27th International Congress on Sound and Vibration
The annual congress of the International Institute of Acoustics and Vibration (IIAV)
11-16 July, 2021
ICSV27
Annual Congress of the International Institute of Acoustics and Vibration (IIAV)

SUPPRESSION OF CORRUGATION GROWTH BY RAIL DAMPER

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Short-pitch (25-50mm) rail corrugation often appears in the low rail in metro curve track on resilient baseplates (stiffness <25kN/mm), which leads to excessive noise with a peak spectrum around 400 to 600Hz. The frequency fixation mechanism of the corrugation is related to the rail lateral pin-pin resonance, which is independent of training speed and tracking curvature as indicated by rail vibration data in a few sites. Slight corrugation (<5μm RMS as measured by Corrugation Analysis Trolley, CAT) increases the rail noise level by 10dB(A) or higher. As observed, the rail corrugation growth rate is reduced by up to 90% after the installation of Tuned Mass Dampers (TMD) tuned to the frequency of the corrugation induced vibration. In a curve track (300m radius, UIC60 rail on resilient baseplates of ~14 to17kN/mm at a spacing of ~610mm), the corrugation wavelength is ~30mm. With a train speed of ~60km/h, the corrugation induced vibration frequency is 570Hz which is the same as the rail lateral pin-pin resonance as measured by point mobility at the mid-span between 2 baseplates. The corrugation growth rate is relatively constant within the 6-month rail grinding cycles. During the 2 grinding cycles before installation of rail damper, rail vertical vibration at 500Hz 1/3 octave band increases by ~7dB, while only by ~1dB immediately after rail damper installation. Rail roughness was measured by CAT before and after rail damper installation in a monthly basis.

Keywords: *Corrugation, resilient baseplates, pin-pin resonance*

1. Introduction

Rail Corrugation and Grindings

Rail corrugation on the running surface of curved track is a significant problem in the transit industry [1]. Short-wavelength corrugation (20-50mm, i.e. around 400Hz to 1kHz for a 70kph train) is a common cause of passenger complaints regarding noise [2]. Wear-type rail corrugation is caused by vehicle vibrations interacting with oscillatory contact conditions between the wheel and rail [3]. Regular grindings to remove the corrugations and re-profile the rail surface is a common practice in the railway maintenance routine. This paper investigates if rail damper can suppress the corrugation growth rate and subsequently reduce the corrugation induced rail vibration and the associated noise generation, then service period between rail grindings can be extended.

Measures to Suppress Corrugation Growth

Several corrugation mitigation methods were suggested throughout the last decades. Nelson J.T. proposed a wheel tuned spring-mass vibration absorber to control wheel squeal, rolling noise and rail corrugation [4]. Testing was conducted at the San Francisco BART system for a speed of about 120kph. The result upon corrugation noise control is, however, limited [4]. Ho et al. reported the use of rail tuned-mass-damper (TMD) for rail noise and corrugation control in Hong Kong and the growth of short-pitch corrugation of an overall critical wavelength of range 10-160mm is slowed down by 41-47% over 2 years [5]. Meehan et al. suggested the use of non-uniform train speed distribution to control rail corrugation growth. Based on the corrugation growth prediction model they developed, the corrugation growth can be reduced with the mean or skewness of the distributed set of passing speeds is biased to lower speeds. A further 12% reduction in corrugation growth rate was achieved in addition to the nominal 41% reduction from symmetric speed variation [3]. It is interesting to notice that to achieve the best reduction, the vehicle speed varies from between 40kph to 140kph in the paper [3], and it is not desirable in terms of service quality.

Corrugation Generation due to Wheel and Rail Dynamics

The corrugation generating and frequency fixation mechanism is often tied to the wheel dynamics, and various models were developed, such as the wheel squeal model [6]. However, Ho et al. reported that the growth of short-pitch corrugation of an overall critical wavelength of range 10-160mm is slowed down by 41-47% when installed with rail TMDs as rail vibration mitigation measures [5]. The results are presented in the later section of this paper. This result triggers the interest to investigate the corrugation problem by controlling the rail dynamics instead of wheel dynamics.

