Application of statistical energy analysis to rail noise predictions

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ABSTRACT

Rail transport in Australia is a key component of the push for more people to use public transport and not their own cars, providing a cost-effective and more environmentally friendly means of getting to and from work. This increase in rail infrastructure through the country means that there will be increased train movements, new rail corridors and extensions to existing lines, which require careful impact assessments be undertaken to ensure that the amenity of existing and future receptors is maintained. A key component of these assessments is modelling and assessment of noise and vibration impact from rail movements which needs to be both accurate and fast when applied to the often complex constructions of rail viaducts and train stations, a task which Statistical Energy Analysis (SEA) is perfectly suited for. This paper outlines a summary of an SEA approach to assessment of structure-borne noise from trains, which has been applied to projects including noise impact on the Adelaide Convention Centre plenary hall which is located above Adelaide's railway station, regenerated noise in the new Springfield Station offices located beneath the upper train station concourse areas, and the contribution of structure-borne noise emissions from an elevated rail viaduct to environmental noise emissions.

1 INTRODUCTION

Rail transport for both passengers and freight is a key component of Australia's infrastructure, improving connectivity, productivity, urban regeneration, unlocking land for affordable housing and livability throughout the country. The Australian Government's commitment to rail transport development in recent years and into the future reflects this importance, with freight task set to double over the next 20 years, and treble along the eastern seaboard. The 2017-2018 budget includes $10 billion over 10 years for a transformational National Rail Program to improve urban and regional rail networks, recognizing that urban rail projects can be truly city-shaping.

Figure 1 Rail corridor through Melbourne

Important components of rail infrastructure include over and under-rail structures to maintain the operability of key vehicle and rail transport corridors, viaducts over transport corridors to minimise the corridor footprint, and the presence of transport hubs and corridors in both rural and urban centers to capitalise on the efficiencies that the new rail infrastructure will offer. This new rail infrastructure, while vital for Australia's growth, has significant engineering challenges to overcome, among these is issues related to noise and vibration impact where rail corridors are located near residential, commercial and other habitable areas. A range of acoustic modelling software is available to assess various noise and vibration impacts from train operations, such as implementation of the Kilde Report 130, Calculation of Railway Noise and other methodologies within SoundPLAN, NoiseMap and CadnaA for environmental noise, and assessment of vibration from rail corridors using software such as Pipe-in-Pipe, and Finite Element Analysis (FEA) packages and Boundary Element Methods (BEM) for acoustic analysis of low-frequency noise and vibration. Since becoming a common tool for assessing structural response and radiated noise from vehicles, ships and aircraft, Statistical Energy Analysis (SEA) has been increasingly applied to noise in rail applications, particularly for determining mid-to-high frequency internal noise and vibration within railway cars and cabins during operation of the train due to a combination of wheel/rail interactions (Chadwyck et al, 2012), as well as other sources such as aerodynamic forces on the carriages (Poisson et al, 2002).

This paper describes recent application of the SEA methodology to structure-borne on noise-sensitive receptors external to the rail carriages (rather than inside the train), including noise-sensitive receptors directly beneath an elevated train station, a highly-sensitive convention space above a rail station, and noise-sensitive residential receptors adjacent an elevated viaduct.

2 NOISE AND VIBRATION FROM RAIL INFRASTRUCTURE

2.1 Wheel Rail Interaction and Excitation by Roughness

The "Transportation Noise – Reference Book" edited by Nelson (1987) includes a chapter by Remington, Kurzweil and Towers on "Low Frequency Noise and Vibration from Trains". Remington et al (1975) and Manning et al (1974) carried out fundamental research into wheel/rail noise and vibration excitation mechanisms, most recently extended and summarised by Thompson (2008). As summarised in Thompson (2008), "the motion of the wheel along the rail can be ignored and replaced by a 'moving excitation' in which the roughness 'strip' is pulled through the gap between wheel and rail". Considering only vertical vibration,

$$v_r = Y_r F \ , \ v_w = -Y_w F \ , \text{ and } v_c = Y_c F = \frac{i\omega}{K_H} \qquad \text{(1a,b,c)}$$

Where F is the vertical harmonic force, $v_{w,r,c}$ and $Y_{w,r,c}$ are the velocity amplitudes and vertical mobilities of the wheel (w), rail (r) and contact (c) spring, K_H is the contact stiffness, and ω is the circular frequency. Introducing a roughness of amplitude r, the derived force can be shown to be given by:

$$F = \frac{i\omega r}{Y_r + Y_w + Y_c} \qquad (2)$$

Typical mobilities are shown below in Figure 2. The mobility of the rail (which can be modelled as a Timoshenko beam) is controlled by the stiffness of the rail from about 100Hz up to a peak at about 1kHz which depends on the rail pad stiffness (stiff pad at about 1000MN/m has a peak at 1kHz, while a softer pad with an order of magnitude less stiffness peaks around 250Hz). The mobility of the wheel (determined from measurements of various wheel types) is stiffness controlled below about 500Hz, and mass controlled above and controls the response below about 70Hz and above about 1kHz. The "contact spring" is obviously controlled only by its stiffness.

