Reducing Secondary Noise on Nanjing Metro, China

Mr. Xi, Yinong (1), Mr. Tao, Sha (2),
Mr. Liu, Peng (3), Mr. Zhang, Xuehua (4), Mr. Du, Maojin (5), Mr. Barlow, Steve (6)

(1) Senior Engineer, China Ship Scientific Research Centre, Wuxi, Jiangsu, China
(2) Engineer, China Ship Scientific Research Centre, Wuxi, Jiangsu, China
(3) Engineer, China Ship Scientific Research Centre, Wuxi, Jiangsu, China
(4) Senior Engineer, Director of Works Centre, Nanjing Metro, China
(5) Engineer, Nanjing Metro, China
(6) Track Engineer, Pandrol Rail Fastenings Ltd., Australia

ABSTRACT

Pandrol Ltd. has been supplying its low stiffness VANGUARD rail fastener to metro operators throughout China since 2004. The Pandrol VANGUARD system uses the principle of rubber in shear to support the running rail by the web and the underside of the railhead, which allows the fastener to develop very low vertical support stiffness. This is demonstrated by the reduction of secondary (or re-radiated) noise inside buildings adjacent to metro tunnels. In 2009 Nanjing Metro made a trial fitting of Pandrol VANGUARD on Line 1. It was retrofitted in place of the existing slab track fasteners thus the performance differences between the two could be measured in terms of the insertion loss. The China Ship Scientific Research Centre was commissioned by Nanjing Metro to make relevant measurements of noise and vibration. This paper describes the results in terms of vibration measured inside the tunnel, the ground vibration above the tunnel and noise inside a building above the trial site.

.

INTRODUCTION

The city of Nanjing, in Jiangsu province, began construction of its Metro system in the year 2000. The 22km Line 1 was opened in September 2005. In May 2010 a 25km extension to Line 1 was opened along with the 41km Line 2. Further lines are under construction and within 20 years there will be a fully integrated metro network serving the city. This network will comprise 17 lines and will be complete by the year 2030.

As is often the case when building metro lines in city environments, precautions are taken to avoid unwanted noise or vibration impact on existing buildings. Nanjing, like all other modern cities, will have metro tunnels running very close to sensitive receivers in residential and commercial buildings. To minimise the impact of regular trains on the occupants of these buildings, mitigation of ground vibration is necessary. This works most efficiently if the treatment is applied at source, i.e. on the track. One of the most effective ways to do this is to install low stiffness rail fasteners, such as Pandrol VANGUARD.

FUNCTION OF LOW STIFFNESS RAIL FASTENERS

The baseplate fastener in use on Nanjing Metro Line 1 and also in common use on metros throughout China is the DT-VI-2 baseplate, (Fig 1). This is a simple cast iron baseplate containing a 12mm thick rail seat pad and a 16mm thick baseplate pad. It is anchored directly to the track slab by means of two offset anchor bolts. The 60kg rail is fastened using two steel spring clips. In terms of stiffness it is a medium stiffness baseplate, which has been previously measured [Pandrol report 85171-22, 2004] at 52kN/mm static vertical.

As with all conventional baseplates of this type, there is a lower limit to the vertical stiffness that can be provided. This is governed by the ability of the baseplate to restrict and control the amount of rail roll, or dynamic gauge widening under train passage. Since the efficiency of vibration isolation is directly related to low vertical stiffness, conventional fasteners are useful to a point, but for anti-vibration performance, alternatives must be considered.

Figure 1 Nanjing Metro DT-VI-2 baseplate

The Pandrol VANGUARD system (Fig 2) consists of two rubber wedges, each shaped to match the rail web, which clamp the rail transversely against the web and support the underside of the rail head. The rubber wedges are firmly mounted in a cast iron cradle that, in turn is directly bolted down to the track slab. The principal advantage of the system over more conventional fastenings is that it allows significantly greater vertical rail deflections under traffic, without an unacceptable accompanying degree of rail roll. The lower stiffness of the track leads to an improved distribution of the impacts generated at the wheel-rail interface. This reduces the level of dynamic forces transmitted through the fastener into the track foundation and beyond.

