Ho, S.L. and Tsang, W.F.S. and Lee, K.K. and Lee, K.Y. and Lai, W.L.W. and Tam, H.Y. and Ho, T.K. (2006) ***Monitoring of the vertical movements of rail sleepers with the passage of trains.*** In: Proceedings of The Institution of Engineering and Technology International Conference on Railway Condition Monitoring, 2006, 29-30 November 2006, Brimingham.

Monitoring of the Vertical Movements of Rail Sleepers With the Passage of Trains

S.L. Ho[1], W.F.S Tsang[2], K.K. Lee[3], K.Y. Lee[3], W.L.W. Lai[2], H.Y. Tam[1], T.K. Ho[1]

[1]Dept. of Electrical Engineering, [2]Dept. of Building and Real Estate
Hong Kong Polytechnic University, Hong Kong
[3]Kowloon-Canton Railway Corporation, Kowloon, Hong Kong

Keywords: Vertical Vibration, Rail Track, Monitoring

Abstract

Due to an ever increasing demand for more frequent and higher volume of train service, the physical conditions of tracks in modern railways are deteriorating more quickly when compared to tracks built decades ago. There are incidences in both the UK and Hong Kong indicating there are needs for a more stringent checks on the rail conditions using suitable and effective non-invasive and non-destructive condition monitoring system.

1 Introduction

The demand for high quality rail services in the twenty-first century has put an ever increasing demand on all rail operators. A recent study carried out by RSSB [1] has confirmed that, because of increase in the traffic volume in modern railways, the vibrations experienced by trains have increased significantly. In the past, trains were designed according to GM/RT2100 to withstand train borne accelerations in the x- (longitudinal), y- (lateral) and z- (vertical) directions of ± 0.2 g, ±0.15 g and ±0.15 g, respectively. However, the findings of RSSB have indicated that such levels of anticipated accelerations are no longer practicable in a modern railway network. RSSB has therefore recommended that modern trains should be designed to withstand train borne accelerations of ± 0.2 g, ±0.40 g and ±0.45 g in the x-, y- and z-directions, respectively.

Towards the end of 2005, Kowloon Canton Railway Corporation (KCRC) has found that one compressor mounted in the underframe of a Mid Life Refurbished (MLR) train was partially detached from its anchor. The partial detachment was due to the failure of welding joints of two brackets. Subsequent scrutiny of the entire fleet revealed that the cracks due to the failure of welds are not isolated incidents. There is no single pattern, in terms of the type of car and the year of manufacture, which were more vulnerable to the unknown cause of excessive vibrations. This led to the initial conclusion that the cause of the cracks were system wide and could not be attributed to poor welds in individual equipments only.

2 Vibration found in Modern Trains

The Polytechnic University Team was invited, firstly to participate in the study of the crack issues and was subsequently invited to help identifying the root causes of excessive vibrations, since the occurrence of the compressor detachment incident. Many tests have been carried out since early January, 2006 using optical strain sensors. It was essentially observed that there were fairly high stress levels in some equipment and there were also fairly conspicuous frequency components of between 7 to 9 Hz in the strain measurements in a number of equipments at different train speeds. Moreover, it was found that the high stresses were generally observed in the z-direction which corresponds to vertical movement.

During some early measurements, there were signs of probable resonance being observed in the strain measurements as well. As the theoretical natural twisting frequency of the trains is around 7.3 Hz and subsequent investigation reveals that it is possible for the trains to vibrate at such frequency at certain train speeds, KCRC has taken a very responsible and prudent approach to look for the possibility of the train body being excited to vibrate at one of its natural frequencies of oscillation.

It is worth noting that the corresponding wavelength on the track when the train is vibrating at 7.3 Hz and at speeds of 70 kph and 80 kph is 2.66 m and 3.04 m, respectively. Since the wavelength of around 3 m corresponds to a sub-multiple of the track length which is 25 m, it might be possible for the track to vibrate with a wavelength of around 3 m and hence a series of investigations were also carried out and reported in this paper.

