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VIADUCT DESIGN FOR MINIMIZATION OF DIRECT AND STRUCTURE-RADIATED TRAIN NOISE

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The Kowloon-Canton Railway Corporation (KCRC) is constructing the West Rail extensions from Kowloon into the New Territories. The Hong Kong Noise Control Ordinance (NCO) stipulates that operational noise levels along parts of this alignment are not to exceed an $L_{eq(30\,min)}$ of 55 dB(A). Satisfying the criteria requires a decrease of roughly 24 dB in the wayside noise level characteristic of an unmitigated viaduct with compulsory reductions in both the direct train and structure-radiated noise. Given the required reduction in noise level, edge sound barrier walls alone will not adequately attenuate direct train noise. Other considerations also rule out extensive use of full enclosure. A mitigation design was developed which consists of augmenting the performance of absorptive parapet walls by creating noise plena beneath the cars and under adjacent walkways. These in-series plena provide source attenuation of undercar noise to supplement the edge walls. A mathematical model is described and results are presented demonstrating that the attenuation achieved with the in-series plena augmenting absorptive edge walls is 12–17 dB greater than the edge walls alone. A model of the structure, trackform and vehicle is developed to determine the structural vibration levels caused by wheel/rail interaction and to predict structure-radiated noise levels from the viaduct vibration. Model predictions are compared with measurement data: resilient baseplates, resiliently supported ties and floating slab trackform (FST) are evaluated with regard to wayside noise reduction. FST with soft resilient baseplates is found to be the only trackform which adequately reduces the structure-radiated noise; however, all trackforms provide less vibration reduction on the viaduct than in tunnels because of the relatively low impedance of the viaduct. Structural changes in the viaduct can affect the level of radiated noise, especially at low frequencies, but not sufficient to eliminate the floating slab. Projections of total wayside noise are obtained by combining the structure-radiated and direct train noise. Results confirm that both the direct and the structure-radiated noise must be adequately attenuated to conform to the NCO. Noise radiated from the floating slab is significant if the rails were attached with stiff fixation; otherwise, the train noise dominates.

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1. INTRODUCTION

The Kowloon-Canton Railway Corporation is constructing system extensions from Kowloon into the New Territories. These extensions will carry heavy mixed transit and freight traffic at speeds up to 130 km/h with short headways and volumes reaching 100 million metric tonnes per year. Current construction plans include 31 track kilometers on viaducts through urban areas with high rise urban residential developments and low rise villages at distances as little as 10 m from the viaducts. The Hong Kong Government requires that all environmental criteria, including noise and vibration, are met without the purchase of property and that future development of wayside areas should not be unreasonably limited by the operation of the railway. With these stringent noise criteria having been adopted, a unique requirement was placed on the project's environmental assessors and acousticians to develop an integrated package of mitigation measures to ensure that the railway will operate within the Government's guidelines.

The Hong Kong Noise Control Ordinance (NCO) sets statutory noise limits on the operation of railways and other sources. During the night-time (2300 to 0700), operational noise levels along sections of the West Rail alignment cannot exceed an $L_{eq(30\,min)}$ of 55 dB(A) at the facades of noise-sensitive receivers. To meet this limit at all properties outside the boundary of the railway, with the proposed peak night-time headway of 4 min, the maximum noise level (L_{max}) cannot exceed 64 dB(A) at 25 m from track centre for 12 car transit trains travelling at 130 km/h. With an assumed reference wayside noise level of 88 dB(A) for an unmitigated viaduct, a 24 dB(A) noise reduction is therefore required for compliance with the legal limit. Achieving compliance requires reductions in both the direct train and structure-radiated noise.

Preliminary analysis indicated that it would not be possible to reduce the structure-radiated noise by much more than a few decibels below the target level of 64 dB(A). This implies that the direct noise component must be of comparable magnitude or less, otherwise the two will sum to more than 64 dB(A). The targeted maximum overalll A-weighted level of the structure-radiated and direct train noise, taken independently, was thus set at at 61 B(dA).

Initially, the viaduct structure was envisaged with full enclosure. The main issue was then to determine the kind of trackform and viaduct section needed for adequate reduction of the vibration transmitted from the rail into the structure which would, in turn, be radiated as (wayside) noise. Later, on account of concerns for safety and ventilation, as well as costs and aesthetics, the search for solutions was widened to include consideration of an open viaduct utilizing noise mitigation measures other than full enclosure. One possible solution was to place tall sound barrier walls on the edge of the viaduct, possibly with sound absorption and cantilevered overhang; however, there would be residual noise impacts. Consequently, an initiative was commenced to review possible alternatives to augment the performance of edge walls based on source attenuation involving design integration of rolling stock, structure and track [1]. The result of that initiative was what is referred to as the Multi-Plenum Noise Reduction System and is described in detail in this paper.

