Wilson Ho
Founder of Wilson Acoustics Limited and Jabez Innovation Limited

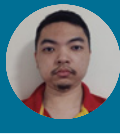
Wilson founded Wilson Acoustics Limited in 2005, and since 2012 it has grown to become the largest acoustic consulting company in Hong Kong.

He has developed several patented products, including SilentUP for easy-to-install and remove noise barrier up to 7m height, the Magnetic Tuned Mass Damper (MTMD) for noise control of pile driving and rock breaking, the Vertical Noise Reducer (VNR) for noise barrier with reduced wind load design, and Rigid Contact Tuned Mass Damper (RCTMD) for railway noise control. The RCTMD is the only rail damper proven to reduce corrugation growth by 90%. Recent laboratory test of a 6m long fastened rail also shows reduction in P2-resonance ground-borne noise.

Max Yiu
Design Engineer, Jabez Innovation Limited

Since 2011, Max has been a noise control specialist for construction sites and railways in densely populated Hong Kong.

Drawing on his practical experience in meeting the strict local noise requirements, he has provided reviews and recommendations to enhance the city's construction noise control practices for the Hong Kong government. Leveraging this industry expertise, Max has since transitioned into research, participating in development of innovative solutions such as SilentUP, Rigid Contact Tuned Mass Rail Damper, and Vertical Noise Reducer.



Cheng Sheng Loong
Site Engineer, Jabez Innovation Limited

Cheng Sheng is currently an MSc Student at the University of Hertfordshire.

He was an acoustic consultant at Wilson Ho and Associates Limited in Hong Kong. Working as an acoustic assistant consultant, Cheng Sheng provided acoustic consultancy services for construction noise including providing construction airborne noise (ABN), ground-borne/structural noise (GBN) assessment, Construction Noise Permit (CNP) application (for night work), Quality Powered Mechanical Equipment (QPME) to ensure the noise of the construction activities is within the regulation. He was also included in the research of Vertical Noise Reducer (VNR).

CORRUGATION SUPPRESSION BY RAIL DAMPER

KNOWLEDGE 200
TRACK

INTRODUCTION

Rail corrugation on curved tracks can be a persistent challenge, even on sections designed with the best geometric specifications. This phenomenon is particularly prevalent on the low rail side of curves, where the combination of rail rotation and lateral pinned-pinned resonance on resilient baseplates with a stiffness of 25kN/mm or less can foster the development of corrugation. While this corrugation may not significantly impact train operations, the associated noise can be a major concern, with even slight corrugation depths of around ten microns in root mean square (RMS) causing a noticeable increase in noise levels of 10dB(A) or more. Reducing ground-borne noise (GBN) along curved tracks by using softer rail pads and elastic baseplates often results in an unintended consequence: the rapid development of corrugation on the low rail of the curve. This article investigates the effectiveness of rail dampers to suppress the growth of short-pitch corrugation of wavelength 20 to 80mm on curved metro tracks, thereby reducing the resulting noise radiation. In the absence of other retrofitted noise control measures, increasing the frequency of rail grinding is currently a common mitigation approach. However, this strategy can significantly increase rail maintenance costs and shorten the service life of the rails.

Rigid Contact Tuned Mass Dampers (RCTMDs) have been installed at six Hong Kong MTR network sites. Based on visual observations on the low rail of curved track sections, installing these RCTMDs has resulted in less corrugation. On a 300m radius curve with UIC60 rails mounted on resilient baseplates (~14kN/mm stiffness), the predominant corrugation wavelength is around 32mm, inducing approximately 520Hz vibrations at 60km/h, which aligns between the 470Hz rotation resonance and 570Hz lateral pinned-pinned resonance. By installing RCTMDs, the corrugation growth rate has been reduced by an average of 90% over a 200 m section, as measured using a Corrugation Analyser Trolley (CAT). These results indicate that installing RCTMDs provides better noise control than simply increasing the frequency of rail grinding, without the drawback of shortened rail service life.

EXPLANATION OF TERMINOLOGY

P1 and P2 Resonances

P1 and P2 resonances are vertical vibration modes of the rail, resulting from P1 and P2 reaction forces at the wheel/rail interface when the wheel passes over a small discontinuity on the rail surface. P1 resonance is primarily driven by the contact stiffness at the wheel/rail interface, caused by the local elastic deformation of the wheel and rail at the contact area. In this mode, the rail vibrates against the wheel. P2 resonance is primarily driven by the vertical stiffness of the resilient fasteners. Here, the rail and wheel vibrate together in phase as a connected body.

P1 and P2 reaction forces were originally defined in the context of a wheel passing over a rail discontinuity, such as a dipped joint. The P1 force occurs at the entry to the dip, where the wheel pushes down on the rail. This force is higher in magnitude and frequency. The P2 force, on the other hand, occurs at the exit of the dip, where the rail returns to contact with the wheel. The P2 force is lower in magnitude and frequency, typically in the range of 50–100 Hz.

Pinned-Pinned Resonance

Rails are typically supported by baseplates and span freely between them. This configuration is referred to as "pinned-pinned," with the "pinned" locations representing the baseplates supporting the rail. The natural frequency of this arrangement is determined by the rail section's modulus and the distance between the supports. Rail bending modes can occur in either the vertical or lateral directions, with the pinned-pinned resonance frequency typically ranging from 400 to 1200 Hz.

