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An overview of structure-radiated noise and vibration assessment for elevated rail infrastructure

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ABSTRACT

Elevated rail infrastructure has potential to cause structure-radiated noise and vibration concerns during rail operations to the neighbouring community. In this paper, an overview of a structure-radiated noise and vibration assessment method is presented for a box girder design, with elevated station platforms fully supported off the viaduct structure. At first, a simplified method to assess structure-radiated noise levels from viaducts during preliminary design stages of rail infrastructure is explained. The paper also provides a detailed assessment method using a Noise of Railway Bridges and Elevated Structures (NORBERT) model. The NORBERT model is also used to predict force inputs on the structures, which are in turn used in a Finite Element Model (FEM) to predict the vibration levels on station platforms. A brief overview on criteria applicable for such assessments is provided. Sensitivity of parameters associated with rolling stock inputs, rail fastening system and bridge design are also briefly reviewed. The advantages and limitations associated with the assessment technique and modelling inputs are further explored in this paper. This assessment method can be used effectively to mitigate noise and vibration risks associated with rail infrastructure, and develop design solutions to address any relevant environmental concerns.

1 INTRODUCTION

The population of all major cities in Australia has been significantly increasing over the last few years, with more than 300,000 people moving into major capital cities every year (ABS, 2017). In order to cater to this demand, new and modern transport infrastructure developments are emerging within central business districts, and also within the suburban areas of cities (Infrastructure Australia, 2017). This urban densification has led to a number of rail infrastructure developments vertically above or below commercial and residential buildings in the form of bridges and tunnels respectively. This paper focuses on noise and vibration associated with bridges.

Elevated rail designs, with steel bridges are known to increase the overall noise levels by up to 20 dB (Kurzweil, 1977). While steel bridges are preferred where there are constructability challenges and restrictions to weight, concrete bridges are known to produce less structure-radiated noise levels in general (Janssens and Thompson, 1996). However, depending on the location and adjacency to sensitive receivers, structure re-radiated noise levels could be a concern to the community. Elevated rail designs often require elevated stations, which may incorporate station platforms and buildings directly supported by the viaducts. These station platforms could be subjected to rail-induced vibrations due to their structural integration with the viaducts.

Rail operational noise levels are assessed against the relevant state environmental regulations and policies. These policies generally have a target/limit on overall noise exposure during day and night periods ($L_{eq,\ day}$ and $L_{eq,\ night}$), along with a target for L_{max} level of a single train pass-by event. Acoustic consultants often conduct operational airborne noise modelling using 3-D noise modelling software (such as SoundPLAN or Cadna). However, the structure-radiated component of the noise can sometimes be overlooked in such a modelling exercise. This could lead to a potential risk of noise levels exceeding the criteria, especially if sensitive receivers are located in close proximity to the bridge.

There are no known statutory requirements for rail-induced vibration in Australia, within the context of human comfort levels on elevated station platforms. Generic guidance for rail-induced vibration can be found in ISO 14837-1. Dynamic loading considerations are covered under the Australian Standard AS 5100.2:2017 for road-bridge design, however, this does not relate to rail-induced vibration, and is overly simplistic in nature. Vibration criteria in dwellings for rail-induced vibrations are often enforced on projects through environmental effect statements, but station platforms are generally not considered as part of the assessments. However, rail operators, who manage the assets, are faced with the challenge of managing the risks and potential complaints from passengers associated with rail-induced vibrations on station platforms. It is therefore essential to assess the rail design for potential structure-radiated noise and vibration issues in order to address human comfort needs.

Structure-radiated noise and vibration levels associated with rail bridges were investigated in detail in 1970s. Kurzweil (1977) reviewed the approaches towards prediction of noise from rail bridges in the U.S. with an empirical method for assessing potential impacts based on comprehensive measurements. The paper also presents an analytical or numerical model to predict noise and vibration impacts based on studies conducted by the U.S. Department of Transportation (Manning et al. 1975). While empirical methods are useful to qualitatively assess different designs, detailed analytical or numerical methods are required in order to quantify the effect of all design parameters on noise and vibration levels. Since then, researchers in Europe have been involved in the development of pure analytical models to predict noise and vibration levels from rail bridges. Some of the notable work includes the development of TWINS and NORBERT models (Thompson et al. 1996; Thompson and Jones, 2002). Finite element methods were also used to design several elements of the bridge structure (Crockett and Pyke, 2000).

