency analysis up to 5,000 Hz, which is well above the wavelengths of interest (see Table 1). Fig. 3 shows the raw data derived from corrugation data archive. These data represents '*combined*' track and rail roughness measured based on AK Car parameters. However, using the smaller cord length filtering (e.g. 500mm cord), the track deflection effect is minimal and negligible.

Based on Fig. 4, although it is difficult to measure due to the transient nature, it could be observed that low rail (or TopLeft/TopL) tends to be much more cyclical than high rail (TopR) data. The '*rms amplitude*' can generally inform the growth of roughness of track. The higher the rougher – and rail running surface control is required (i.e. rail grinding, top of rail lubrication). In this case, noticeably the rms amplitude has decreased over the time as the rail is worn out by running wheels. But, the real question is that can one see if there is a clearer growth of rail corrugation? It is unclear at this stage if any corrugation could be detected since the overall rms amplitudes decrease. Sometimes, data analyses of the time-domain rms amplitude can be time consuming and such the ambiguous data could lead to uncertainties.

To evaluate rail corrugation growth from this data, more analyses are required. Wavelength analysis would ensure that correct rail surface irregularity is emphasised. Rail corrugation on curves tends to be frequently associated with the wavelength bands from 30 to 100 mm. The rail roughness (obtained from CAT measurement tool) is plotted against logarithm of wavelength (mm). The decibel RMS of roughness amplitude is based on:

