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Current state of practice in railway track vibration isolation: an Australian overview

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ABSTRACT
Inevitably, train and track interaction generates a travelling source of noise and vibration along the railway corridor. Railway noise is generated in various forms and spectra. The undesirable railway sound and vibration include rolling noise, impact noise, curve noise, mechanical noise, airborne noise, wheel/rail noise, structure- and ground-borne noises. The noise that is carried through the vehicle body mainly affects ride quality, customer experience and structural integrity of the rolling stocks, whereas the vibration that is transmitted from the rails to the supporting structure of the track plays a main role in rapid track degradation and potentially affects the surrounding structures. This study highlights the practical guidelines for track vibration isolation resulting from the operation of railways. Its emphases are placed on the contemporary vibration mitigation methods used in existing and ageing railway infrastructures (the so-called 'brown field project'). Its aim was to provide the overview and lessons learnt for the future development of new vibration isolation strategies in practice.

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Noise and vibration; Wheel–rail interface; train–track interaction; vibration isolation; practical guideline

Introduction

The studies to mitigate railway noise and vibration problems are not a young topic. Many of them have been mitigated using ad hoc technology and contemporary insight at a particular point in time. Although there have been significant effort in progression of noise and vibration mitigation by both industry and academia, the technological adoptions are still limited due to practical and physical constrains, tight budgets and timeframe, and trade-off priority. In most cases, such adoption decisions must strike the balance between the costs for extra maintenance and inspection activities and the need for environmental benefits, which often creates a transient situational conflict.

There are a variety of problems related to railway noises and vibrations depending on radiation characteristic such as airborne noise, wheel/rail noise, structural-borne noise and ground-borne vibrations. In Australia, the railway noises that community typically experiences are often derived from wheel/rail radiations such as rolling noise, impact noise and curve noises (i.e. flanging and squeal). On the other hand, in high-speed rail operation, aerodynamic noise from pantographs may be a serious issue to railway neighbourhoods. A recent national research project pioneered to mitigate curve noises, funded by Australian Cooperative Research Centre for Rail Innovation (RailCRC), showed that wheel/rail mechanism is a complex source of wheel squeals, and the mitigation methods could be much more effective by tactically dealing with the noise source, e.g. by applying friction modification and/or rail lubrication strategy, or by controlling the angle of attack of bogie's wheelset (Anderson 2013, 2014).

Undesirable sounds are commonly called 'noise'. Whether a sound is undesirable or not depends on the sound pressure level and corresponding frequency spectra (or 'tonal' content) of the sound (Remennikov and Kaewunruen 2008; Thompson 2010). At a high level, hearing damage could occur, and at a lower level, the noise can disturb human well-being or social activity. Although the acoustic radiation seems to be the pressing issue at present, many other hidden and critical problems also exist such as rapid track degradation, ballast pulverisation, differential track settlement, audible sound within buildings adjacent to railway lines, depression at bridge ends, ballast dilation at turnouts and crossings, steel bridge noises and so on (Remennikov and Kaewunruen 2008; Thompson 2010; Kaewunruen and Remennikov 2010b; Kaewunruen et al. 2014). The source of these problems is often generated by the transmission of impact vibrations from irregular wheel/rail interface to other components in railway track (Remennikov and Kaewunruen

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2005; Rolling Stock Access Integrity Standards 2008). Accordingly, track vibration isolation is one of effective strategies to mitigate these infrastructure issues. In principle, the vibration isolation will suppress dynamic content of force spectra transferred to supporting track structures. When the dynamic content is eliminated, the structural components behave under static or quasi-static manner and importantly, structural resonant behaviours can be avoided (Kaewunruen and Remennikov 2006, 2008b, 2010a; Remennikov and Kaewunruen 2014).

This study highlights the current practices for the isolation of railway track vibration transmitted from the wheel/rail interface during the operations of railways. Its emphases are placed on structural and ground-borne vibration mitigation methods, which have especially been employed in existing and ageing railway infrastructures (the so-called 'brown field project'). The lessons learnt will assist rail engineers and acoustic or environmental engineers working collaboratively to find a reasonable solution with respect to noise and vibration problems in railways. It is aimed at building the collaboration that will innovate the future development of vibration isolation strategies in practice.