Rail Corrugations related to Low-Rail Resonance at Lateral Direction

The effect of rail TMD on corrugation growth reduction was further investigated for 18 months, which lasted for 3 rail surface grinding cycles. Rail TMDs of the latest design were installed for the last grinding cycle. Track-decay-rate (TDR) test and rail surface roughness measurement by corrugation-analysis-trolley (CAT) were conducted before and after installation of rail TMDs. The relationship between rail vibration and corrugation development was also studied and presented in this paper.

2. Rail Damper Effect on Corrugation

2.1 TMD tuned to Lateral Pin-Pin Resonance for Corrugation Suppression

Rail is usually supported at discrete points with regular spacing, and its pin-pin resonances are easy to excite in which the modes could be in vertical and lateral directions. The vertical pin-pin resonance is mainly at frequencies of 700 to 1100Hz, which forms the major source of rolling noise. The lateral pin-pin resonance is mainly excited in a curved track at frequencies of 300 to 600Hz. In some cases, the lateral pin-pin resonance relates to the generation of short-pitch corrugation in curves [7].

A track section of 200m in length with 300m curvature was selected for rail damper installation. The project's primary goals were to reduce the saloon noise level. The TMDs were tuned to match lateral pin-pin resonance in order to control rail vibration-induced noise.

2.2 Site condition, TMDs Installation and Measurement Schedule

The TMDs installation and measurement schedule were summarised in Table 1. The data was compared between before and after damper installation of the same 200m section. The photos of the dampers are shown in Fig.1.

Table 1. Measurement schedule and grinding cycles

Event Descriptions	Weeks after Damper install	Weeks after grinding	Measurement Types [1]		
			Rail Vibration	CAT	TDR
1st Grinding	-32	0			
Baseline 2nd month after grinding	-24	8	✓	✓	✓
Baseline 4th month after grinding	-16	16	✓	✓	
2nd Grinding	-12	0			
Baseline 2nd month after grinding	-8	8		✓	
Baseline 3rd month after grinding	-4	12	✓	✓	
Damper Installation on Low Rail	0	16	✓	✓	
3rd Grinding	2	0			

Performance 1st month after grinding	6	4		✓	
Performance 2nd month after grinding	10	8	✓	✓	✓
Performance 3rd month after grinding	14	12		✓	
Performance 4th month after grinding	18	16	✓	✓	

Remarks:
1) Measurement data presented in this paper is average of 3 passbys for saloon noise, 10 passbys for tunnel noise and rail vibration, 3 measurement lines for CAT and 10 impacts for TDR. Saloon noise was also measured in this project but it will not presented in this paper.

Fig. 1. 3D-views of the modular rail damper, photos of installed dampers and corrugation mark

3. Measurement results

3.1 Track mobility measurement

The rail dynamics are investigated using the point mobility test and the results are shown in Fig. 2. The vertical pin-pin resonance occurs at around 1030Hz, and lateral pin-pin resonance occurs at around 570Hz. Lateral mobility is much higher than vertical mobility.

