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MEASUREMENT OF LONGITUDINAL RAIL IRREGULARITIES AND CRITERIA FOR ACCEPTABLE GRINDING

S. L. GRASSIE,
Loram Rail Ltd, 8–10 *Glasgow Road*, *Kirkintilloch*, *G*66 1*SH*, *Scotland*
M. J. SAXON,
4 *The Coppice*, *Impington*, *CB*4 4*PP*, *England*
AND
J. D. SMITH
Department of Engineering, *University of Cambridge*, *Trumpington St*., *Cambridge CB*1 2*PZ*

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A portable instrument has been developed with which it is possible to measure longitudinal railhead irregularities to an accuracy of about 1 micron r.m.s. in the 30–100 mm wavelength range, with slightly poorer accuracies in shorter and longer wavelength ranges. Profile data are recorded on an industry-standard laptop computer using a software package written for this purpose. This software also provides the means of analyzing data rapidly and routinely to show components of the profile in different wavelength ranges, and to calculate statistical quantities such as the r.m.s. amplitude which can be used to characterize corrugation severity. It is proposed that the fraction of track over which the r.m.s. amplitude of longitudinal irregularities exceeds specified limits is a useful criterion to assess grinding quality. Limits of 3, 7, 7, 45 and 100 microns should be exceeded over less than 5% of the length of ground track in the wavelength ranges 10–30 mm, 30–100 mm, 100–300 mm, 300–1000 mm and 1000–3000 mm respectively.

1. INTRODUCTION

The principal means of removing rail corrugation and other surface irregularities is by grinding the rail *in situ*, for which several companies offer purpose-built trains. Not only is the recurrence of corrugation accelerated if an irregularity remains on the rail in the wavelength range of the predominant corrugation, but also longitudinal irregularities in general give rise to wheel/rail noise and to dynamic loads which can exacerbate damage to track components. It is accordingly desirable to monitor closely the residual irregularities which remain on the rail after grinding, and preferable also to limit the amplitude of such irregularities as far as is reasonably possible. This is particularly important since

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the conventional way of grinding, with motors which rotate about an axis normal to the rail, can leave a periodic irregularity at the stone-passing pitch: i.e., the distance the grinding train moves forward during one revolution of the stone [1, 2]. For typical rotational speeds of 50-60 Hz and grinding speeds of 5–10 km/h, the stone-passing pitch is similar to the 25–80 mm wavelength of corrugation commonly found on high speed main lines [3].

Increasingly stringent specifications have been developed for the residual irregularities which may remain on the rail after grinding. Although the basis of the specified limits is usually unclear, it is nevertheless evident that lower amplitudes of irregularity in general cause corrugation to recur less quickly and also give rise to less noise. In Europe, allowable residual longitudinal irregularities are at present typically specified in terms of limits on a moving average of peak-to-peak amplitudes in different wavelength ranges. Different lengths are specified for the "window" within which the moving average is calculated. For example, one railway administration specifies limits on the moving average of 0·010 mm, 0·020 mm, 0·020 mm, 0·130 mm and 0·300 mm for the 10–20 mm, 30–100 mm, 100–300 mm, 300–1000 mm and 1000–3000 mm wavelength ranges respectively. It is probably fair to say that at present most, if not all, grinding contractors operating in Europe can produce ground rail to these standards, but no contractor has train-borne equipment which demonstrates that such quality has been achieved throughout the wavelength range of interest in grinding.

Since a typical "rule of thumb" for a satisfactory piece of measuring equipment is that its accuracy should be one tenth of the measurement required, current grinding specifications imply a required accuracy of, for example, 0·001 mm (i.e., 1 micron) in the 10–30 mm wavelength range. This is a considerable challenge: it is, for example, the typical accuracy required of numerically controlled machine tools in a controlled environment. Verification of the accuracy of such equipment is also difficult, particularly for the entire 10–3000 mm wavelength range. If such equipment could be developed, it would clearly also have an application for more scientific purposes not only in the field of rail corrugation but also, for example, to measure rail profiles for prediction of wheel/rail rolling noise.

The approach which has been adopted to this challenging problem by Loram Rail Ltd has been first to develop profile measuring equipment which can be used by a single person separately from the train, which can be carried by hand and transported by air as normal check-in baggage. Such equipment, whose accuracy is rather easier to measure, can be used for quality assurance of the grinding process within the company: to ascertain how well the company's grinding trains are performing, particularly compared to typical grinding specifications. The information thus gained also helps considerably to understand the problems involved in the even more challenging task of developing equipment to work on a grinding train with similar levels of accuracy.