Analytical and/or numerical models can be cumbersome, and often require detailed inputs which may not be developed during the preliminary stages of a project. This therefore calls for a simplified empirical approach during the initial stages of the design, followed by comprehensive analytical/numerical methods during detailed design stages. In this paper, the following aspects are discussed:

- Acceptability criteria that may be relevant to structure-radiated noise and vibration levels
- Simplified empirical/preliminary study to assess structure-radiated noise and vibration impacts
- Advanced Finite Element Modelling (FEM) and NORBERT assessments
- Sensitivity of key parameters
- Advantages and limitations of such assessment methods

2 ACCEPTABILITY CRITERIA

2.1 Structure-radiated noise

There are no appropriate international standards that relate to ground-borne or structure-radiated noise. While ground-borne noise guidelines are generally covered through U.S. Department of Transportation (APTA, 1981; FTA, 2006), structure-radiated noise levels would form part of the overall noise levels in the external environment. Operational airborne noise assessments are generally conducted using site measurements, followed by modelling and validation. Structure-radiated levels may be calculated independently and combined with the predicted airborne noise levels to obtain the overall noise levels. These overall levels should be controlled to meet the relevant airborne noise level criteria. Alternatively, structure-radiated sound power levels can be predicted and added on to the airborne source inputs to predict the overall noise levels. In this way, the overall propagation, including the effects of frequency-dependant attenuation, can be appropriately computed. However, this would be applicable only if the prediction algorithm can accommodate noise spectra calculations (such as NORD 2000).

It is important to consider structure-radiated component of the noise early in the design. Structure-radiated noise may have a different characteristic (spectrum shape) compared to airborne noise, and hence may attract more adverse comments from the community. In this regard, it may be more favourable to control structure-radiated noise to be sufficiently lower than the airborne noise (by 10-15 dB) in mid-high frequency ranges during a train pass-by such that the structure-radiated component is not clearly perceivable. This could however be challenging, especially for steel bridges.

2.2 Vibration

There are several standards used in Australia which relate to assessment of vibration (ISO 10137, AS 2670, etc.). For many structures, vibration levels are often assessed in accordance with the method described in BS 6472 which provides targets in the form of Vibration Dosage Values (VDVs), which consider the number, duration and severity of events. However there has been no research conducted to apply VDVs to passengers standing on elevated station platforms; the commonly accepted threshold values as quoted in BS 6472 pertain to offices and residential dwellings only.

One approach to developing a suitable criteria, in lieu of any relevant research, is to benchmark against other similar structures, for which published acceptability criteria exists. For elevated platform structures supported by a viaduct structure, a reasonable comparison can be made to pedestrian bridges. The British National Annex to EN1991-2 makes reference to a number of factors affecting perception of vibration for pedestrian bridges, which allows a more tailored approach to determining an acceptability criteria (acceleration limit - a_{limit}), as expressed in equation 1:

$$a_{limit} = 1.0\ k_1\ k_2\ k_3\ k_4 m/s^2 \quad (1)$$

The additional '*k*' factors relate to:

- a *Site Usage* factor - a primary means of access has, for example, more onerous requirements than a rural bridge – elevated station structures could be considered 'high usage routes, and would attract a more onerous criteria (i.e. smaller k factor).
- a *Route Redundancy* factor - the redundancy of the route affects the likelihood of particularly sensitive persons being exposed to a level of vibration that would case them discomfort. i.e. could passengers take an alternative path if they felt uncomfortable – in the context of an elevated station structure, as a principal means of accessing public transport, it is reasonable that no redundancy would be considered.
- a *Structure Height* factor - pertaining to a general feeling of exposure and the feeling of vertigo that is experienced by many people. Taller structures attract a more onerous factor. In the case of a partially enclosed station structure, the sight lines may be obstructed such that passengers may or may not get a true sense of the height of the bridge, hence a less onerous criteria may be considered appropriate.
- a *General* factor - to reflect 'other conditions that may affect the users' perception towards vibration - These may include consideration of parapet design (such as height, solidity or opacity), quality of the walking surface (such as solidity or opacity) and provision of other comfort-enhancing features.