CORRUGATION NOISE AND RAIL MAINTENANCE COST

Rail Corrugation and Resilient Fastener

Over the past 30 years, railway transportation has grown rapidly worldwide. Modern railway fasteners employ softer rail pads and elastic baseplates with a stiffness of 25kN/mm or less to reduce potential GBN from railway tracks. However, this track system allows for small lateral movements of the rail head when trains run on

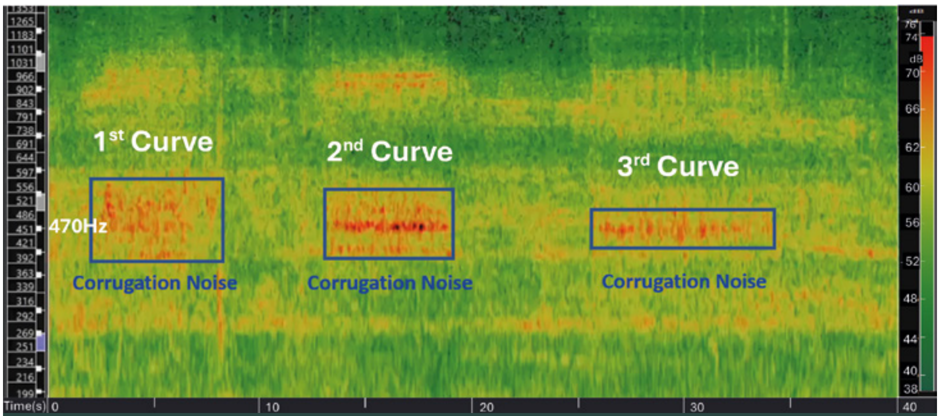


Figure 1: Spectrogram of Noise Level at S-curve Track.

curved tracks. In many cases, this prompts the rail head rotational resonance, typically between 300 and 700Hz depending on the dynamic stiffness of the rail pad and baseplates, which produces short-pitch corrugations on the running surface, especially at the low rail of the curved tracks. Therefore, reducing GBN along curved tracks by using softer rail fasteners often results in an unintended consequence of rapid development of corrugation, especially on the low rail of the curve.

Curve Track Short-Pitch Corrugation

Figure 1 illustrates the saloon noise spectrum over time as a train traverses a curved track with three distinct curves. The spectrogram representation shows the noise levels by colours, with the y-axis indicating the frequency in Hz and the x-axis denoting the elapsed time in seconds. The image shows that all three curves on the track exhibit tonal noise around 470Hz. At this specific frequency, the saloon noise levels increase by 10 to 15 dB compared to the relatively straight track sections between the curves.

This tonal noise phenomenon is attributed to the periodic up-and-down movement of the wheel-rail contact force, resulting from the short-pitch corrugation that forms on the rail surface. In this particular case, where the track utilizes a soft baseplate with a stiffness of approximately 14kN/mm, the rail head exhibits a rotational resonance at around 470Hz. This resonance triggers a lateral stick-slip behaviour at the wheel-rail interface, leading to the periodic removal of rail surface material and the subsequent formation of corrugations at regular intervals.

Corrugation Maintenance Cost and Train Speed Reduction

While the corrugation formation on curved track sections does not typically pose any significant operational safety concerns, it does present a common challenge for rail operators worldwide. The increased noise levels resulting from corrugation lead to high rail maintenance costs, as more frequent rail grinding is required at curved track locations to smooth the corrugation and maintain train operation noise within acceptable limits. In some cases of rapidly growing corrugation, even with rail grinding every three months, the corrugation-induced noise may still exceed the stipulated noise limits. In such scenarios, many rail operators choose to not only increase the grinding frequency but also reduce train speeds to further mitigate the noise and corrugation formation. In the absence of effective corrugation mitigation measures, more frequent rail grinding and reduced train speeds have become common industry practices to manage the issue, although these approaches are not ideal long-term solutions. Besides, the need for frequent grinding and speed restrictions can be disruptive to operations and add significant maintenance costs for rail operators. Alternatively, retrofitting rail dampers can serve as a viable alternative, offering a significantly lower cost solution compared to frequent rail grinding without requiring a reduction in train speed.

CORRUGATION FORMATION THROUGH LATERAL STICK-SLIP

Rail Corrugation and Track Dynamics

Rail corrugation is a widespread phenomenon where periodic wear patterns form on the rail surface. This article focuses on short-pitch rail corrugations of wavelength 20 to 80mm on metro curve tracks. As proposed by Stuart Grassie [1], these types of corrugation are closely associated with wheel/rail resonances (see **Table 1** below), which is affected by the employment of different stiffness fasteners in modern rail.

Type	Wave-length-fixing mechanism	Where?	Typical frequency, Hz	Damage Mechanism	Treatments demonstrably successful	Effective solution if feasible
Heavy haul	P2 resonance	Straight track or curves	50 - 100	Plastic flow in troughs	Hard rails	Reduce cant excess when corrugation on low rail
Light rail	P2 resonance	Straight track or curves	50 - 100	Plastic bending	Increase rail strength and EI	Reduce unsprung mass
Other P2 resonance	P2 resonance	Straight track, high rail of curves	50 - 100	Wear	Hard rails and low stiffness trackforms	Reduce unsprung mass
Rutting	2nd torsional resonance of driven axles	Low rail of curves	250 - 400	Wear	Apply friction control, hard rails, reduce cant excess, asymmetric profiling in curve	Reduce applied traction in curving, improve curving behaviour of vehicle dynamic vibration absorber
Pinned-pinned resonance	Pinned-pinned resonance	Straight track, high rail of curves	400 - 1200	Wear	Hard rails, control friction	Increase pinned-pinned frequency so that corrugation wavelength < 20mm
Trackform specific	Trackform specific	Straight track or curves	-	Wear	Hard rails, friction control	Avoid 'peaky resonance, improved steering

Table 1: Six Types of Rail Corrugations [1]

Corrugation Wavelength-fixing and Damage Mechanisms

As shown in **Table 1** on the previous page, the development of short-pitch corrugation involves two simultaneous mechanisms: a wavelength-fixing mechanism and a damage mechanism, leading to six types of rail corrugations with corresponding wheel/rail resonances.