This paper first reviews some of the work which has been done to measure longitudinal irregularities on the rail, and then describes the Corrugation

Analysis Trolley (or "CAT") which has been developed for this purpose. A means is described of quantifying the accuracy of the equipment in a manner which is relevant to its common use, as a means of measuring the amplitude of irregularities in different wavelength ranges. Measurements are presented of ground and severely corrugated rail. There is some discussion of different ways in which the allowable amplitude of residual irregularities might be specified, in particular as moving averages of peak-to-peak amplitudes or as r.m.s amplitudes in different wavelength ranges. Conclusions are made with regard to both the measuring equipment and to specification of residual irregularities.

2. EQUIPMENT

2.1. PREVIOUS EQUIPMENT

An obvious way of measuring the longitudinal railhead profile is with a straight edge as a reference and some form of displacement transducer which is moved along the straight edge, in contact with the rail. Although devices of this type are used in the field to monitor grinding, their accuracies (typically of the order of 0·050 mm) are scarcely adequate for ensuring that irregularities of less than 0·01 mm have been left after grinding. Moreover, it is impractical to monitor either longer wavelength irregularities or hundreds of metres of track with such instruments as their length is typically about 1 m.

Devices have been developed which are based on a straight edge with linear displacement transducers measuring the relative distance between this and the rail [2], or with the straight edge merely acting as a convenient base for an accelerometer which runs over the rail [4]. By using the accelerometer-based device described in reference [4], roughness spectra were obtained in the 2·5–250 mm wavelength range for several wheels and rails, and used to calculate wheel/rail rolling noise [5]. The device described in reference [2], whose repeatability was the order of a few microns, was used to monitor detailed changes in the railhead profile at several sites over a length of 670 mm for a period of years; wear rates and rates of corrugation development were thus measured. A straight-edge device is now available commercially whose "precision" is allegedly 3 microns [6]. Such a device is valuable for scientific purposes and for detailed measurement of short lengths of track, but it is somewhat impractical to use as a tool for routine monitoring.

Another approach to profile measurement is to use a small, mobile trolley with the profile found by integrating the signal from a resiliently mounted accelerometer which is in contact with the rail. Instruments have again been developed primarily for wheel/rail noise and for corrugation research [2, 7]. The latter instrument, which was developed at Cambridge University in the mid-1970s, was found to have a repeatability of about 3·5 microns r.m.s. when measuring steps of 50–100 microns in height [8]. The "accuracy" of these various straight-edge and trolley-based instruments appears otherwise not to have been quantified in any simple way.

For wheel/rail noise prediction, it has become clear that it is necessary to have profile measurements at different distances across the railhead (and indeed also the wheel tread). Development and validation of appropriate roughness measuring equipment for this purpose has been identified by Thompson [9] as an area in which work is required in order to validate theoretical models of wheel/rail noise.

A comparison of various instruments for measuring longitudinal irregularities was undertaken in the 1980s by the ORE (Office for Research and Experimentation of the International Union of Railways, or UIC) as part of a project on wheel/rail noise generation [10]. This comparison included both accelerometer-based trolleys and a variety of straight-edge devices. It was found that the various systems gave similar results when measuring corrugated rail, but the measurements of a relatively smooth rail differed significantly: indeed, r.m.s. amplitudes of irregularity in the 30–80 mm wavelength range differed by up to an order of magnitude. Noise calculations based on roughness measurements from the accelerometer-based trolley gave "quite good agreement" with the measured noise [10]. Both Galaitsis and Bender [4] and Thompson [10] have mentioned that displacement-based systems are more sensitive to instrumentation noise at high frequencies, i.e., short wavelengths, while accelerometer-based systems are usually more sensitive to instrumentation noise at lower frequencies, i.e., longer wavelengths. Since wheel/rail noise results largely from shorter wavelength irregularities, Galaitsis and Bender used an accelerometer as their transducer.

The requirements of train-based corrugation measuring equipment have to date been rather less demanding in terms of accuracy than equipment for scientific purposes, although much more demanding in terms of robustness. Basically two types of instrument have been used for relatively low speed measurement: chord-based systems, such as those described by Cooper for a grinding train working at less than 5 km/h [11], and accelerometer-based systems such as those described by Ohtake *et al*., which operate on a train running at about 30–40 km/h [12, 13]. In both cases, the devices are allegedly satisfactory for detecting irregularities with depths of about 0·01 mm; no specific statement is available regarding their accuracy. Several systems exist which are based on measurement of axlebox accelerations to detect railhead irregularities, usually at speeds of 60–120 km/h. Probably the first such systems were developed at about the same time in Japan and in Britain [14, 15]. More powerful personal computers have made it both relatively straightforward and inexpensive to undertake the signal processing required for axlebox accelerometer systems. For example, Loram Rail Ltd has supplied PC-based axlebox accelerometer systems, which are essentially developments of those described in reference [16], to European railway administrations where they are used to detect corrugation and to determine where grinding is required on the railway system.