Based on a typical elevated platform configuration, a maximum r.m.s. acceleration in the range of 0.3m/s^2 to 0.5m/s^2 may be considered appropriate. This is consistent with other references, such as CCIP-016 which suggests a maximum acceleration of 0.32m/s^2 for 'outdoor footbridges'. For simplicity, acceleration criteria for typical structural applications are often quoted in terms of a Response Factor, which is simply a multiplier of the baseline acceleration level of 0.005m/s^2; considered the threshold of human perception (ISO10137:2007). Hence an acceleration of 0.32m/s^2 can be expressed as a Response Factor of 64. For frequency domain analysis, the criteria may also be expressed as a function of the appropriate Frequency Weighting curve if desired.

Other criteria may also apply, such as for sensitive equipment mounted on the platform structures. For example, the VRIOGS criteria in Victoria, Australia, provides criteria for various equipment in terms of maximum displacement under dynamic loads. Whilst this paper is primarily concerned with human comfort, the methodology described herein can also be used to determine performance serviceability against another metrics.

3 PRELIMINARY ASSESSMENT

Calculation of structure-radiated noise and vibration from rail bridges involves a multi-degree-of-freedom (MDOF) analysis with rolling stock, tracks, fixings, and bridge parameters. During the early stages of a project, it may not be feasible to obtain every parameter to conduct any detailed assessments. Therefore, an empirical approach based on measurements is preferred. However, every bridge, track fixing and rolling stock is different, and hence requires certain basic methodologies to assess a design. This section provides simplified equations to assess vibration and radiated noise levels from a bridge structure, based on measurements conducted on similar rolling stock, rail roughness and bridge conditions.

Force, acceleration or velocity measurements, of a typical rolling stock, taken at a number of locations along the bridge deck, similar to the proposed design (such as steel or concrete), can be utilised to assess noise and vibration impacts. Alternatively, published data from available literature can be used. The measured average force per unit length (F_m) on the deck can be roughly corrected to the proposed design deck geometry based on equation 2 (assuming the material properties are similar) to obtain the force per unit length on the proposed deck (F_p),

$$\frac{F_p}{F_m} \approx \frac{t_m . w_m}{t_p . w_p} \quad (2)$$

where t and w are thickness and width of the deck respectively. Note that the exact stiffness and mobility of the bridge structure is not considered in this approach. The measurements shall be conducted in one-third octave spectrum.

Track fixing system plays a major role in the force input to the bridge structure, and hence the rail fastener stiffness should be considered in the assessment. Ideally, the track-fixing system of the measurement scenario should be similar to the proposed design. Else, further sensitivity studies and may be required to adjust the measured values to account for the differences in the insertion gains.

The force/velocity input on the bridge deck travels through to other segments of the bridge structure such as the parapets and side webs. For a well-coupled structure, the average velocity on segment 2 (v_2), can be derived from the average velocity of segment 1 (v_1) by using equation 3:

$$v_2 = \frac{t_1}{t_2} \eta \, v_1 \tag{3}$$

where $t_{1,2}$ is the thickness of the segments 1 and 2, and η is the mechanical loss factor which is governed by the relative fixing type and orientation of the two segments. The structure-radiated sound power (P_{rad}) can then be calculated for each segment by using equation 4:

$$P_{rad} = \rho_{air} C_{air} \, \sigma \, S \, v^2 \tag{4}$$

where ρ is density, C is velocity of sound, σ is radiation efficiency of the segment, and S is surface area of segment. In order to estimate the radiation efficiency of the segments across the spectrum, the segments can be assumed as a plate with characteristic radiation efficiencies as defined in equations 5 and 6 (derived from Cremer et al. 1973):

$$\sigma \approx \begin{cases} \frac{1}{\pi^2} \frac{U C_{air}}{S f_c} \sqrt{\frac{f}{f_c}} & for\ f \ll f_c \\ 0.45 \sqrt{\frac{U C_{air}}{f_c}} & for\ f \approx f_c \\ 1 & for\ f \gg f_c \end{cases} \tag{5}$$

$$\text{where } f_c = \frac{\sqrt{3} C_{air}^2}{\pi t} \sqrt{\frac{\rho_{plate}}{Y}} \tag{6}$$

where U is perimeter of plate, Y is Young's modulus of plate, f is input frequency, and f_c is the coincidence frequency, dependant on the material properties and geometry of the plate. Note that the material damping factors and boundary conditions are not considered in this assessment as these factors could add to the complexity of the assessment and may not be feasible to incorporate in a simplified method. The total radiated sound power can be estimated by combining the sound powers of all the segments of the viaduct.