Radiation of noise and vibration

Wheel/rail vertical interaction generates the dynamic force, which will be transferred to adjacent components by means of vibration and deformation. The dynamic content is usually filtered out by the damping coefficients of materials or components through the track cross-section layers. A simplified track model, which is still being considered and utilised nowadays, can be revisited in Figure 1 (Remennikov and Kaewunruen 2005; Kaewunruen and Remennikov 2007). From the simplified model, it can be observed that dominant resilient track components (spring–dashpot elements) include the third party materials at wheel/rail contact, rail pads, insulators (or sometimes called 'biscuits'), ballast and formation. Often, these traditional components were designed initially to support the traffic load, without considering vibration isolation characteristic. However, recent practices display some design variations of track components to alleviate impact vibrations (Kaewunruen and Remennikov 2007, 2008a).

If railway track is laid directly on the ground or fastened to a tunnel floor, then the ground vibrations could cause low-frequency or rumble noise (sometimes called

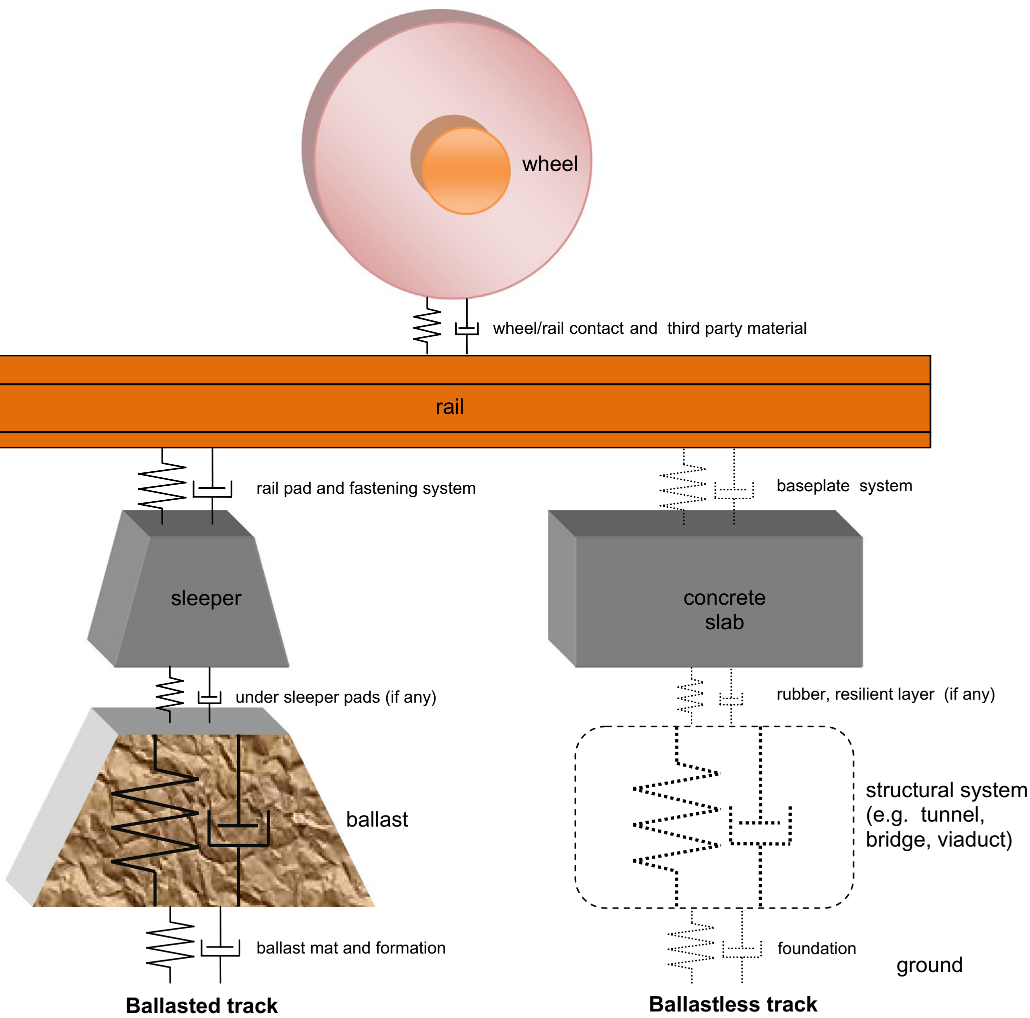


Figure 1. Simplified modelling of train–track interaction, adapted from (Remennikov and Kaewunruen 2005).

'infrasound'). Although the infrasound might not be audible, it could also cause annoyances, damages and vibrations of loose panels, windows, signalling equipment, point motor and other constructed facilities. In relation to a railway bridge or a viaduct, some re-emission of structure-borne noise can cause a coupled noise issue when combined with the excitation from wheel/rail abnormalities. Common incidents of excessive structure-borne noises could be observed on steel railway bridges, short- and long-span viaducts, bridge approaches, etc.