2.2. CORRUGATION ANALYSIS TROLLEY AND SOFTWARE

For present purposes, it was decided that the principal requirements were for an instrument with the following properties: it could measure hundreds of metres of track at a time with an accuracy of the order of microns; verification of that accuracy in a transparent way; portability, so that the equipment could be carried and used by one person, and taken onto an aeroplane as normal check-in baggage; a useful life between recharge of any batteries of several hours; the ability to run on all commonly-used rail sections, with all types of rail fastening system, and with track having a central conductor rail; the ability to run on damp rail and for the trolley itself to be showerproof. The equipment was to be used within Loram primarily for internal Quality Assurance and for calibration and verification of the accuracy of the company's train-based measuring equipment: both that on the grinding trains and axlebox accelerometer systems which have been supplied to others. By doing the latter, it would be possible to provide the railways for which the company grinds rail with records of the longitudinal profile of the finished rail which had been measured and validated with equipment whose accuracy was known, and which was known to be better than the tolerances to which grinding is required. It was also desirable that the data logging, analysis and display should be done using industry standard components and software, as far as reasonably possible. In particular, for ease of use and portability of the data, the software should run under Microsoft Windows.

The basis of the design was the trolley profilometer which was developed more than 20 years ago in the Cambridge University Engineering Department [2, 8]. This had proved valuable for corrugation measurement and also subsequently, in a slightly modified form, for acoustics measurements for British Rail Research. A more robust version had been made in 1988 for Australian National Railways [16] to monitor the development of long wavelength (generally 300–1500 mm wavelength) corrugations. One major modification to the original design was to dispense with the motorized drive, thereby not only saving considerable weight in both the motor and the batteries, but also making it possible to run on damp rail: the driven wheel on the original trolley tended to spin in these conditions. Also, transducer technology has advanced in 20 years, and so a servo accelerometer is now used rather than the previous high sensitivity piezo-electric device.

The new trolley is shown in use in Figure 1. The total weight of the device with outrigger arm to the opposite rail is about 7 kg: it is easily lifted onto and off the rail with one hand. The total weight of trolley plus its carrying box, which has dimensions of $800\ \mathrm{mm} \times 220\ \mathrm{mm} \times 250\ \mathrm{mm}$ is about 13 kg. The trolley can be pushed by hand along the rail in either direction by using a collapsible pole, similar to a tent pole, which is located in (but is not attached to) small hollows in the body of the trolley. The system was specified to collect data reliably at speeds of 0·5–1·5 m/s. Because of electronic filtering and analogue integration, data are collected with some impairment outside this speed range, particularly at lower speeds. The accelerometer slides along the rail on a plastic stud which can be replaced when it becomes worn, and provides some filtering of extremely short wavelength irregularities; a tungsten carbide ball is at present under test as a more durable alternative to this slider. Two wheels run along the gauge face of the rail, 14 mm down from the centre of the railhead: i.e., at the

Figure 1. Corrugation analysis trolley.

gauge point. The measuring position across the railhead can be varied in the range 20–40 mm, thereby giving the ability to measure several tracks along the railhead in successive runs, so developing a "map" of the railhead profile. The trolley is designed to run on railheads of 60–75 mm width and 35–40 mm depth, but can be used on rails outside this range. Although data are at present collected on one rail at a time, it would be simple to make a device to measure both rails, with an obvious cost in weight and portability.

For data collection, industry-standard components and software are used as far as possible: the principal items are a PC-compatible laptop computer with analogue/digital conversion undertaken on a PCMCIA card. Filtering and one stage of integration from the raw acceleration signal are undertaken on the trolley, and the second is done digitally in the data collection software. Distance along the rail is found from a tachometer which is fitted to a freely running wheel. Since data collection starts when a tachometer signal is detected, and conversely stops when there is no tachometer signal, data collection can be interrupted and restarted simply by lifting the trolley from the track and repositioning it subsequently at the same point. This is convenient when taking measurements on a track which is in service. Data can be observed as they are collected, which enables the user to see if any mishaps occur. Alternatively the laptop computer can be folded away and the data examined afterwards. At present, data are stored at 2 mm intervals with a precision of 1 micron (0·001 mm).

The data analysis software has a range of features including the calculation, display, printing and output to ASCII files of the following quantities: displacement, either raw or filtered into specified wavelength ranges (commonly 10–30 mm, 30–100 mm, 100–300 mm, 300–1000 mm, 1000–3000 mm, 30–300 mm and 300–3000 mm); moving average (MA) of peak-to-peak amplitudes of raw or filtered data in a "window" of specified length; moving average of r.m.s. amplitude of raw or filtered data in a "window" of specified length; r.m.s. amplitude of raw or filtered data in "blocks" of specified length. Overall averages (r.m.s) can be displayed for specified sections of the record, and the percentage of signal (displacement, MA or r.m.s.) displayed which exceeds a specified level. The latter is a particularly useful criterion to use to assess the acceptability of grinding work (see section 5). Graphs can be produced with automatic scaling, with user-specified axes, or to fixed magnifications and reductions, e.g., 1:4000. The latter is currently a common means of displaying longitudinal profile information for railway staff.