Moreover, several consultants working for KCRC have taken a lot of measurements since January, 2006 and it was found that the accelerations picked up by the Cars were on the high side, in most cases exceeding the original designed limits of ± 0.2 g, ±0.15 g and ±0.15 g in the x-, y- and z-directions. It was also observed that are possible track irregularities having a wavelength of 3.1 m on the track.

It is well known that there is a natural frequency of oscillation in the bodyshells of a train and hence it is expected that the strains would trace out a sinusoidal wave pattern on the sole bar if the bodyshell does vibrate at one of its natural frequencies of oscillation. Obviously there could be other frequencies on the vibration pattern as well due to other vibration sources such as from air-compressors which have local rotary movements. It should also be noted that if there are un-synchronized impacts onto the bodyshell due to the wheels hitting onto the welded joints on the rail, the smooth oscillation (due to natural vibrations of the bodyshell themselves) might be interrupted and there could be "sharp" turns observed. Fig.1 is one of the typical strain measurements taken and it is clear that there are "sharp turns" in the strains. It is further postulated that the time period between these "sharp" turns could be small if the impacts are generated by the impacts of two different axles (2.5 m in separation) of the same bogie as the wheels are hitting onto the rail joint. It could also be longer in time separation if the impacts are due to wheel axles of different bogies (i.e. the separation could be more than 13.6 m) hitting onto the same rail joint. When the excitations due to wheels hitting onto the rail joints are exciting the car body to vibrate at its natural oscillation frequency, the bending forces upon the bodyshells would be stronger and both the passengers and equipment, and to some extent even the rail track, will experience a strong vibration force.

In addition, it was subsequently found that some of the equipments, such as the compressor and the MA sets, are generating frequencies of their own due to the local rotary movements and the amplitude of these self generating frequencies could be fairly high. Such high self-generating vibrations could also speed up the fatigue life of some welds and hence should be addressed carefully.

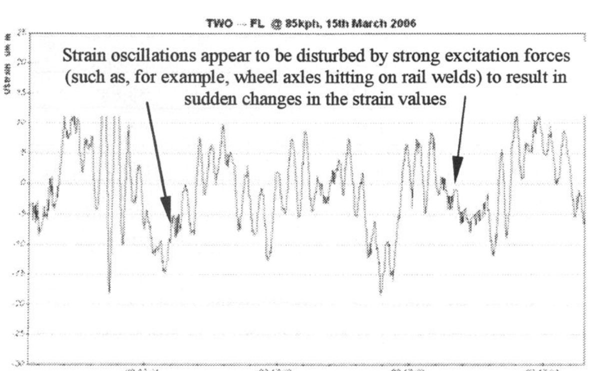

Fig. 1 Strain on the the sole bar of trailer car

3 Imprinting Theory

During the course of investigation it was found that the trains tend to vibrate at its natural frequency of oscillations of around 7 to 8 Hz and the vibrations appears to be strongest when the train is running at speeds of around 70 to 80 kph. Coupled with the observation that the trains appears to be hitting a track irregularity having a wavelength of 3.1 m, it leads one to suspect that either there is some inherent features in the track that has (either statically or dynamically) a track irregularity with a wavelength of 3.1 m or it could be due to the train imprinting a 3.1 m irregularity onto the track (and the track is able to respond positively to this imprinting force). Noting that the rail track are rolled out in lengths of hundreds of meters and then cut into lengths of 25 m (for KCRC) before being assembled *in situ*, it is not obvious why there are rich amount of 3.1 m irregularities on virtually the entire batch of rails from one supplier, notwithstanding the fact there are also some (particularly during dynamic measurements) 3.1 m wavelengths in tracks from other suppliers. One explanation to this observation is that this is due to the manufacturing process of the rail and indeed it was found that some tracks from a certain supplier have more prominent 3.1 m irregularities on the track. However such observation is not true in the same batch of tracks laid on concrete supports and hence such theory cannot fully explain the presence of 3.1 m irregularities. On the other hand, it is possible that during the manufacturing process, particularly during the straightening process of the rails, some memories could be left in the rail track to render such tracks more vulnerable to respond to certain wavelengths (which for the rails in issue, a wavelength of 3.1 m) of imprinting force. Hence a hypothesis is put forward which stipulates that the trains are stamping onto the rails with a regular wavelength of 3.1 m and if the rail or the ballast does have an inherent memory, the rail would respond positively to such stamping wavelengths.