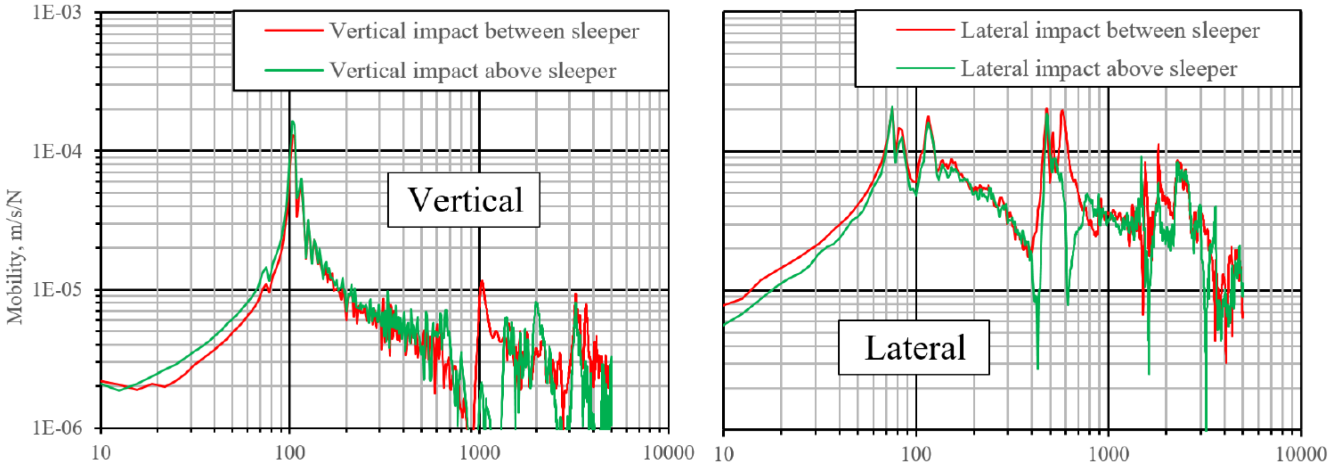


Fig. 2. Point mobility of the rail

3.2 Track decay rate before and after TMD installation

The TDR measurement results were plotted in Fig. 3. The TMDs were tuned to 550Hz for vertical and lateral oscillation with damping coverage from 400Hz to 700Hz. The TMD improve TDR in both vertical and lateral directions at frequencies higher than 250Hz.

The presented TDRs are measured with single impulse hammer impact according to ISO standard - *BS EN 15461:2008+A1:2010*, where the TMD damping effect is only partially included. TMD reduces vibrational energy on the rail by dissipating the energy by gradually amplified oscillation within a few milliseconds after the trigger of the first vibration impulse. The measurement of single impulse amplitude does not or only partially take the reduced vibration amplitude after the initial impulse amplitude into account.

The single impulse test by impact hammer does not reflect the real situation where train passby has continuous force excitation on the rail, where TMD damping effect have maximum effectiveness.

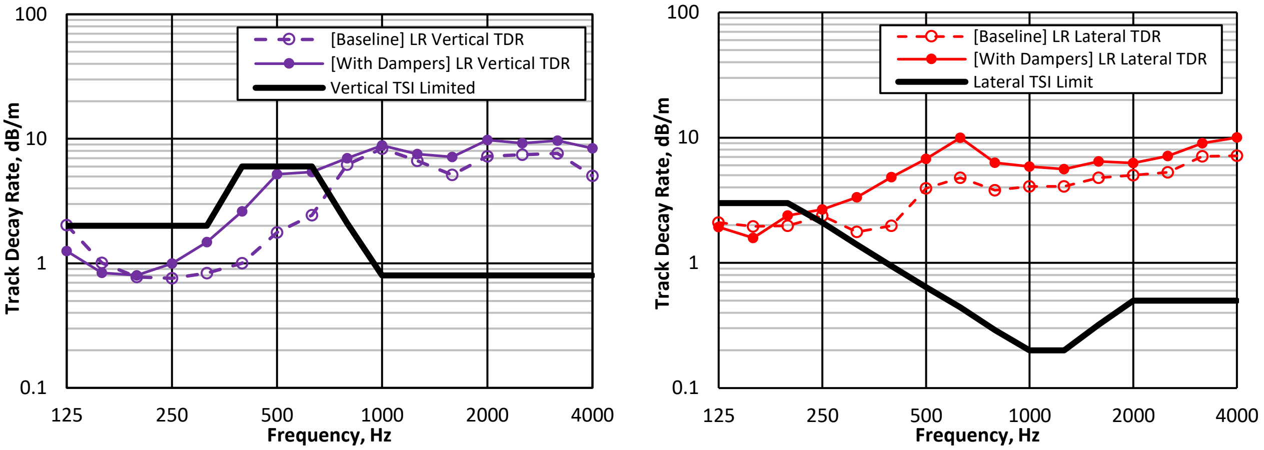


Fig. 3. Vertical (left) and Lateral (right) TDR before and after rail TMD installation

3.3 Rail roughness measurement

The 1/3 octave spectrum of the measured roughness is plotted in Fig. 4. The roughness wavelength could be co-related to a frequency using the train speed v and roughness wavelength λ by

$$f = \frac{v}{\lambda} \tag{1}$$

where the measured train speed at the vibration measurement point was 16.6m/s, the relative frequency was included in the paper as a reference.

Roughness peaks of 31.5mm and 50mm wavelength were measured at the 1st and 2nd grinding cycles, in which the RMS roughness at 31.5mm wavelength band reached 2.4μm and 3.8μm, and at the 50mm wavelength reached 1.7μm and 3.4μm band respectively. After installing rail TMDs for the 3rd grinding cycle, the peaks flatten to 1.3μm and 1.5 μm at 31.5mm and 50mm wavelength band at the end of the cycle, respectively.