It was proposed to replace the existing DT-VI-2 baseplates at one vibration sensitive location with Pandrol VANGUARD, and importantly, the new baseplate had to be a straight swap for the existing one. In particular, it would have to be an exact match for the existing rail height and fit on to the existing anchor bolt pattern. Additionally, it would have to replace the existing fastener with zero disruption to operating traffic.

The vertical static stiffness of Pandrol VANGUARD is around 5kN/mm, which is a factor of ten less than the incumbent baseplate. This large change in stiffness is the key to reducing wheel-rail generated ground vibration. Large reductions in the vertical support stiffness result in reductions to the loaded track resonance frequency, which attenuates ground vibration in the critical low frequency bands. The efficiency of the system in controlling in-tunnel and surface ground vibration has been widely reported [Sunley & Cox, 2000, Wang et al, 2008, Barlow, 2004].

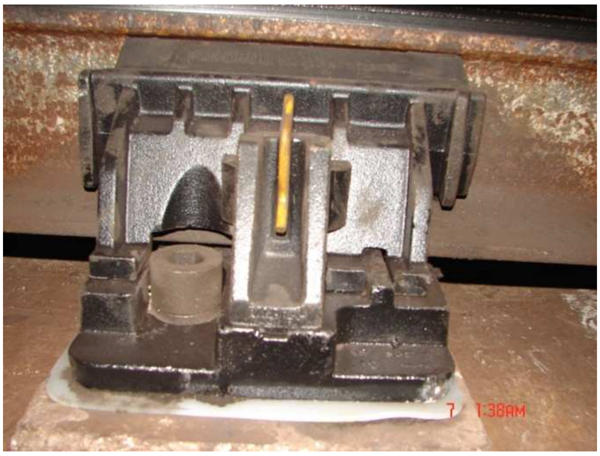

Figure 2 Pandrol VANGUARD low stiffness fastener

DESCRIPTION OF STUDY

This track trial in Nanjing Metro was commissioned to investigate several aspects of vibration and noise pollution from underground railways, as follows:

- The vibration insertion loss as measured at track level in the railway tunnel.
- The vibration insertion loss as measured at the ground surface above the operating tunnel.
- The reduction of secondary (re-radiated) noise inside a building immediately above the operating tunnel.
- The change in surface vibration as a result of routine grinding of the rail head.

The test site was located at chainage 13K+139, the centre point of a 120 metre test fit of Pandrol VANGUARD on the northbound tunnel of Line 1 between Xinmofan Road and Nanjing Main railway stations (Fig 3). The test site was on a right hand curve of 360 metre radius. Average train speed through the site was 60kmh. The rolling stock was 6 car EMU's, track gauge is 1435mm.

It is known that this section of track is subject to rail head wear. Routine maintenance grinding of the rail is used to control excessive growth of rail roughness.

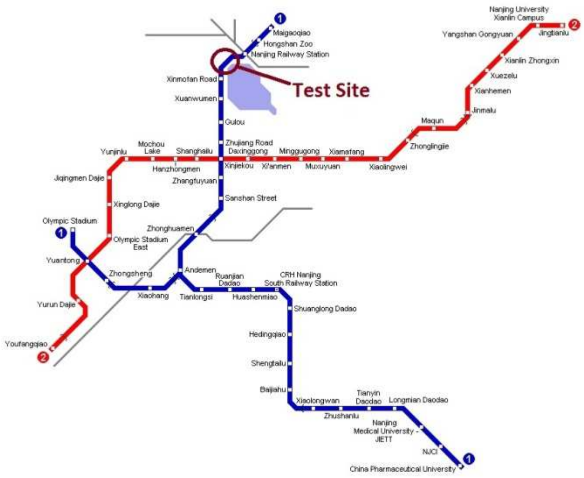

Figure 3 Location of test site on Line 1

Sequence of measurements

The sequence of testing is shown in Table 1. The Pandrol VANGUARD fastener was retrofitted during December 2010. Since some four months had elapsed since the original measurements, it was thought that some deterioration of the condition of the rail head through excess wear, might have affected the results. The rail was therefore subjected to a maintenance grind on 4th March 2011 and a new set of measurements taken shortly thereafter.