The roughness level is shown below in Figure 3 (taken from Grassie (1982)), with the roughness wavelength varying logarithmically with train speed. Also shown in Figure 3 is the track decay rate (taken from Thompson (2011)), which as noted by Janssens and Thompson (1996) is given by:

$$\langle v^2 \rangle = \frac{1}{T}\int_0^T v_r^2 10^{-\frac{DVt}{10}} dt = \frac{4.34}{DVT} v_r^2 \qquad (3)$$

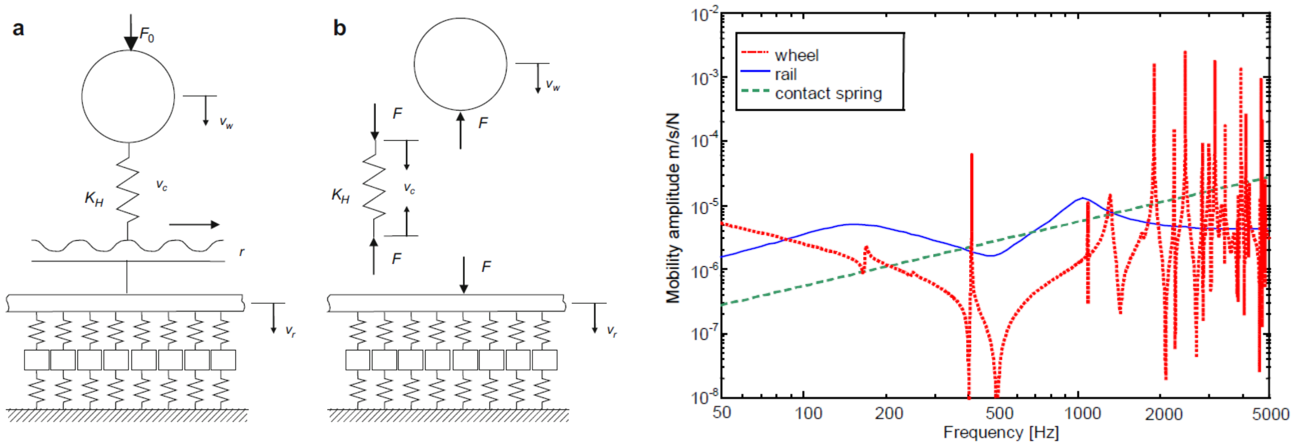

Figure 2 Model of Rail and Wheel Excitation [LEFT] and typical mobilities [RIGHT]

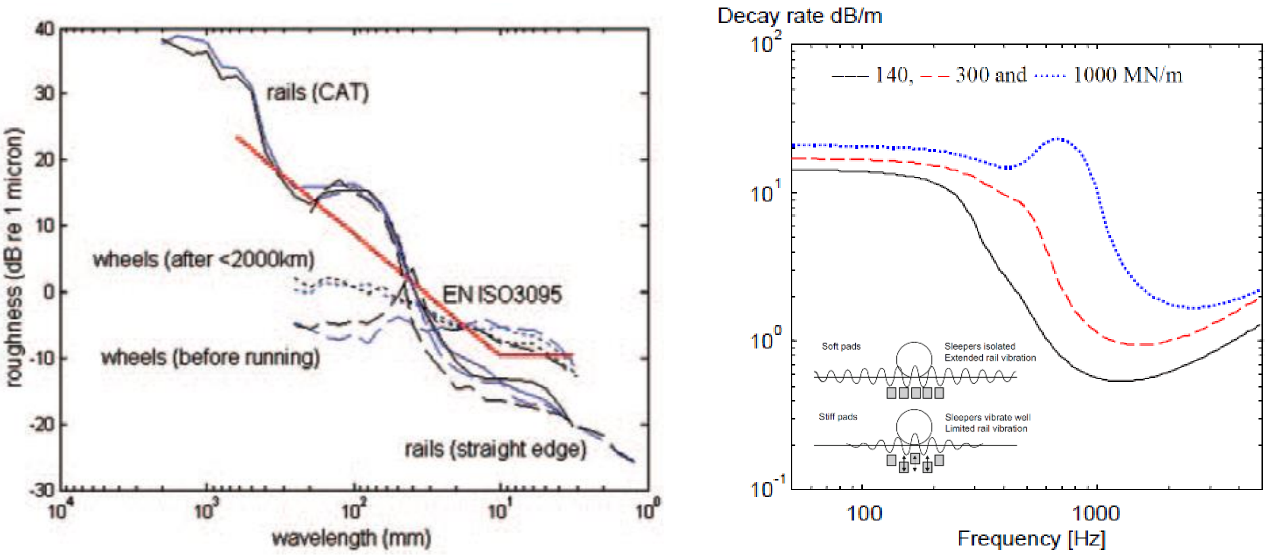

Figure 3 Roughness Spectrum [LEFT] and track decay rate [RIGHT]

