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Railway ground borne noise (GBN) reduction by rail dampers

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ABSTRACT

Railway GBN impact has raised increasing concerns due to underground metro expansion. Reducing train speed or replacing standard baseplates with high resilient baseplates are sometimes adopted for GBN control. Both mitigations are not satisfactory considering the installation difficulty and limited performance, e.g. only ~3dB noise reduction for 30% train speed reduction. On the other hand, FST (Floating Slab Track) are commonly used. In many cases, to accommodate the FST, tunnel diameter is enlarged for the TBM (Tunnel Boring Machine) tunnel section. Also, rail dampers are used for air-borne noise control, but never used for GBN control due to its relatively small mass. P2 resonance is a main cause of railway GBN. It is a simple harmonic motion of a lump mass (wheel and rail combined) oscillating on top of resilient baseplates. Laboratory test with a 6m fastened rail and a ~450kg weight to simulate train wheel and track system. A retrofit rail damper with TMD (Tuned Mass Damping) oscillators is tested. The mass TMD oscillators along the rail with ~2m effective length of P2 resonance is more than 10% of the wheel mass. Around 7dB vibration reduction is recorded at the rail and floor when allowing the TMD oscillation.

1. INTRODUCTION

When a train runs in tunnels, broadband vibration is generated at wheel/rail interface. While high-frequency vibration is mostly retained in the rail generating airborne noise inside the tunnel, significant vibration energy at low-frequency transmits into tunnel structure, ground earth and adjacent buildings [1]. Subject to distance and building dynamic property, Groundborne Noise (GBN) may be generated inside the buildings and creating nuisance.

1.1 P2 resonance and Fastener passing frequency

One of sources of GBN from a running track is P2 resonance. Transmission of rail vibration is seriously affected by track system resonant modes, where P2 resonance amplifies certain spectrum of rail vibration below 100Hz. For P2 resonance, rail and wheel are connected together to perform in-phase bouncing oscillation, which is a simple harmonic motion on the resilient rail support (e.g. resilient fastener). It is also called unsprung-mass resonance or wheel-set/track resonance. P2 resonance is the major vibration source of GBN when floor vibration peak at P2 resonance frequency.

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Besides, when train runs at speed of 70 to 220kph, the fastener passing frequency (~35 to 100Hz) may be coincident with P2 resonance, which makes GBN more serious.

1.2 Floating Slab Tracks and High Resilient Fasteners

Replacing the rail fasteners with high resilient fasteners is sometime considered but it creates loud airborne noise and prompts rail corrugation at curves. Replacing the trackform with Floating Slab Track [2] (FST) is generally impracticable due to limited working hours in operation railway. FST implementation requires shutting down the train operation. Also, FST requires more space and larger tunnel, which leads to significant higher construction cost [3].

1.3 Slowing Train Speed to Reduce GBN Being Forced

GBN complaints on the newly operation railway lines are not uncommon. Because of no retrofit GBN mitigation is available, administrative measure to reduce GBN by slowing down train speed [4] is sometime being forced, especially when complaints received during nighttime sensitive period. Although the slowing down train speed only need to be conducted at the complaint track sections, the overall journey time increases in the range of 10 to 60 seconds. There is a need to develop a GBN mitigation by retrofit measures on the track system.

1.4 GBN Mitigation Design in Planning Stage

In the planning stage, railway GBN is predicted with worst-case assumptions whenever uncertain issues are encountered due to uncertain track resonance, complex geology conditions and unpredicted structure connections. Due to no retrofit solution, additional 5-10dB(A) safety factor is commonly added into the already conservative GBN predictions [5]. In many cases, those additional safety factor would lead to a long sections GBN mitigation design of high resilient fasteners or FST for some individual marginal locations.

1.5 New Shearing Tuned Mass Rail Damper for Groundboune Noise Reduction

Rail dampers have been commonly used as a retrofit solution primarily for airborne noise control, but not for GBN control [6-13]. A study shows that ground vibration at frequencies 160 Hz or above can be reduced up to 9dB. However, for ground vibration at frequencies below 125 Hz, rail dampers did not have a noticeable effect [9]. In short, existing rail dampers are not able to reduce GBN where railway induced ground vibration at frequency below 100Hz practically. A new type of rail damper, Shearing Tuned Mass Damper (STMD), was developed and successfully tuned into the range of 35-100Hz. Laboratory tests were conducted to investigate its potential performance to reduce GBN.

