The Fourth International
Heavy Haul Railway Conference 1989
Brisbane, 11 - 15 September 1989

Corrugation on Australian National: Cause, Measurement and Rectification

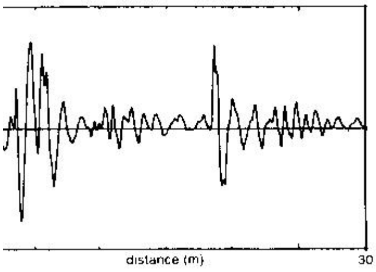
S.L. GRASSIE

Consulting Engineer, High Cross, Cambridge, UK

previously undocumented type of long wavelength corrugation is discussed. The cause of the
n is explained and criteria are accordingly established to rectify the problem. Two types
nt which have been developed to measure the railhead profile are described.

DUCTION

few railways which do not suffer from
of corrugation of the rails. The variety
f corrugation may often appear as great
ıber of railway systems: wavelengths vary
25mm to 1.5m, while the depth of a well
corrugation varies from less than 0.1mm
r corrugations to several millimetres for
rugations. Variations in the railhead
e caused by different mechanisms: those
ns which were once an uncontrolled
heavy haul railways arise from gross
ow of the railhead (Mair, 1986), gross
ow is also associated with corrugation
he low rail of curves in Canada
1975), while short wavelength, "roaring
ugations are a phenomenon of periodic
sie, 1983). The corrugation wavelength
ases may variously arise from excitation
cal or lateral resonance of the vehicle
ck (Mair, 1977; Kalousek, 1975), or
preferential filtering of railhead
by the contact patch (Clark, 1988)



ure 1 Profile of corrugated rail

considers a type of corrugation with a
characteristics which is a severe problem
ck of Australian National Railways (AN).
ngth is typically 0.5-1.0m and the depth
developed corrugation may be several
s. The profile of a particularly severe
n, measured using equipment developed as
is project (Section 3), is shown in Fig
ation was first observed by AN on 40kg
as later found on 47kg rail and then on
It is worse on the high rail in curves,
most severe at badly dipped welds. The
n is evident primarily as full section
n (or crippling) of the rail; gross
ow of the railhead is unusual. There had
been a gradual increase in vehicle speeds over the affected track (from a maximum of about 80km/h to 110km/h) and in the volume of traffic. Both traffic and speeds were destined to increase further for commercial reasons, while it was clear that there could not be widespread renewal of the track: existing resources had to be carefully husbanded.

The author's assistance was sought by AN in 1986, through Pandrol Australia Pty. Ltd., to assist in finding an effective treatment of this corrugation problem. At that time it had become apparent that ballast on some sections of corrugated track required packing almost weekly, while staff complained of the bad ride. There appeared also to be an exacerbation of fatigue failures on bogies of both locomotives and rolling stock.

The cause of the corrugation has now been identified, treatment of the problem has begun, standards have been set for track and vehicles which should prevent its recurrence, and measuring apparatus has been developed with which AN can monitor the success of the treatments.

2 CAUSE

It was proposed that corrugation was caused by vehicles responding dynamically to the severe dipped welds which were present on AN's track, with an ensuing periodic variation in the wheel/rail force of sufficient amplitude to deform the rails plastically in bending. The force of interest, the "P2" force, was at relatively low frequency (about 30Hz for a typical wavelength of 0.7m and speed of 80km/h): accordingly, the response would be at the "loaded track resonance", associated by Mair (1977) with formation of corrugation on heavy haul lines. Vehicles with high unsprung mass were of particular interest as these cause high P2 forces: attention was accordingly directed to locomotives.

Experiments were carried out in the field using a test train to examine this hypothesis. This train comprised a locomotive, with the nose-hung, axle-mounted DC traction motors common to all of AN's locomotive fleet, a converted coach containing instrumentation, a flat wagon with generator set, and the guard's van. Instrumentation, comprising accelerometers on the axleboxes of one axle of both the locomotive and the instrumented coach, was simple and was confined to the train. This instrumentation was used also because it was proposed that it be the basis of a measuring system (Section 3).