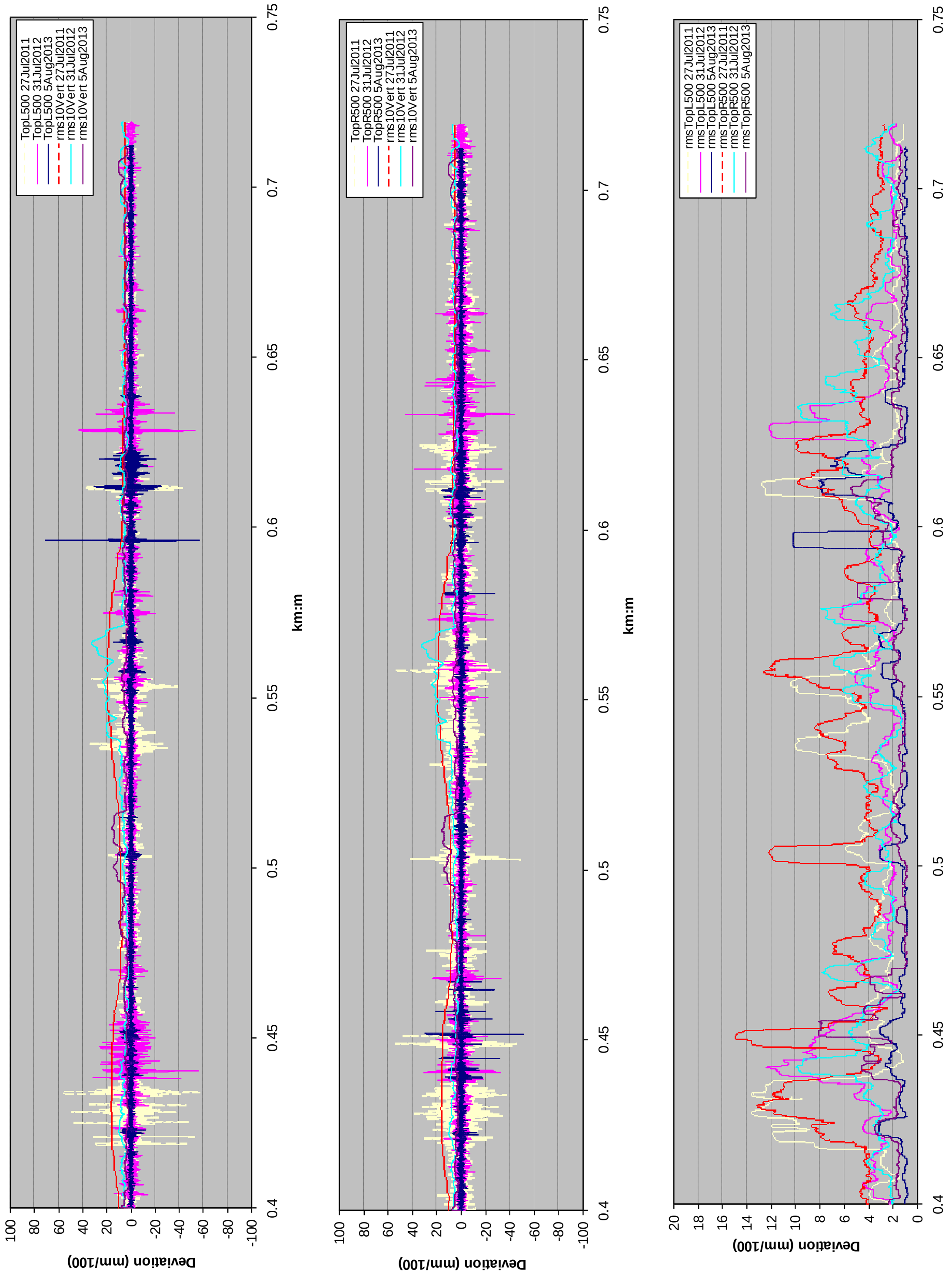

Fig. 4 Corrugation growth from km0.400 to km0.800 (Top 500)

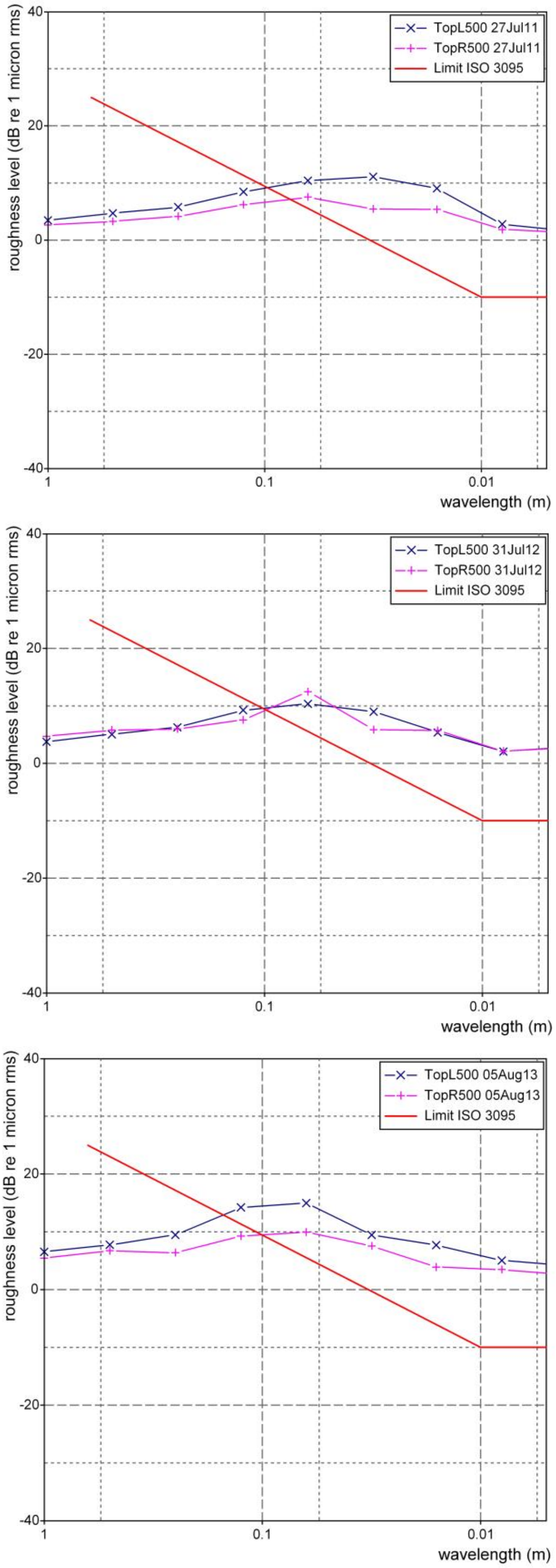

Fig. 5 Roughness level using Top500 data (TopL – low rail; TopR – high rail)

