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MODELLING NOISE FROM ELEVATED RAILWAY STRUCTURES

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1. INTRODUCTION

This paper reports a case study which details the prediction of noise from a railway running on viaduct. Measurements taken to determine the source level of the train type showed that the noise from trains running on viaduct was significantly louder than expected from airborne noise alone. Close microphone measurements were taken to determine the level of noise being radiated from the viaduct structure. A prediction procedure was developed to assess the re-radiated noise level at locations of interest. The procedure compares well with measurements and shows that the re-radiated effect is directional, being strongest at locations close to and perpendicular to the structure.

2. STUDY AIM

The aim of this case study was to predict the noise from an elevated section of railway in Kowloon in Hong Kong. The railway emerges from tunnel at the north of the area, and runs on viaduct for several kilometres through Kowloon Bay before returning to tunnel. The railway viaduct runs immediately adjacent to or directly above major roads in the area forming a transportation corridor. Residential and commercial buildings flank this corridor on both sides. The residential buildings are generally multi-storey apartment blocks ranging up to 38 stories tall.

The Hong Kong Environmental Protection Department (EPD) has specified noise levels which define an Acceptable Noise Level (ANL). For the study area the ANL is 70dB L_{Aeq} between 07:00 and 23:00 and 60dB L_{Aeq} between 23:00 and 07:00 which is assessed over any 30 minute period and considers the total noise level from all sources. The rail company have been asked by the EPD to reduce the noise levels from the railway. The rail company are proposing to overhaul the stock. We were asked to investigate options which did not involve alterations to the track or the main viaduct structure.

Since the Acceptable Noise Level considers all noise sources, it was necessary to investigate the different noise contributions from both the road network and the railway. Any rail mitigation option is going to be more effective in areas where the noise from the railway dominates the noise from the road network.

3. PREDICTION METHODOLOGIES

The Hong Kong EPD use the UK Department of Transport's *Calculation of Road Traffic Noise* (CRTN) procedure for predictions of noise from road traffic sources. We were able to use our RoadNoise software to create a noise model of the road network.

We used the UK Department of Transport's *Calculation of Railway Noise* (CRN) procedure to predict the noise from the railway. The CRN procedure gives details for predicting the noise level from rolling stock found on UK railways. To enable predictions of the rail noise, it was first necessary to establish the source level of the rolling stock used on this railway. Procedures are given in CRN allowing us to measure the source level for any type of rolling stock. In this case the rolling stock is an overhead powered EMU.

4. RAIL NOISE SOURCE LEVELS

A survey was undertaken to determine the SEL correction factor for the EMU train for use with CRN. Measurements were taken at a rail depot near to area of the study, of trains running on open ballasted track and of trains running on viaduct track with parapets. The procedure used to determine the correction factor is given in CRN pp65-68, the *Procedure to Adopt for New Train Types*. There are ballasted tracks between the mainline track and the measurement position, these are sidings within the depot. The microphone was mounted about 1.5m above local ground level during the survey. The measurement positions were 4.9m inside the depot boundary wall. It is judged that reflections from this wall will not influence the results of the surveys.

4.1 Ballast Track and Viaduct Track Measurements

The microphone position was 42.5m from the centreline of the ballasted track. The ground is essentially open and flat between the measurement position and the track which is mounted on approximately 0.3m of ballast.

The microphone position was 32.5m from the centreline of the viaduct track. The viaduct is approximately 9m above local ground level. The ground is essentially open and flat between the measurement position and the viaduct. The measurement position can be seen in Figure 4.1.

For each train pass-by measured, the direction of travel, the pass-by time and the SEL were recorded. The speed is calculated from the pass-by time since the train body length is known to be 182.8m. Care was taken to ensure that no extraneous noises influenced the levels during the measurements, including maintenance trains moving in the depot. Background measurements were taken to assess the existing noise levels in the area in the absence of trains.