Table 1 Sequence of testing

Case	Test date	Time since previous rail grind	Fastener type	Sound and vibration readings taken?
1	20th Sept 2010	6 months	DT-VI-2	Yes
2	6th Jan 2011	10 months	VANGUARD	Yes
3	9th March 2011	5 days	VANGUARD	Surface vibration only

MEASUREMENTS AND RECORDING

Nanjing Metro Company commissioned the China Ship Scientific Research Centre to conduct all of the testing throughout the trial. The principle areas of interest were:

- In-tunnel vertical vibration of the low rail (A1)
- In-tunnel vertical vibration of the track slab adjacent to fasteners (A7)
- Tunnel wall vertical vibration (A9)
- Vibration of ground surface positions above tunnel (G1 and G2 vertical)
- In-building noise above tunnel (secondary noise)

In-tunnel vibration

Rigidly mounted accelerometers were used for measuring vibration in the vertical plane on the rail, on the track slab (Fig. 4) and on the tunnel wall. These were located in identical locations for both the DT-VI-2 and Pandrol VANGUARD measurements. Data was recorded on a multi-channel Data Acquisition System with direct capture and analysis capability. Data was processed using a PC.

Acceleration levels in ⅓ octave bands were then determined. All in-tunnel results and plots shown are based on these ⅓ octave band vibration levels. The total vibration levels across the entire frequency range were also calculated. All vibration results were expressed in decibels relative to a reference acceleration of $1x10^{-6}$ m/s^2.

Given the known train axle and bogie spacings, the vibration readings were used to derive train speed. It was found that all test trains were running between 58 and 61kmh.

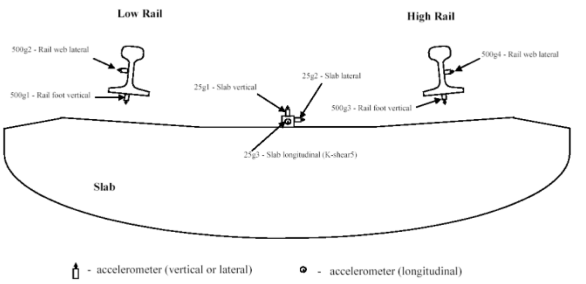

Figure 4 Positions of rail and slab-mounted accelerometers

Ground surface vibration

The position of the ground surface accelerometers G1 and G2 are shown in Figure 5. They were rigidly mounted at ground level in the yard located outside Room 101, No. 6 Building, No. 2 Liaojiaxiang, Nanjing (Fig. 6). G1 was located at the south side of the entrance courtyard, G2 was central in the yard.

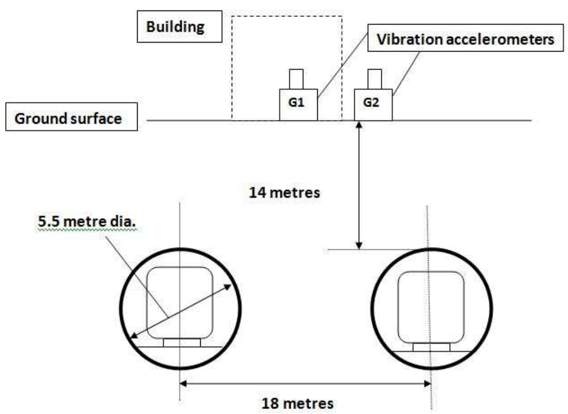

Figure 5 Schematic cross section showing location of surface measurement

For vibration measured on the ground surface, Chinese National Standards prescribe both the method of measurement (GB10071-88) and the limits that have to apply (GB10070-88). These standards use vibration acceleration levels weighted and expressed in units of dB(Z) using parameters defined in ISO2631-1 (Evaluation of human exposure to whole-body vibration). Linear levels of vertical ground vibration in the frequency range 1 Hz to 80 Hz were measured, weighted and expressed in dB(Z) in accordance with the National Standard.