A finite element model (FEM) of the structure, trackform and vehicle was also developed to determine the structural (spectral) vibration levels during train passbys. An analytical model takes these vibration levels as input and determines the wayside structure-radiated noise. After some model validation, structure-radiated noise reduction is determined for several trackform alternatives. Projections of total wayside noise are also obtained by combining the structure-radiated and direct train noise.

2. DIRECT TRAIN NOISE

2.1. INADEQUACY OF EDGE WALLS

A number of studies [2–5] report overall A weighted noise reductions in the range of 5–12 dB(A) for edge barriers with heights ranging from 1 to 1·5 m, with generally better performance where sound absorption has been applied. Of those considered, the best performance was achieved at the San Francisco Bay Area Rapid Transportation Authority (BART) where a wall with height reaching the vehicle floor was placed 200 mm from the vehicle, which is just outside the kinematic envelope, with 100 mm of fibre glass attached to the inner surface.

As the starting point for predicting noise performance of tall edge barriers, a 1/3 octave band reference spectrum was developed from wayside noise measurements taken on the BART system during train passbys on an unmitigated concrete viaduct with a concrete deck [6, 7]. These data were averaged and corrected to KCRC conditions [8]; namely, 12 car trains travelling at 130 km/h with noise receivers at 25 m setback from the track centreline. The overall A-weighted level for this spectrum is 88 dB(A), which corresponds to the reference level adopted by the KCRC West Rail Project.

A model to predict the noise reduction obtained from tall edge barriers was developed based on the modified theory of Maekawa [9], with source height above rail adjusted so that low barrier predictions were consistent with the measured attenuation [2]. Sound barrier wall attenuation was calculated with a variation of

TABLE 1

Prediction of direct train noise levels (L_{max}) for edge barriers with and without the multi-plenum system-25 m *from the track centreline and level with rail*

Receptor location	Mitigation	Edge barrier height—measured from deck				
		0·0 m (dB (A))	2·9 m (dB(A))	4·2 m (dB(A))	5·9 m (dB(A))	7·1 m (dB(A))
Wayside	Without plena	88	72	68	68	68
Wayside	With plena	—	56	52	50	49
Trackside	Without plena	88	75	70	68	68
Trackside	With plena	—	62	58	55	54

the analytic expression provided by Kurze and Anderson [10], which closely fits the experiemental results otained by Maekawa. The projection formulae developed by them determines the excess attenuation of noise from a point source provided by thin barriers, with no noise absorption applied, and depends on the path length difference between the direct and diffracted sound paths. Crockett *et al.* [11] adapted this model to train passbys on the KCRC viaducts, including sound absorption on the wall, a correction from point to line source and a limit of attenuation of 21 dB [12, 13], which is caused by the scattering effects on the volume of air above the barrier being insonified by the source. Work by Marsden *et al.* [1] has limited the barrier performance for wayside predictions to 15 dB to account for degradation in performance due to turbulence.

The wayside noise levels (L_{max}), presented in Table 1, are predicted on the wayside and the trackside of a twin viaduct, at a set back of 25 m from the track centreline, and level with the top of rail (tor), which is assumed to be 7 m above the ground and 770 mm above the deck. Results are given for edge barriers of heights of 2·9, 4·2, 5·9 and 7·1 m, measured from the deck. A cantilever addition to the top of the sound wall is not considered practical, as it would require very tall walls to accommodate the catenary system. Although feasible, tall edge walls would be very expensive, due to engineering design requirements imposed by wind loading from typhoos which occur in the region. For 130 km/h train passbys, no barrier of any practical height provides sufficient attenuation to reduce the direct train noise to the target level of 61 dB(A). The 7·1 m wall provides the best performance (68 dB(A)), whereas the 2·9 m wall on the trackside provides the worst (75 dB(A)).

2.2. MULTI-PLENUM NOISE REDUCTION SYSTEM

Because edge noise barriers are by themselves inadequate, additional mitigation is necessary. The proposed noise reduction scheme, called the multi-plenum noise reduction system, consists of three components: an undercar sound-absorbing plenum; under walkway sound absorbing plena on either side of the vehicle; and edge walls with sound absorption applied, as shown in Figure 1.

The undercar plenum is created by emplacement of vehicle skirts on the sides of the cars, particularly over the trucks, and by installation of noise absorption on the under side of the floor near the bolsters and on the interior facing of the skirts. The plenum outlet is formed between the bottom of the skirts and the top of the derailment constraint. The noise reduction effectiveness of this undercar plenum is in part determined by the size of the outlet gap, with "smaller" being better from a noise standpoint. Kinematic envelope and clearance requirements limit this gap to a minimum of 250 mm.