Further data analysis and display are undertaken at present by using MATLAB and the ASCII files of raw profile. Additional data analysis capabilities could easily be added to the existing software if these were required, e.g., one-third octave band spectra, or narrow band spectra for fixed "blocks" of track.

3. ACCURACY AND REPEATABILITY

A critical requirement for the instrument was to assess its "accuracy" in some readily quantifiable, simple and meaningful way which could also be used with comparable instruments. It would also be desirable if the means of demonstrating the device's accuracy were portable, so that this could be shown in the field. These requirements, which were self-imposed, arose because it would otherwise be difficult on the one hand to have confidence from the measurements that longitudinal irregularities after grinding were indeed below the amplitudes which are specified, and on the other to know how accurately train-based measuring equipment was in fact measuring longitudinal irregularities.

A reference beam, of 1·2 m length, was therefore made, in which several forms of irregularities were machined. These have depths and lengths similar to those of the irregularities which the instrument measures in the field. The irregularities were not sinusoidal as not only would this be difficult to machine but also it would restrict the wavelength range over which the accuracy could be assessed. The profile of the reference beam is shown in Figure 2, as measured in a co-ordinate measuring machine (CMM) in the metrology laboratory at Cambridge University Engineering Department. Because of the restricted measuring length of the CMM, it was necessary to make two overlapping sets of measurement in order to cover the full 1·2 m length of the datum beam. For the overlapping section, the two sets of measurements differed by a maximum of about 4 microns, and more typically 1–2 microns. While it would have been preferable to make these datum measurements in a single pass in a CMM, an instrument was not available to measure over the l·2 m length.

Measurements were also made with the trolley profilometer by running this along the reference beam while the stabilizing outrigger wheel ran along a second beam. Clearly it is difficult to maintain a speed within the design range of 0·5–1·5 m/s over much of the beam, and so it was anticipated that data at the ends of the beam would be irrelevant. Both the datum beam and the second beam for the outrigger wheel pack into a length of plastic drainpipe, with an overall weight of 9·4 kg.

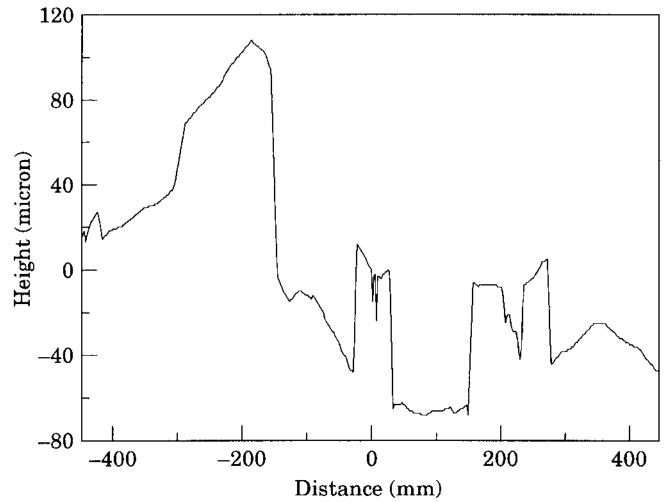

Figure 2. Profile of reference beam.

The accuracy has been assessed by comparing datum measurements and trolley measurements filtered into the wavelength ranges which are commonly used for assessing grinding quality. Due to the limited length of the beam, only the 10–30 mm, 30–100 mm and 100–300 mm ranges can sensibly be examined. The datum and trolley measurements for the central 900 mm of the 1200 mm beam, filtered into the 30–100 mm wavelength range, are shown in Figure 3. (This comparison can be made relatively easily, as the datum measurements have been written in a file which is readable by the CAT software.) Filtering introduces a slight phase difference at some points between the two sets of filtered data, but overall the correlation of measurements in this wavelength range is good, with the CAT and datum measurements differing by only a few microns, if some allowance is made for the phase shift.