Using these parameters, rail vibration can be predicted accurately from knowledge of the rolling stock parameters (speed, length, mass (sprung/unsprung), wheel type etc), and the track parameters (rail type, support spacing, pad stiffness etc). Once the average velocity of the rail has been calculated, the force applied to a structure or the ground is given by the transfer impedance (inverse of mobility), Z_F, through the fastener:

$$F_B = vZ_F \tag{4}$$

As noted by Janssens and Thompson (1996), based on the theory from Cremer and Heckl (1988), the power input to a structure (eg. Bridge) or the ground (ie. Elastic half-space) is calculated using:

$$W_{in} = \frac{1}{2}|F^2|Re\{Y\} \tag{5}$$

The mobility of the bridge can be determined using analytical formulations outlined in Cremer & Heckl (1988) and Ver and Beranek (2005), with for example, the power input to an infinite beam, plate and elastic half-space (ground) are given by the following equations:

$$\frac{|F^2|}{8\rho_M S c_B(\omega)},\ \frac{|F^2|}{4.6\rho_M h^2 c_L}\ \text{and}\ \frac{48|F^2|}{\omega\rho_M \pi\lambda_S^3} \tag{6a,b,c}$$

Where $c_L = \sqrt{E/\rho_M}$ is the longitudinal wave speed, $c_B = \sqrt{\omega E/I\rho_M S}$ is the bending wave speed, and $\lambda_S = \sqrt{G/\rho_M f}$ is the shear wavelength, with S the cross sectional area of the beam, I the second moment of inertia about the axis of bending, h the thickness of the plate, ρ_M the material density, E the Young's modulus and G the shear modulus of the material. From the above equations it can be seen the power input per unit force is greatest for the plate (nominally 600mm thick concrete), and order(s) of magnitude less for the ground (soil) and beam (2.4m deep 600 wide typical element of a concrete viaduct).

3 STATISTICAL ENERGY ANALYSIS

The power input to the ground (or elastic half-space) can be calculated using elasto-dynamics theory, and predicted using common finite element software such as Plaxis to enable interaction of ground-borne vibration with nearby building foundations. A coupling loss exists between ground vibration and that transferred into the building foundation (measurements were originally made by Wilson, Ihrwig & Assoc (Nelson and Saurenman (1983)).

Once the power input into a structure is determined the power flow between sub-systems can be represented as shown in Figure 4 below, with E_i the energy and η_i the dissipative loss factor of each subsystem. The coupling loss factors, η_{ij}, and modal densities, $n_i = \Delta N/\Delta\omega$ (with ΔN being the number of modes in frequency band $\Delta\omega$), such that $n_1\eta_{12} = n_2\eta_{21}$.

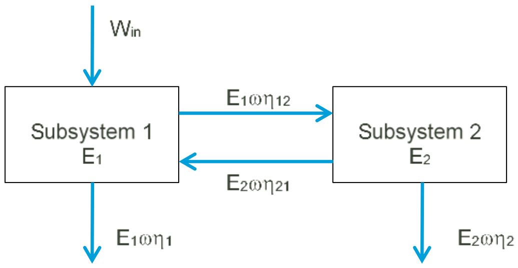

Figure 4 Power flow between two subsystems

For multiple sub-systems, with the introduction of vectors of power inputs, $\boldsymbol{W}$, and energies, $\boldsymbol{E}$, for each sub-system and a loss matrix, $\boldsymbol{C}$, it can be shown that:

$$\boldsymbol{W} = \omega\boldsymbol{C}\boldsymbol{E}, \text{ or } \boldsymbol{E} = \frac{1}{\omega}\boldsymbol{C}^{-1}\boldsymbol{W} \tag{7}$$

The time averaged energy in a spatial or structural sub-system can be expressed as (with $\langle p_i^2 \rangle$ the space and time averaged mean square pressure and velocity, S the area of the structure, V the volume of the space, ρ_S the surface mass of the structure, and $\rho_o c_o$ the impedance of the space):

$$E_i = \frac{\langle p_i^2 \rangle}{\rho_o c_o^2} V \text{ and } E_i = \langle v_i^2 \rangle \rho_S S \tag{8}$$

Modal densities can be calculated based on the spatial or structural characteristics. Coupling loss factors have been calculated, for example between a plate (sub-system 2) and a space (sub-system 1) given by (with σ_{rad} the radiation efficiency of the plate):

$$\eta_{21} = \frac{\rho_o c_o \sigma_{rad}}{\rho_S \omega} \tag{9}$$

With the power radiated by the plate determined from the expression in Figure 4, equations (8) and (9) as:

$$W_{21} = \langle v_i^2 \rangle \rho_o c_o S \sigma_{rad} \tag{10}$$

Dissipative or damping loss factors for structures have been measured (though are subject to conjecture), while that for an acoustic space is determined from the average absorption coefficient within the space. Using these concepts power flow within complex structures can be estimated, radiated noise estimated, and noise control methods optimised.