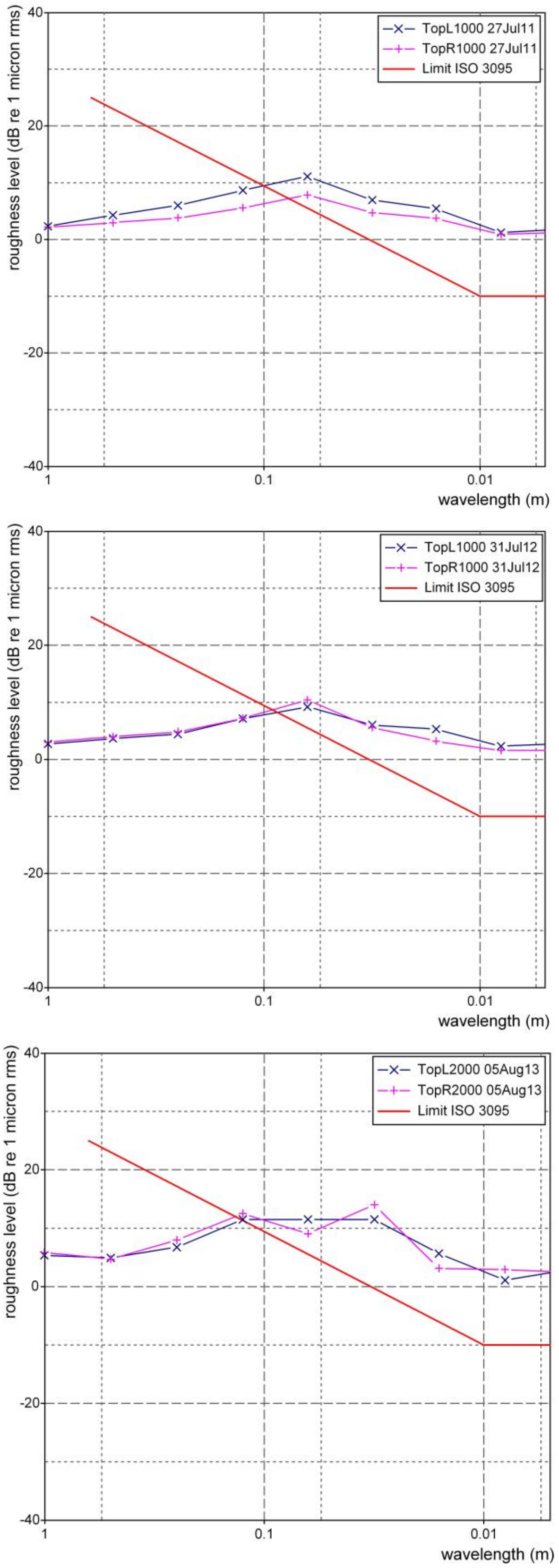

Fig. 6 Roughness level using Top500 data (TopL – low rail; TopR – high rail)