A simple quantification of the accuracy has been made by comparing r.m.s. amplitudes of the datum and measured profiles in the three different wavelength

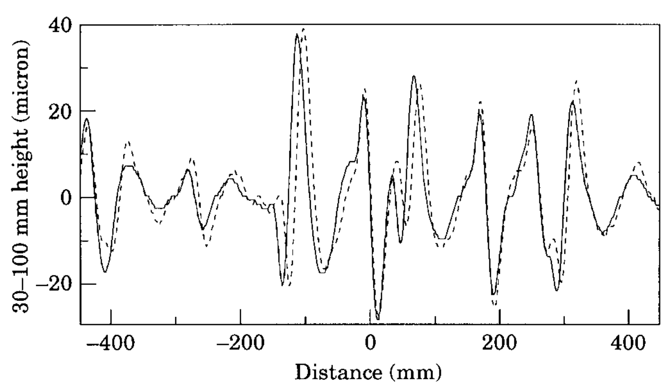

Figure 3. Datum profile in CMM (—) and CAT measured profile (----) 30–100 mm wavelengths.

TABLE 1

R.m.s. amplitudes of measured profiles of reference beam

Wavelength (mm)	Datum measurements (micron)	CAT run 1 (micron)	CAT run 2 (micron)	Accuracy (micron)
10–30	4·04	5·81	6·51	2·5
30–100	11·81	12·54	12·38	1
100–300	17·16	20·97	20·60	4

ranges over the central 900 mm of the reference beam. The use of r.m.s. amplitudes for this purpose is consistent with the approach adopted in acoustics, where the use of various types of spectra and r.m.s. amplitudes is standard practice. It is, however, slightly unusual in monitoring the severity of corrugation, where a mean of peak-to-peak amplitudes is more common. The latter approach, which is extremely sensitive to details of the signal processing, is not used here but is discussed further in section 5. Data for two CAT measurements are shown in Table 1, together with the approximate "accuracy" (in terms of micron r.m.s. difference between CAT and datum measurements) which can be concluded from these figures.

Clearly in all wavelength ranges the CAT slightly overestimates the amplitude of the irregularity. This measuring instrument works particularly well in the 30–100 mm wavelength range, where the difference of 1 micron r.m.s. between datum and CAT measurements is significantly less than a typical limit of 20 microns on the moving average of peak-to-peak amplitudes. If a signal were perfectly sinusoidal, a peak-to-peak amplitude of 20 microns would be equivalent to about 7 microns r.m.s. Very much smaller amplitudes than the limiting amplitudes in the specifications can therefore be measured accurately in this wavelength range. In the other wavelength ranges the accuracy is only about half of the smallest amplitudes. Since the CAT consistently slightly *overestimates* r.m.s. amplitudes in the test on the datum beam, it could be used to demonstrate confidently that rail has been ground to comply with a specification, even if in doing so it would place greater demands on the grinding operation.

4. MEASUREMENTS OF LONGITUDINAL RAIL PROFILE

Conceptually the simplest type of information which can be provided by the profile measuring trolley is the physical profile as a function of distance along the rail. Both the "raw" profile, with wavelength components of at least 10–3000 mm, and the components of the profile in different constituent wavelength ranges can be found. The CAT software provides the means to calculate and display the physical profile and statistical information such as r.m.s. amplitudes and the mean of peak-to-peak amplitudes as functions of distance. Graphs can be printed directly or copied to other applications running on the computer, while profile data can be exported to ASCII files. For purposes of clarity, the