The wheel/rail vibrations travel vertically along the path of mechanical interconnection: from rail, rail pad, sleeper, ballast and then to either the viaduct/bridge or the ground. In the case of ballasted tracks, a large amount of vibration energy is absorbed by the friction between contact surfaces of the ballast aggregates. On the other hand, in ballastless tracks, the vibration transmission is found to be much more efficient. Very little vibration is dissipated in the hysteresis of the elastic pads or resilient sleepers (e.g. timber, fibre-reinforced foamed urethane material). The dynamically excited bridge and viaduct generally vibrate at their own natural frequencies and corresponding mode shapes. The resonant behaviours of the bridge and viaduct depend on the rigidity of the structure as a whole and each individual component. The dominant frequencies emitting structural-borne noises are often observed in a lower frequency range of the infrasound spectrum.

For the foundation of ballastless tracks, ground-borne vibration could disturb the surface infrastructure and buildings over operating underground railways. The ground vibrations propagate through the ground medium in the form of compression waves (P-wave), shear waves (S-wave) and as Rayleigh waves (R-wave). P- and S-waves are the body waves, whilst R-wave is a surface wave similar to waves on the surface of a lake. In practice, it is found that the P- and S-waves dominate the vibration transfer in the deep underground tunnel. In the shallow underground (subsurface), all three waves play a major role, whereas in the surface rail track, only R-wave contributes to the vibration propagation.

Track vibration isolations

The wheel/rail interaction induces dynamic actions to supporting track structure in a wide range of frequency spectrum and amplitude (Remennikov and Kaewunruen 2008; Thompson 2010). Figure 2 shows different types of common rail infrastructure. For ballasted tracks built on the ground, rail pads can filter dynamic contents at a high frequency range above 1000 Hz, whilst the sleepers respond to the dynamic force spectra. Concrete, composite, hard-plastic and steel sleepers tend to have much poorer damping capability compared with timber and