Figure 6 No 6 Building Laojiaxiang Road, Nanjing

Secondary (in-room) Noise

In-room (secondary) noise was measured using a B+K handheld detector (Fig 7). The applicable Chinese Standards are GB 22337-2008 "Social limits for environmental noise emission standards" and GB3096-2008 "Environmental sound quality standards". The location of measurements was in a ground floor bedroom, which is defined in the Standards as a Class A room. There are two applicable requirements. Firstly GB22337-2008 limits the maximum A-weighted daytime sound level to 40dB(A) for a single train pass event. Secondly in the same standard, five octave band sound pressure level limits are defined between 31.5Hz and 500Hz. Each octave band limit must be met.

Figure 7 Measuring indoor sound levels

DISCUSSION OF RESULTS

Note. In tunnel vibration readings were taken in Case 1 and 2 (see table 1), but were not repeated after rail grinding, Case 3.

Key to Figures 8 to 10
Blue curve = Pandrol VANGUARD
Purple curve = DT-VI-2

Rail vibration

Note. Apart from vertical vibration, readings of lateral vibration were also taken on the rail, at slab centre and on the tunnel wall, but are not shown here for clarity. The results from lateral vibration readings were very similar in nature to the vertical measurements.

Figure 8 shows vertical vibration measured on the low rail for both DT-VI-2 and Pandrol VANGUARD fasteners (A1).

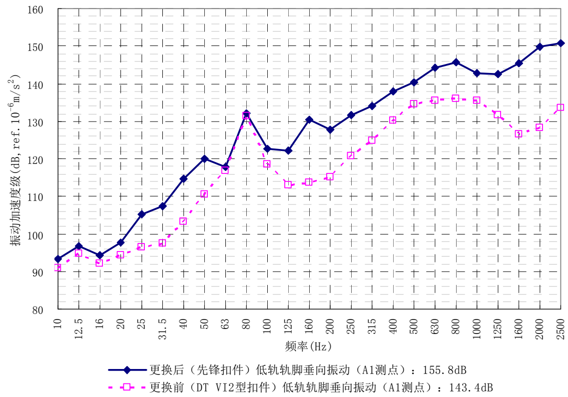

Figure 8 Low rail vertical vibration (A1)

In each case there is a characteristic peak vibration at 80Hz. It should be noted that, although not shown here, similar measurements on the high rail showed a characteristic peak at 50Hz. The reason for these peaks is presently unknown, but may come from a system resonance or external source. This is discussed later. Both of these frequencies have a dominant effect on ground vibration.

It should also be noted that the rail vibration increases when Pandrol VANGUARD fasteners are installed. This behaviour is expected because of the increased level of rail mobility with the low stiffness fasteners.

Slab vibration

Figure 9 shows the vertical vibration recorded at the centre slab position, midway between the two running rails (A7). The characteristic peaks of rail vibration identified on the rail at 50Hz and 80Hz can be seen in these plots. Despite the predominance of these peaks it can also be clearly seen that there is considerable mitigation of the slab vibration in the range 40Hz to 150Hz, the most vital range for controlling ground vibration. This is the expected outcome from installing Pandrol VANGUARD, due to the reduction in overall track support stiffness. The overall slab insertion loss, or reduction in vertical vibration is 7.4dB.