Similarly, a preliminary assessment of the station platform decks can be undertaken on the basis of a simplified SDOF representation of the structure, using well established methods. In the event that project specific similar rolling stock, track, and fixing input parameters are not known during the early stages of a project, this assessment could be undertaken on the basis of a force input spectra for similar parameters. A conservative approach could also consider shifting the generic frequency spectra so as to align the peak input force with the natural frequency of the structure (or mode of interest), such that the maximum resonant response could be estimated.

4 DETAILED ASSESSMENT

The preliminary assessment outlined in the previous section has a wide range of assumptions, and is dependent on the accuracy and relevance of the force input on the bridge. Nevertheless, the method can be useful for looking at the effects of changes in the basic bridge design and track support on noise and vibration. To predict the noise and vibration levels associated with the bridge and to further optimise the design, a more detailed assessment is required. Important parameters such as rail roughness, rail pad stiffness, rolling stock parameters (weight and suspension) and bridge mobility affect the force input on the deck, and hence should be a part of the calculations. Moreover, the radiation efficiency of bridge segments is non-trivial and depends on the nature of input spectrum, boundary conditions and material damping.

4.1 Noise modelling

The NORBERT model calculates the noise from railway bridges in terms of the sound radiated from a railway bridge structure and rolling noise emitted by the rail and wheel during the passage of a train. Figure 1 shows a flowchart of the main aspects of the model. In the NORBERT model, all the noise arises from the vibration caused by the combined roughness of wheel and rail running surfaces. NORBERT uses a model of the vehicle suspension and track to predict the force at the base of the track structure. Using a simple model for the mechanical impedance of the bridge at the support position of the track, the vibration power input to the bridge is calculated.

The sound radiated from the bridge is calculated using a combination of analytical and statistical energy analysis (SEA) methods, described in (Janssens and Thompson, 1996; Harrison et al. 2000). The bridge structure is described in terms of its gross dimensions and the thicknesses of the deck and supporting beams. The rolling noise model incorporated within NORBERT is based on the well-established TWINS model (Thompson and Jones, 2000). The model is written in the MATLAB environment and is developed at the Institute of Sound and Vibration Research (ISVR, University of Southampton). This model has been validated for few different types of steel-concrete and all-concrete bridges, and good agreement has been found between modelling and measurements (Bewes et al. 2006).

The model works in a frequency domain, in one-third octave band spectra. The combination of wheel-rail roughness is an input to the model and is usually provided as spectra from 20 Hz to 4000 Hz. Modal excitation of moving loads are not considered in this model - whilst this does not impact the sound level predictions (due to the low frequency nature of the excitation), they may have an effect on perceivable vibration levels on station platforms. The vibrational power input to the bridge is calculated from the product of the mean square force transmitted through the track supports and the real part of the bridge mobility.