The principal series of test runs *involved running* the test *train at a range* of speeds over a section of badly corrugated track, of which the rail shown in Fig 1 was a part, used *almost exclusively by* unit coal *trains*. This line was selected because of the uniformity of both speeds and vehicles: it was expected that corrugation *would have a* correspondingly *uniform* wavelength. With regard to testing the hypothesis, if corrugation was caused by locomotives resonating on *the track stiffness*, resonance of *the locomotives* would be forced by the existing corrugation, and there would be particularly large accelerations *of the unsprung* mass when *the train* travelled over the corrugation at the predominant line speed. Conversely it would be expected that the instrumented *coach would not* respond *preferentially* to the corrugation when travelling at the line speed (although it would clearly be excited by the corrugation).

This difference in response was indeed found and is illustrated in Figs 2. *Figures 2(a)* and *2(b) show* the power spectra *of axlebox* acceleration on the locomotive and coach respectively for speeds of 65.9km/h, 79.1k/h and 95.9km/h; the *predominant* speed of traffic *on this* section of track is 80km/h. In both sets of spectra there is a prominent peak at a frequency which is *proportional* to train speed (*at about* 24Hz, 30Hz and 36Hz) and which corresponds to a wavelength of about 700m. Sleeper spacing at this site is 610mm. *The* responses of *the locomotive* and coach differ significantly in that the peak in the locomotive spectrum is extremely large at the line speed, whereas the *amplitude* of *the* peak for the coach spectrum increases steadily with train speed. Accordingly it may be concluded that the periodicity of the *corrugation* arises from excitation of resonance of the locomotive on the track stiffness.

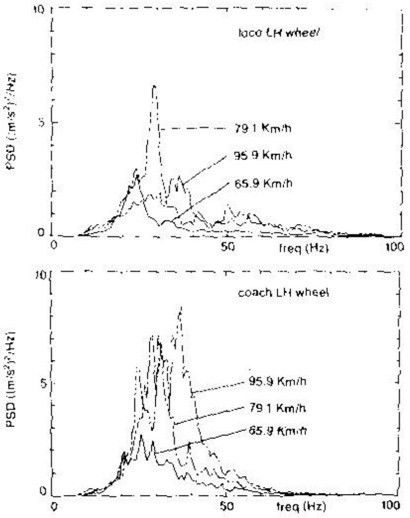


Figure 2 Power spectra of axlebox accelerations
(a) locomotive (b) coach

The validity of this was further demonstrated by calculation of the wheel/rail force arising from a ramp irregularity, which was used to represent a *weld* (Fig 3). *The wavelength of the contact force was found to be* 760mm for the measured locomotive unsprung mass of about 1900kg per wheel at a speed *of 80km/h with a ballast stiffness of 70MPa and* damping of 70kNsm-2 (Grassie, 1984). The corresponding *wavelength* for the 750kg unsprung *mass* of the coach was 640mm. The amplitude of th force for the coach is much smaller than *that for* the locomotive.

Measurements were made on track with *different* sleeper spacings to *ensure* that corrugation did i *fact* arise from the free response of the locomoti excited by railhead irregularities rather *than fr* the differential track *stiffness* caused by the *support*.

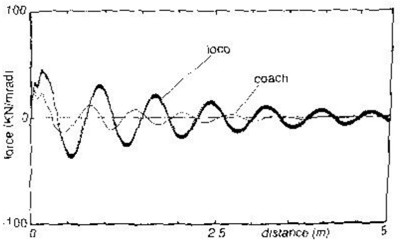


Figure 3 Calculated contact force at a ramp
speed = 80 km/h

A second *part of* validating the hypothesis was t *demonstrate* that the wheel/rail force caused by welds, or by the locomotive on *existing corrugation*, was sufficient to cripple the rail. This force was calculated from a simple analysis which it was assumed that the *rail is an* infinit Euler *beam of* flexural rigidity EI resting on ballast with stiffness β per unit length. It wa thus found that full section plastic *deformatio* would occur for a normal force

$$P \geqslant \frac{(64\beta EI^3)^{1/4}}{h}\left(\frac{Y}{E}-\alpha T\right) \qquad (1)$$

where h is the depth of the extremity of the rai from its neutral axis, Y is the rail's *yield* strength, *and T* is the difference between the r *temperature and* its stress-free temperature. E the Young's modulus and α is the *coefficient* of *thermal expansion*.