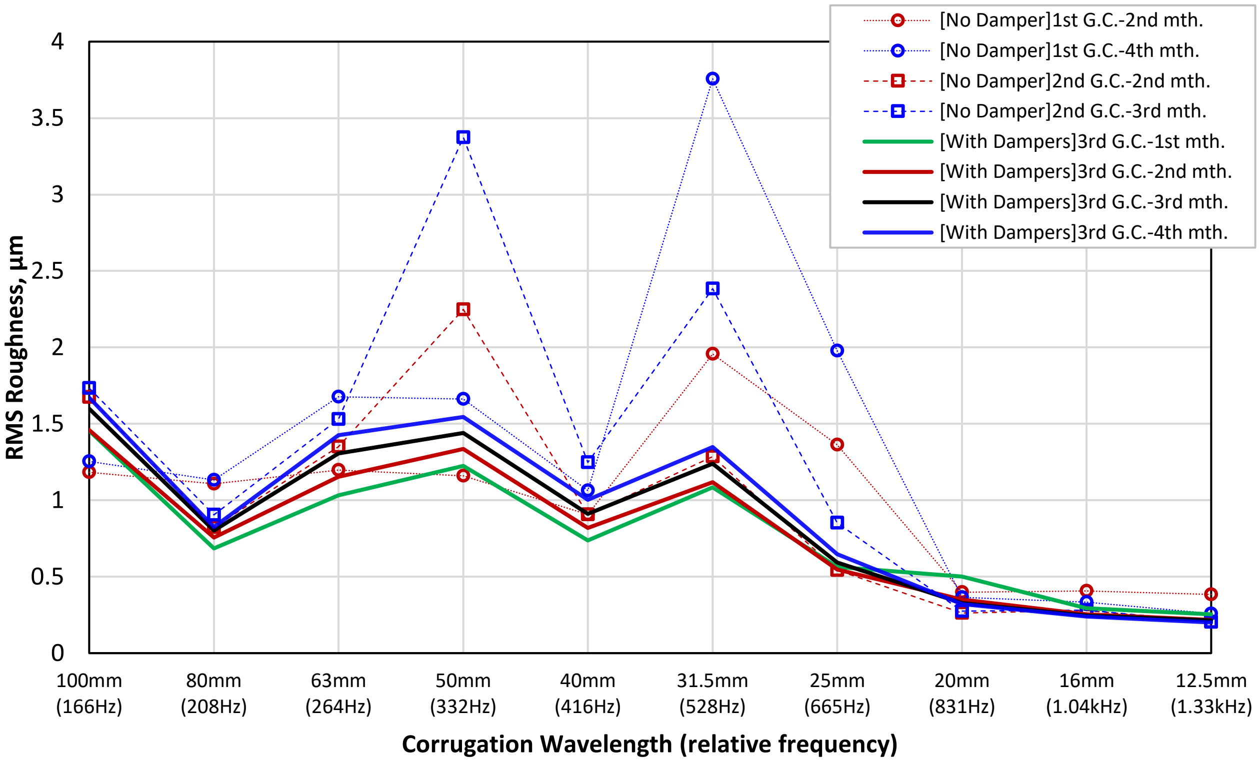
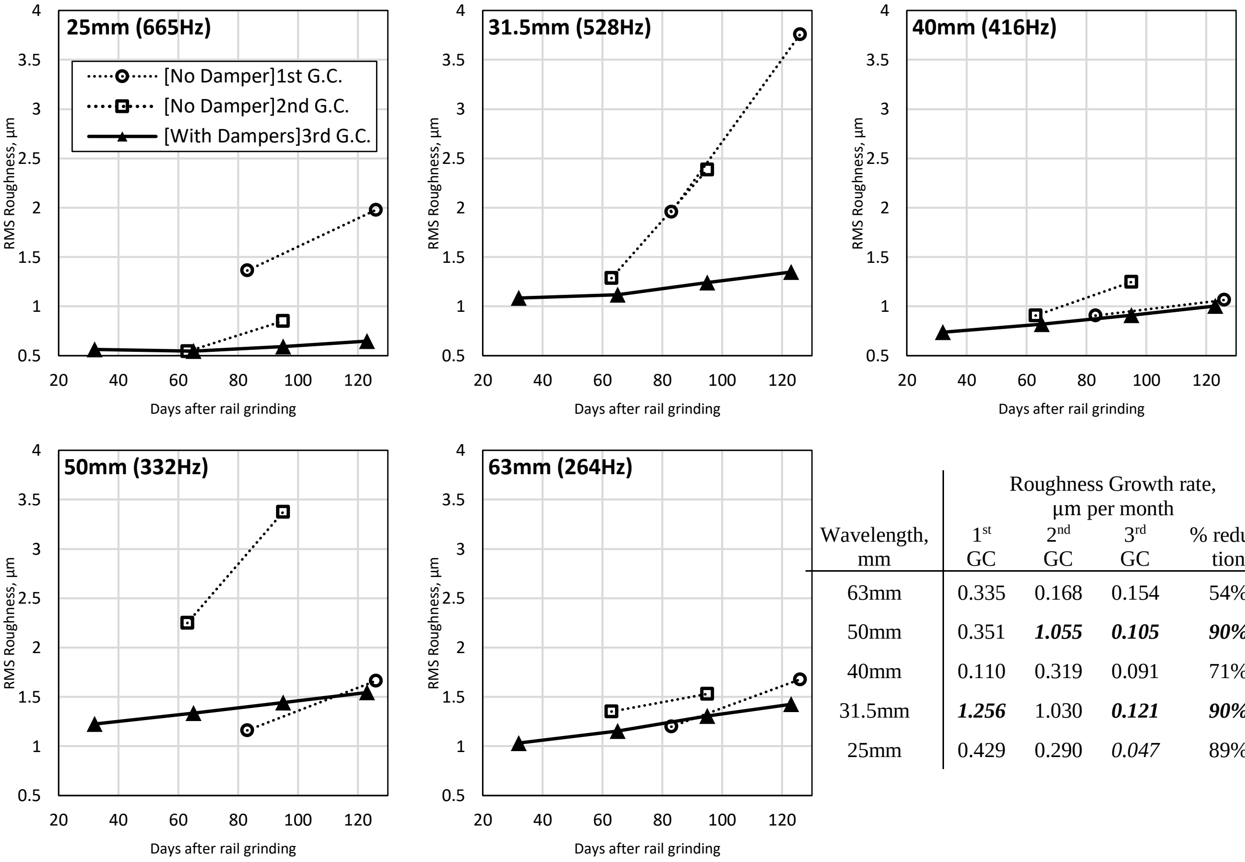