The under walkway plenum on the outside of the viaduct is bounded by the parapet, the deck, the safety walk and the vehicle. Sound absorption is placed on the edge wall and the underside of the safety walk. The outlet of the plenum is the gap between the safety walk and the vehicle which is required by the vehicle kinematic and curvature envelopes. For KCRC West Rail, the minimum gap size is 250 mm on tangent track and 350–400 mm on curves. Derailment safety requires

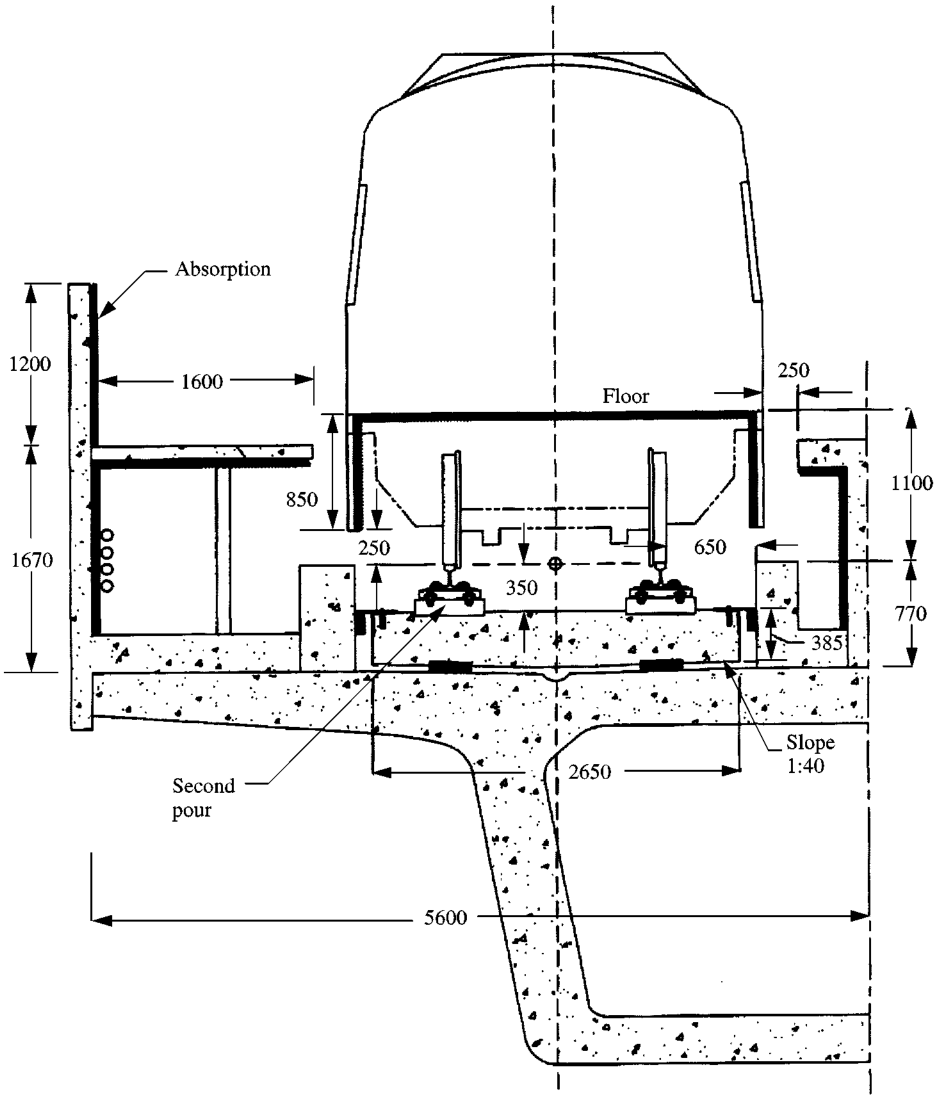

Figure 1. Cross-section of the KCRC West Rail two track viaduct design concept.

that the vehicle can move laterally by roughly 600 mm during derailment, implying that part of the walkway must be friable to prevent damage to or detachment of the parapet.

The under walkway plenum at the centre of the viaduct is bounded by a median wall, the deck, the top plate, which can act as another walkway, and the vehicle. Because of viaduct width limitations, the volume of this plenum is not as large as those beneath the edge walkways and, therefore, is not as effective at attenuating noise. The median wall must be strong enough so that a contained derailment will not send debris onto the other track.

The use of any of these noise attenuation schemes, by themselves, is not unprecedented: (low) parapet walls are commonly installed on viaducts; the under walkway (or under station platform) plenum with median noise barrier between tracks has been installed in stations and vehicle skirts with undercar sound absorption have been tested on transit vehicles and is in service on some "people movers". KCRC West Rail represents the first instance where these components have been put together in a fully integrated noise attenuation system.