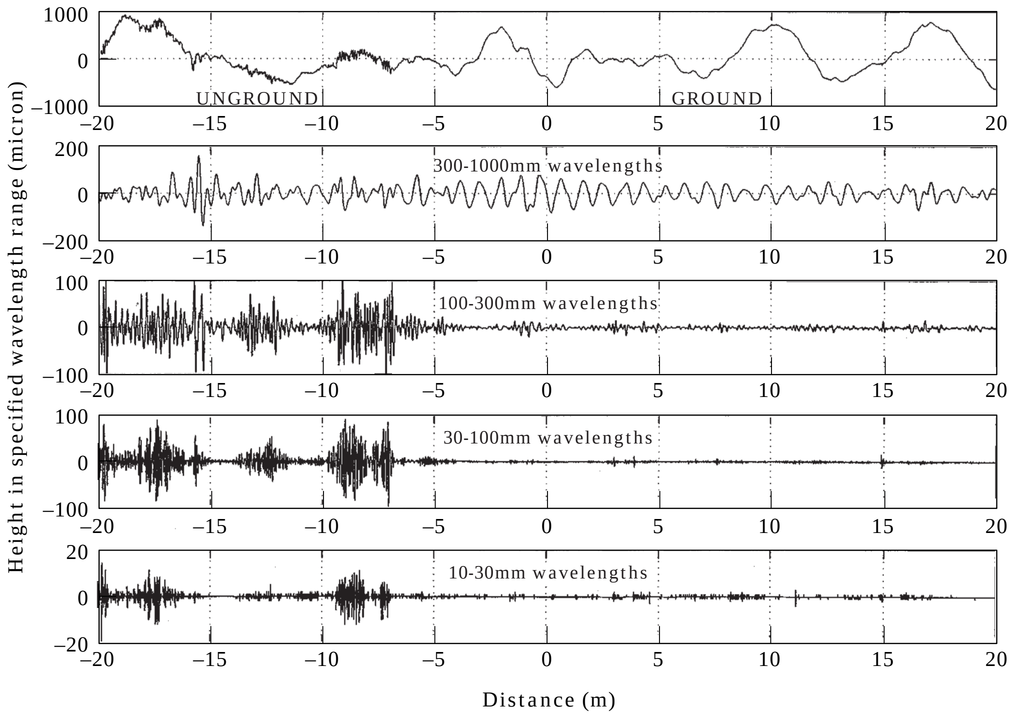

Figure 4. Overall profile of rail and wavelength components.

graphs here have been produced by exporting data from the analysis software and replotting in MATLAB.

An illustration both of some of the facilities of the analysis software and of some effects of grinding is given in Figure 4. In the 40 m length of track for which the profile is shown, the left half has not been ground while the right half has been ground. In the top part of this figure, some corrugation is clear in the left section even at a scale of ± 1 mm. It is also clear that there is a significant component of the railhead irregularity at a wavelength of about 5 m and with an amplitude of more than 1 mm. This is affected relatively little by grinding. The profile components in wavelength ranges 10–30 mm, 30–100 mm, 100–300 mm and 300–1000 mm are shown in the lower parts of the figure. The corrugation on the unground section of track is very much clearer in the filtered profile, and has components primarily in the 30–100 mm and 100–300 mm wavelength ranges. Grinding has reduced the amplitude of corrugation from about 200 microns peak-to-peak in the 100–300 mm range and about 150 microns peak-to-peak in the 30–100 mm wavelength range by more than an order of magnitude in some places. On this section of track, which is on a heavily used metropolitan railway, corrugation is particularly severe at the many discrete irregularities, such as welds and joints: these "bursts" of corrugation are clear on the left side of the parts of Figure 4. The residual irregularities which are apparent after grinding occur primarily at the equivalent points on the ground section of track.

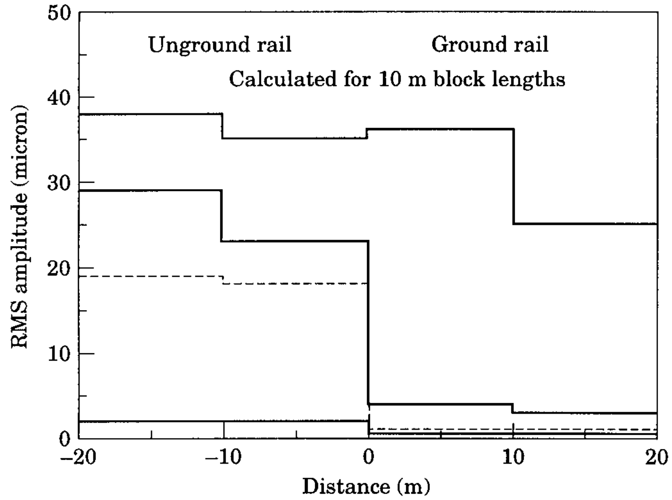

Figure 5. r.m.s. amplitudes of irregularity.

Data of this type have the attraction that they give a clear physical appreciation of the corrugation severity: it should be possible, for example, to compare the amplitude of an individual irregularity on such a graph and that which would be measured with a simple instrument such as a micrometer and straight edge. Such data are also essential for time-domain calculations of vehicle/track interaction, such as those undertaken by Ilias to model corrugation development [17]. They are, however, a cumbersome way of examining the profile for all but short lengths of track, particularly if five wavelength components are of interest. For this purpose, summary information is more valuable. An example of such summary information is shown in Figure 5 for the same 40 m length of track as used in Figure 4. The r.m.s. amplitudes are calculated in this case for 10 m lengths (or "blocks") of track. With such a representation, the section of track which has been ground is extremely clear, and it is also clear that grinding has reduced the amplitude of irregularities in the 30–100 mm and 100–300 mm wavelength ranges by about an order of magnitude (from 18–19 and 23–29 microns r.m.s. to 1 and 3–4 microns r.m.s., respectively). It is clear from both this graph and from that of the filtered profile that the 300–1000 mm wavelength range has been relatively unaffected by grinding, which was undertaken here by using a grinder with a short wheelbase and only two grinding modules on each rail. With a larger, main-line grinder, longer wavelength irregularities are also significantly reduced.