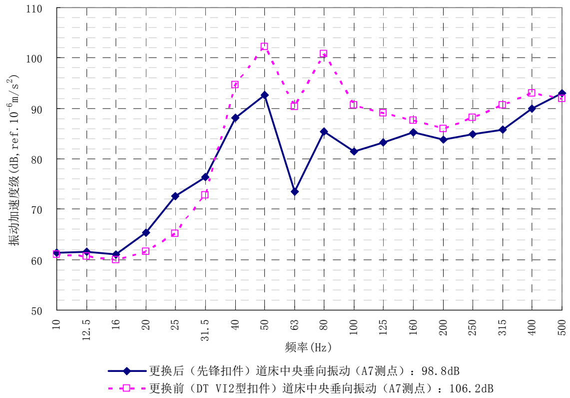

Figure 9 Slab centre vertical vibration (A7)

Tunnel wall vibration

Figure 10 shows vertical vibration measured on the tunnel wall (A9). There are substantial reductions in ground vibration in the important frequency range above 40Hz, particularly in the 50Hz and 80Hz bands where the characteristic system resonance is mitigated.

Overall tunnel wall vertical vibration insertion loss was measured at 7.9dB.

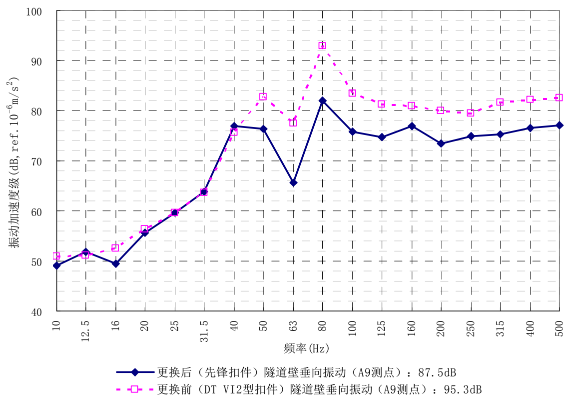

Figure 10 Tunnel wall vertical vibration (A9)

Ground surface vibration

The Z-weighted vibration readings taken at points G1 and G2 on three occasions are shown in Table 2. The figures are given in dB(Z), the maximum (Lmax) vertical vibration between 1Hz and 80Hz according to the Chinese Standard. It can be seen that the prescribed daytime limits are met after fitting Pandrol VANGUARD. After grinding of the rail, further reductions in ground surface vibration were recorded. These final measurements fell within the night time limits set out in the National Standard.

Table 2 Ground vibration readings

Vertical surface vibration Lmax (1 - 80Hz), dB(Z)	Point G1	Point G2
DT-VI-2 fastener	74.3	74.1
VANGUARD before rail grinding	68.7	66.2
VANGUARD after rail grinding	63.8	62.5
GB10070-88 defined vibration LIMITS	Daytime max 70.0 dB(Z) Night-time max 67.0 dB(Z)	

The unweighted spectra for points G1 and G2 are plotted in Figures 11 and 12 respectively. The charts show the changes at each phase of the testing. Swapping fasteners for the low stiffness Pandrol VANGUARD has a significant effect on ground vibration, particularly in the 50Hz and 80Hz bands. Further improvements are evident after the rail has been subjected to maintenance grinding. The overall linear insertion loss as a combined result of Pandrol VANGUARD and rail grinding is 13.2dB at point G1 and 13.6dB at point G2.

Key to Figures 11 and 12 (also refer to Table 1)

Brown	First case DT VI 2 measurements
Dark Green	Second case after Vanguard installed
Purple	Third case after rail grind
Blue hashed	Average background vibration