2.3. PERFORMANCE OF THE MULTI-PLENUM SYSTEM

The model for the edge wall noise attenuation is exactly the same as that described above, except that the source is relocated from axle height to a position on the car body just above the under walkway plenum outlet (100 mm higher than the platform). The plena attenuation achieved by this system was estimated by Crockett *et al.* [11] based upon point source geometry, and by Marsdan *et al.* [1], based on a line source approach, both using the Plenum Chamber Transmission Loss equations, as described by Beranek [14] and ASHRAE [15]. The levels predicted by this equation are considered to be conservative [11] by about 5 dB at low frequencies because the size of the plena is comparable with the wavelength of the sound at these frequencies. To determine the surface area of the gap under the vehicle skirts and between the vehicle and the walkway in the point source approach, a characteristic length of 4 m was assumed. Sound absorption coefficients used in the analysis are equal to those for fibreglass with thickness of 50 mm.

The basic components of the model were adjusted so that predicted results coincide with measurement data for special cases. The effects of undercar absorption and vehicle skirts were calibrated by adjusting the distance from direct source to outlet in the plenum equation so that a mitigation of approximately 3 dB(A) was predicted by the model when the gap under the skirt was 600 mm, corresponding to the attenuation measured at BART. Similarly, the under platform plenum attenuation was calibrated by adjusting the distance between the skirt gap and the gap between the vehicle and the walkway until the predicted attenuation obtained was similar to that measured at BART for the absorbent close-in barrier referred to above.

The wayside noise levels (L_{max}) for the Multi-Plenum System are presented in Table 1. The plenum gaps are assumed to be 250 mm. The geometry of the viaduct, the height to top of rail, the positions of the receptors and the edge wall heights are the same as in the edge barrier model. For 130 km/h train passbys, the results show that all wall heights considered provide attenuation to within 1 dB of the targeted level of 61 dB(A). The projections for the Multi-Plenum System improve the attenuation performance over that for edge wall barriers alone by roughly 17 dB(A) on the wayside and 12 dB(A) on the trackside.

3. STRUCTURE-RADIATED NOISE

This section describes the model developed for the prediction of the structure-radiated or re-radiated noise. Central to this model is a finite element analysis (FEA) of the vibration transmisson from the train into the trackform and down through the structure [16]. The structure-radiated wayside noise is then obtained from the vibration levels assuming standard conditions: 12-car train travelling at 130 km/h and at 25 m setback from the track centreline.

3.1. FINITE ELEMENT MODEL OF THE STRUCTURE

The FEA of the structure is performed using the ANSYS 5·3 Finite Element Computer Program. The vibration levels in the structure are obtained from a frequency domain analysis of the simply supported viaduct, with pier spacing of 30 m, and with cross-section as shown in Figure 1. Pier spacing will have an effect only at very low frequencies, affecting ride quality and structural stability, but not radiated noise.

Since vibration levels are reduced as much as 20 dB across an expansion joint [17], the relevant viaduct section for vibration modeling lies between two consecutive joints, which is one span for the simply supported KCRC viaducts. The viaduct loading consists of one axle set on one track applied at midspan. Geometric symmetry allows reduction of the model to one-half span, taken from midspan to the pier. The model size can be further reduced by an additional factor of two if the viaduct is longitudinally divided, as shown in Figure 1. The original problem is recovered by applying symmetric and antisymmetric boundary conditions along the viaduct centre line, running the model for each case, and averaging the results.

The reduction of the model to quarter size is necessary for computational efficiency in order that a fine element mesh can be deployed for resolution of the vibration at high frequency, this fine mesh results in a finite element model (FEM) with as many as 60 000 degrees of freedom. Beam elements are used for the rail, plate elements for the floating slab, and brick elements for the structure. Effort was made to keep the characteristic length of an element of the order of 0·2 m, thus allowing resolution of propagating waveforms in the 125–630 Hz frequency range, which is the critical range for determining the overall A-weighted structure radiated noise level.

Because the reduction of vibration across an expansion joint is of the order of 20 dB, vibratory excitation of the span between joints is predominantly caused by the wheel sets located on the span. In the FEM, one wheel set is applied to the rail, with primary and secondary suspensions incorporated, and with inclusion of the unsprung, bogie and coach masses. Excitation is applied at each frequency by a vertical force couple with magnitude equal to the wheel/rail roughness displacement times the contact patch stiffness. It is thus assumed that roughness excitation is the major source of vibration in the structure as opposed to the moving impact load. At any point in a cross-section along the span (the observation point), the vibration level due to all axles exciting the structure is obtained by an energy (incoherent) sum of the contributions due to each axle. The contribution from any axle acting to the span is obtained from the FEA solution for a single wheel set located at midspan, by keeping the distance from source (wheel set) to observation point the same.