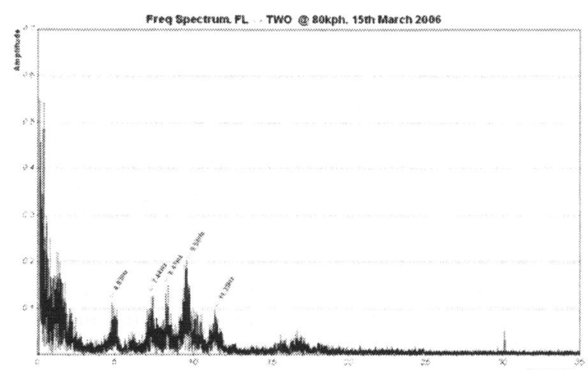

Fig. 2 Spectral Analysis of the strains on the sole bar of trailer car

Before describing the theory in details, one notes that the length of each train car is 25m. There are welded joints every 25 m in the rail and the separation of wheel-centres in the same bogie is 2.5 m. The distance separating the two nearest wheels of two different bogies of the same train coach is 13.6 m.

It is believed that an impulse is generated every time when a wheel hits onto a welded rail joint to generate a characteristic vibration pattern to give rise to the corresponding "roam-roam" sound. For trains running at a speed of "*v* meters per second", the two wheels separating by a distance of 2.5 m will generate a frequency of (v/2.5) Hz (hereinafter referred as frequency $\boldsymbol{A}$). For wheels separated by a distance of 13.6 m, it will generate a frequency of (v/13.6) Hz (hereinafter referred as frequency $\boldsymbol{B}$). The two frequencies will be picked up by the bodyshells and interact with each other and this is similar to the Pole-Amplitude Modulation in large induction machines which reverses the current flow in some windings to produce a modulated pole number [2]. Noting moreover that

$$\cos(\boldsymbol{A} - \boldsymbol{B}) = \cos \boldsymbol{A} \cos \boldsymbol{B} + \sin \boldsymbol{A} \sin \boldsymbol{B} \qquad (1)$$
$$\cos(\boldsymbol{A} + \boldsymbol{B}) = \cos \boldsymbol{A} \cos \boldsymbol{B} - \sin \boldsymbol{A} \sin \boldsymbol{B} \qquad (2)$$

By adding equations (1) and (2) together, one obtains

$$\cos \boldsymbol{A} \cos \boldsymbol{B} = 0.5\,[\,\cos(\boldsymbol{A} - \boldsymbol{B}) + \cos(\boldsymbol{A} + \boldsymbol{B})\,] \qquad (3)$$

where $\boldsymbol{A}$ and $\boldsymbol{B}$ in the equations correspond to the two frequencies generated as mentioned earlier. For the MLR trains, the train body hitting a rail weld joint will generate, at a speed of v meter per second, a vibration having a wavelength of :

$$\frac{v}{(v/2.5 \pm v/13.6)} = \frac{13.6 \times 2.5}{13.6 \pm 2.5} = 3.06m \ or \ 2.11m$$

In other words, it is possible for trains to stamp onto the rail track with wavelengths of 2.11 m and 3.06 m. Noting that the rail tracks are very rigid and hence it is easier for the rail to vibrate with a relatively longer wavelength, it is more likely that the track would vibrate at wavelengths of 3.1 m rather than 2.1 m, even though one could not eliminate the possibility of the rail track vibrating at 2.1 m if the conditions are favourable for the rail to vibrate with short wavelengths. In any case, the rail track will tend to vibrate at frequencies with a wavelength which is a sub-multiple of the rail length. Hence the track will respond favourably to excitations with wavelengths of 12.5 m (25/2m), 8.3 m (25/3m), 6.25 m (25/4), 5 m (25/5m), 4.17 m (25/6m), 3.57 m (25/7m), 3.125 m (25/8), 2.78 m (25/9), 2.5 m (25/10m), 2.27 m (25/11m), 2.08 m (25/12) and so forth. However the longer the wavelength, the more ready is the rail responding to such excitations since the rails are, after all, a long length of rigid steel. As the imprinting wavelengths are in the vicinity of 3 m and 2 m, the rail track is expected to respond more readily to the 3 m imprinting excitation.