2. THEORY OF DAMPING IN THE SYSTEMS WITH TMD

2.1 Using TMD to Suppress the P2 Resonance

The vibration energy of the P2 resonance could be significantly dissipated by attachment of a tuned mass damper (TMD) at the rail tuned at same frequency of the P2 resonance (**Figure 1**). A TMD includes the mass-spring-damper system which counter-act the rail vibration and dissipate the energy at a resilient layer via amplified hysteresis motion of oscillator. In the **Figure 1**, m_r, m_{ws}, md are the mass of the rail, wheelset, and TMD respectively. k_d and cd are the stiffness and damping coefficient of TMD which are produced at the resilient layer in the TMD. k_{pv} and c_{pv} are the stiffness and damping coefficient from the resilient fastener.

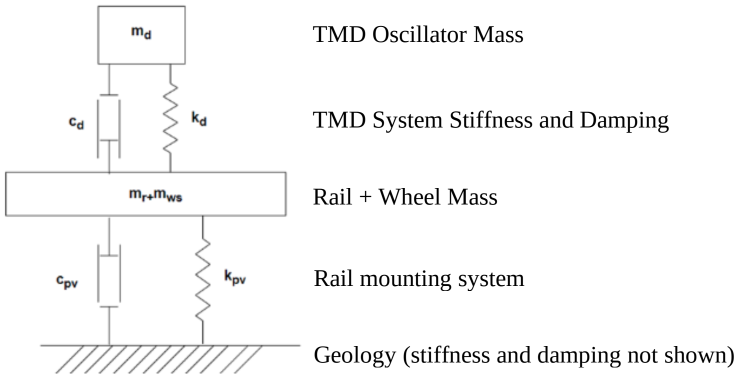

Figure 1: Mass-Spring-Damper system of the Rail, wheelset and TMD

The P2 resonance frequency can be calculated according to the equation by Wubin and Maoru [12]

$$\boldsymbol{f_{P2}} = \frac{\mathbf{1}}{\mathbf{2\pi}}\sqrt{\frac{\boldsymbol{K_{Tr}}}{(\boldsymbol{M_{Tr}}+\boldsymbol{M_{w}})}} \tag{1}$$

Where M_{Tr} and M_w are half of the equivalent mass of track and wheelset and K_{Tr} is the half of the equivalent track stiffness. The above notation can be further expressed as

$$\boldsymbol{K_{Tr}} = \mathbf{2} \times (\mathbf{4} \times \boldsymbol{EI_z} \times \boldsymbol{k_f}^{\mathbf{3}})^{\frac{\mathbf{1}}{\mathbf{4}}} \tag{2}$$

$$\boldsymbol{k_f} = \frac{\boldsymbol{k_{pv}}}{\boldsymbol{l_0}} \tag{3}$$

$$\boldsymbol{M_{Tr}} = \mathbf{3} \times \boldsymbol{m_{tr}} \times (\frac{\boldsymbol{EI_z}}{\boldsymbol{K_{Tr}}})^{\frac{\mathbf{1}}{\mathbf{3}}} = \mathbf{3} \times \boldsymbol{\rho A} \times (\frac{\boldsymbol{EI_z}}{\boldsymbol{K_{Tr}}})^{\frac{\mathbf{1}}{\mathbf{3}}} \tag{4}$$

where EI_z is the bending stiffness of rail, k_f is the equivalent support stiffness under rail per unit length, and m_{tr} is track mass per unit length. Hence, f_{P2} becomes:

$$\boldsymbol{f_{P2}} = \frac{\mathbf{1}}{\mathbf{2\pi}}\sqrt{\frac{\mathbf{2}\times(\mathbf{4}\times\boldsymbol{EI_z}\times\frac{\boldsymbol{k_{pv}}}{\boldsymbol{l_0}}^{\mathbf{3}})^{\frac{\mathbf{1}}{\mathbf{4}}}}{(\mathbf{3}\times\boldsymbol{\rho A}\times(\frac{\boldsymbol{EI_z}}{\boldsymbol{K_{Tr}}})^{\frac{\mathbf{1}}{\mathbf{3}}}+\boldsymbol{M_w})}} \tag{5}$$