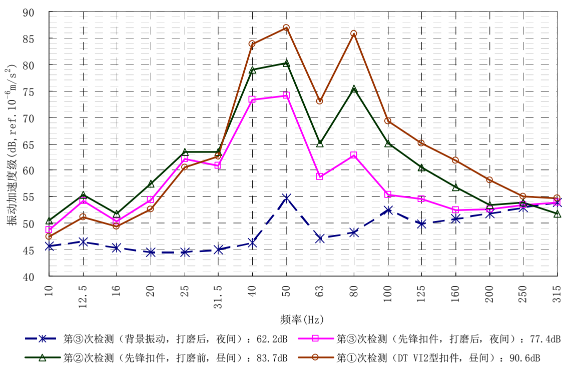

Figure 11 Surface vibration at point G1

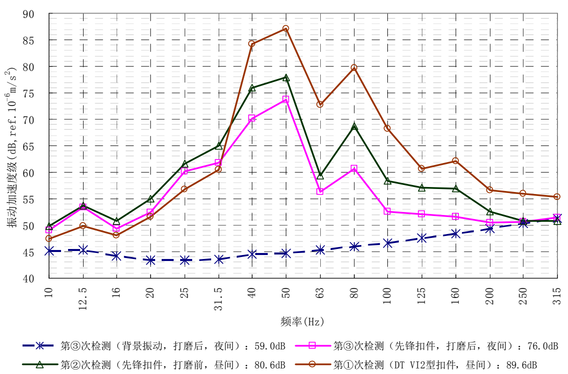

Figure 12 Surface vibration at point G2

It should be noted that approximately 4 months had elapsed between the DT-VI-2 and Pandrol VANGUARD measurements. As this section of track is susceptible to rail head surface wear, the comparison between the first two sets of results would have been affected. Ideally, for a direct comparison between fasteners and to eliminate the effect of rail smoothness changes, measurements should be taken immediately before and after the retrofit.

Secondary (in-room) Noise

Indoor noise measurements were taken both before and after the replacement of the fastener, but were not repeated after rail grinding. Multiple train pass events were recorded for each case. Some of these were eliminated from the results where background interference was too great (aircraft and other internal noises from neighbouring residences).

Indoor noise was measured according to Chinese Standard limits imposed for a Class A ground floor bedroom location (see description above). Table 3 shows LAeq, the average A-weighted sound for train pass-by events with DT-VI-2 and Pandrol VANGUARD fasteners installed.

Table 3 A-weighted sound for train pass-by event

	Average A-weighted sound per train pass, LAeq (ref. $2x10^{-5}$ N/m^2)
DT-VI-2	55.1dB(A)
VANGUARD [Insertion Loss]	35.3dB(A) [19.8dB(A)]
NATIONAL LIMIT (daytime)	**40.0 dB(A)**

Figure 13 shows the linear sound pressure levels between 10Hz and 2500Hz measured before and after Pandrol VANGUARD was installed. The replacement with a low stiffness fastener resulted in a significant reduction in secondary noise levels. On the linear scale, the total level has reduced by 12.8dB. The A-weighted sound reduction, from Table 3 is 19.8dB(A).

It can be seen that for these secondary sound readings there is still a notable peak in the 50Hz region.

Key to Figure 13
Blue curve = VANGUARD
Purple curve = DT-VI-2

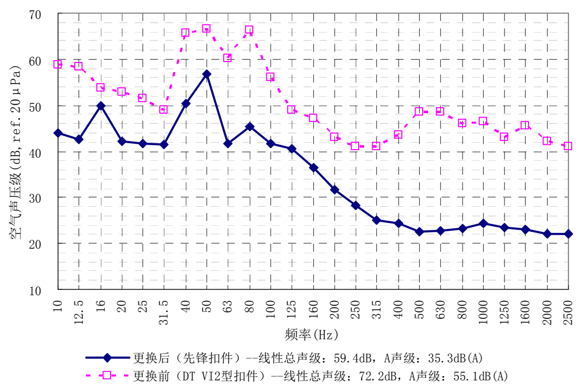

Figure 13 Linear sound pressure levels before and after VANGUARD (ref. $2x10^{-5}$ N/m^2)

Finally, the 5 octave band linear peak sound readings for Pandrol VANGUARD are given in Table 4 in accordance with Chinese Standard GB22337-2008. In each case these comply with the maximum defined daytime noise limits.

Table 4 Peak sound levels in 5 octave bands (VANGUARD)

Peak sound pressure levels - dB linear (ref. $2x10^{-5}$ N/m^2)					
Octave band	31.5Hz	63Hz	125Hz	250Hz	500Hz
Average of 8 trains (dB)	51.3	57.1	44.8	33.6	27.7
GB22337-2008 LIMITS	**76.0**	**59.0**	**48.0**	**39.0**	**34.0**

CONCLUSIONS

As expected, rail vibration increased when a low stiffness Pandrol VANGUARD fastener was installed in place of the DT-VI-2. This is due to the increased dynamic mobility of the rail as a result of the changeover.