1. Heavy haul corrugation (50-100Hz) due to P2 resonance leading to plastic flow rail surface damage
2. Light rail corrugation (50-100Hz) due to P2 resonance leading to plastic bending on rail surface
3. Other P2 resonance corrugation (50-100Hz) causing wear on the rail surface
4. Rutting corrugation (250-400Hz) due to driven axle's torsional resonance causing wear on the rail surface
5. Pinned-pinned resonance corrugation (400-1200Hz) causing wear on rail surface of straight track and high rail of curves
6. Trackform-specific corrugation (varying frequencies) causing wear on the rail surface, for example, rail rotation induced corrugation often occurs when soft fasteners are employed.

The wavelength-fixing mechanisms for five of these corrugation types (excluding Rutting) are directly linked to certain rail resonances, such as the P2 resonance, pinned-pinned resonance, rail torsional resonance, and railhead rotational resonance. The corrugation wavelength is determined by the train speed divided by the frequency of the governing rail resonance - a higher resonance frequency results in a shorter corrugation wavelength, and vice versa.

Regarding the damage mechanisms, the formation of rail corrugation involves plastic flow, plastic bending, and wear. Plastic flow and plastic bending are caused by overloading at the wheel-rail contact, leading to changes in the rail shape without material removal. In contrast, the wear mechanism involves the gradual removal of material from the rail surface due to stick-slip oscillations.

This article focuses specifically on short-pitch corrugation resulting from the periodic stick-slip wear mechanisms where the period is governed by the certain types of rail lateral vibration resonance. Corrugation is commonly observed during curve negotiation on modern rail systems, where soft fasteners with stiffness of 25kN/mm or less are employed to reduce potential ground-borne noise from railway tracks [2]. The use of these softer rail fasteners allows for increased lateral movement of the rail, which can contribute to the formation of short-pitch corrugation.

Micrometre Scale Stick-Slip Motions at Exceptional High Acceleration

Stick-slip oscillation is the primary mechanism driving the wear of the rail surface leading to the formation of short-pitch corrugation. During curve negotiation, in addition to rolling forward, the wheel also experiences lateral creepage, which supplies the energy for continuous stick-slip actions. The slip amplitude in each stick-slip cycle is very small, typically in the range of 0.01 to 0.05mm [3]. It should be noted that a slip amplitude of 0.05mm at 500Hz stick-slip oscillation corresponds to an exceptionally high acceleration of ≈ 50g (Earth's gravitational acceleration) as illustrated in the following estimation:

$$\text{Acceleration (m/s}^2\text{)} = \text{Displacement (m)} \times (2\pi \times \text{Frequency (Hz)})^2$$

$$\text{Acceleration} = 0.00005\text{m} \times (2\pi \times 500\text{ Hz})^2 = 493\text{m/s}^2 \approx 50\text{g}$$

(Earth's gravitational force)

The wheel-rail stick-slip phenomenon involves a relative oscillation between the wheel and rail, where one component (either the wheel or the rail) remains relatively stationary while the other undergoes significant lateral oscillation, at high acceleration of tens of Earth's gravitational acceleration, which generates exceptionally high dynamic forces at the wheel-rail contact patch. These forces result in material wear on the running surfaces of both the wheel and the rail.

Wheel and Rail Mobility during Stick-Slip Oscillations

Conventionally, it is often assumed that during the wheel-rail stick-slip process, the rail remains fixed while the wheel moves laterally in a repeated fashion [4]. This assumption is valid for wheel squeal generation, where the stick-slip motion is driven by a resonance of the wheel's lateral modes because the wheel has very high mobility and low damping at its resonance. However, this assumption is generally not correct for the formation of short-pitch corrugation, where rail resonance is the major driving force of the stick-slip oscillation.
In modern railway systems, the use of softer rail pads and elastic baseplates allows for small lateral movements of the rail head with resonance frequencies between 300 to 700 Hz. At the rail resonance frequency, the rail mobility is much higher than the wheel mobility, and the stick-slip movement mostly occurs at the rail, rather than at the wheel. In this case, the rail moves laterally in a repeated fashion while the wheel remains relatively fixed.

Suppression of Rail Corrugation through the use of Rail Dampers

Since rail resonance is the primary driving force behind the lateral stick-slip oscillation on the low rail, rail dampers should be effective at suppressing this stick-slip motion and the resulting rail corrugation. However, conventional rail dampers with rubber interface layers may be too soft to effectively transmit the small-amplitude rail oscillations for energy dissipation and reaction force amplification by a tuned mass damping mechanism. For conventional dampers, using a soft rubber layer is necessary to maximise the interface contact area to maximise the energy dissipation. Viewing from another angle, the rubber interface may be unable to effectively transfer the amplified TMD force from the damper back to the rail. To effectively dissipate the stick-slip-induced rail vibrations, it is necessary to have a rigid interface that can transmit strong damping forces even at small amplitudes (0.01 to 0.05mm) of rail movement.

The engineering challenges for a damper to suppress rail corrugation:

1. Generate a strong resistant force by using a relatively small mass by mechanism of Tuned Mass Damper (TMD).
2. Control the overall stiffness to ensure appropriate frequency TMD. This overall stiffness includes the stiffness of the contact interface layer, which is difficult to manage during retrofitting damper onto a profiled rail surface.
3. Use a rigid interface to ensure that small amplitude rail oscillations are transmitted to the TMD. This enables the TMD to respond with amplified oscillations, generating a strong damping force against rail movement.
4. Ensure the amplified damping force from the TMD also has a rigid interface to effectively transmit the damping force back to the rail, thereby reducing rail movement.