2.2 Equivalent Damping Ratio of the System and Optimal Damping

Figure 1 shows a resonant system with 2 degree of freedom. The equivalent damping ratio ($\boldsymbol{\xi_e}$) of the entire system can be obtained by equation 6 below, where the mass ratio ($\boldsymbol{\overline{m}}$, ratio of the TMD mass (md) to the total mass of the rail and wheelset (mr +mws)), resilient fastener damping ratio ($\boldsymbol{\xi_{pv}}$) and the TMD damping ratio ($\boldsymbol{\xi_d}$) are the parameters controlling the equivalent damping ratio ($\boldsymbol{\xi_e}$).

$$\xi_e = \frac{\overline{m}}{2}\sqrt{1 + (\frac{2\xi_{pv}}{\overline{m}} + \frac{1}{2\xi_d})^2} \tag{6}$$

In order to find the best performance, the maximum displacement ($u_{1,\,max}$) in the rail should be optimized. The maximum displacement is shown in terms of the amplification factor ($\frac{u_{,max}}{u_{,stat}}$) in **Figure 2** [14]. Considering no damping from the fastener to the system (simplification), the amplification factor under different damping ratio (ξ_e) is found. It is observed that there is an optimized damping ratio at which the amplification factor would be flatten near the resonance frequency hence maximum overall reduction occurs.

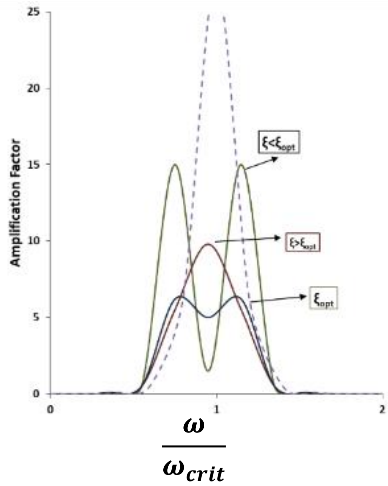

Figure 2: The amplification factor for different damping ratios

The optimal damping ratio can be obtained from the equation below:

$$\xi_{opt} = \sqrt{\frac{3\bar{m}}{8.(1+\bar{m})^3}} \tag{7}$$

2.3 Alternative to Optimal Damping for Suppression of P2 Resonance by Multiple TMD

From **Figure 2**, it is found that the maximum reduction at the tuned frequency occurs when the equivalent damping ratio is smaller than the optimized value, but adjacent peaks appear at both sides. If the adjacent peaks be reduced by additional TMDs, it is anticipated that the overall energy reduction would be higher than the classical system with optimal damping ratio approach. In order to provide a large damping force to counter act the P2 resonance vibration, TMD with high oscillator amplification (small damping ratio) is required. In this study, the effect from multiple TMDs tuned at different frequencies would be investigated in order to achieve high energy dissipation.

3. SHEARING TUNED MASS RAIL DAMPER (STMD) DESIGN

The STMD utilized the spring constant and damping properties of the resilient layer in shearing direction in which the STMD could provide damping in both vertical and lateral direction. Tuned mass damping force is generally proportional to the mass of its oscillator(s) when other parameters are fixed. In order to provide strong counter-action force to the rail movement under 50 g-forces acceleration, a strong mounting plate and rigid rail connection are required. For other engineering concerns, the total damper mass should not be significantly more than the rail mass. Within the limited space between rail fasteners at 0.6 to 0.7m regular spacing, the maximum damper length is limited within 0.3 to 0.45m depending on types of fasteners. The rail damper is designed to be composed of smaller modules installed at a rail space between 2 fasteners. Each damper module is design to achieve a high oscillator mass ratio. The current design has oscillator mass 4 to 5 times of the mounting plate mass while achieving vertical mounting force around 100 g-forces times the oscillator mass.

3.1 Multiple modular dampers in space between 2 fasteners and tunable frequency

Each STMD module contains 4 oscillators in 2 groups and installed on both sides of rail by mounting plates (**Figure 1**). Resilient material is attached between the mounting plates and oscillators to provide amplified hysteresis damping oscillations, where oscillation frequency of the oscillators can be individually tuned to match any specific P2 resonance between 35 and 100Hz.

The modular design allows maximum of 3 damper set to be installed into the space between 2 fasteners, which is also depending on types of fasteners and fastener spacing.