4 RAIL NOISE IMPACT ON OFFICES BELOW AN ELEVATED TRAIN STATION

Due to the unique nature of Springfield Station in that it is an elevated platform with an operating public concourse directly below (including staff and ticketing offices and passenger thoroughfare), the Trackstar Alliance identified the need to carry out assessment of the station with regard to train noise and vibration impact on the offices for control of speech intelligibility and to provide an appropriate level of amenity for the office spaces. A combination of finite element analysis (FEA) and statistical energy analysis (SEA) was used to assess both human response to vibration and structure-borne regenerated noise impact on the areas beneath the elevated platform.

Figure 5 shows a render of the Springfield Station on the right (including the passenger concourse and thoroughfare areas at ground level, with the train station concourse above), and on the right side of Figure 5 is the simplified SEA model of the station showing the significant noise radiating elements (columns, cavities, slabs and canopy supports).

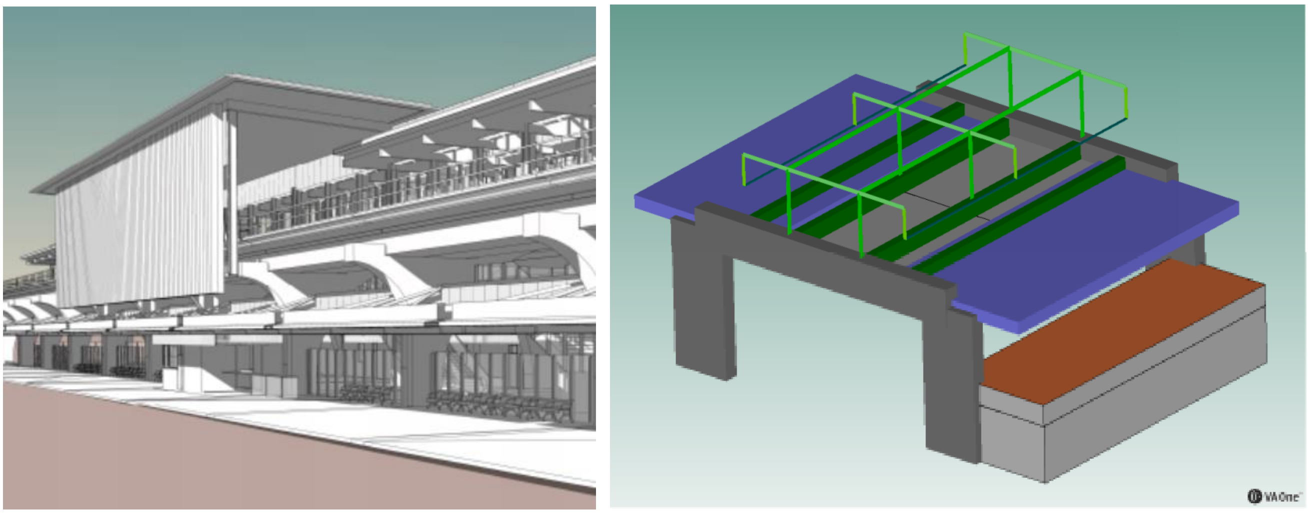

Figure 5: Springfield Station shown on the left, with the VAOne SEA model shown on the right

As the concourse areas directly beneath the railway station will function primarily as a passenger thoroughfare, with commercial facilities (offices, shops, retail outlets, etc) on each side, it was considered that no adverse impact on the amenity of people below the rail platform would occur provided that speech intelligibility is maintained within these areas. Therefore, criteria for maintaining speech intelligibility within the spaces below was referenced from the World Health Organisation Guidelines for Community Noise (Berglund et al, 1999) which states “Speech in relaxed conversation is 100% intelligible in background noise levels of about 35 dB(A)”. From this, a continuous equivalent noise criterion of 35 dB(A) was adopted for structure-borne train noise levels within the ground level concourse area.