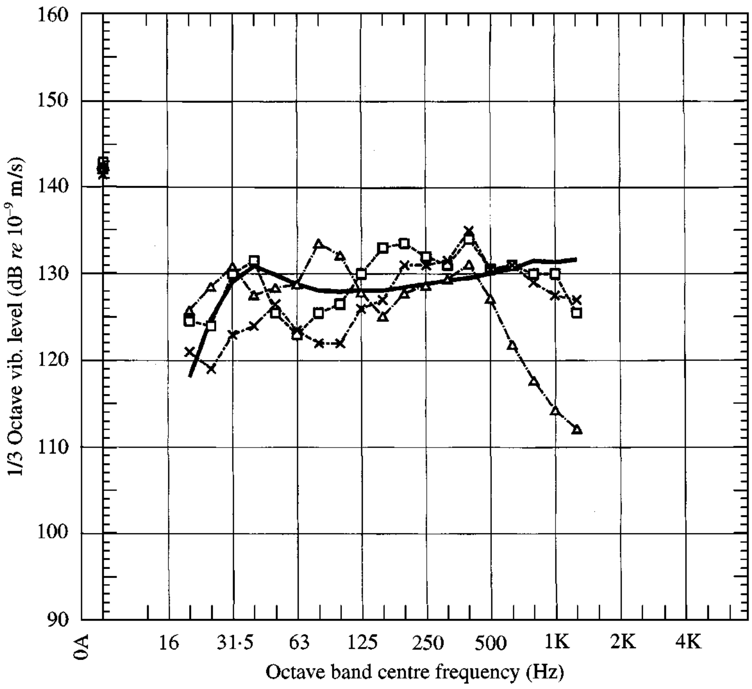

Figure 2. Comparison of measured and calculated rail vibration. □-----□, WMATA A13-soft baseplates; ×·-·-·-·-·-·×, WMATA A13-stiff baseplates; △·-·-·-·-·-·△, MARTA-stiff baseplates; ——○, Calculated-21 kN/mm baseplate.

3.2. WHEEL RAIL ROUGHNESS EXCITATION

The rail roughness spectrum used in this analysis is very similar to that given by Remington [18]. Comparison with other rail roughness displacement spectra [19] indicate that this spectrum is representative of average condition rail. The wheel roughness is assumed to be the same as that for the rail. For system-wide projections of noise, an average condition of maintenance is the most appropriate.

As a check of the assumed wheel/rail roughness spectrum, a FEA was performed on a generic viaduct with 54 kg/m rail and (soft) 21 kN/mm baseplates to determine the vertical vibration of the rail, which incidentally, is not very sensitive in the acoustic range to the details of the support system beneath the trackform. The calculated vertical vibration is presented in Figure 2 and compared with measured values obtained at the Washington Metro A-13 aerial structure [20] and the MARTA Hightower Bridge [17]. Measurements at WMATA were made along sections of track with several types of baseplates installed, the average vibration levels for stiff and soft baseplates are presented in Figure 2. The rails at the measurement locations and the wheels of most of the passby vehicles were in moderately good condition.

3.3. CONVERSION OF VIBRATION TO NOISE

The vibration of the viaduct is converted to (reradiated) noise using a model developed for the analysis of the Tsing Ma Bridge [21] (TMB), the Ma Wan Viaduct and the Kap Tsui Mun Bridge [22]. In the conversion to noise, the vibration levels of the radiating structural components at each cross-section are weighted by cross-section perimeter and cut-off frequency and energetically summed to obtain a sound intensity level for the cross-section at a given radial (cylindrical) distance from the viaduct. This sound intensity level per unit length of viaduct is then considered generic and incoherently integrated over the length of the train to obtain the sound intensity level due to the whole train. The structure-radiated noise is considered only to be that noise which comes off the edge walls, the bottom of the viaduct deck and the web and flange of the concrete box girder. Directivity is not considered as issue because of ground reflection. The noise radiated from the top of the deck and from the FST is energetically added to the direct train noise, rather than to the considered part of the structure radiated noise, as it will be attenuated by the edge walls and the Multi-Plenum System.

3.4. MODEL EVALUATION

The vibration to noise conversion was recently evaluated using vibration and measurement data obtained on a steel suspension bridge during passbys of electric