3.2 In-phase Oscillators to Improve Damping Power

Since out-of-phase vibration of the 4 oscillator masses may reduce the efficiency of the TMD in counter-acting the vibration from the rail. Each oscillator groups are configured to allow in-phase oscillation, i.e., each group of oscillators become single mass, which eliminates the counter-acting force between the same oscillator group, as well as increase the effective oscillator-to-rail mass ratio to allow greater damping force for low frequency range. [15]

4. MEASUREMENT RESULTS

4.1 Measurement Setup

Laboratory tests were carried out for STMD installed on a 6m UIC60 rail fastened on resilient fastener with a stiffness of ~22MN/m. The fastened rail is supporting a ~450kg mass, simulating wheel weight on a rail (equivalent to half wheelset mass) located in the middle of the rail. The laboratory is located on the 1/F which sits on a concrete floor slab. The shaker generates a white-noise vibration applied on the 450kg wheel mass. The system has the P2 resonance frequency of ~47Hz. Rail vibration and floor vibration were measured from the sensors installed on the rail and on the floor just below the middle of the rail. To minimize rail end wave reflection, acoustics blackhole were installed at the rail ends. The schematic view of the laboratory arrangement is shown in **Figure 3**. The system mobility was measured as shown in **Figure 4** and the floor resonates at ~35Hz. The input shaker force is a broadband signal measured with ~165dB at the shaker force sensor (**Figure 3**) to minimize background vibration influence.

The measurement was conducted with total of 6 sets of STMD installed on the rail, with 2 sets of dampers installed at each fastener spacing. The results are compared between STMD oscillation effect turned on and off, i.e., the total mass of the system remains unchanged. Turning on STMD oscillation effect means allow the oscillation masses to vibrate normally at the tuned frequency, while turning off oscillation effect means the vibration of oscillation masses were restricted on purpose by filling up the gap between the oscillators and the rail (**Figure 5**), therefore the vibration from rail will directly transfer to the oscillation mass and the amplified hysteresis damping effect of the resilient material would not occurs.