Lower limits on the crippling force were *found* taking a *reasonable* maximum value of T; a *reasonable minimum* value of the ballast stiff β; the pertinent values of h and EI *for the* ra section; and the lower limit Y of yield stren *On AN the rail may often* be as much as 25C be the stress-free temperature of 40C; *in these* circumstances *yield* is most likely to occur *in tension in the railfoot*. Ballast stiffn low as 8MPa have been found (Mair, *1977*): thi value is assumed *here*. The corresponding cr *forces calculated from (1) for* the four size rail used on AN are shown in Table *I*.

TABLE I

FORCE REQUIRED TO CRIPPLE RAIL

rail size	AS41	AS47	AS53
EI (*MNm2*)	2.74	3.30	4.72
h (mm)	64.7	68.3	73
force (kN), *case A*	231	252	308
force (kN), case B	303	330	404

Case A: semi-killed rail steel: Y = 370 370-440MPa)
Case B: fully killed rail steel: Y = 465 465-545MPa)

rly the force required to cripple AN's older l, which is predominantly of semi-killed steel, be significantly lower than forces which are rated on many railways: on British Rail, for ple, a P2 force limit of 250kN has been posed (Jenkins, 1975).

had been intended that the wheel/rail force f ld be found in track from the well known formula

$$f = m * a \qquad (2)$$

ere m is the effective unsprung mass of the locomotive at a wheel and a is the measured axlebox acceleration. However, the force calculated from this formula was very much less than that required according to (1). For example, for the severely corrugated rail of Fig 1, the peak acceleration measured on the locomotive axlebox is about 50ms-2 (Fig 4). This corresponds to a dynamic force of 95kN, or static plus dynamic force of about 200kN which would be barely sufficient to cripple the lightest rail.

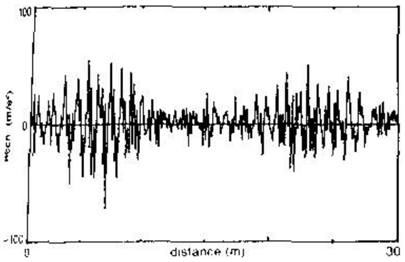


Figure 4 Measured locomotive axlebox acceleration for rail shown in Figure 1; speed = 80km/h

For reasons which are at present under investigation it appears that the contact force cannot be found in such a simple way from the axlebox acceleration. In other experiments (Jenkins, 1975) the measured contact force was also substantially greater than the product of unsprung mass and measured axlebox acceleration.

The lack of gross plastic flow of the railhead despite the crippling of the rail exemplifies the significance of the bulk material properties to crippling of the section and of the properties of the work hardened surface layer to gross plastic flow. AN's relatively light rail becomes crippled before it flows not only because of the low flexural rigidity of the rail, but also because the yield strength of the work hardened layer in the railhead is very much greater than that of the bulk material. It has been found (Marich, 1986) that the yield stress for heavily work hardened standard carbon rail is over 91-94% of the tensile stress, which is at least 770MPa for AN's semi-killed rails (c.f. yield of 370-440MPa). However, for fully-killed and head hardened steels the yield and tensile strengths are more similar. Rails made of these steels will tend to flow before they are crippled.

Some slight waviness of the rail would occur simply as a result of elastic deformation caused by periodic residual stresses existing in the railhead after an irregularity. This effect has not been examined to date.