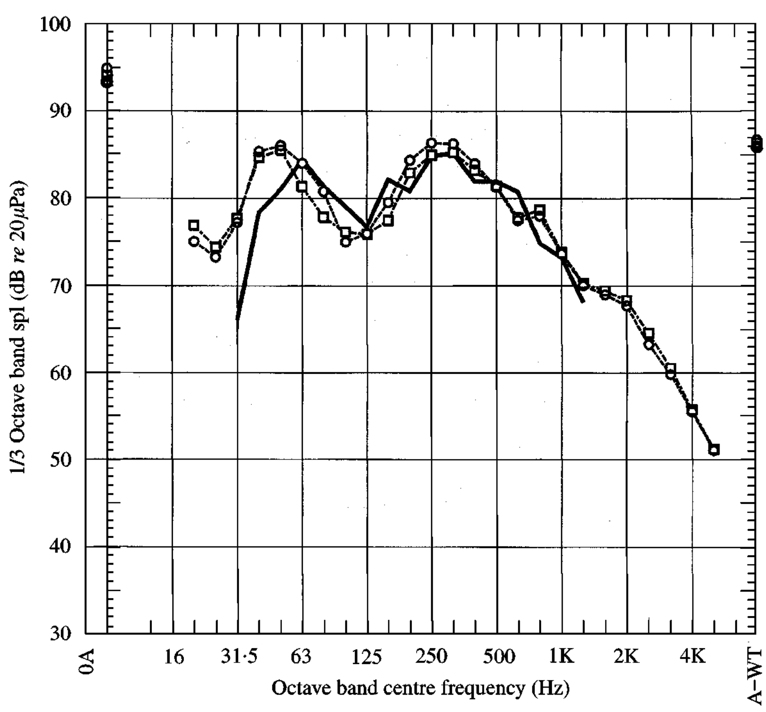

Figure 3. Noise calculated from measured vibration—electric work train passby on steel suspension bridge. ○-----○, 25 m below track deck——measured noise; □··········□, 25 m diagonally below——measured noise, ——○, noise calculated from vibration levels.

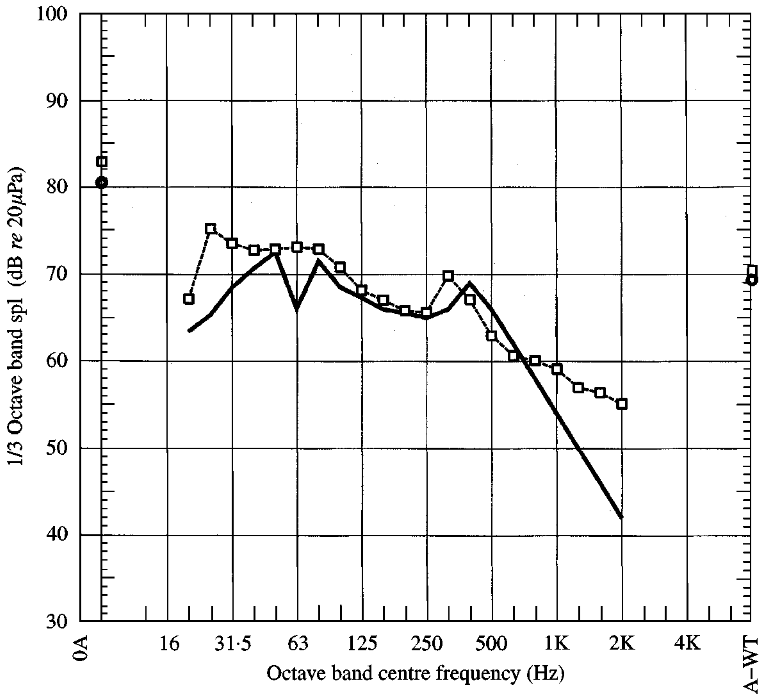

Figure 4. Comparison of structure radiated noise from the covered MTRC Kwai Fong viaduct with 12 Hz FST and stiff rail Support—corrected to KCRC conditions. □------□, measured; ——— ○, predicted.

work trains [23]. During the passbys, vibration measurements were taken on all of the major trackform and bridge components. The noise radiated from each component was determined from the vibration levels, as described above. The total re-radiated noise was obtained by incoherent summation of the noise from each of the components. The direct train noise is not significant because, in this case, it is roughly 10 dB lower than the structure radiated noise. In Figure 3, the total calculated re-radiated noise is compared with the measured noise levels 25 m below and 25 m diagonally below the track deck.

Another evaluation of the structure-radiated noise model is presented in Figure 4, wherein the measured wayside noise level measured at the covered viaduct near the Kwai Fong Estate (MTRC) and adjusted to KCRC reference conditions, is compared with a prediction of re-radiated noise using the method described above, with trackform parameters corresponding to support stiffness and slab running weights at the Kwai Fong Estate. Note that the resonance associated with the first longitudinal bending mode of the floating mini-slabs appears in both the measured and predicted results as a major determinant in the overall A-weighted level.

3.5. EFFECT OF TRACKFORM ON ATTENUATION OF STRUCTURE-RADIATED NOISE

A comparative evaluation of three trackforms was performed to determine the effect on attenuation of structure radiated noise. These trackforms are: (1) resiliently supported ties (sometimes called Low Vibration Track or LVT) with dynamic stiffness of 20 kN/mm per bloc, bloc mass of 100 kg, and rail pad with dynamic stiffness of 200 kN/mm; (2) soft resilient baseplates with dynamic stiffness of 12 kN/mm; and (3) 12 Hz Concrete floating min-slab trackform of 1·5 m length, 2800 kg/m mass, four bearing support points, bearing dynamic stiffness of 6·5 kN/mm and rail fixation stiffness of 12 (soft), 30 (moderate) and 70 (stiff) kN/mm. Fixation spacing in all cases is assumed to be 750 mm.