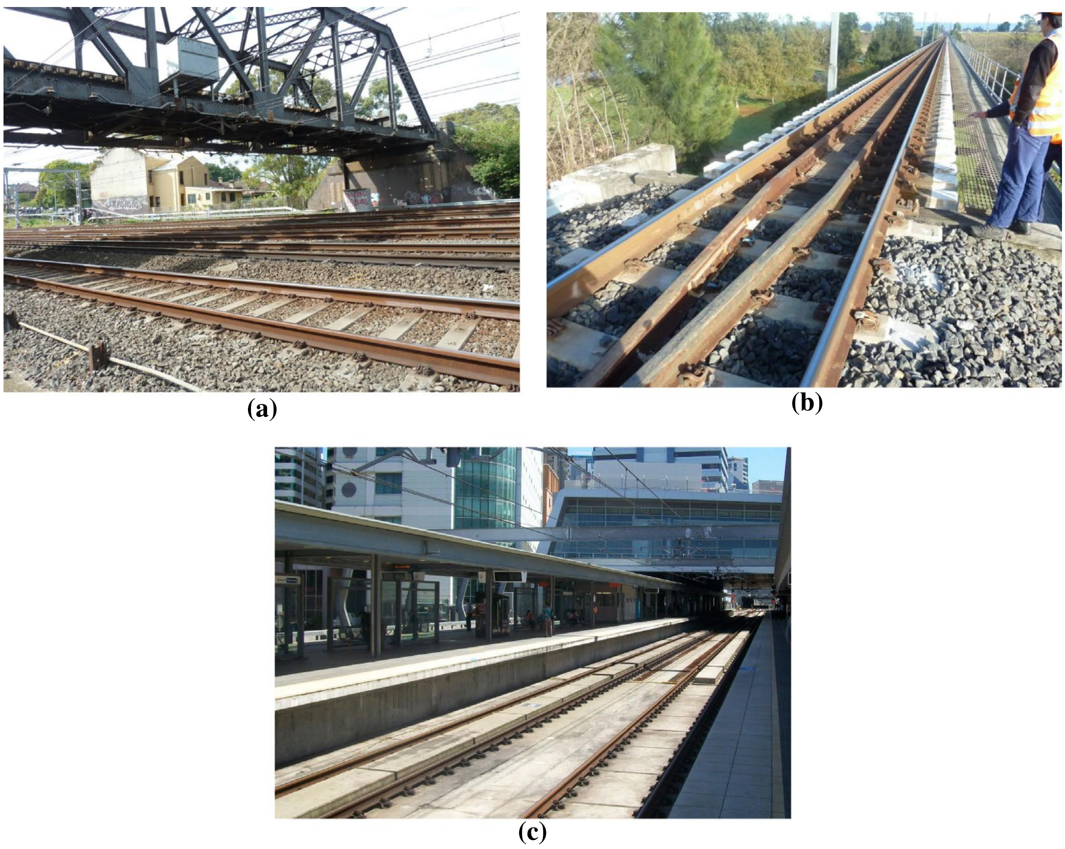


Figure 2. Railway infrastructure, (a) typical ballasted track, (b) ageing railway transom bridge and (c) railway slab track or direct fixation adjacent to existing platforms.

fibre-reinforced foamed urethane sleepers (Kaewunruen, Sussman, and Einstein 2013; Kaewunruen 2014a, 2014b). Ballast and compacted soil could potentially damp out most remaining frequencies above 150–200 Hz. As a result, most vibration issues are in the range between 2 and 150 Hz for the neighbourhood near railway lines in tunnels, on embankments, in a cutting or on the level ground.

For bridges, viaducts and other elevated structures, the vibrations can also later transfer to the ground via the bridge piers, piles and foundation structure. The natural frequencies of bridges and viaducts depend largely on individual bridge components and on the deformation modes of the bridge. The length of bridge span often determines the dynamic behaviour. The long-span bridges (e.g. 70–100 m) tend to be more slender and contain lower natural frequencies, ranging from 30 to 125 Hz. The natural frequencies of short span bridges (e.g. 30 m) on the other hand are centred between 65 and 1000 Hz. For transom bridges, the transom deflection and vibration resulted from large flexible girder plates can generate additional secondary noise effects. These are the specific ranges of frequencies to be suppressed in order to prolong the lives of railway track components. Figure 3 demonstrates the actual consequences and track deteriorations due to dynamic effects, associated with specific resonant frequency range of such component.

Structural damage and track deterioration due to dynamic effects in railway systems (courtesy: RailCorp), (a) pulverised ballast due to dynamic impact (20–150 Hz), (b) broken concrete sleeper due to poor energy dissipation of material (100–300 Hz), (c) pulverised ballast (or attrition) and track pumping at the interface between timber and concrete sleepers due to the change in track stiffness (20–150 Hz), (d) sleeper resonances induce large permanent settlement of track at bridge ends (0–70 Hz), (e) crack of the fastening system at railway bridge ends (150–500 Hz), (f) bog hole or mud pumping deteriorated by vertical error and dynamic increment of wheel/rail interaction (0–70 Hz) and (g) bed rock formation pumping deteriorated by wide range of dynamic frequencies of wheel/rail interaction.