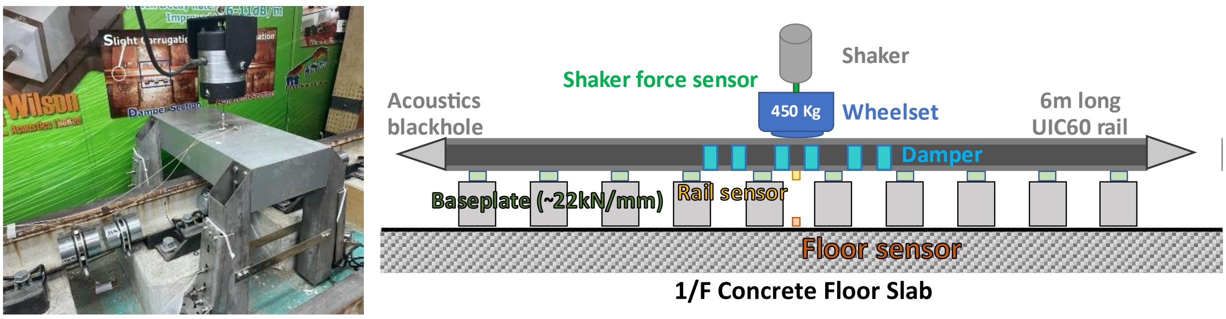

Figure 3: Schematic view of laboratory tests set-up

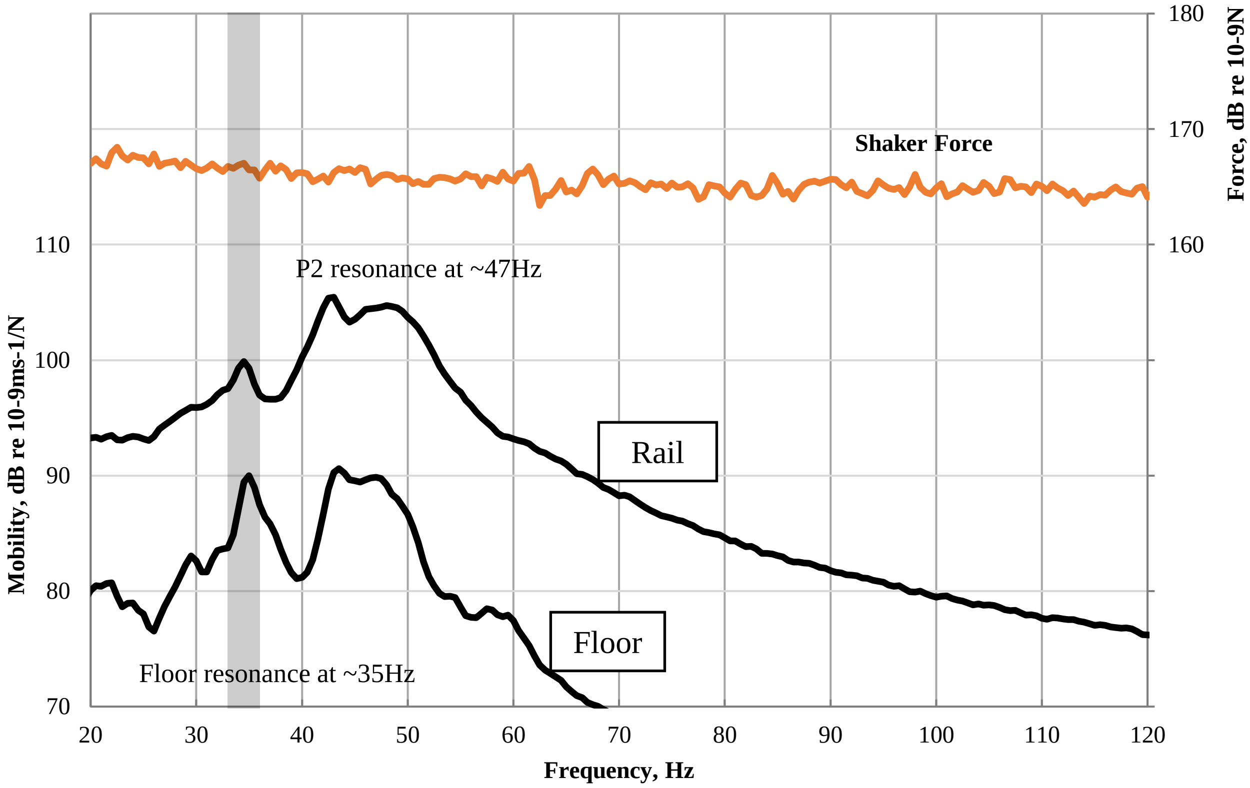

Figure 4: 2 sets of GBN STMD with in-phase oscillators

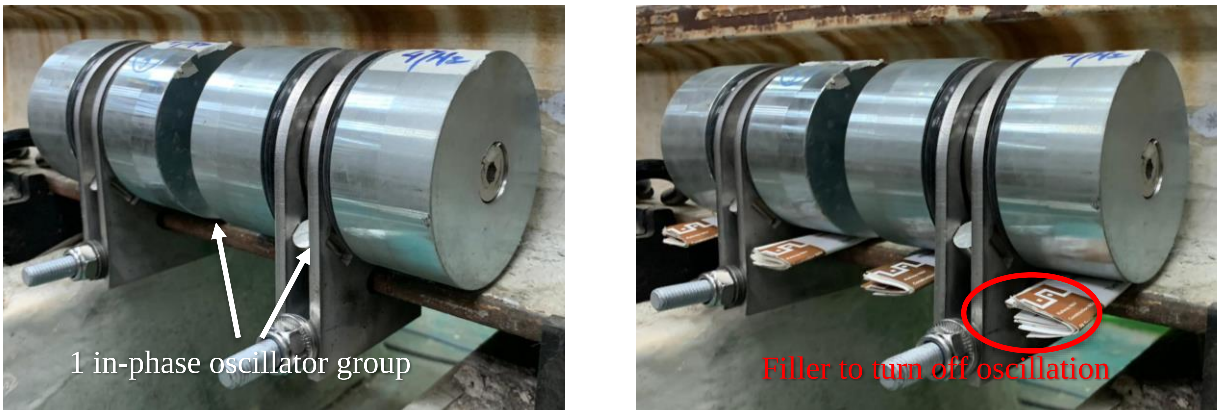

Figure 5: 2 sets of GBN STMD with in-phase oscillators

4.2 Measurement Results with All STMD Tuned to 47Hz

In the first test, all 6 STMD were tuned to 47 Hz. There are >10dB(A) vibration reduction around the system resonance frequency and 7 dB(A) peak-to-peak floor vibration reduction. As shown in **Figure 6** below, the peak-to-peak vibration reduction was limited by adjacent peaks at both sides from the tuned frequency of 47Hz.