The estimated structure radiated wayside noise for the five different trackforms is given in Figure 5. Only the FSTs with moderate to soft baseplates have overall A-weighted levels (63 and 58 dB(A) respectively) less than the target of 64 dB(A). The levels for the soft baseplate and the LVT are 75 and 74 dB(A) respectively, which is roughly 10 dB(A) higher than the criterion. The noise level with FST and stiff baseplates is 69 dB(A), indicating that the benefits of the floating slab in the frequency range affecting the A-weighted noise levels can be compromised by selection of a baseplate which is too stiff. As mentoned previously, the 400 Hz

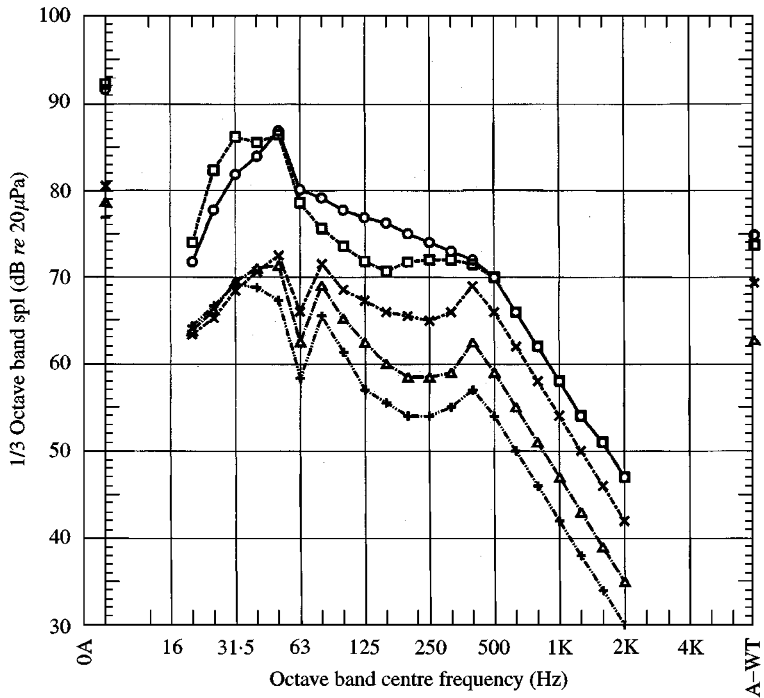

Figure 5. Estimated structure-radiated noise from the KCRC viaduct-re: 12 car train, 130 km/h, 25 m from track centreline. ○——○, 12 kN/mm baseplate; □----□, LVT-20 kN/mm; ×··········×, 12 Hz FST with 70 kN/mm baseplate; △··········△, 12 Hz FST with 30 kN/mm baseplate; +················+, 12 Hz FST ith 12 kN/mm baseplate.

resonance appearing in the spectra associated with the floating slab is attributable to the first longitudinal bending mode of the slab. Simulations in which the slab is lengthened, however, indicate that there are other resonances, caused primarily by the bending of the viaduct structural elements and occurring near 400 Hz, which become evident and tend to dominate the A-weighted level once the slab resonance is shifted to a lower frequency. It is thus not a simple matter of just lengthening the slab to gain a significant reduction in the A-weighted level.

3.6. EFFECT OF STRUCTURE ON NOISE LEVELS

The effect of the viaduct design on the re-radiated noise is examined in order to resolve the issue of whether floating slab trackform can be eliminated by altering the design of the viaduct. The alterations considered are within or approaching the limit of practicality but may lead to lower levels of re-radiated noise. The three changes considered are to reduce the radiating area of the structure, to increase its mass and to increase its stiffness. Recall that re-design is limited by the fact that the multi-plenum/edge wall system must be installed on top of the viaduct for adequate reduction of the undercar noise and that this system has certain spatial requirements.