To establish an effective isolation system, track engineers must design the damping and isolation capabilities in order to filter out the dynamic forces essentially in the resonant bands of the structure. It is often recommended that, due to coupling train–track system complexity, a field test is carried out to determine the dynamic performance of a particular isolation system. In practice, there exist many methods and techniques for track vibration isolation between the source and the receiver. It is important to note that the isolation is most effective when it is dealt close to the noise source, i.e. applying third party suppression material between wheel and rail, or placing an isolator between rail and supporting structure.

In a conventional ballasted track with timber sleepers, acceptable vibration isolation was achieved by timber and high-surface-friction ballast. In recent years, concrete sleepers have been adopted to cater faster and heavier trains. Elastic rail pads and fastenings have been used for this purpose (Pfeil 1988; Esveld 2001; Griffin et al. forthcoming). On the elevated structure, ballast component in such a ballast-top bridge is often neglected to reduce weight and rail pads are thus overly exploited. This results in significant bridge vibration with the regenerated noise, and therefore, premature lives and damages of concrete sleepers and elastic pads can frequently be observed.

For the ballasted tracks, the track system may comprise lesser components but the complex interaction between sleeper/ballast and large variations in soil dynamics and geotechnical system cannot be underestimated (Esveld 2001). The following techniques for vibration suppression have been designed to cater either passenger or freight trains and they have been adopted in the field (Coulier et al. 2013; Connolly et al. forthcoming; Griffin et al. forthcoming):

- Increased ballast depth
- Resilient rail pads and insulators
- Soft baseplates
- Thicker resilient rubber under the baseplates
- Resilient pads under sleepers (or called ‘under sleeper pads’)
- Resilient mat under ballast (or called ‘ballast mat’)
- Rail dampers
- Ballast geo-synthetics and capping material (or sometimes called ‘sub-ballast’)
- Ballast glue/bond to increase mass and cohesion (stiffness)
- Sheet piles and bored piles for suppressing ground-borne vibration

In the ballastless tracks, although the structural system can be more complicated, a vibration control technique can generally be designed and implemented more precisely. The vibration control technique for track system as a whole sometimes adopts more than one method. The following are the example of techniques for vibration suppression subject to both passenger and freight traffics (Coulier et al. 2013; Connolly et al. forthcoming; Griffin et al. forthcoming):

- Resilient soft baseplates (e.g. Cologne eggs) between rail and track slab
- Resilient pads between the rail foot and the baseplate
- Resilient rubber between the baseplate and track slab
- Soft elastic fastening system (e.g. vanguard system, etc.)
- Rail dampers