A statistical energy analysis model of the station was developed using the VA One modelling software, which was simplified to a 15 metre long span, with a concrete supporting arch at either end of the span, and the platform and track slabs supported by the concrete arch at either end. Two acoustic models of the Springfield Station were developed, with the first consisting of a base model with the rail tracks mounted directly onto an N50 concrete slab (4000mm wide x 1150mm deep) simply supported at both ends of a 15 metre span by the concrete arch. For worst-case (non-isolated) assessment of structure-borne noise transfer into the concourse area below, no vibration isolation was modelled at the connection between each end of the track slab and the concrete arch (ie worst-case vibration transmission into the arch, platform, and surrounding structures).

The second model included rail tracks mounted directly onto the N50 concrete slab supported at both ends of a 15 metre span by the concrete arch as above, with AS 5100.4-2004 standard vibration isolation bearings (041202R) installed at each connection between the rail slab and the concrete arch, with the spring constants of each bearing having a compressive stiffness of 433 kN/mm and a shear stiffness of 1.88 kN/mm. With 16 bearings per pier at 5 locations, the average stiffness per support point in a pier used in the SEA model was a vertical spring constant of 1386 kN/mm, and horizontal spring constant of 6.02 kN/mm.

Excitation of the N50 concrete slab was modelled based on vibration measurements of train pass-bys, input into the track slab on both sides of the platform in the SEA model, simulating two trains moving simultaneously on either side of the platform.

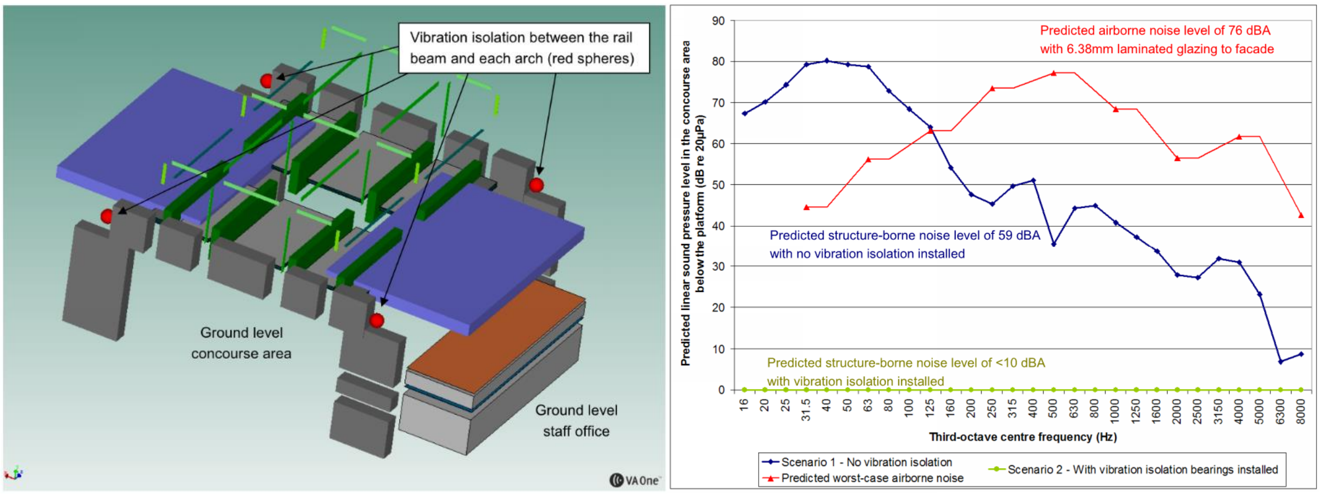

Figure 6: SEA model of the Springfield station shown on the left (including vibration isolation bearings), and a graph of the predicted structure-borne noise impact on the concourse areas below (shown on the right)

Predicted structure-borne noise levels in the concourse area below the platform are summarised on the right side of Figure 6, which shows the predicted linear sound pressure levels at third-octave band centre frequencies. Predicted sound pressure levels are shown for the scenario with no vibration isolation between the track and the platform, and for the scenario with vibration isolation bearings installed. Also shown is the predicted reverberant sound pressure level due to airborne noise transmission into the concourse level staff office area, for comparison with the predicted structure-borne transmission into the office.

Of particular note is the predicted low-frequency noise impact in the 20 Hz to 100 Hz range when the slab is not isolated, which would be clearly audible within the concourse areas below the station as a low rumbling noise. This low-frequency regenerated noise impact was fully controlled through implementation of the vibration isolation bearings (required for control of human response to vibration from the train movements), reducing the predicted regenerated noise levels below the concourse to less than 10 dB(A). Outcomes of the SEA modelling provided the design team with clarification on both the slab isolation requirements (which were further developed in conjunction with the FEA modelling undertaken by the structural engineer), and other acoustic considerations including control of external noise impact via the glazing, and control of reverberation times within the various enclosed spaces (the concourse and offices).