3 MEASUREMENT

It was foreseen that AN would require two measuring requirements. The major need was for a system which could rapidly survey all of AN's track to determine the extent and severity of corrugation, both initially to ascertain the severity and distribution of the corrugation and thereafter to monitor the improvement in track quality. For this purpose it was proposed that a system be developed based on measurement of axlebox accelerations. Such systems have been developed, for example, in Britain (lewis, 1986) and Holland (Esveld, 1986), and it had been found from preliminary work on AN that axlebox accelerations on the instrumented coach were a reliable indication of corrugation. In view of the particular need for a relatively inexpensive system, the following principal requirements were specified:

(i) equipment to be based on an IBM PC compatible microcomputer;

(ii) processing of acceleration data from both rails to be done in real time with a vehicle travelling at about 80km/h over the track;

(iii) separate indices to be produced for welds (discrete irregularities) and for corrugation in the range 0.3-1.5m;

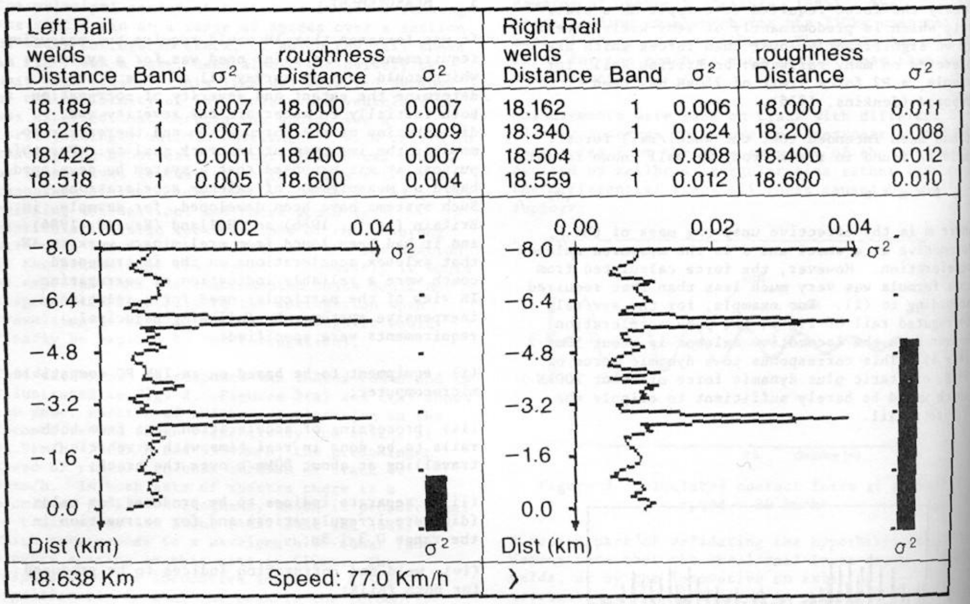
(iv) weld and corrugation indices to be produced for both rails;

(v) both hardware and software should also be directly useful for analysis of data acquired in a variety of experiments on vehicles and track.

A system satisfying these requirements, using a Compaq Portable III or Portable 386 microcomputer, has been developed, calibrated and tested. It is now used routinely by AN to measure railhead quality: by April 1989 almost all of the standard gauge system (about 6000km) had been surveyed twice. A full survey takes about a week. Separate indices for welds and corrugation are produced because these are treated differently: welds are straightened using STRAIT equipment while more general corrugation is removed by grinding. A third index is produced of the severity of corrugation on the rail following a weld to identify corrugated rails which may more economically be replaced rather than ground.

In operation, acceleration signals are first low-pass filtered and then digitised. The vehicle speed is found from a tachometer on a freely-running wheel of the instrumented coach; this signal is used to ensure that indices pertain to a datum speed of 80km/h and is integrated to determine distance along the track. Discrete irregularities are detected and their severity noted by detecting exceedences of acceleration thresholds. The severity of corrugation is given as the variance of the railhead roughness in the wavelength range 0.3-1.5m; this is found from the power spectra of axlebox accelerations, and is calculated for prescribed lengths of track; the index for severity of corrugation on the rail following a weld is found likewise.