The imprinting force is expected to be highest when the imprinting force excites the train to vibrate at its natural frequency. As the train travels at a speed of 80 kph (i.e. 80/3.6 m per second), and if the natural frequency of oscillation of the train is around 7.3 Hz (80/3.6 m per second / 7.3 cycles per second to give a wavelength of 3.04 m), the imprinting force is indeed exciting the train body to vibrate at its natural frequency of oscillation and leave behind imprinting marks with a wavelength of 3.04 m on the track. Of course, even if the natural frequency of oscillation of the bodyshell is not exactly 7.3 Hz, impulses exciting the bodyshell to vibrate in the vicinity of 7.3 Hz would also cause the bodyshell to vibrate with relatively large amplitudes.

Moreover, it should be noted that as the train is loaded with passengers, the natural frequency of oscillation is reduced and the train would be excited to vibrate at its newer (and in fact lower) frequency of oscillation. Under such condition, the imprinting energy onto the track is lower as the train is travelling at a lower speed (i.e. a lower resonating speed will require the train to run at a lower speed in order to resonate. If the resonating frequency is 4 Hz, then the train will need to run at 45 kph in order to resonate) and hits on the rail welds with less force and less energy. It could indeed be shown that there are characteristic frequencies generated at different train speeds and most of the identifiable frequencies in Fig. 2 could be explained by referring to the imprinting theory.

4 Rail Irregularities

As it is possible that the trains vibrate because of rail irregularities in the vertical direction, a section of rail was measured using a "precision level" instrument which has a resolution of 0.1 mm. It was found there was no major cyclic variation that has a wavelength of 3.1m. Instead the more prominent waveforms were 6.4 m, 9.6 m or 12.8 m and all these are multiples of 3.2 m.

Table 1 Measured Vertical Variation of the rail surface

Wavelength (m)	Peak-to-peak amplitude (mm)	% of peak-to-peak values when compared to that at 6.4 m
2.56	0.0695	62.20
2.84	0.0582	52.06
3.1	0.0127	11.39
3.2	0.0022	1.99
3.3	0.0376	33.68
3.5	0.0271	24.30
6.4	0.1117	100.00
9.6	0.1301	116.42
12.8	0.1216	108.82
16	0.0518	46.40

The power spectral density of the measured rail top vertical undulations is as shown in Fig. 3. It can also be seen from the figure that there is no prominent wavelengths in the order of 3 m.

5 Vibrations measured on the Rail Tracks

In a typical modern railway, there are rail joints every 25 m. However the locations of these rail joints (on the left and right hand side of a track) are randomly staggered along a track and are seldom synchronized along the track length. Moreover, due to the differences in material hardness and surface undulations of rails and the rail joints, the wheels would appear to be hitting a small obstacle as the wheels are running over the joints and as a result the knocking of the rails on the train wheels, it would cause the train itself to vibrate though this vibration should somewhat be attenuated by the train carriage's suspension system. Additional vibrations occur when trains pass over switches and crossings. The level of shock and vibration transmitted to the train carriage/body is dependent on the effectiveness of the train's passive suspension system. If the suspension system is unable to absorb most of the shock and vibration which is picked up between the wheel and rail as well as the train carriage and the bogie, the train ride would appear to be rather bumpy. Excessive shock and vibration could be further aggravated by wheel imperfection/flatness or eccentricity of axle or out of roundness in the wheels.

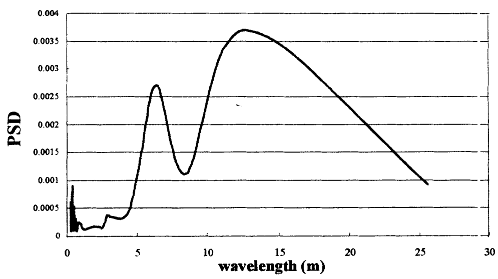

Fig. 3 Power Spectral Density pf the rail top vertical undulations

With excessive vibrations, it is not only the equipments on board a train that would suffer from mechanical and electrical damage. The shock and vibration could also implant some physical damages onto the rail track or to leave behind some ballast memory along the rail. Trains running over tracks in poor conditions will suffer faster deterioration (in terms of materials strength and integrity) than good tracks. Failures of materials as a result of exposure to extremely high stresses (due to great shock) and metal fatigue (due to stress reversal) would ultimately be detrimental to the overall structural integrity of the rolling stocks as well as the rail tracks.