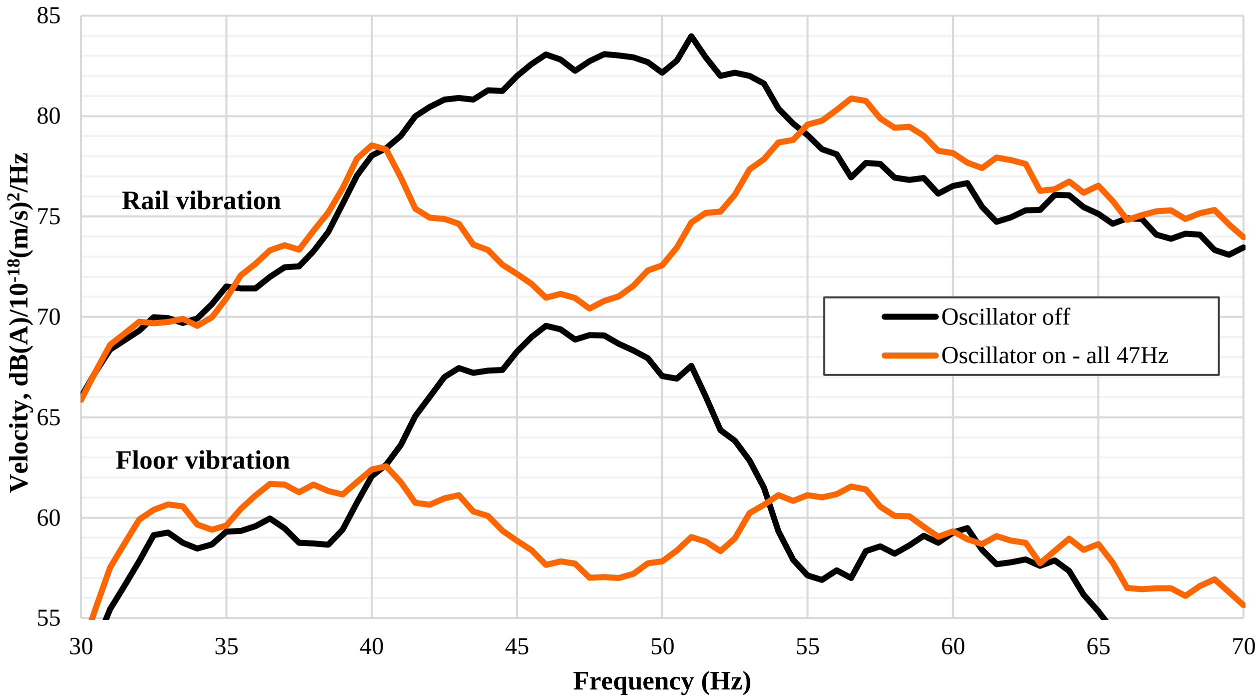

Figure 6: 2 sets of GBN rail damper with in-phase oscillators tuned at the same frequency

4.3 Measurement Results with STMD Tuned to Different Frequencies

To achieve broadband vibration reduction, i.e., overall vibration level reduction, the test was repeated with STMD oscillator group tuned to 41Hz, 47Hz and 52Hz to reduce vibration level at the adjacent peaks. Although the results show the reduction around the system resonance frequency had reduced, higher peak-to-peak floor vibration reduction of 8.9 dB(A) was achieved, as shown in **Figure 7**.