Fig. 4 1/3 octave spectrum of the rail roughness during each grinding cycle (denoted as GC in the figure)

3.4 Rail roughness growth rate

The growth rate of the 1st (no dampers) and 3rd (with dampers) grinding cycle were calculated with the data of the 2nd month and 4th month. The growth rate of 2nd (no damper) grinding cycle was calculated with the data of the 2nd month and 3rd month.

The roughness growth rate before and after damper installation were ranging from 0.110µm/month to 1.256µm/month and from 0.047µm/month to 0.154 µm/month respectively. The growth rate of the peak roughness at 31.5mm and 50mm wavelength band, as shown in Fig. 6, were reduced up to 90%.



Wavelength, mm	Roughness Growth rate, µm per month 1st GC	2nd GC	3rd GC	% reduction
63mm	0.335	0.168	0.154	54%
50mm	0.351	***1.055***	***0.105***	***90%***
40mm	0.110	0.319	0.091	71%
31.5mm	***1.256***	1.030	***0.121***	***90%***
25mm	0.429	0.290	*0.047*	89%

Fig. 5. Short pitch corrugation growth from 25mm to 63mm wavelength bands.

3.5 Relationship of rail roughness, vibration and pin-pin resonance

The relationship between rail roughness and rail vibration in vertical and lateral direction (no dampers) is shown in in Fig. 6 below. Both the vertical and lateral has a significant increase in vibration level at 570Hz, which coincided with the roughness peak frequency at 563Hz developed over the next two months and also close to the lateral pin-pin resonance frequency of 570Hz. The corrugation growth could be contributed by the lateral pin-pin resonance of the rail, which leads to believed that suppressing lateral pin-pin resonance excitation could also reduce corrugation growth.