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Experimental observations reveal that the vertical displacements of a rail at some sleeper position along the rail are more serious than the others. This is believed to be a result of the ballast memory effect due to the "wheel knocking" phenomenon on rail joints. To obtain valuable experimental and quantitative data, a videograpahic and image processing based technique using a cameral is proposed and has been employed successfully to monitor the dynamic vertical displacement of a target/marker fitted to a rail track at a position just on above a sleeper.

Literature search found two recent International Conferences on 'Maintenance & Renewal of Permanent Way; Power & Signalling; Structures & Earthworks' held in UK in 2004 and 2005 [3, 4]. A number of track condition monitoring techniques has been reported. However, the search found no previous attempt of the application of this kind except the one [5] that used a non-contact measurement system by utilizing two line lasers and a digital camera mounted to the underside of a railcar truck, Each laser generated a curve across the rail head. The monitoring system provided the relative displacement of the rail and the railcar truck by measuring the distance between the two generated laser curves by the two lasers.

5.1 The videographic and image processing based track deflection/condition Monitoring System

This system relies on continuous pattern matching of the changes of target images produced by the vertical loads imposed by the passing train bogies. The system offers remote sensing capability so that no instrument and hardware (except a paper marker) needs to be attached to the rail, as any large physical attachment on rails would endanger or de-rail a running train. Moreover, no test personnel is required to work close to a running train during the measuring process. As the technique is visual, it offers easy checking and the whole monitoring process is both intuitive and informative even to lay-person. The system is also relatively cheap, offers easy expandability and provides accurate measurement, in which the spatial resolution of deflection of the detection system is 0.1 mm.

The target is a sticker with a chequer board style pattern in black and white with correct grid size. An example of this sticker is shown in the Figure 4. Part of the pattern printed on the sticker would be learnt by the *NI IMAG* image processing card and its movement/displacement measured in pixel units. The latter would then be converted to real displacement unit in mm.

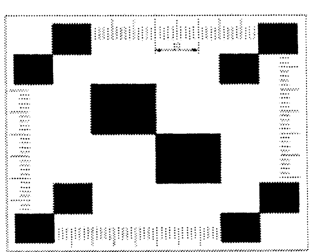

Fig. 4 Target for Videographic measurement

A series of improvement have subsequently been attempted. The Mark II version of the system is more rudimentary and involves the use of up to 8 separate channels/systems with artificial synchronization of a number of human operators. The Mark III version makes use of external light illumination. Each of the target is illuminated with 'bright light' by up to 8 series connected LED lights to create a simultaneous 'over-float' response/ condition as the bright light cause the pattern recognition software to go into an 'indeterminate' condition.. The Mark IV version improves this by using synchronization through an arbitrary start 'string' received via a daisy-chained Ethernet connection between the 7 to 8 separate systems.

An ultimate goal of acquiring and building a hard-wired synchronized multiple camera system has not been attempted as the cost of purchase of these high-speed hard-wire with synchronizeable camera system are prohibitively high and beyond our reach.

5.2 Evaluation of the System

This system can offer many advantages: i.e. it offers remote sensing capability without the need of any test personnel. Initial findings based on a trial using just one camera are in agreement with the observations i.e. some sleepers are indeed observed to have large vertical displacement when compared to others.

The integrated multiple-camera system is able to give a more comprehensive picture of the way different sleepers respond to the same passing train. Figures 5.1 to 5.7 show the dynamic vertical displacement of 7 consecutive sleepers with designated marking M1, M2, …, to M7. It can be seen that the vertical displacement of all sleepers are of similar pattern although there are variation in the vertical amplitudes. In other words, it appears that the trains would experience different vertical movement as it moves over different sleepers. Such different vertical movement could in fact excite the trains to vibrate at its resonance frequency if the conditions are favourable for such vibrations.