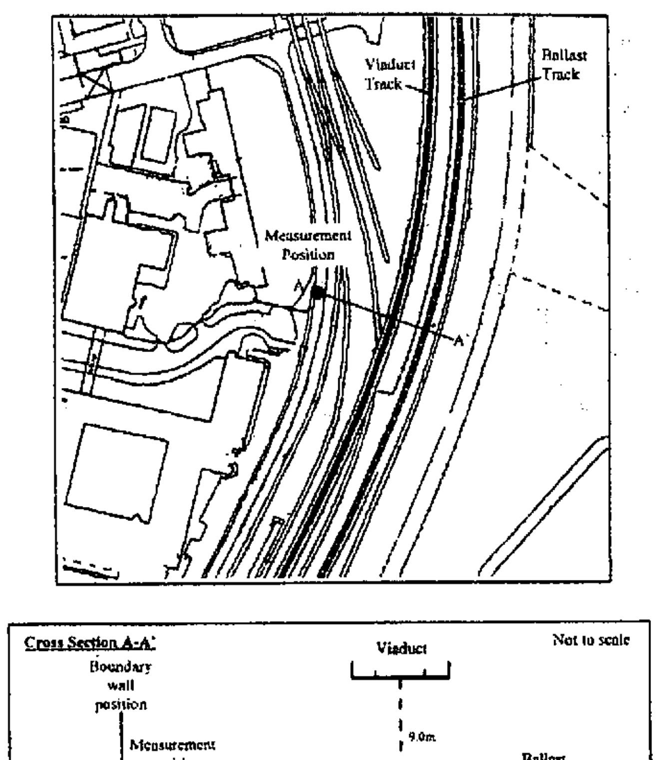

Figure 4.1 Depot Measurement Location.

4.2 Analysis of Measurements.

A total of nine passbys were measured for the ballasted track and a further five for the viaduct track. To evaluate the SEL source correction for a train for use with the CRN procedure, both the ballast and viaduct measurement positions are corrected back to a 25m open site ballasted track measurement of a one carriage train, using the relevant formula given in CRN. When these corrections had been applied, allowing for the screening which the parapet is expected to give, it was found that the on-viaduct measurements were 6.6dB(A) louder than the on-ballast measurements.

The mean measured SEL for ballast trains was found to be 76.8dB(A) with a standard deviation of 0.8dB(A). The trains were travelling at a geometric mean speed of 30.0 km/hr with a standard deviation of 1.9km/hr. The correction for one vehicle for use with CRN was found to be +11.6dB(A). This correction factor is similar to that of +11.3 for Class 319 British Rail EMU stock and +12.9dB(A) for London Underground-A Stock, given in CRN, and therefore is within the expected range. We were then able to use our RailNoise software to create an airborne noise model of the rail network, however the significant difference between measured and expected levels from the viaduct suggests that the viaduct structure and/or parapets are radiating noise, requiring further investigation.

5. STRUCTURE RE-RADIATION ANALYSIS

CRN allows a 1dB 'source enhancement' for railways running on concrete viaduct. It also states that if measured values are available then they should be used. In this case each track slab is mounted on a concrete box-girder. The parapet is made of separate panels approximately 1.8m long. These panels are bolted to the track slab.

Initially a 7.6dB(A) source enhancement (1dB from CRN + 6.6dB difference from measurements) was arithmetically added to the results from the airborne noise model, in the manner CRN deals with similar source enhancements. This resulted in a significant over-prediction at elevated receivers and distant receivers, suggesting that the viaduct re-radiation effect is directional. The measurements at the Depot enabled the relative effect of structural re-radiation to be assessed, but gave no information on a directivity effect.

Since the methods of mitigating airborne noise and structure radiated noise are different, it is also necessary, for this study, to be able to model each of these factors separately. We need to be able to model the effect of the viaduct re-radiation as an absolute level, rather than an additive source enhancement.

The viaduct structure can be considered to be a series of additional sources, each radiating a certain level of sound energy. The propagation of the sound energy will follow the usual acoustic principles, both in terms of directional effect and decay with distance. It is therefore possible to obtain the source strength by suitable measurements and then to calculate distance and direction corrections, before adding to the airborne noise level at each location of interest.