4. Grinding mark and trackside noise

As an additional information, grinding mark on the rail surface could cause additional noise generation. From trackside noise measurements conducted in another site at different days, the averaged noise spectrum of all train passby event within the same 30 minutes period shows there is a 630Hz noise peak appears right after rail grinding. The noise gradually reduced after grinding. The data is shown in Fig. 7 below.

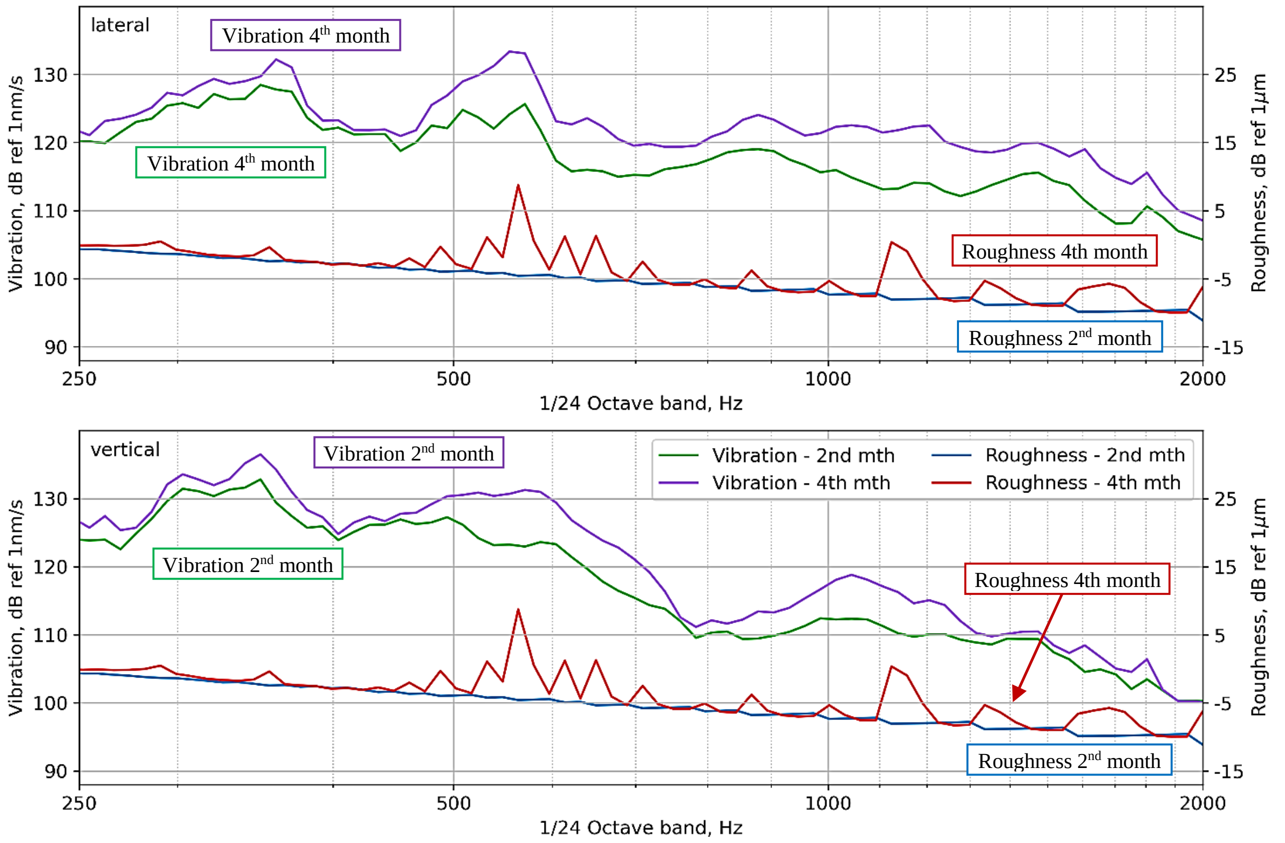


Fig. 6. 1/24 octave vertical and lateral vibration and rail roughness during the 1st grinding cycle (no damper).