5. CRITERIA FOR GRINDING QUALITY

Both "raw" and filtered displacement data are of limited use when assessing the severity of corrugation and the quality of ground track. Criteria could be stated such as, "there shall remain no irregularities greater than x microns deep in the wavelength range 30–100 mm". However, this apparently simple criterion could be difficult to monitor: if corrugation exists in the same place with a wide range of wavelengths (as for the track in Figure 4), how are the effects of corrugation in one wavelength range distinguished from those in another? Moreover, it would be essential to include allowance for exceptional events such as bad welds, wheelburns and the like, over which the grinding company has no control. At such places it may be both time-consuming and inevitably uneconomical to grind sufficiently to reduce irregularities to a level which could reasonably be expected elsewhere on the track.

It is proposed here that a more realistic criterion for assessment of grinding quality can be based on the r.m.s. amplitude of irregularity in a specified wavelength range calculated for blocks of specified length over the track section of interest. It is reasonable to use the wavelength ranges 10–30 mm, 30–100 mm, ... , 1000–3000 mm as these are already used by some railway adminstrations and they have a logical progression in powers of about 3 (or $10^{0\cdot 5}$), which gives a modest number of ranges to cover the overall range of 10–3000 mm of interest. Although there would be many attractions in bringing together work such as this with the specification of wheel and rail roughnesses in octave or third-octave band ranges for acoustics work, such as has been proposed by Dings *et al.* [18], this would require considerably more wavelength ranges to cover the range of interest and may be too large a leap from current practice to be readily accepted, despite its intellectual consistency. It would be a relatively short leap from the proposal made here to accepting a common basis for assessing railhead roughness for both acoustics and grinding needs.

A statistical quantity which is sometimes used at present to assess the severity of corrugation or residual longitudinal irregularities is the moving average of peak-to-peak amplitudes of the irregularity in a "window" of specified length for different wavelength ranges. While this quantity has the superficial appearance of being similar to a quantity which one might measure (such as the 200 micron

TABLE 2
Moving average and r.m.s. amplitudes of irregularity in different wavelength ranges

	Amplitude (micron)					
	Moving average			r.m.s.		
Wavelength range (mm)	30–100	100–300	30–300	30–100	100–300	30–300
1 corrugation	52	62	66	24	38	46
2 corrugation	39	55	55	20	33	39
3 curve, outside rail	11	21	17	5	10	12
4 curve, inside rail	24	56	53	11	26	28
5 ground	3	6	5	2	3	4
6 ground	3	3	4	1	2	2
7 ground	4	4	4	2	2	3
8 ground	5	5	5	3	3	4

N.B. All calculations are for a "window" length for the moving average or "block" length for the r.m.s. amplitude of 0·6 m.

deep irregularities in the 100–300 mm wavelength range of Figure 4), in practice it suffers from several deficiencies. In particular, for a given "raw" profile of railhead irregularities, it would be reasonable to expect that the statistical measure of amplitude would be greater the wider the wavelength range. Whereas this is always the case for the r.m.s. amplitude, it is not necessarily the case for the moving average. This is illustrated in Table 2, where some examples are shown of r.m.s. amplitude and moving average for the several sections of track for 30–100 mm, 100–300 mm and 30–300 mm wavelength ranges. The moving average for the 30–300 mm wavelength range is often less than for one of the narrower, constituent wavelength ranges whereas the r.m.s. amplitude c for the overall range is always related to the other two amplitudes a and b as $c^2 = a^2 + b^2$ (within the 1 micron precision to which the r.m.s. values are at present given by the CAT software). The r.m.s. amplitude is also insensitive to details of the signal processing, such as digitization rates and levels, and filtering characteristics, which is not the case for the moving average. The r.m.s. amplitude is accordingly a quantity which could be used by different organizations without having to specify details of the signal processing in order to obtain similar results for the same measured profile.

There is also a good reason in principle to use the r.m.s. amplitude as the important statistical measure of railhead irregularities. This results from the essentially linear dependence of wheel/rail rolling noise on the irregularities between wheel and rail [10]. Noise is commonly characterized by using spectra and sound pressure levels in specified frequency ranges. The analogies of this for the irregularities which give rise to wheel/rail rolling noise are spectra of the railhead irregularities and their r.m.s. amplitudes in corresponding wavelength ranges.

It has been found that a sensitive criterion for assessing the quality of the longitudinal profile can be based on calculation of the r.m.s. amplitudes of the longitudinal irregularity for the aforementioned wavelength ranges for blocks of, say, 10 m length (as in Figure 5) over a site at least several hundred metres long. The fraction of track for which the r.m.s. amplitude exceeds a prescribed limit is then calculated. This fractional exceedence is the criterion for assessing quality of the longitudinal profile, and particularly of the ground rail. The limits which have been used here for the r.m.s. amplitudes are 3, 7, 7, 45 and 100 microns in the 10–30 mm, 30–100 mm, 100–300 mm, 300–1000 mm and 1000–3000 mm wavelength ranges respectively: these limits correspond approximately to the limits of 10, 20, 20, 130 and 300 microns on the moving average of peak-to-peak amplitudes which are currently used by at least one railway administration for the same wavelength ranges.