5 RAIL NOISE IMPACT ON CONVENTION CENTRE LOCATED ABOVE A TRAIN STATION

The most recent extension of the Adelaide Convention Centre redevelopment consists of a new exhibition hall located above the Adelaide Railway Station. This exhibition hall is a multi-purpose space, facilitating conference presentations (speech), ballroom functions and acting as an exhibition and gallery space, with potential for general conversations, amplified / reinforced speech, and music meaning that the acoustics of the space are critical in providing a high-quality exhibition space. The new exhibition hall slab sits directly above the main railway corridor into the Adelaide Railway Station, supported on columns which are interspersed between the railway tracks. The potential for adverse vibration and structure-borne noise impact from the rail corridor travelling up the columns and into the exhibition space was identified early in the project, and Aurecon were engaged to undertake an acoustic assessment of the floor and support structure.

Vibration impact criteria on the floor of the exhibition space due to train passbys was selected based on AS 2670 (a maximum multiplying factor of 2 times the base curve based on the average of train movements) for all third octave band levels at and below 40 Hz for human response to vibration in the floor. In addition, an upper limiting structure-borne noise level of 30 dB(A) was stipulated for the hall, with a corresponding third-octave band root mean square (rms) vibration criterion of 0.025 mm/sec in the 50 Hz, 63 Hz and 80 Hz bands (based on the levels achieved for the previous redevelopment).

In order to assess the potential impact of structure-borne noise, a statistical energy analysis (SEA) model was developed based on the design elements of the Adelaide Convention Centre, with excitation of the ground-level railway input based on vibration measurements conducted at ground level in the immediate vicinity of the train pass-bys. The structure-borne noise levels were predicted within the occupied ballroom above the railway, and assessed against the internal noise design criteria in order to determine compliance. A statistical energy analysis model was developed using the VAOne modelling software. The acoustic model of the Adelaide Convention Centre exhibition hall was simplified to an acoustic cavity on a concrete slab, supported by concrete columns as per the structural drawings and specifications (including material properties for the specific concrete). Figure 7 shows the SEA model of the Convention Centre exhibition hall, representing each of the main elements of the facility through which energy is transmitted from the rail induced vibration.

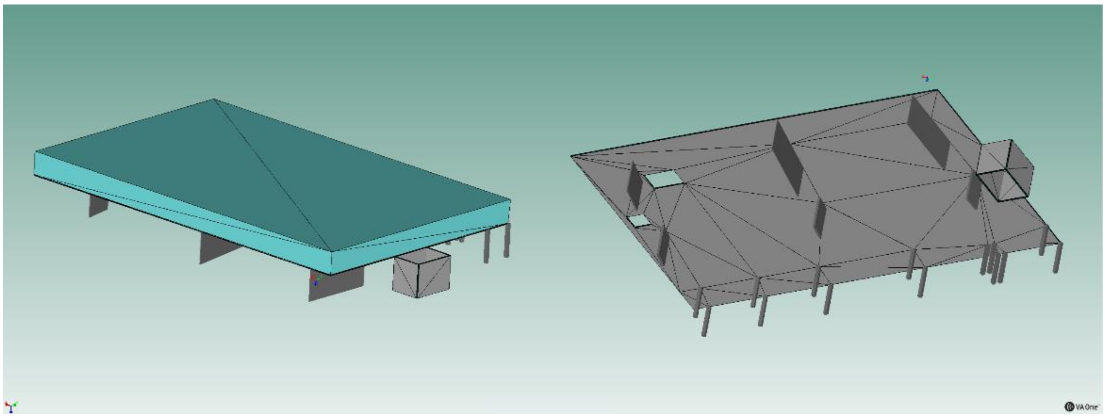

Figure 7: SEA model of Adelaide Convention Centre

Two acoustic models of the Adelaide Convention Centre were developed including a base scenario with no vibration isolation, with the support columns connected directly into the ballroom slab (worst-case structure-borne noise transfer into the hall), and a second scenario with the support columns isolated from the ballroom slab, with the spring constants of each bearing having a compressive stiffness and shear stiffness of 50 kN/mm (shear bearings will be identical to the compressive bearings, mounted horizontally).

Train movement excitation of the support columns beneath the exhibition hall slab was modelled based on vibration measurements of diesel train pass-bys as a worst-case (continuous equivalent vibration velocities measured over a period of 1-minute during a train pass-by), which was input into the support columns supporting the ballroom slab, simulating a single train movement occurring below the ballroom.