The change to a lower stiffness fastener has brought a significant reduction in the track slab vibration, which is consistent with similar measurements made in other locations (Wang et al, 2008).

Tunnel wall vibration has been significantly reduced, although the resonances at 50Hz and 80Hz are still notable.

Ground surface vibration readings were conducted on three separate occasions. There was a significant reduction in ground vibration after Pandrol VANGUARD was installed. It should be noted that there was an interval of approximately 4 months in between the original (DT-VI-2) measurements and the Pandrol VANGUARD readings. The ground surface vibration reductions were nonetheless impressive, and more so after a routine maintenance grinding of the rail.

Indoor secondary noise readings show that the criteria required by the applicable Chinese National Standards inside this building were met. This had been one of the main project objectives.

The A-weighted insertion loss (10 to 2500Hz) of 19.8dB(A) means that train pass-by events that had been clearly audible inside the building became barely audible after Pandrol VANGUARD was installed.

As a result of this study further installations of Pandrol VANGUARD are planned by the Nanjing Metro authorities.

FURTHER DISCUSSION

Insertion loss

The units of measurement used in this study are based on the Standards that apply in China. For surface vibration, the unit dB(Z) has a defined spectral content and weighting. The secondary noise measurements taken inside the building were defined in dB(A). Reports of insertion loss at each measurement location should therefore be treated in isolation.

Resonance Peaks

The reductions in ground vibration and secondary noise were for the most part in line with expectations prior to the trial. This is despite the contribution of the vibration peaks seen at 50Hz and 80Hz. The reason for these peaks has not been established at the time of writing, although there are several possibilities. Given that the 50Hz peak shows up quite clearly in the surface background vibration (G1, Fig 11) this implies that it is not a characteristic resonance of the train/track system. It could be due to an external disturbing force in the locality around or within the building. Possible candidates for this are air-conditioning units, extraction/ventilation systems or other large electrical plant. There also remains the possibility that it could be A/C electrical interference, although this would not explain the rail vibration resonance. Identifying of the cause of these peaks should be the subject of further investigation.

Rail grinding

Given the results from Table 2 and Figures 11 & 12, it would be useful to study the relationship between rail head roughness and surface vibration. This would establish the individual contributions made by both fastener change and rail grinding.

It is unlikely that the low frequency peaks at 50Hz and 80Hz would be affected by rail grinding, since at 60kmh train speed, these frequencies correspond to 33cm and 21cm wavelengths respectively. Rail grinding is not effective at mitigating acoustic rail roughness at such long wavelengths. However the reduction in overall surface vibration after grinding is clear, so further study to establish the contribution of grinding is merited.

REFERENCES

V. Sunley and S. J. Cox *Pandrol Vanguard on London Underground*. Proceedings of Railtex 2000 (99-104)

Wang, Adedipe, Sun, Jiang and Ren *Ground Vibration Control on Beijing Subway Line 5*, Internoise 2008

Barlow S.C *Field measurements of slab track vibration to demonstrate the insertion loss of low stiffness rail fasteners*. Proceedings Acoustics 2004

GB10071-88 *Measurement method of environmental vibration in urban areas*, 1988, Chinese National Standard

GB10070-88 *Standard for vibration in urban area environment,* 1988, Chinese National Standard

International Organisation for Standardisation 1997, *Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 1: General requirements*, ISO 2631-1:1997, International Organisation for Standardisation, Geneva.

GB 22337-*2008 Social limits for environmental noise emission standards.* 2008, Chinese National Standard

GB3096-2008 *Environmental sound quality standards*. 2008, Chinese National Standard

Pandrol published report 85171-22, 2004, Pandrol Ltd., UK