The conventional rail damper design with maximised contact area at the interface of the rail surface is not effective in providing strong damping force to the rail, because of the following reasons:

1. The TMD effect is required to generate a strong damping force by a small mass, whereas for a conventional damper with rubber layer interface it is difficult to control the overall stiffness for appropriate TMD effect.
2. Rubber interface is a vibration isolation layer that retains the vibration energy in the rail with very little dissipation to the rail damper.
3. The conventional damper, which uses an elastic clamping method to clip onto the rail, does not provide sufficient clamping force to rigidly connect the damper to the rail during violent rail vibrations.

RIGID CONTACT TUNED MASS DAMPER (RCTMD)

Two Types of Rail Dampers Based On Mounting Interface

Primarily, rail dampers can be divided into two types based on the mounting interface, elastic and rigid contact. Elastic contact rail

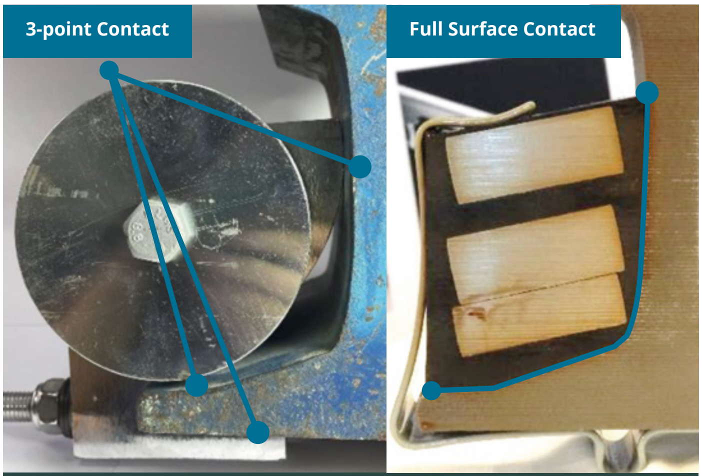


Figure 2: Three-point Contact (Left) and Full Surface Contact (Right) of Rail Damper.

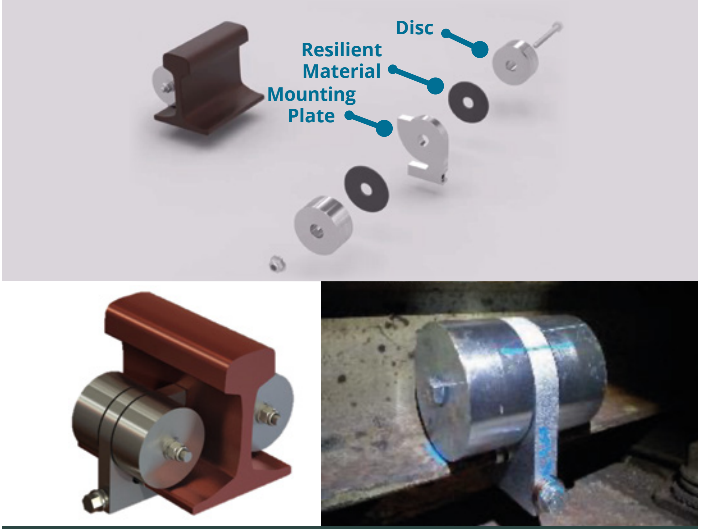


Figure 3: Design (top, lower left) and Prototype (lower right) of Rigid Contact Tuned Mass Damper (RCTMD).

dampers rely heavily on maximising the contact area connecting to the rail surface to capture maximum rail surface vibration energy. However, due to the local irregularities of the rail side profile, e.g. rust, it is very difficult to achieve the continuous contact area even using rubber material as the interfacing layer, thus deteriorating damper performance and corrugation mitigation. On the other hand, a rigid contact rail damper facilitates the strong transmission of TMD forces to the rail, effectively suppressing rail resonance by eliminating the rubber interface layer. It only requires 3-point rigid contact at the rail web, rail foot tip and under rail as shown in **Figure 2**. Rigid contact at these points can also ensure the effective transmission of small displacement vibration to the dampers with minimum disturbance from the irregularities of the rail surface.

Design of Rigid Contact Tuned Mass Damper (RCTMD)

The design of a Rigid Contact Tuned Mass Damper (RCTMD) is presented in **Figure 3**. It comprises four metal discs and two mounting plates on the rail. Resilient materials are attached between the discs and the mounting plate. Inside the damper, the discs act as oscillators and are held together with the resilient material using a bolt passing through them and the mounting plate which is held by a nut at the other end. Dampers are located on either side of the rail web and are connected as a pair by a long bolt passing through the base of the mounting plates and below the rail foot. This arrangement greatly simplifies the mounting arrangement so that it can deliver its full mitigation performance in nearly all conditions and does not obstruct the rail inspection.

Reactive Amplification of Damping Force By TMD

The oscillators and the shear direction resilient layers amplify oscillation amplitude up to ten times for both lateral and vertical rail vibration, generating a strong damping force against the rail movement. The oscillation frequency of TMD can be tuned individually to specific resonance frequencies such as pinned-pinned resonance, P2 resonance and rail rotational resonance by tuning the mass of the oscillator and the properties of the resilient material.