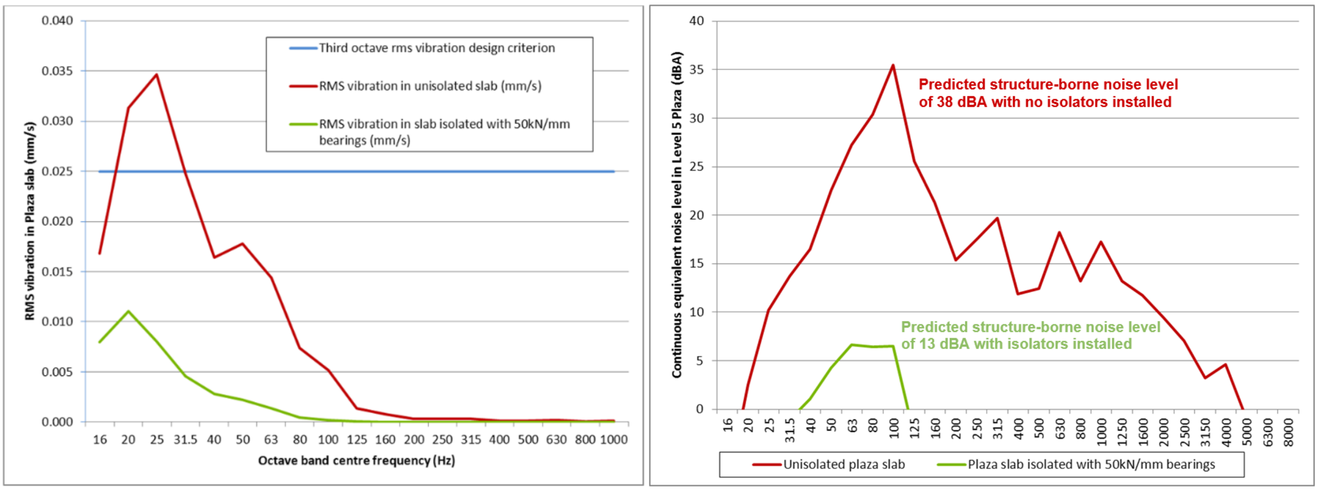

Figure 8: Predicted vibration velocities in the Adelaide Convention Centre exhibition hall slab during train movement (left) and structure-borne A-weighted sound pressure levels (right)

Predicted vibration velocities in the Adelaide Convention Centre exhibition hall slab are shown on the left of Figure 8 (predicted continuous equivalent rms vibration velocities) for situations with and without the isolation bearings implemented between the support columns and the slab. The graph on the right side of Figure 8 shows the corresponding structure-borne noise levels in the exhibition hall, demonstrating the improvement provided by appropriate slab isolation bearings. Based on the results of our assessment we note a predicted worst-case continuous rms vibration velocity of 0.0346 mm/s in the ballroom slab with no vibration isolation installed, which reduced to 0.0111 mm/s with vibration isolation is installed, meeting the design criterion for the space. A predicted worst-case structure-borne noise level of 38 dB(A) was predicted in the ballroom with no vibration isolation installed, which reduced to less than 20 dB(A) with vibration isolation is installed, allowing the design rail noise ingress criterion of 36 dB(A) to be achieved.

6 ENVIRONMENTAL RAIL NOISE EMISSIONS

The Sydney Metro Northwest project is a rapid transit rail link currently under construction in the north-western suburbs on Sydney (previously known as the North West Rail Link), and is the first stage of the new Sydney Metro System. As part of the project, a new elevated viaduct is to be constructed over a 4 km section of the rail link, for which structure-borne noise impact was identified as a potential issue due to excitation and noise radiation from the elevated viaduct (rather than direct airborne noise from the trains).

The project scope of works and technical criteria stipulated strict structure-borne noise level of no greater than 70 dB(A) be achieved at a height of 1.5 metres above ground level beneath the viaduct, based on a train speed of 80 km/hr. The structure-borne noise modelling was to be performed using the NORBERT (Software for Predicting the Noise of Railway Bridges and Elevated Structures), undertaken by Matthew Harrison with Aurecon providing technical review of the modelling results.

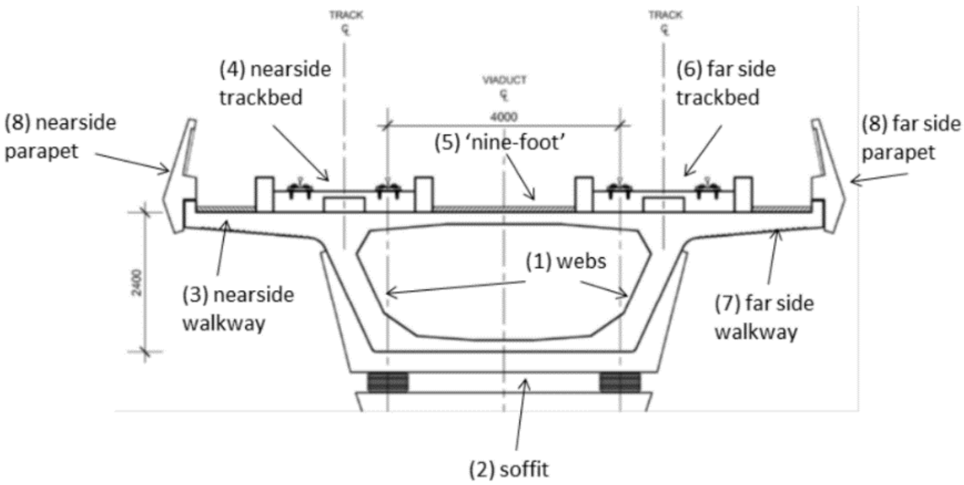

Figure 9: Cross-section of the NWRL viaduct, including the position of the various radiating subsystems