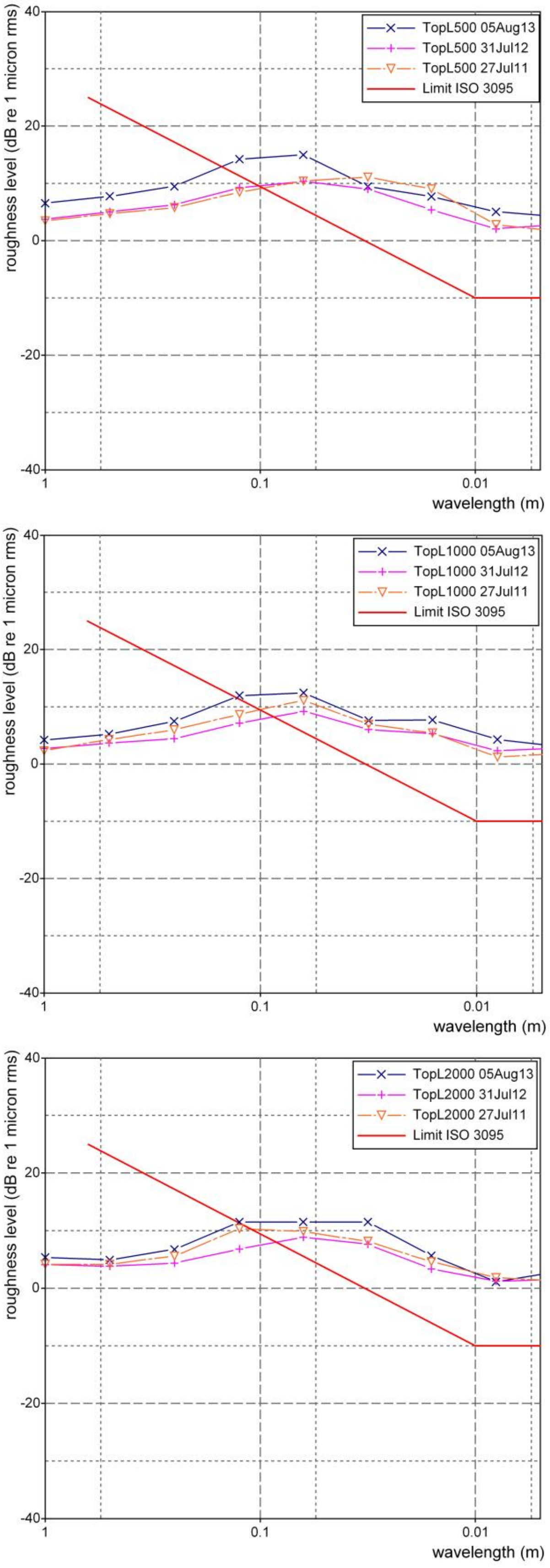

Fig. 7 Roughness growth of low rail

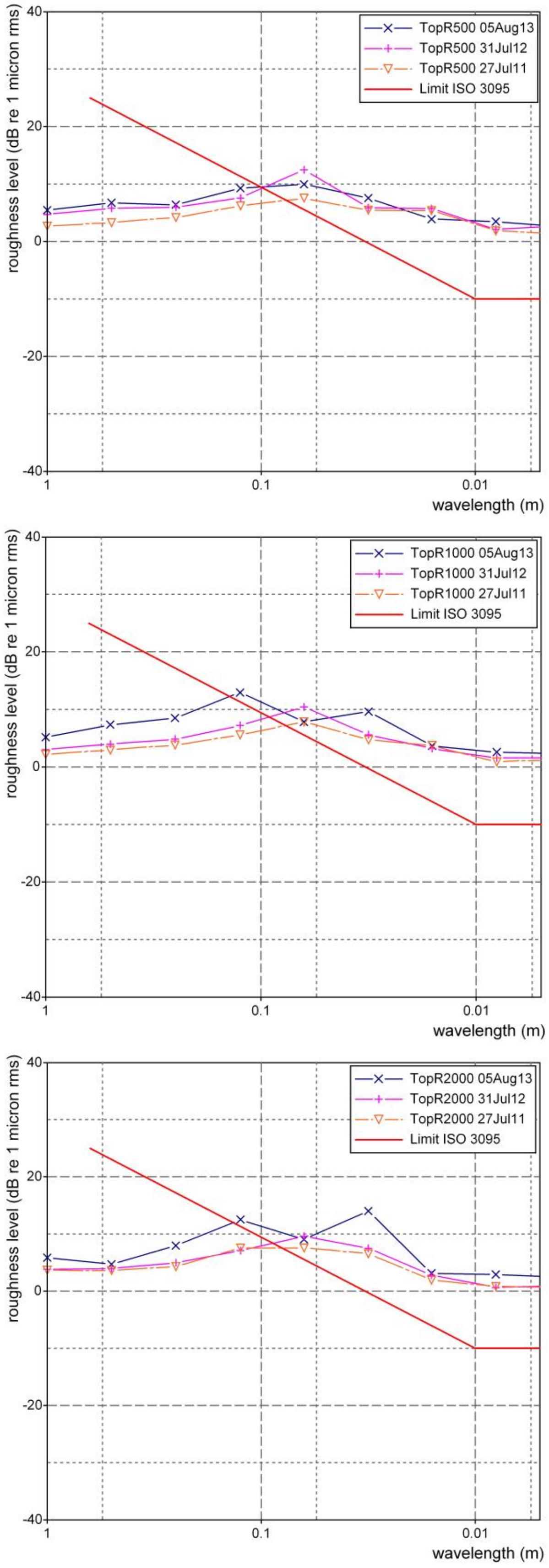

Fig. 8 Roughness growth of high rail

$$R = 20\log_{10}[r/r_0] \quad (1)$$

where the reference r_0 = 1 micron (= 0.001mm)

The rail roughness, r, (obtained from AK Car corrugation data) is plotted against logarithm of wavelength (mm). Equation (1) shows the calculation method for decibel RMS of roughness amplitude.

Figs. 5 and 6 show the roughness level using Top500 and Top1000 (Top500: a filtered displacement between 0.25 and 0.5m; and, Top1000: a filtered displacement between 0.5 and 1.0m). It is clear that rail corrugation exists at the wavelength band between 30 to 100 mm (0.03 to 0.1m). To monitor the rail corrugation growth, the data is re-plotted to evaluate the movement of roughness overtime. Figs. 7 and 8 clearly show that rail corrugation growth on low rail is evident over time. Ones could also notice that high rail wavelike irregularity also grows with a slower rate compared to that of low rail. On this basis, it is evident that one is able to determine the growth rate of rail corrugation over a timeframe or per million gross tonnages (MGTs) of revenue services. It is recommended for practice that filtered RMS data be used for evaluation and monitoring. The limits of RMS data depend on the operational requirements [25-28].

For example, asset damage control may consider peak to peak roughness [25] as: mild corrugation >300 microns; moderate corrugation >500 microns; and significant corrugation >2000 microns. For a noise control [28]: Top 500 rms should be less than 50 microns or 5 mm/100; or Top 1000 rms may adopt the limit of 100 microns or 10 mm/100. The track section with RMS over the limit should be closely monitored and inspected for any structural damage of assets or excessive noise. Rail engineers can make use of this data to efficiently plan for rail grinding or asset control strategy [29-31].

4. Conclusions

Significant demand for rail asset management has resulted in an application of vehicle-track interaction for assessment and monitoring of rail assets. This paper demonstrates an application of vibration-based data obtained from an inspection vehicle to assist track maintenance engineers controlling rail corrugation growth on curves. A case study using the vehicle data on a selected track section with a very sharp curve radius was carried out as a demonstration.

This study demonstrates that ones can use the inspection vehicle to *monitoring* rail corrugation growth. Top500 seems to be a stable data, which could be used for corrugation monitoring. The efficiency of track maintenance can be improved by using such application. The improvement will also enhance ride comfort and quality of lives of railway neighbors. The data analytics also suggest area of improvement. The higher quality and sampling rate of data collection are essential to the improvement of accuracy of rail roughness back-calculation at a micro-meter level. Automated inspection system, condition monitoring, and trend analysis are among the demanding and important future research topics related to railway structural monitoring and maintenance.

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