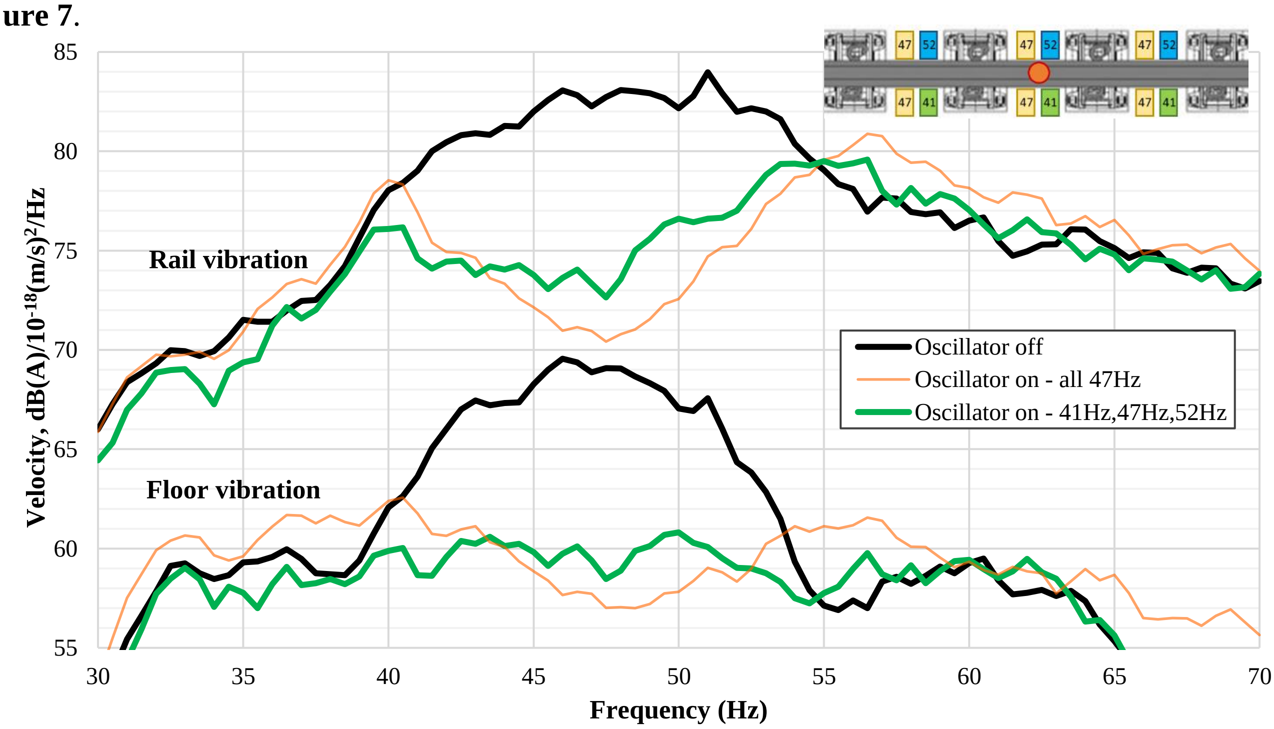

Figure 7: 2 sets of GBN rail damper with in-phase oscillators tuned at different frequency

5. CONCLUSIONS

In this project, a new type of Shearing Tuned Mass Rail Damper (STMD) was developed and successfully tuned to 35-100 Hz targeting P2 resonance to reduce groundborne noise (GBN). Multiple STMD was installed and tested in a laboratory setup, that includes a 450kg mass on the rail as half wheel mass, with 47Hz system resonance. Rail and floor vibrations were measured to study 1) the STMD oscillation effect at P2 resonance frequency all tuned at 47 Hz, and 2) multiple tuned frequency effect at 41Hz, 47Hz and 52 Hz for adjacent vibration peak to reduce broadband vibration. The peak-to-peak vibration was reduced by 7dB(A) and 8.9dB(A) respectively.

After further design improvement, 3 retrofit STMD can be installed at each fastener spacing and it is anticipated that the GBN reduce performance can achieve better than 3-5dB. With this new technology being used in a few railway lines, the following changes in the railway industry are anticipated in long-term:

- Slow down the train speed to reduce GBN can be totally eliminated because effect due to train speed reduction is less than 3-5dB normally.
- Railway GBN mitigation for marginal case can be planned at later stages of railway development (trackwork construction stage or train operation trial run stage).
- The additional safety factor of 5-10dB(A) for railway GBN assessment can be reduced or removed in the Environmental Impact Assessment.
- The use of Floating Slab Track (FST) to reduce potential GBN nuisance will be significantly reduced in order to save trackwork cost.
- Increasing the railway tunnel size due to FST installation will less occur.

6. ACKNOWLEDGEMENTS

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