Key input parameters into the model included the rain speed, wheel roughness, train and carriage length, number of wheels, suspension stiffness and track parameters such as rail roughness and resilient layer stiffness. From the model inputs, the noise radiated from each element of the viaduct as shown in Figure 9 was calculated using an analytical track model coupled with a statistical energy analysis model (where the vibration energy is transmitted into the structure and radiated as sound from the various subsystems modelled as plates and beams).

The left graph in Figure 10 presents the predicted noise levels at the ground level receptor location, including a breakdown of the noise radiation from each element of the viaduct. The predictive model shows soffit as the dominant radiating element (ie the underside of the viaduct), with only a minor contribution of the deck, parapets and web elements to the overall predicted noise level at ground level receptors.

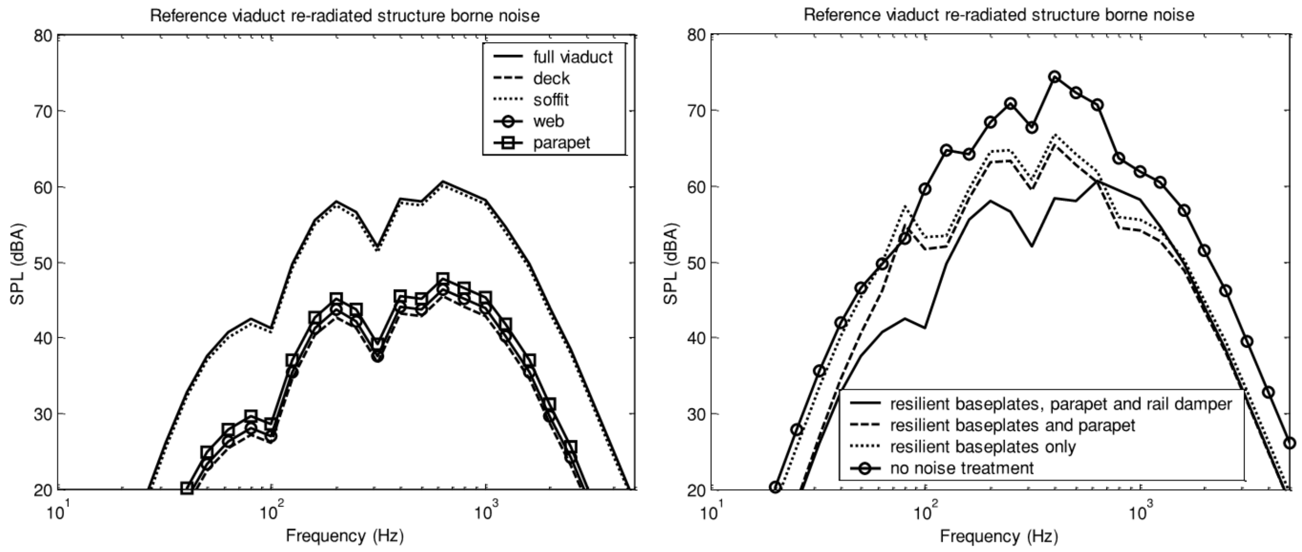

Figure 10: A breakdown of the individual noise radiating elements from the viaduct (right), and the predicted noise levels with resilient acoustic treatment implemented (left)

The right graph in Figure 10 presents the predicted noise levels at the ground level receptor location for various untreated and treated options, including implementation of resilient baseplates to the track, resilient parapet fixings, and application of a rail damper. With no treatment installed, the predicted overall A-weighted noise level was 80 dB(A), and therefore installation of all acoustic treatment was important to ensure the design objectives were met (ie resilient baseplates, resilient parapet connections and rail damper which were predicted to achieve 68 dB(A)).

7 CONCLUSIONS

With the expansion of rail corridors throughout cities and metropolitan areas around Australia, there is an increased risk of adverse noise and vibration impact on sensitive receptors if not properly controlled, especially where rail corridors are located directly above and below highly-sensitive commercial and residential spaces. SEA has been used as a fast and reliable method of assessing structure-borne noise impact on these spaces, controlling the risk of adverse noise impact on sensitive receptors, and allowing optimisation of resilient rail isolation treatment.

8 ACKNOWLEDGEMENTS

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