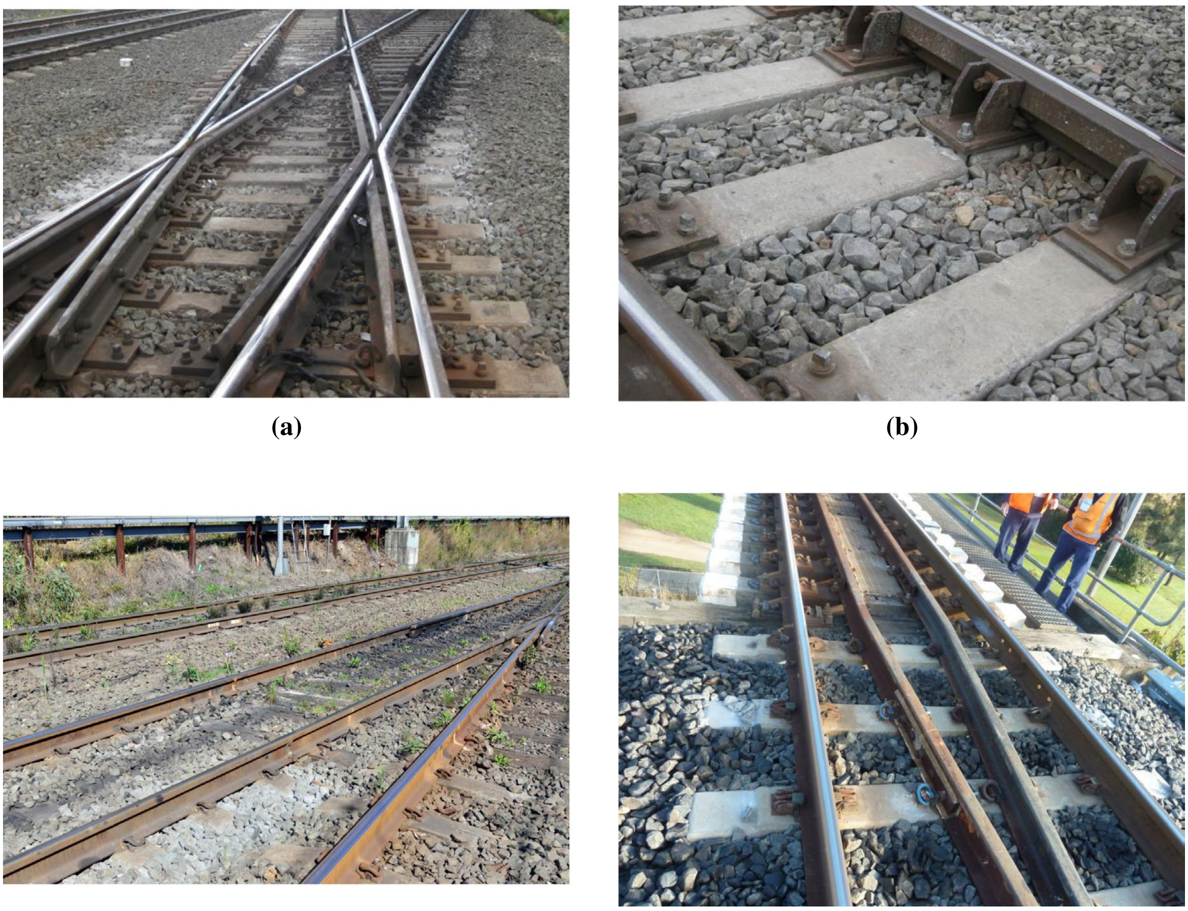
- Resilient track form (i.e. booted sleepers, floated slab, rubber-shear lock slab)
- Slab mass control (e.g. increasing slab mass to suppress vibration)
- Tuned mass damper on the bridge structure
- Bridge bracing system

Ballasted tracks

It is important to note that the isolation effectiveness depends on dynamic stiffness of track system and resonance behaviour of track support components. The dynamic attenuation is maximised when a very soft system is used. However, the soft system is easily damaged and rapidly deteriorated by heats generated from the fast movement and heavy tonnage of train operations. The initial design resiliency of the material could not be retained over a certain period of time. As a result, utilisation of materials with higher strengths (often also with higher stiffness) is often a practical compromise in reality. Effectiveness of such a resilient pad material also depends on other factors including the thickness of ballast and the type of foundation. The softer-pad isolation techniques can yield better improvement in a thinner ballast depth installed over a stiff support (e.g. viaduct, rock layer). In contrast, the vibration losses could be little from the technique when applied in railway track comprising of a thick ballast layer on compacted soil formation.

Interestingly, a measurement campaign in the past decades (Pfeil 1988; Esveld 2001; Coulier et al. 2013; Connolly et al. forthcoming; Griffin et al. forthcoming) shows that increasing the ballast depth from 300 to 750 mm could result in a potential insertion loss of 6 dB in a low frequency range under 10 Hz, whilst very little or none of insertion loss could be obtained at higher frequency spectra. Variations of rail pad materials and stiffness can attenuate impact forces over 100 Hz on concrete sleepers (Kaewunruen and Remennikov 2006, 2007, 2008a). However, little effect could be observed on lower frequency range. Using an under sleeper pad of 15 mm thick (cork rubber) has showed a reduction of vibration level by 8 dB in the range from 25 to 80 Hz (Pfeil 1988; Coulier et al. 2013). Another benefit of the under sleeper pads is the improvement of the aggregate noise and impact vibration due to sleeper hanging (the issue with ballast void and pockets).