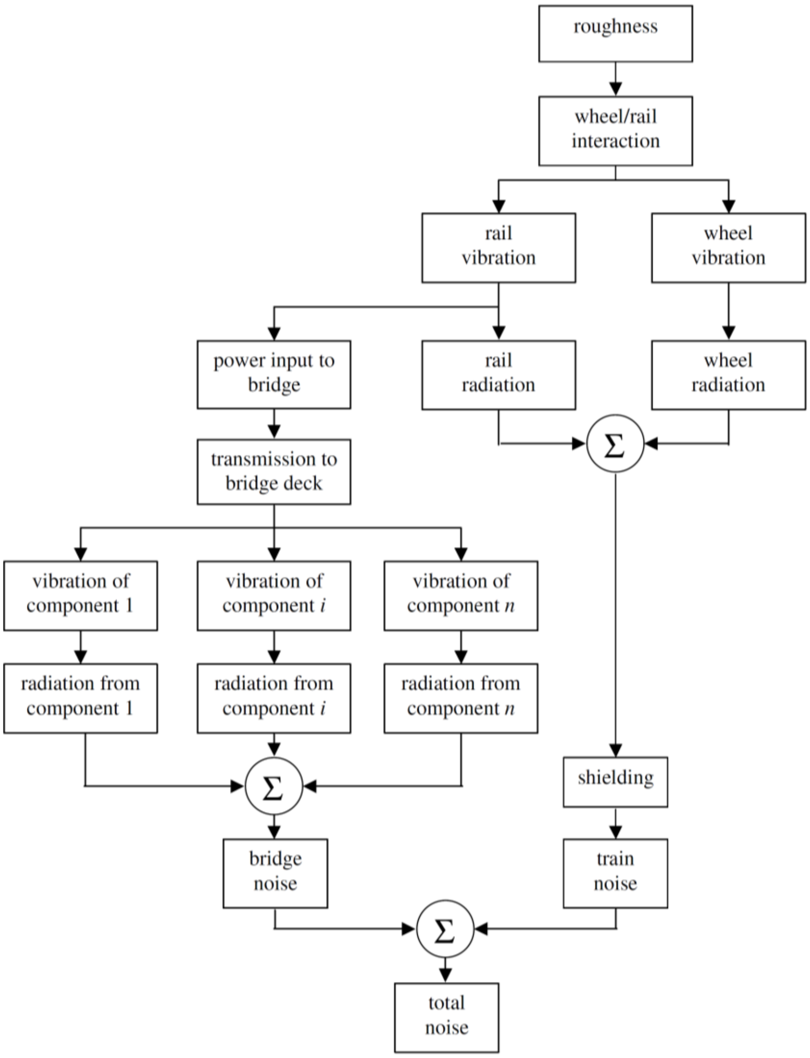

Figure 1: Flowchart explaining the elements considered in NORBERT modelling

4.2 Vibration modelling

In addition to noise outputs, the NORBERT assessment can provide the mean forces acting on the bridge deck based on the specific input parameters. The force outputs from the NORBERT model subsequently form an input for a structural FE model. By excluding the complex MDOF components of rolling stock, track and track-fixings, the structure vibration analysis is reduced to a simple 3-D FE model, of sufficient fidelity to capture all modes of interest. A steady-state (frequency domain) analysis is undertaken to estimate vibration levels at critical locations of the structure, such as the on the station platform and any parapets or canopy structures.

The NORBERT model reports the output as a power spectra, in one-third octave bands. This has been approximated to a continuous narrow-band function (Fourier amplitude spectra) and the data extrapolated to lower frequencies (5 Hz – 20 Hz) using a simple regression analysis, such that the maximum steady state response to specific structural modes can be captured. Some caution should be observed when applying the model to these low frequencies. Below 20 Hz, 'quasi-static' excitation (moving axle loads) becomes increasingly important and this form of excitation is not accounted for in the NORBERT model. Also, at these frequencies the response depends more strongly on the details of the bridge modes and therefore other models (e.g. FE model) may be more appropriate.

5 CASE STUDY

An example bridge design was studied based on the assessment techniques described in the sections above. A direct-fix continuously welded track design, on a concrete box girder viaduct was selected for this study. A twin-pad/base plate track fastening system was considered. This has an upper pad (stiffness of 700 MN/m) aimed at reducing rolling noise and a lower pad (23 MN/m) aimed at reducing vibration transmitted to the structure, and a steel base plate is located between the two pads. The rolling noise will be a combination of contributions of the wheel, rail and the base plates. If one of these is dominant, then reducing the others will have negligible effect on the rolling noise. The assessment was based on a typical suburban electric 6 car train, travelling at 80 km/hr. The viaduct dimensions are provided in Table 1, and the schematic is indicated Figure 2.

Table 1: Dimensions of the box girder used in the case study

Segment	Thickness (m)	Width (m)
A (box deck)	0.25	3
B (box deck)	0.2	1.25
C (box side web)	0.25	2.3
D (box bottom)	0.25	2
E (parapet)	0.15	0.6

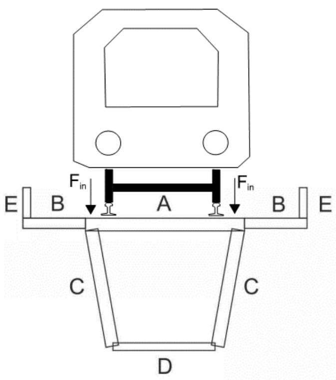

Figure 2: Schematic of the box girder cross-section

In order to compare the preliminary assessment and detailed assessments accurately, the NORBERT modelling was first conducted. The force input spectra on the bridge deck, derived from NORBERT, was then used to compare the structure-radiated noise levels.