Track Decay Rate Shortfall

The current Track Decay Rate (TDR) measurement standard, ISO standard BS EN 15461:2008+A1:2010 measures vibration responses to individual hammer impacts to obtain TDR. A single hammer impact in a track cannot fully excite the rail resonance modes. The reactive

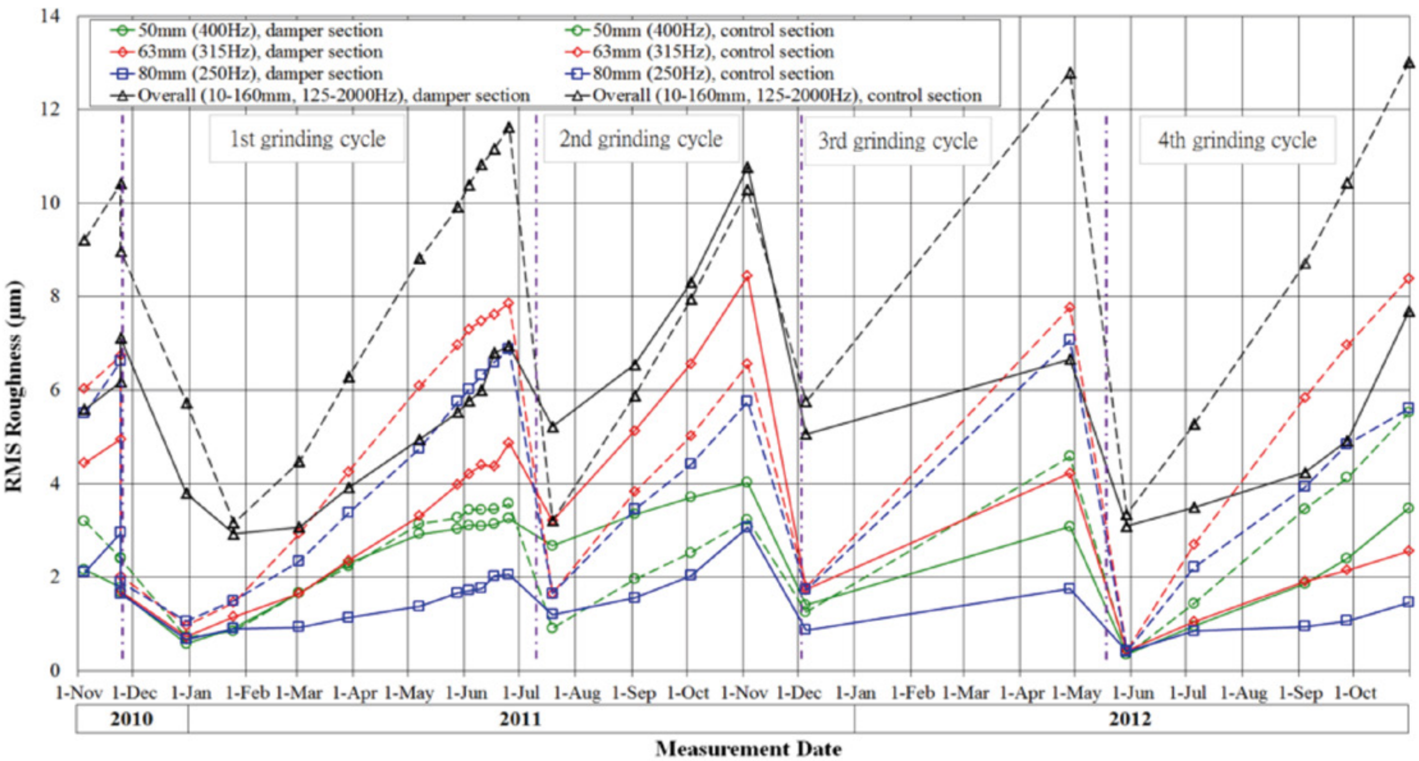


Figure 4: RMS Roughness Over Two-Year Period [7]. Solid Lines show section with damper; Dotted Lines show control section without damper.

Figure 5: Corrugation of Test Rail.

Figure 6: Installation of RCTMD on Testing Rails.

Dampers?	Grinding Cycle (GC)	Months after Grinding			
		1	2	3	4
No Dampers	1st			√	√
	2nd		√	√	
With Dampers	3rd	√	√	√	√

Table 2: Rail Roughness Measurement schedule and grinding cycles.

amplification by TMD needs time to react with 90-degree phase lag oscillations against rail resonance modes. The TMD damping effect may not be fully accounted for in the current TDR test. In contrast, continuous excitation may allow TMD to have enough time to respond and achieve better performance [5].

CASE STUDY

Previous Cases of Rail Corrugation Mitigations in 2012

Meehan et al. [6] recommended using a non-uniform train speed distribution to control the growth of rail corrugation. According to their prediction model, reducing train speeds can significantly diminish corrugation growth. They observed a 41% reduction from symmetric speed variation, with an additional 12% reduction in growth rate. Ho et al. [7] previously employed a rail tuned-mass-damper (TMD) to control rail corrugation in Hong Kong. Their approach successfully reduced the growth of short-pitch corrugation by around 40 to 70% for critical corrugation frequencies of 250Hz, 315Hz and 400Hz as shown in **Figure 4**. There were only three valid grinding cycles out of four grinding cycles in two years, as one of the four cycles was conducted by a malfunctioning grinding machine. The effectiveness of rail corrugation mitigation by TMDs is well-demonstrated within the three valid grinding cycles.

Testing Site in 2021

The present testing site is a 200m segment of curved track with a radius of 300m supported by a resilient baseplate with stiffness of about 14kN/mm. On this track segment, the rail head rotation and lateral pinned-pinned resonance are observed to dominate the corrugation frequency fixing mechanism. In **Figure 5**, the corrugation depth is approximately 15μm RMS roughness. The TMDs were tuned to ~520Hz with a damping coverage ranging from 400Hz to 1200Hz.