Furthermore, the observed pattern is characterized by the fact that the sleepers' vertical displacements always return to the initial positions before and after each passing of a bogie.

5.3 Snap-shots of rail track deflection profile at different Time Instant

The information and data gathered with this monitoring system are the deflection amplitudes at the locations mounted with the stickers/targets at the time instants when data were taken. An example of that is shown in Fig. 6. A flowchart showing the process of the videographic and image processing algorithm is shown in Fig. 7.

Individual monitoring channel provides the deflection of the target position over time. With an assembly of the 7 monitoring target positions as shown in Fig. 8, the track deflection at the same time instant over the spatial distribution and layout of the placement of the targets can be plotted. Subjected to the choice of appropriate acquisition time interval, a 'virtual' (and not exactly a 'true' instantaneous profile) can be obtained. Had the true instantaneous profile been available, then the stress analysis of each profile can be performed to yield information on the stress related behaviour/response of the track. An example of such a profile is shown in the Fig. 9

6 Limitations of the system

The monitoring basically integrate together a number of commercially available hard- and software, such as: a digital video Camera with composite video output, a *National Instrument (NI)* Image grabber card, the *NI IMAG* image processing card, a PC running on *PXI* platform (which is more stable and robust than *PCI* platform) and an in-house developed software based on *LabView*.

The overriding factor or bottle-net as far as the speed of processing involved is concerned is the video frame refresh rate of the composite video output of the camera and the *IMAG* card. The fastest rate of around 25 frames per second is achievable per each monitoring channel. This will in turn dictate the fastest time sampling rate of track deflection per channel. Fortunately, the track deflection with a train running no faster than 120 km/hour is considered slow or quasi-static enough for this time sampling rate to suffice. If a maxima or minima of track deflection happened between time sampling rate the, then their correct amplitudes would not be captured correctly.

It is generally difficult to inspect and monitor track movement with the train running over it or without any instrumentation physically attached to it. The system being advocated and reported here provides an option for remote-sensing monitoring without the need or risk of inspection by workers walking on the track or very close to it. Unlike other approaches and methods which are not conducted on a train in normal running condition, the system provides a direct, intuitive behaviour of the train and the track as it happen on the spot (not in an inspection yard/depot).

7 Conclusions

In a modern railway, the stress imposed upon the rail tracks are becoming increasingly high. There are many causes of rail deflection and it is important to identify appropriate parameters for suitable condition monitoring. The use of videographic and image processing based track deflection/condition Monitoring System is one of the possible platform to assess the condition of rail tracks to ensure the trains could continue to provide a smooth ride for the patrons who are, understandably, demanding an ever-improving train ride comfort.

Figs. 5.1 to 5.7 showing the vertical deflection of the sleepers with the passing of 12 cars

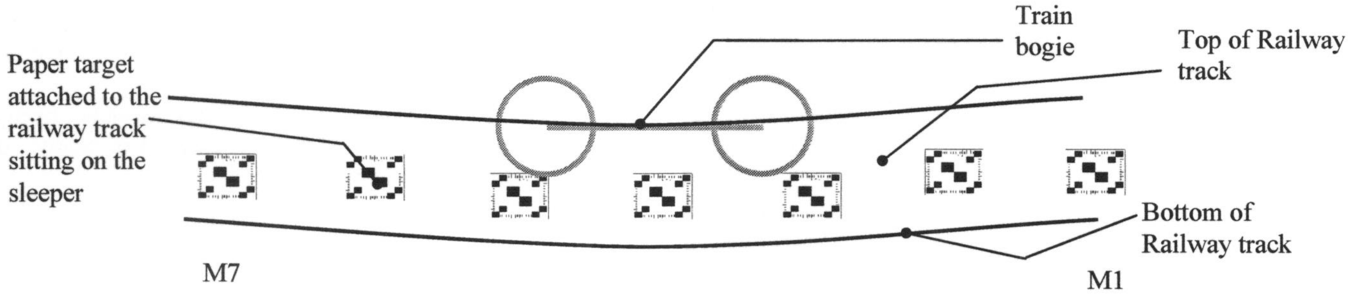

Fig. 6 Schematic showing a train bogie on top of a rail with target stickers on the rail