A transfer function is required in order to calculate the railhead roughness from the axlebox acceleration. The shape of this transfer function, the lengths over which the corrugation indices are calculated, the rail length, starting distance along the track and the acceleration thresholds for the welds are specified by the user.



Left Rail

welds Distance	Band	σ^2	roughness Distance	σ^2
18.189	1	0.007	18.000	0.007
18.216	1	0.007	18.200	0.009
18.422	1	0.001	18.400	0.007
18.518	1	0.005	18.600	0.004

Right Rail

welds Distance	Band	σ^2	roughness Distance	σ^2
18.162	1	0.006	18.000	0.011
18.340	1	0.024	18.200	0.008
18.504	1	0.008	18.400	0.012
18.559	1	0.012	18.600	0.010

18.638 Km Speed: 77.0 Km/h ›

Figure 5 Screen displayed by *software for measuring railhead profile*

Data for welds and roughness are displayed in real *time on* the computer's VDU (Fig 5), thereby *allowing* a comparison to be made between the *measurement* and a subjective assessment of track *quality*. This is in fact a vivid demonstration of *well known* differences such as newly laid rail and curves. *Both* weld and roughness indices are stored *on disc for* later processing; one set of data may *also be printed* as it is collected. Because there *is some slight* sensitivity of the measurements to *vehicle speed*, data are flagged with the speed when *this falls* outside a range of 65-95km/h. Software has been written to produce from these detailed data the track quality indices which are most pertinent to programmes of grinding and straightening rail. The software can readily be modified in the light of experience and of developing requirements

The *digital signal processing* (DSP) boards used by the system are available off-the-shelf and were developed *initially* for general purpose analysis of noise and *vibration data*. Accordingly much of the signal *processing* is done on these boards, thereby *contributing to the* speed of the system. The principal *constraint on* speed is the rate at which the parent computer handles data from the DSP boards. *Although AN's* requirements were to measure long *wavelength irregularities*, the system could be *adapted to measure* shorter wavelengths. With microcomputers which are now available it should be *possible to* measure irregularities with wavelengths of 50-100mm.

AN's second requirement was for equipment which could accurately and quickly measure the profile of at most *a few hundred* metres of rail, such as the *rail length shown* in Fig 1. This equipment was required *in the first* instance to calibrate the measuring system based on instrumented axleboxes. It would *subsequently* be used, for example, to monitor grinding and changes in railhead profile at a few selected sites. For purposes of calibration, equipment was *obtained* which had been developed at Cambridge *University for measurement* of short wavelength *corrugation* (Grassie, 1983); slight modifications were *made to* allow the measurement of long wavelength *irregularities*. This equipment comprises a portable, *self*-propelled trolley which runs along one *rail* at *walking* speed; an outrigger and wheel run along *the other rail* to improve stability. The *profile is measured* with a sensitive accelerometer *which* is isolated dynamically from the *trolley and* which is in contact with the *rail*; *the acceleration* is integrated twice to *give the* railhead profile.

Measurement of *railhead profiles* using the axlebox accelerometers has been *calibrated* using the Cambridge equipment to *measure* accurately the profile of several *prescribed* lengths of corrugated track, each of about 200*m in* length. Axlebox accelerations were recorded at different speeds over the same sections of *track*; the amplitude of the transfer function was *calculated* from the power spectra. An example is *shown in* Fig 6 in which the transfer function calculated *for* the track and coach parameters of Fig 2 is *superposed* on the measured data. The close *correspondence* of calculation and experiment gives *confidence* in use of the equipment.

Measurements which have been *made to date* show, for example, a consistent *difference between* the transfer functions for track *on concrete* and on timber sleepers. Further work *is in* progress to obtain better estimates for *the transfer* function for different track. These *measurements* may also be used to estimate dynamic *ballast* characteristics.