It was found that conventional ballast mats must be used on a case-by-case basis. The stiffness of ballast mats should be designed to establish insertion loss at the frequency range of concerned noise. Previous utilisation of the ballast mat in NSW, Australia, showed insignificant improvement in the frequency range under 40 Hz for

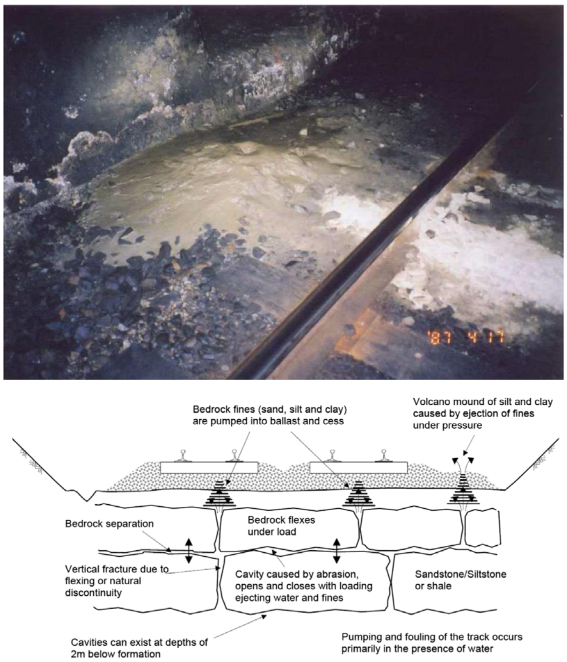


(a) (b) (c) (d)

Figure 3. Structural damage and track deterioration due to dynamic effects in railway systems (courtesy: RailCorp).

(e)

(f)



(g)

Figure 3. (*Continued*)

ballasted track on a standard formation (Esveld 2001; Connolly et al. forthcoming). However, if properly designed, the ballast mat can suppress vibration over a wide range of frequency on the ballast–top viaduct or bridge, especially when the ballast depth over a rigid concrete floor is insufficient. It is noted that composition of multi-stiffness layers, surface hardness, surface roughness and surface profile of the ballast mats plays a role in vibration attenuation through increased friction between aggregates and the mats. Some soft ballast mats can suppress more than 6 dB of vibration in the frequency range from 50 to 150 Hz, but the soft rubber could in turn increase the track vibration at a lower range (e.g. less than 30 Hz).

Ballastless tracks

Ballastless or ballast-free track systems are normally used in tunnels, on viaducts and bridges, or sometimes on the plain tracks (in a high-speed rail network) in order to reduce track maintenance, reduce size/dimension of track cross-sections in tunnel construction and reduce dead loads on the supporting structures. Without ballast and other resilient materials, the vibration due to the wheel/rail interaction can transfer to the supporting structures and the ground almost unimpeded. As a result, resilient components are critical in the design of ballastless tracks. Depending on the component suppliers, special baseplates, rail pads and baseplate pads can attenuate to an extent in a frequency range between 50 and 400 Hz but to a lesser influence compared with ballast aggregates. A special baseplate (e.g. cologne eggs) between rails and concrete slab can be designed to effectively attenuate track vibrations. The use of elastomeric collar of the Cologne eggs can reduce the vibration of 7 dB in the frequency range from 31.5 to 45 Hz and up to 18 dB in the range from 63 to 80 Hz (Pfeil 1988). The special baseplates and the pads underneath them, however, have a limitation to suppress the lower frequency range of vibration (<50 Hz) due to rail deflection control (they require certain level of static stiffness for smooth unevenness), and also a soft rubber could exacerbate the vibration and reduce service lives of other adjacent fastening components (e.g. screw spikes, clips). The use of rail dampers is comparatively more effective to suppress rail vibration for the ballastless tracks but only a certain frequency band could be suppressed using this technique. As a result, the rail dampers must be designed on a case-by-case basis to achieve its best practice. Note that rail dampers often shield the operational capabilities to inspect the rail integrity, visually or automatically by a mechanised track patrol vehicle, a laser profiling equipment or an ultrasonic wheel.