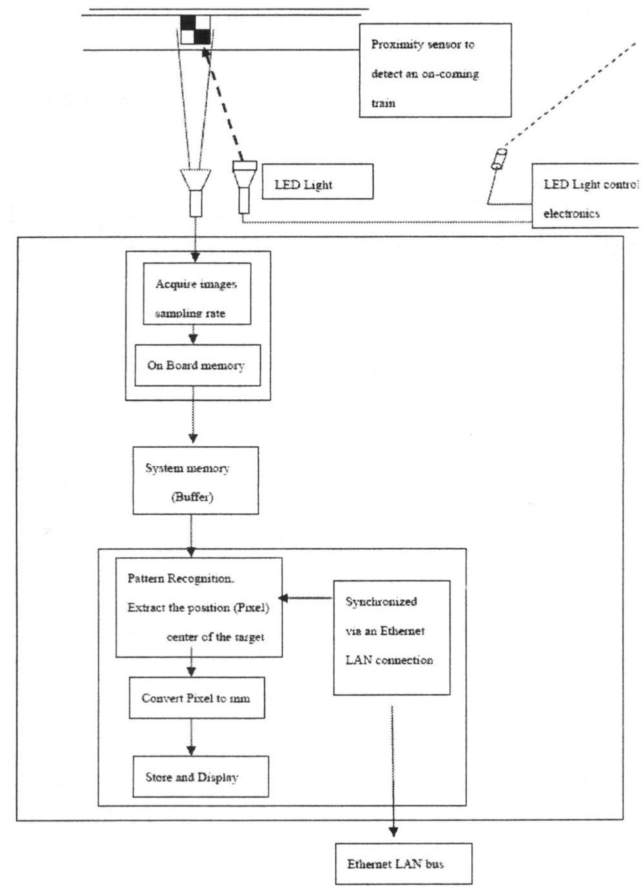

Fig. 7 Schematic showing the flowchart for the videographic and image processing algorithm

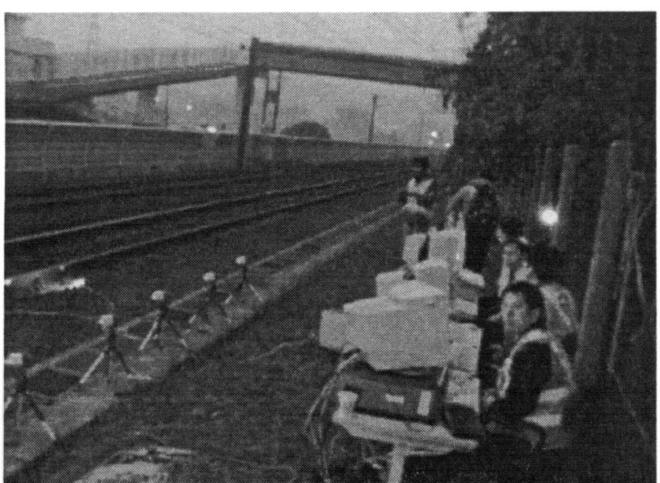

Fig. 8 Setup of the Multi-camera monitoring System along a rail track

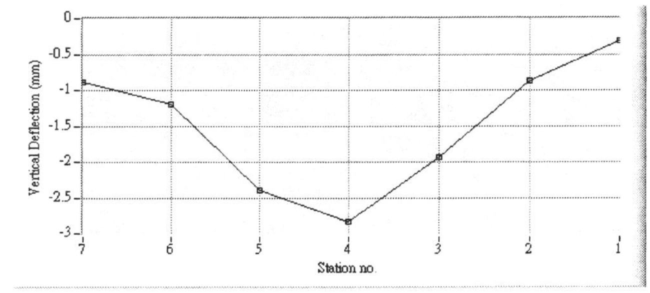

Fig. 9 An example of a track deflection profile

8 Acknowledgement

The authors wish to express their grateful to KCRC for supporting the investigations and allowing the authors to publish the work as described in this paper.

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