These fractional exceedences are shown in Figure 6 as functions of wavelength for a variety of tracks in different stages of degradation: recently ground rail; new, unground rail; and corrugated rail. For ground rail, it is reasonable to expect that the r.m.s. amplitude of residual irregularity exceeds the appropriate limit for less than 5% of the total track length in each wavelength range, as is the case here (which includes track ground by both main grinding contractors operating in Europe). Indeed, for the ground sites shown, the fractional

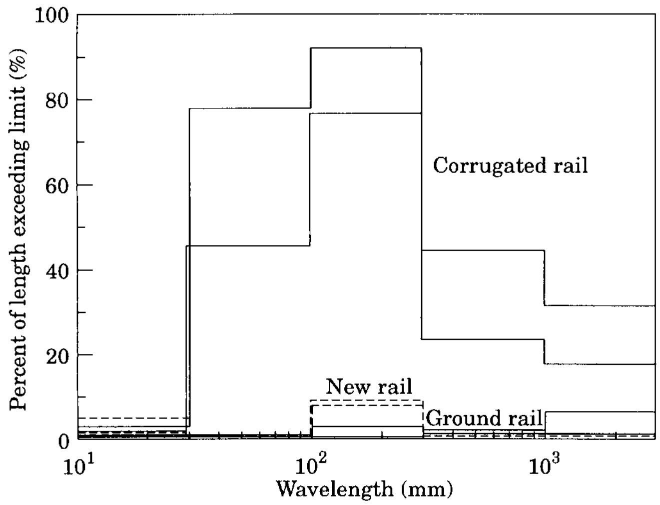

Figure 6. Fraction of rail exceeding amplitude limit.

exceedence is zero for most wavelength ranges (but for clarity is plotted fractionally above the axis).

Clearly there can be considerable flexibility in specifying both the exceedence limits and the fraction of track allowed to exceed the limit. In particular, if there were initially many discrete irregularities such as welds, joints or wheelburns on the track, it may be difficult, and in some extreme cases perhaps impossible, to achieve a fractional exceedence of less than 5%.

It has been found that for new rail, the limiting r.m.s. irregularity is exceeded much more frequently than for ground rail (see Figure 6). Insofar as corrugation is initiated by railhead irregularities and noise arises similarly, this provides some justification for the common practice of grinding new rail. Conversely, on a rail which has been in service and subsequently ground, there may be slightly more longer wavelength irregularities (1000–3000 mm) than on a new rail. Such long wavelength corrugation tends to be rather deep, and although it can be removed by grinding, this is at some expense both in reduced productivity of the operation itself and in removal of rail. Many railway administrations would indeed question the value of grinding as a maintenance procedure for removing 1000–3000 mm irregularities.

6. CONCLUSIONS

Increasingly stringent demands are being made of grinding to reduce longitudinal irregularities on the rail to amplitudes of less than 10 microns, largely to reduce wheel/rail rolling noise and delay the recurrence of corrugation. Greater demands are in turn made of measuring equipment to demonstrate confidently that there are indeed extremely small amplitudes of residual irregularity. Measuring equipment of the required accuracy does not at present exist on grinding trains, but a small, portable profile measuring trolley has been developed which has satisfactory accuracy in the wavelength ranges of interest and which can be propelled manually along the rail. The accuracy of the trolley has been determined by measuring a reference beam whose profile has also been measured in an independently calibrated instrument, and by comparing r.m.s. amplitudes of the datum and measured profiles in different wavelength ranges. The accuracy so found is about 2·5 microns, 1 micron and 4 microns at worst in the 10–30 mm, 30–100 mm and 100–300 mm wavelength ranges.

The trolley has been used to demonstrate that grinding reduces the amplitude of corrugation by about an order of magnitude in these wavelength ranges. It is proposed that a useful and objective basis for a criterion for assessing the quality of ground rail or the severity of corrugated rail, is to calculate the r.m.s. amplitude of longitudinal irregularities in the prescribed wavelength ranges for "blocks" of specified length along the track. The fraction of the track length for which the r.m.s. amplitude exceeds the specified limit is the criterion used to assess grinding quality or corrugation severity. For ground track, it is reasonable to expect that r.m.s. limits of 3, 7, 7, 45 and 100 microns in the 10–30 mm, 30–100 mm, 100–300 mm, 300–1000 mm and 1000–3000 mm wavelength ranges would be exceeded over less than 5% of the track length. While such a criterion is ideally suited to equipment which gives a continuous measurement of the railhead profile, it could in principle be extended to measurements made over a discrete interval, provided that sufficient measurements were taken to gain confidence in the conclusions.

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