In view of the success of the *Cambridge* equipment, another instrument has been *derived from* it with detailed modifications to make *it more* suitable for AN's requirements and also to *take* advantage of developments in transducers and *recording*

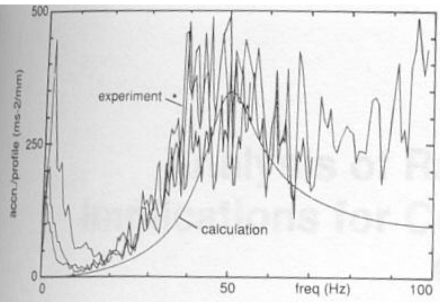


Figure 6 Transfer function of axlebox acceleration/railhead profile

equipment.

Both types of instrumentation developed for AN are now available commercially.

4 RECTIFICATION

Several strategies were examined to eliminate the corrugation problem, such as improvement in railhead quality, the use of resilient wheels on locomotives, reductions of speed and installation of heavier rail. It was clear from this study that the most significant and economical treatment was to improve railhead quality. This is now being undertaken in conjunction with a policy to ensure that locomotives which are purchased in future give substantially lower dynamic loads than those which have existed to date.

Limits on dynamic loading and on allowable railhead irregularities have been based largely on the loads required to cripple the rail and on calculation of vehicle response to a dipped weld or corrugation. The limit on allowable low frequency dynamic load (P2 force) which has been specified in light of the calculations of Table I is 200kN. For AN's locomotives this load would be exceeded on corrugation of 0.3mm amplitude peak to peak or at a weld misalignment of 0.4mm on a 1m chord (1.6 milliradians). It is intended steadily to improve AN's railhead quality to this standard in a combined programme of grinding of rail and straightening of welds using STRAIT equipment.

The requirement that vehicles give rise to dynamic loading of less than 200kN on track of the above standard at future operating speeds has already been used as one criterion in the selection of new locomotives for AN.

5 ACKNOWLEDGEMENTS

The author is grateful to his colleagues at Australian National, Pandrol Australia Pty Ltd, Cambridge Control Ltd, ACET Ltd and Thoroughbred Digital Systems Ltd whose diverse assistance during this project has contributed to its success.

6 REFERENCES

CLARK, R.A., SCOTT, G.A. and POOLE, W. (1988). Short wave corrugations - an explanation based on stick-slip vibrations. ASME Winter Annual meeting, Chicago

ESVELD, C. (1986). Measuring and rectifying rail roughness and bad welds, Proc. 3rd Intnl. Heavy Haul Railway Conference, Vancouver

GRASSIE, S.L., GREGORY, R.W. and JOHNSON, K.L. (1983). Dynamic loading of rails at corrugation frequencies. Rail Technology C.O. Frederick and D.J. Round (eds.), Derby, UK, pp225-236

GRASSIE, S.L. and COX, S.J. (1984). The dynamic response of railway track with flexible sleepers to high frequency vertical excitation. J. of Mech. Engng. Sci. vol. 198D, pp117-124

JENKINS, H.H., STEPHENSON, J.E., CLAYTON, G.A., MORLAND, G.W. and LYON, D. (1974). The effect of track and vehicle parameters on wheel/rail vertical dynamic forces. Railway Engineering Journal, vol. 3, pp2-16

KALOUSEK, J. (1975). Track-train dynamics. Canadian Pacific Railways, Report S488-75, unpublished

LEWIS, R.B. and RICHARDS, A.N. (1986). A new method for the routine measurement of railhead corrugations, Rail International, February 1986, pp37-41

MAIR, R.I. (1977). Natural frequency of rail track and its relationship to rail corrugation. Civil Engng. Trans., I.E.Aust., Paper 3494

MAIR, R.I., JUPP, R.A. and GROENHOUT, R. (1986). The characteristics and control of long pitch rail corrugation at heavy axle loads. Rail Research Papers, vol. 1, pp95-103, BHP Melbourne Research Labs. (reprint)

MARICH, S. and MAASS, U. (1986). Higher axle loads are feasible: economics and technology agree. Proc. 3rd Intnl. Heavy Haul Railway Conference, Vancouver