5.1 Noise assessment

The structure-radiated noise predictions, based on the preliminary and NORBERT assessments are compared in Figure 3. The noise levels from only 31.5 Hz -1000 Hz are presented as this is the frequency range of interest for structure-radiated noise in this case study. The wheel/rail noise predictions, obtained from the TWINS model is also plotted for comparison purposes. The results indicate that the overall structure-borne noise predictions are very similar between the preliminary and NORBERT assessments (with 1 dB difference). This indicates that for a given force input, preliminary assessment can be useful to make early predictions. However, a difference in the noise spectrum between the two assessment methods is observed. The preliminary assessment indicates a higher energy content at 50 Hz - 125 Hz range. This may be attributed to the conservative assumptions associated with material damping loss factors and radiation efficiencies. That said, the preliminary assessment predicts lower noise levels than NORBERT model at higher frequencies. NORBERT model uses a frequency dependant damping factor, and models the radiation efficiencies to greater detail, and hence is believed to be closer to real measurement spectra. However, at these frequencies, the wheel-rail noise levels are found to be significantly higher, and hence dominating the overall noise levels. Due to the lesser lower pad stiffness of the resilient track fixing system, and high stiffness and mass of the concrete bridge design used in this case study, the overall noise levels are found to be dominated by the wheel-rail interactions.

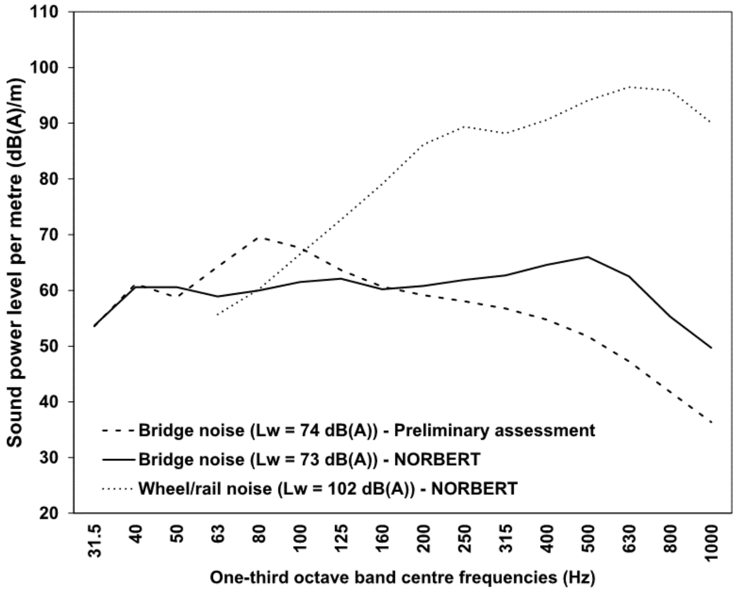

Figure 3: Predicted noise spectra based on preliminary and NORBERT assessments

5.2 Vibration assessment

A finite element structural model was created in SAP2000 with a platform suspended between the two viaducts (schematic shown in Figure 4). The station platform was modelled with 2D shell elements, rigidly linked to the viaducts which were modelled as beam elements. The mesh size was optimised to capture sufficient modes of interest, without unduly adding computation effort. The material properties of the viaduct, including bearings, and tracks were based on a realistic structural design, including typically accepted values for dynamic concrete moduli.

Load patterns were applied to the up and/or down tracks as a unit uniform load, which was then assessed as a steady state load case, based on the force output spectra from the NORBERT analysis; having been converted from power terms in 1/3 octave bands, to a Fourier spectrum in 1Hz bands. In the steady state analysis, the uniform unit load pattern is pre-multiplied by the respective Fourier coefficient at each 1Hz frequency step (5Hz to 100Hz), to obtain a frequency-domain acceleration response spectra at each node, based on a simple MDOF modal approach.