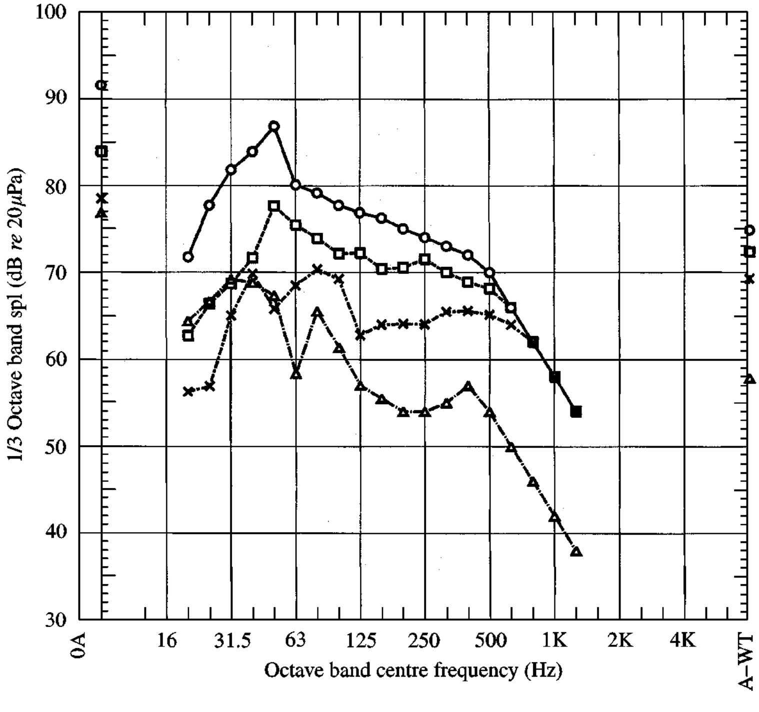

Figure 6. Estimated structure radiated noise for different viaduct designs re: 12 car train, 130 km/h, 25 m from track centreline. ○——○, twin viaduct; □----□, standard single track; ×··········×, stiff massive single track; △··········△, twin viaduct with 12 Hz FST.

One design which significantly reduces the radiating area is a single track as opposed to a twin-track viaduct. The concept can be taken further by doubling the thickness of all of the structural members. Although this example probably goes beyond what is buildable, it will illustrate the advantages of a very significant increase in the mass and stiffness of the viaduct. The estimated re-radiated noise for different viaduct designs is given in Figure 6 for baseplate (dynamic) stiffness of 12 kN/mm. As given earlier, the overall A-weighted levels for the twin-track viaduct, with and without the 12 Hz FST, are 58 and 75 dB(A) respectively. The level for the standard single-track viaduct, with no FST, is 72 dB(A), whereas for the stiff massive version it is 69 dB(A). Thus, for a single-track structure with significantly reduced radiating area and significantly increased mass and stiffness, the re-radiated noise level is still 8 dB(A) over the target, even with very soft baseplates. It is therefore unlikely that noise compliance can be achieved by eliminating the floating slab and optimising the structure. The low frequency rumble, however, is significantly reduced by the viaduct changes, almost to the level of the FST.

Viewed from a different perspective, optimization of the structure can be very beneficial. The more the re-radiated noise reduction can be achieved from the structural design, the more latitude there will be for civil considerations in the trackform design. In Figure 6, a 6 dB(A) advantage in noise level is shown between the standard two-track viaduct and the stiff massive single-track viaduct.

4. COMBINED DIRECT AND STRUCTURE-RADIATED NOISE

Direct and structure-radiated noise projections are combined, spectrally, to obtain overall A-weighted wayside noise estimates and are presented for different trackform options in Table 2. The direct noise includes the noise radiated from the rail, the floating slab, the upper surface of the deck and the train. Only FST with soft baseplates is able to reduce total wayside noise to within compliance. Also, the placement of stiff base plates on FST not only increases the noise radiated from the viaduct, but also from the slab itself.

TABLE 2

Estimated total wayside noise levels (L_{max}) for different trackform options

Trackform	No noise mitigation (dB(A))	Direct noise (dB(A))	Re-radiated noise (dB(A))	Total noise (dB(A))
1. Baseplate 12 kN/mm	88	62	75	75
2. LVT 20 kN/mm	88	62	74	74
3. FST 70 kN/mm	88	66	69	71
4. FST 30 kN/mm	88	64	63	66
5. FST 12 kN/mm	88	63	58	64

In this example, neither the FST nor the viaduct structure are optimizd for maximum reduction of re-radiated noise. The edge wall can also be made higher to further reduce the contribution from the undercar noise. Thus, although the FST with relatively soft baseplates is necessary for wayside noise compliance, the extent to which the noise can be reduced depends significantly on the detailed design of the viaduct, the trackform and the multi-plenum/edge wall system.

5. CONCLUSION

No simple edge barrier of any height considered adequately attenuates the direct train noise. However, the Multi-Plenum System provides a noise reduction of 17 dB(A) on the wayside and 12 dB(A) on the track side, independent of the edge barrier. Taken together, 2·9 m edge walls, augmented by the plena, provide sufficient attenuation of the direct train noise to within 1 dB of the target level of 61 dB(A). Tall edge walls may only be necessary adjacent to high rise structures.

In spite of the fact that trackforms provide less vibration isolation on a viaduct than in tunnels on account of the relatively low impedance of the viaduct structure, FST with soft DF fasteners reduces the structure radiated noise to the target level of 61 dB(A). Structural improvements to the viaduct, namely increasing stiffness and mass, can improve the re-radiated noise levels, especially at low frequencies, but not enough to eliminate the FST.

The placement of stiff base plates on floating slab causes significant noise radiation, not only from the viaduct, but also from the floating slabs. The use of soft baseplates to fix the rail to the FST significantly decreases the radiated noise from both the viaduct and the FST, with a small penalty paid in the increase in noise radiated from the rail. Taking all of these effects into account, only the combination of the Multi-Plenum System and edge walls, together with FST and soft baseplates, sufficiently reduces the total wayside noise to the targeted level of 64 dB(A).

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