Rail Corrugation Testing Procedures

Figure 6 illustrates the installation of the RCTMDs. Two configurations were used: a single damper installation between the fastenings, and a quarter installation (one damper for every four fastenings), on the low rail and high rail respectively. The test involved three types of measurements: rail vibration, Track Decay Rate (TDR) test, and rail surface roughness measurement using a corrugation-analysis trolley (CAT). Rail dynamic properties were assessed via a point mobility test. Additionally, TDR tests were conducted according to the ISO standard BS EN 15461:2008+A1:2010 using a single hammer impact. **Table 2** details the measurement schedule for the testing year. Data from the same 200-metre section was compared pre- and post-damper installation.

RESULTS AND DISCUSSION

Mobility of Rail

A measurement of rail mobility is conducted for the vertical and lateral direction of impact above the baseplates and at the mid-point between two baseplates. This is to find the resonance frequencies that could lead to corrugation growth. **Figure 7** shows the spectrum of rail mobility in both vertical and lateral directions to illustrate the rail dynamics. It is revealed that the vertical pinned-pinned resonance, lateral pinned-pinned resonance and rotation resonance occur at around 1030Hz, 570Hz and 470Hz respectively. It shows that lateral mobility is much higher than vertical mobility for this resonance in general. Another peak region is found around 100 Hz, which corresponds to the rail's natural resonance on the resilient baseplate and is unrelated to corrugation. When the wheel runs on the rail, this natural resonance shifts downward, transitioning to P2 resonance, where the oscillating mass consists of the combined mass of the rail and the wheel, which are considered as a single rigid body during P2 resonance.

Track Decay Rate Improvement of The Rail

The Track Decay Rate (TDR) (the decay of vibration level in dB per metre), test results are demonstrated in **Figure 8**. The presence of RCTMD increases the decay rate starting from 250Hz (Purple and red solid lines). The most significant improvement of decay rate occurs at 400Hz along lateral direction and 500Hz along vertical direction, where 520Hz was the tuned frequency of the present TMD.

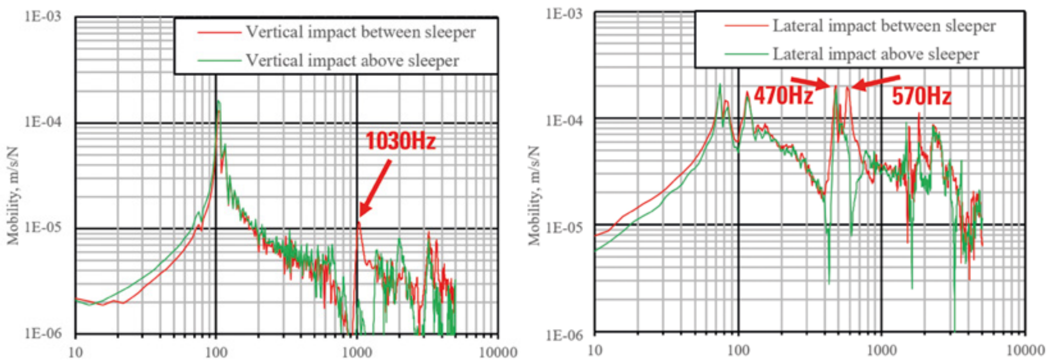


Figure 7: Results of point mobility test for Vertical (Left) and Lateral (Right) direction.

It is noted that the TMD's damping effect is only partially captured in the TDR test. This is because the TMD dissipates rail vibrational energy that gradually amplifies oscillations within a few milliseconds after the initial vibration impulse. Therefore, measuring a single impulse amplitude does not fully account for the reduction in vibration amplitude that occurs after the initial impulse. However, the continuous excitation should be the excitation that is close to the real case of wheel/rail interaction excitation. In this case, the TMD will have sufficient time to include reactive TMD force. Hence, the TMD can indeed achieve better performance under continuous excitation, such as when a train passes by [5].

CORRUGATION GROWTH RATE REDUCTION

Overall Corrugation Reduction Averaged over 200m Track

The important parameter about the rail surface condition is the root mean squared (RMS) roughness, as shown in **Figures 9** and **10**, presenting the low rail corrugation value average over 200m segment. Since the train generally travels at a speed v=16.6m/s (60kph) on this rail, the corresponding corrugated wavelength can be calculated by λ=v/f. According to the 1/3 Octave spectrum of the measured roughness, the dominant corrugation wavelength λ is 31.5mm, followed by 50mm in the first two grinding cycles. These two wavelengths correspond to 528Hz and 332Hz respectively. The 528Hz can be considered as the combined frequency of two mobility peaks (470Hz and 570Hz) in the lateral direction as shown in Figure 7. After the installation of TMD, the two corrugation peaks (wavelength 31.5mm and 50mm) are both greatly reduced by 90%.

Individual Segment Corrugation Reduction at 31.5mm Wavelength

The rail corrugation growth rate reduction for each segment of 20m, was calculated in **Figure 11** at f=528Hz (λ=31.5mm). The ISO 3095 roughness standard is provided for reference. This standard is designed for test tracks used in new train commissioning tests and is not intended for operational tracks. In practice, it is generally acceptable for running tracks to have corrugation slightly above the ISO 3095 roughness standard.

In **Figure 12**, the left and right images show the effect of rail dampers on the rail corrugation growth before and after damper installation, respectively. Both images were taken four months after the grinding process but during different grinding cycles. This figure shows that rail corrugation grows at a significantly slower rate after RCTMD installation.