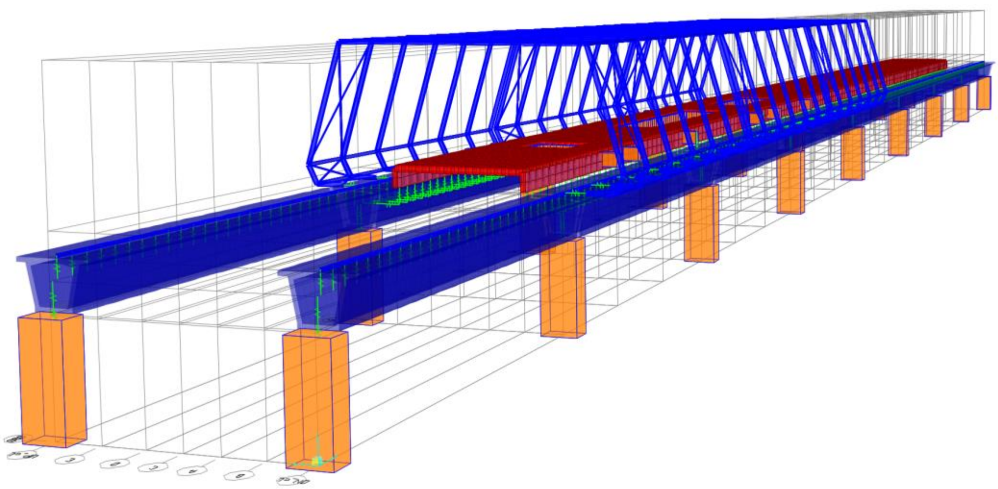

Figure 4: FE model of the elevated station platform used in the case study

Figure 5 indicates the acceleration response of the worst-affected node on the station platform, compared against the criteria proposed in Section 2.1. The two scenarios considered in this study are of a single train pass-by and two trains simultaneously crossing the station platform. Noting the logarithmic scale in Figure 5, the results indicate that whilst the predicted vibration is generally of a level that would be perceptible to most people, the magnitude of response is sufficiently below the suggested criteria, which is consistent with the findings of the noise study, in regards to the efficiency of the track fixing system.

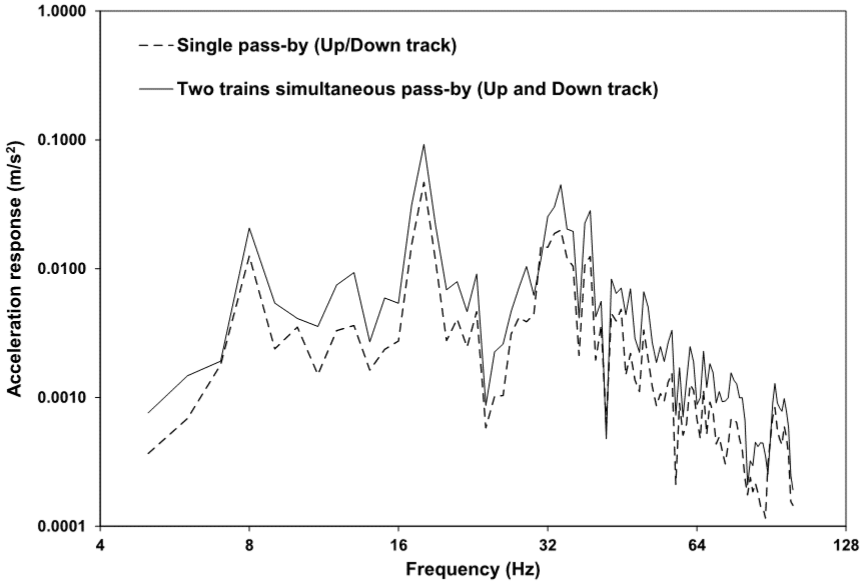

Figure 5: Acceleration response prediction on elevated station platforms (on worst-affected node)

6 DISCUSSION

The structure-radiated noise and vibration predictions are useful and also essential to minimise noise and vibration impacts. The sections below provide commentary on certain key parameters that can be optimised in order to reduce noise and vibration levels. Some of the key aspects associated with the assessment techniques are also discussed.

6.1 Rail fasteners

Rail fasteners play a pivotal role in the bridge noise and vibration impact. In order to reduce structure-borne noise and vibration impacts, resiliently mounted tracks should be adopted. Softer rail fastener pads with lower transmissibility aid in minimising energy transfer to the structure. However, with softer pads, the energy is retained in the rails, thereby increasing the rail-noise (Kostli et al. 2008). However, this increase may not equivalently contribute to the overall noise as the noise radiated from the wheels should also be considered. In the case study described in Section 5, when the resilient track-fixings were replaced by typical ballasted tracks with concrete sleepers, the structure-radiated noise was predicted to increase by 6.5 dB (approximate doubling of vibration levels on bridge), while the wheel-rail noise was predicted to increase only by 0.5 dB (due to contributions from wheel radiation).

6.2 Rolling stock

Rolling stock parameters include mass of the car, primary suspension stiffness, bogie and wheel loads (un-sprung mass), secondary suspension stiffness, and damping coefficients of the suspension system. However, the un-sprung mass and primary suspension stiffness are known to be the dominating factors that impact noise and vibration (Mirza et al. 2012). Freight trains, with higher mass and suspension stiffness, would therefore produce higher noise and vibration levels. The rolling stock parameters are however not possible to optimize as they are governed by vehicle stability, pay loads and riding comfort. Thus it is important to understand the role these parameters play in the mechanics of structure re-radiated noise and vibration, whilst acknowledging that they would most likely not be subject to optimization by the design engineers.