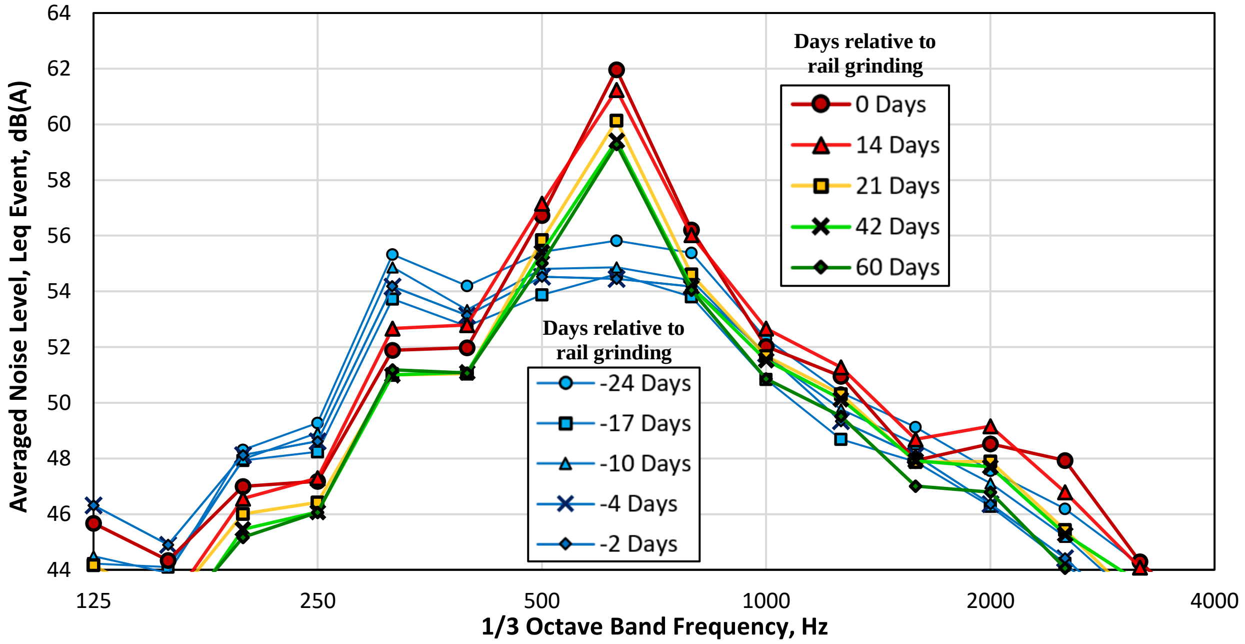


Fig. 7. 1/3 octave noise spectrum of passby before and after grinding

5. Corrugation growth rate reduction in other site

Back in 2010, a 50m long track section was installed with the first-generation rail damper, photos are shown in Fig. 8. The test site is a tunnel curve track of 300m radius of curvature. An adjacent 50m long track with the same curvature was defined control section for comparison purpose. Corrugation measurement by CAT was also conducted for damper and control section from 2010 to

2012, the results are shown in Fig. 9. For this project, the critical wavelengths were identified by saloon noise measurement and ranged differently from previously mentioned site.

Table 2 shows percentage reduction in corrugation growth at the low rail for three grinding cycles. The dampers succeeded in slowing down the corrugation growth of critical wavelengths of 80mm, 63mm and 50mm of the low rail by the dampers 72-75%, 41-69% and 10-37% respectively, or equivalently slowing down the corrugation growth of overall critical wavelengths of range 10-160mm by 41-47%.

Fig. 8. 3D-views of the first-generation rail damper, photos of installed dampers and corrugation mark installed in 2010