Before Installation of RCTMD

Before the installation of RCTMD, corrugation was observed throughout the entire track section. Inconsistencies in rail roughness were noted between the first and second grinding cycles, particularly between 980-1060m and 920-940m. This indicates the

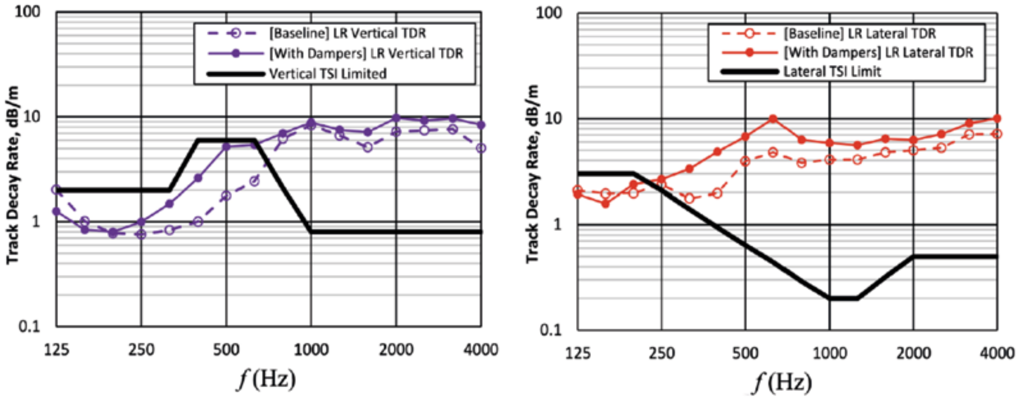


Figure 8: Results of TDR test for Vertical (Left) and Lateral (Right) direction.

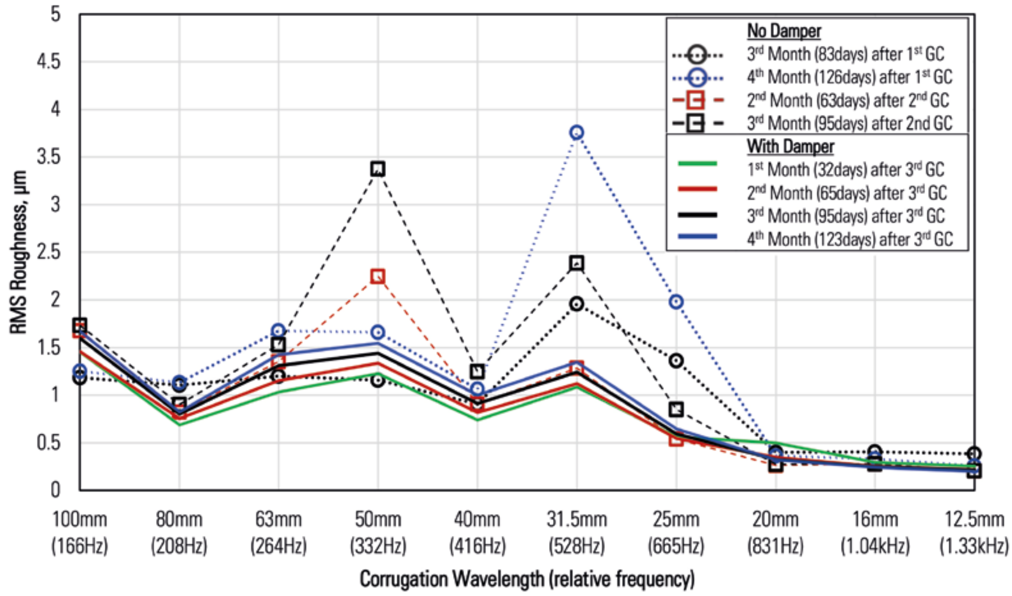
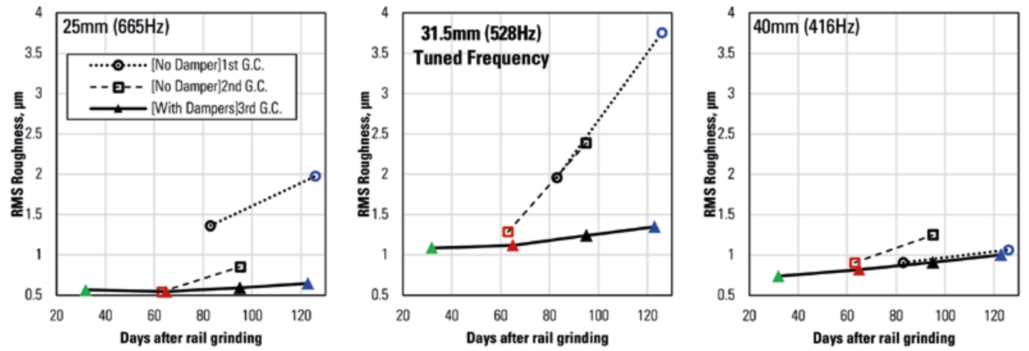
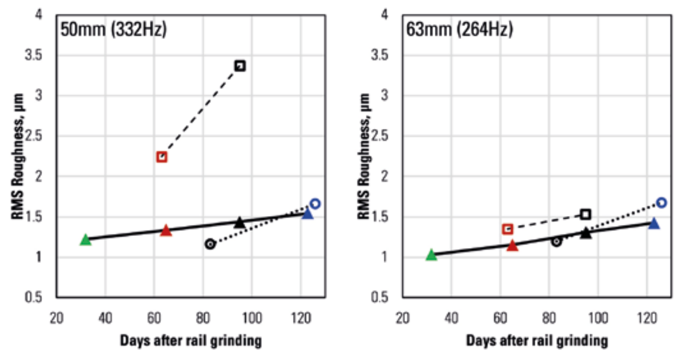