In the Western NSW, some areas of track were designed to accommodate resilient rubber strips between rail foot and concrete slab over the full length of rails. The resilient rubbers were used to simulate the vertical stiffness or elasticity of a ballasted track bed. In the past, track pumping over the rock fill layer due to excessive slab vibration was observed frequently prior to the adoption of a more resilient rubber. Although some improvement was observed, field data showed that a conventional ballasted track performs better in vibration suppression over a wide range of frequency. It is very important to note that in addition to vibration isolation property, electrical isolation property of the rubber strips must be prioritised in order to provide operational signalling compliance for this type of track system.

Using mass–spring–dashpot theory, the slab track can be laid on a stiffness-tuned rubber, which could isolate railway track vibration at various frequency bands. For example, the 'Eisenmann' slab track can reduce 12 dB in the 20–40 Hz band, 18 dB in the 40–125 Hz band and 25 dB in the 125–400 Hz band (Esveld 2001; Griffin et al. forthcoming). However, the drainage of the floating slab should be specifically taken care of. Poor drainage can lead to water ponding in the joints between concrete track slabs. The incompressible fluid can increase the dynamic stiffness of the track system and reduce its damping capabilities. The viscosity of stored stagnant water can increase the level of ground-borne vibration on adjacent buildings and the water pressure can also damage the track slabs. In some practical cases, added mass of existing concrete slabs (by concrete top) could be established in order to retard the slab vibration and to allow the resilient fastening systems to perform (Dai et al. forthcoming).

Conclusion

Current transportation technology using steel wheels and rails to carry heavy freights and other loads has been proven to be one of the most economically efficient logistic systems in modern days. However, train and track interaction generates a travelling source of sound and vibration along the railway line. A variety of forms and spectra of the sound and vibration have raised concerns to rail engineers and acoustic professionals. The undesirable sound is often called 'noise'. Common noises and vibration in railway systems are rolling noise, impact noise, curve noises, mechanical noise, airborne noise, structure- and ground-borne noises. The multiple effects of the noise and vibration exist. Those carried through the vehicle body mainly affect ride quality, customer experience and comfort, and structural integrity of the rolling stocks. On the other hand, the vibration that is transmitted from the rails to the track-supporting structure plays a main role in rapid degradation of the track and its supporting and surrounding structures.

This study highlights the current state of practice for railway track vibration isolation commonly used in existing railway lines. Its aim was to provide technical understandings, lessons learnt and relevant and contemporary practical issues for both track and acoustic engineers, in order to develop a common and compatible solution for track vibration isolation that is economical, practical and environmentally effective. The common ground can lead to the future development of novel vibration isolation strategies in practice.

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Zac is a positive and self-motivated technical manager and specialist with extensive experience across civil, transport and rail industry in public and private sectors. He has extensive expertise in transport infrastructure engineering and management, successfully dealing with all stages of infrastructure life cycle and assuring safety, reliability, resilience and sustainability of rail infrastructure systems. He has high skills in business management and continuous improvement of customer experience. He held visiting appointments at various institutions, including Massachusetts Institute of Technology (MIT), Chalmers University of Technology's Railway Mechanics Centre in Gothenburg Sweden and Railway Technical Research Institute in Tokyo Japan. He has over 200 technical publications and consultancy reports, and has served on the editorial boards of many international journals, including Structural Monitoring and Maintenance, Shock and Vibration, Journal of Structures, Scientific World Journal and International Conference of Railway Technology.

Zac is the lead guest editor for a special issue on "Safety, Reliability, Risks and Uncertainties in Railway and Transport Systems". His current research focuses cover a wide range of civil and railway engineering, including: civil and rail infrastructure, train/track interface and interaction, track systems, rail dynamics, structural dynamics, reliability and resilience, shock/blast and impact, high speed rails, railway and transportation systems, risks, economics, strategy, systems and urbanisation. He is Chief Editor of Frontiers in Transportation and Transit Systems.

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