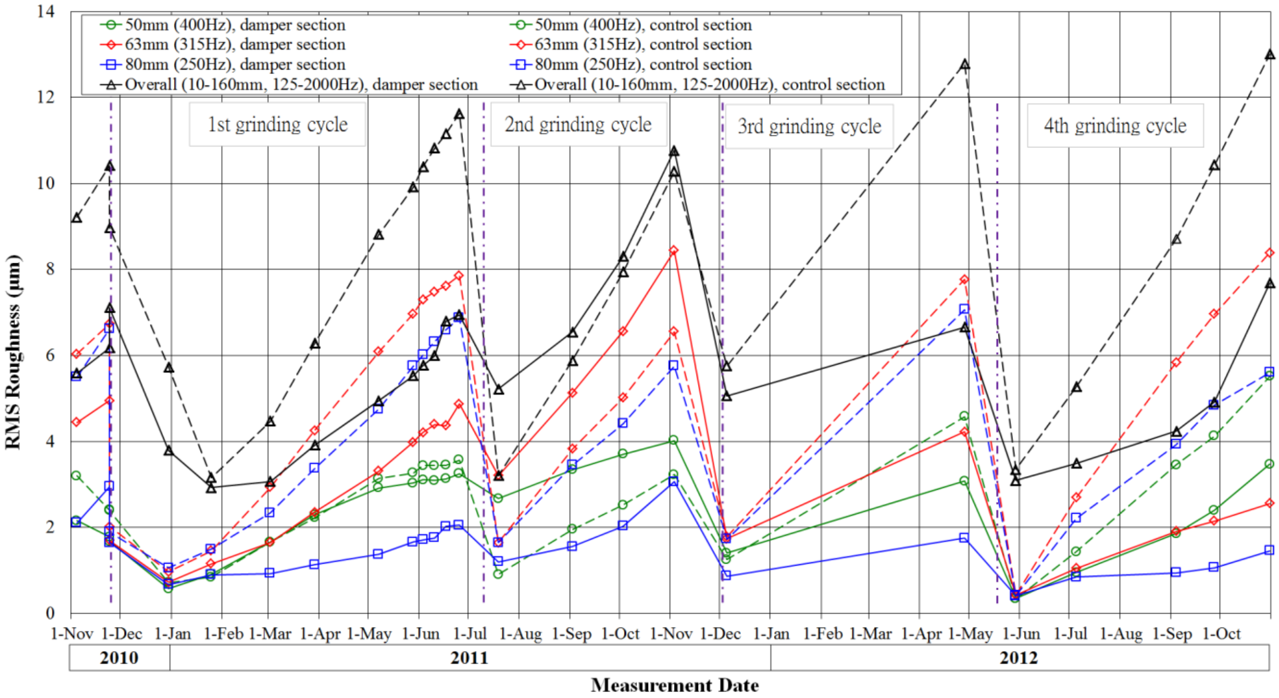


Fig. 9. Rail roughness variation in damper and control sections at the low rail from 01/11/2010 to 31/10/2012 of the first-generation rail damper

Table 2. Percentage reduction by the first-generation rail dampers, installed in 2010, in corrugation growth.

Corrugation wavelength (relative frequency)	Percentage reduction by dampers in corrugation growth			
	At the end of 1st grinding cycle (10/06/2011)	At the end of 2nd grinding cycle (03/11/2011)	At the end of 3rd grinding cycle (28/04/2012)	At the end of 4th grinding cycle (31/10/2012)
80mm (250Hz)	72.2%	46.8%*	75.2%	74.1%
63mm (315Hz)	41.2%	-28.8%*	45.6%	69.5%
50mm (400Hz)	10.2%	-24.6%*	32.8%	37.1%
Overall 10-160mm (125-2000Hz)	44.5%	4.8%*	47.9%	41.0%

Remarks:
* The measurement data in the 2nd grinding cycle is discarded in analysis due to incomplete grinding.

6. Conclusion

Short-pitch (25-50mm) rail corrugation often appears in the low rail of metro curve track on resilient baseplates (stiffness <30kN/mm), which leads to excessive noise with peak frequencies around 400 to 600Hz. It is observed that the corrugation growth rate is significantly reduced by the installation of the latest TMDs tuned to the lateral pin-pin resonance. In a curved track with a radius of 300m and resilient baseplates, the peak corrugation wavelength was found to be at 31.5mm (1/3 octave) or 29.5mm (1//24 octave) wavelength.

During the three monitored grinding cycles, the roughness peaks were suppressed throughout the whole short-pitch corrugation frequency after TMDs installation, especially at 31.5mm wavelength and at 50mm wavelength. Moreover, the corrugation growth rate was reduced by 90% at 31.5mm and 50mm.

As a side note, a side-by-side comparison between the vibration spectrum and the roughness wavelength spectrum within a grinding cycle shows its relative frequency of 563Hz (calculated by the train speed of 16.6m/s with peaked roughness wavelength) matched the increase in lateral rail vibration frequency of 570Hz and the measured pin-pin resonance frequency of 570Hz. The corrugation growth could be contributed by the lateral pin-pin resonance of the rail, which leads to believed that suppressing lateral pin-pin resonance excitation could also reduce corrugation growth.

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