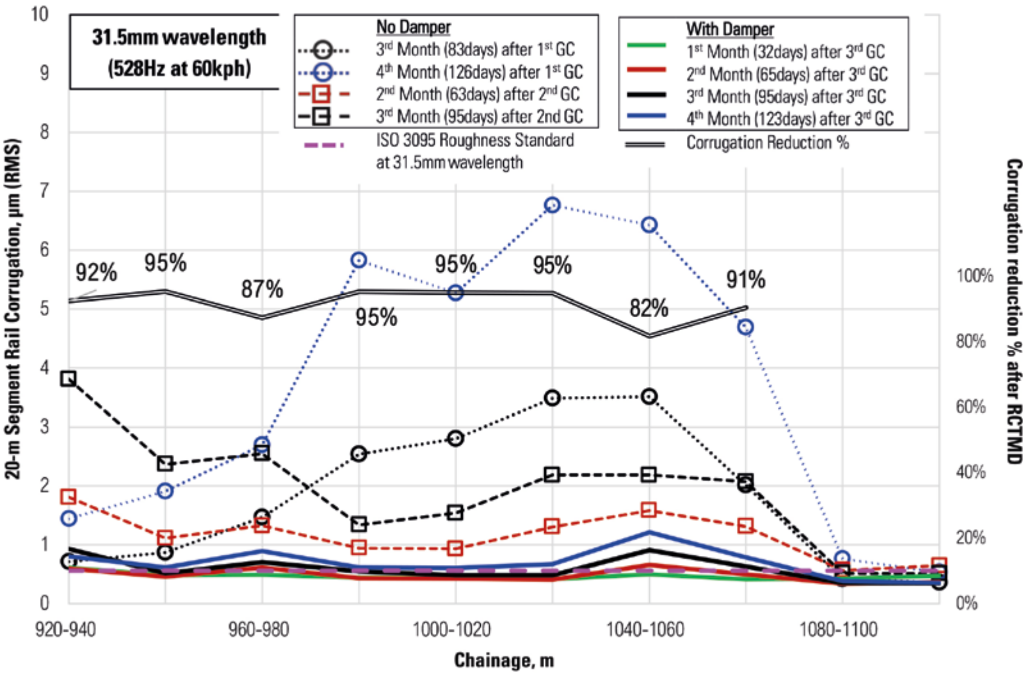
Figure 9: One-third octave spectrum of whole curved track surface roughness, Rrms,200m.





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 (tuned)	***1.256***	1.030	***0.121***	***90%***
25mm	0.429	0.290	*0.047*	89%

Figure 10: Average Corrugation Growth Rate Reduction for 200m from the wavelength of 25mm to 63mm.



31.5mm Wavelength Corrugation Growth rate, µm per month								
Chainage, m	920-940	940-960	960-980	980-1000	1000-1020	1020-1040	1040-1060	1060-1080
1st GC (without damper)	0.506	0.728	0.861	2.297	1.726	2.289	2.033	1.868
2nd GC (without damper)	1.879	1.178	1.148	0.371	0.569	0.826	0.561	0.710
Average of 1st and 2nd GC	1.193	0.953	1.005	1.334	1.147	1.558	1.297	1.289
3rd GC (with damper)	0.090	0.044	0.126	0.061	0.057	0.080	0.237	0.122
Corrugation reduction %	**92%**	**95%**	**87%**	**95%**	**95%**	**95%**	**82%**	**91%**

Figure 11: Rail Corrugation reduction at every 20m segment f=528Hz (λ =31.5mm).

non-uniformity of corrugation development, as track conditions and irregularities change after each grinding. Despite these changes, the dominant corrugation wavelengths (31.5mm and 50mm) remained consistent as shown in **Figure 9**, although the locations of the corrugation varied as shown in **Figure 11**. Rapid growth of corrugation continued at chainages 980 – 1060 in the 1st GC, and 920 – 980 in the 2nd GC.

After Installation of RCTMD

In Figure 11, following the installation of the RCTMD, the overall corrugation growth rate along the track is significantly reduced by approximately 90%. As a result, it appears that corrugation does not grow, except in two localized segments: 960-980 m and 1040-1060 m, where the reductions in growth rate are 88% and 86%, respectively. While the average reduction in corrugation growth rate over 200 m is 90%, a few segments experienced reductions of 95%.

Figure 12: Rail Roughness immediately after damper installation - four months after grinding (Left) and one year after damper installation - four months after grinding (Right).

CONCLUSIONS

Short-pitch rail corrugation (20-80mm) frequently appears on the low rail of metro curves with resilient baseplates (stiffness < 25kN/mm), causing excessive noise with peak frequencies between 300 and 700Hz. In a 200-metre curved track section with a 300-metre radius, a corrugation that peaked at 31.5mm wavelength (1/3 octave) was measured, corresponding to approximately 528Hz when trains travel at 60kph. A comparative analysis between rail mobility and corrugation spectrum was conducted. The 528Hz corrugation frequency can be considered as the combined frequency of two mobility peaks in the lateral direction: the rail head rotation resonance at 470Hz and lateral pinned-pinned resonance at 570Hz. Following the installation of Rigid Contact Tuned Mass Dampers (RCTMDs), the overall corrugation growth rate along the track is significantly reduced by approximately 90%. As a result, it appears that corrugation does not grow, except in two localized segments: 960-980 m and 1040-1060 m, where the reductions in growth rate are still achieving 88% and 86%, respectively. While the average reduction in corrugation growth rate over 200 m is 90%, a few segments experienced reductions of 95%. For the railway industry, retrofitting the RCTMD offers a viable alternative for mitigating curve corrugation and its associated loud noise. This approach provides a significantly lower-cost solution compared to frequent rail grinding, while also eliminating the need to reduce train speeds.

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