6.3 Wheel-rail roughness

Wheel flats and track joints are known to provide impact-based vibration, and associated noise impacts. These factors are not generally included in the NORBERT as the roughness of these transients do not have a linear correlation with noise, but they can be added to the roughness spectrum as an additional element if they can be appropriately quantified. It is not possible to quantify this during a preliminary study as a complex MDOF vehicle dynamic model would likely be required. However, a number of different rail roughness wavelength spectra have been measured and used as inputs in NORBERT models. That said, rail/wheel roughness increases over time, and hence would require regular maintenance by the rail operator to minimise ongoing impacts.

6.4 Bridge design

Steel bridges are known to provide higher noise and vibration issues in comparison to concrete bridges. This is due to the lack of mass, lower damping, and higher radiation efficiencies of steel. A greater number of bridge segments and elements may also increase the noise and vibration levels, depending on the design. The bridge mobility plays an important part in the power input on the bridge deck (Bewes et al. 2006). Considering noise and vibration impacts early in the design process will provide an opportunity to optimise the structural aspects of the bridge design to develop a 'low noise and vibration' bridge.

6.5 Limitations of steady-state frequency domain analysis

NORBERT model works on a steady-state one-third octave band frequency domain. While the force inputs derived from NORBERT model may be sufficient for a noise assessment, the simplified method of applying a continuous function, explained in Section 4.2, is still considered a coarse method for a detailed structural dynamic assessment. Moreover, the geometry and inertia of the rolling stock wheels and axles are required to reasonably predict the dynamic behavior of the system at lower frequencies (below 20 Hz). While these aspects can be accurately captured by modelling the rolling stock in FE packages such as Universal Mechanisms, these data are not often available, and can also be time-consuming to model. In this regard, it should be noted that the vibration assessment detailed in this paper is only limited to the serviceability performance of the infrastructure. Detailed dynamic analysis covering ultimate limit states, and fatigue related issues, is covered through other relevant rail bridge codes and standards.

6.6 Modal summation methods

Human response to vibration is inherently a time-domain consideration, hence a direct summation of modal responses in the time domain would be the most accurate method to estimate the *real* response of the structure. Ideally, this data would be used to determine a VDV response, which could then be compared to appropriate criteria. Due the nature of the NORBERT analysis, it is not possible to reconstruct accurate time-domain data, as phase information is not available. Hence a statistical method is required to estimate the time domain RMS response, from the frequency information.

Modal summation methods adopted for other forms of structural analyses of non-stationary signals in the frequency domain (e.g. wind or earthquake analysis) include square root of the sum of the squares (SRSS) for problems of low modal density, or a complete-quadratic combination (CQC) method for problems of high modal density. Given the coarse nature of the NORBERT modelling in the context of structural vibration, particularly in the lower end of the frequency range, a modal summation method such as SRSS or CQC is considered an appropriate estimation of the total response.

7 CONCLUSION AND FUTURE WORK

Rail-induced vibration and structure-radiated noise assessment is a complex MDOF dynamic problem that involves several stages of assessment and suitable risk mitigations. It is possible that if these assessments are not undertaken during the design phase, the actual infrastructure may need several mitigation measures post-construction, which can add significant cost, and further occupation of the rail corridor to retro-fit dampers and appropriately tuned rail-fasteners. Instead, noise and vibration impacts associated with elevated rail infrastructure should be considered early in the design. This would provide an opportunity for the structural engineers and rail system designers to iteratively tune the relevant parameters if these impacts are considered a risk to the project. Assessment methods described in this paper allow for quick and simple ways to estimate the impacts, and to optimize the key parameters for the best possible project outcome.

Future work would involve extensive site measurements to validate the preliminary and detailed assessment methodologies. Further, assessment methods that operate in a time domain could be investigated, and these outcomes can be compared with the frequency domain analyses to identify the best approach towards these problems. Modifications for estimating realistic radiation efficiencies during the preliminary stages can also be investigated as part of the future work. Nevertheless, with the advent of modern elevated rail infrastructure in Australia, these rail-induced vibration and structure-radiated noise assessment techniques become more relevant, and act as powerful tools to influence the bridge design and achieve a favourable outcome to the community.

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