5.1 Close Microphone Measurements

A location was found to measure at close proximity to the viaduct structure. This location was distant from the nearest road traffic sources, and on a section of track where the trains were running at line speed of 60km/h. The close noise and vibration measurements had the following main aims:

1. Identify the relative sound levels being radiated by
   - the viaduct parapet
   - the viaduct deck
   - the viaduct under-girder support

2. Identify the vibration behaviour of each of the above components

3. Identify the time history of a passby event, which could last longer than the passby itself.

5.1.1 Measurement Procedure

Measurements of noise and vibration levels were taken simultaneously. The microphones and accelerometers were positioned in close proximity to the parapet. There were three positions at the Centre, Top and Bottom of the parapet panel, and further positions, one on the underside of the deck and one on the vertical side of the box girder support. A microphone was also located 3m perpendicular to the parapet, as a control position.

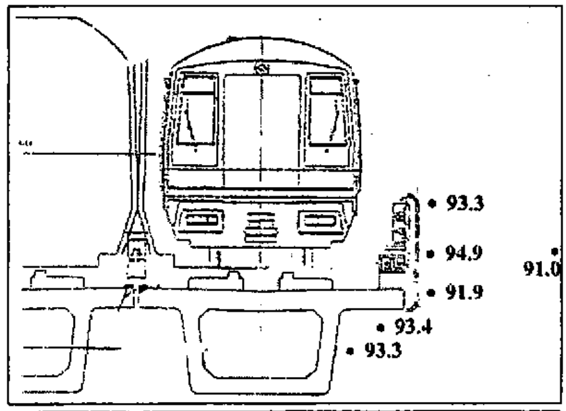

Figure 5.1 Close Microphone Measurements – Noise Levels.

The vibration levels are particularly high in the centre of the parapet. The level at the top of the parapet is relatively low. The deck and box girder support have intermediate levels of vibration.

The Noise measurements follow the same broad pattern and can be seen in figure 5.1. The highest levels averaged 94.6 dB(A) in the centre of the parapet. The other positions all had values of 92 to 93 dB(A). The energy-average of noise levels at the (nominally) vertical surfaces was 93.5 dB(A). These results indicate that the parapet and the other surfaces of the structure are approximately equal contributors to the total noise energy re-radiated by the external surfaces of the viaduct.

5.2 Directivity Effect

The literature suggests that the sound level radiated by a long, narrow source could be estimated from the formula:

$$R = K + 10 \log (\{\cos(\alpha)+\cos(\beta)\}/2)$$

where K is a source level and α and β are the angles to the top and bottom of the source strip, as shown in Figure 5.2.

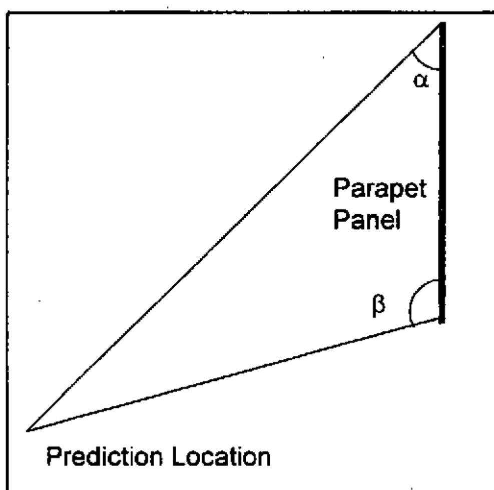

Figure 5.1 Definition of α and β

The above formula can be applied to the close microphone and 3m control microphone positions. The close microphone was about 50 mm from the viaduct surface, which was 1780 mm high. Therefore the angles to the top and bottom of the parapet were:

$$\alpha = \beta = \tan^{-1}(\{2 \times 50\}/1780) = 3.2°$$

Therefore the correction factor is 10 log (cos(3.2)) = -0.007 dB ≈ 0dB. The average level over the parapet is 93.5 dB, which suggests that K = 93.5 dB.

The control mic can see not only the parapet, but also the vertical part of the under-girder support. This gives a vertical surface of about 3 m height. The control mic is 3 m from the viaduct and perpendicular from the centre of the parapet panel. The noise level expected at the field mic would be as follows:

$$\alpha = \tan^{-1}(3/0.9) = 73° \qquad \beta = \tan^{-1}(4.3/2.2) = 63°$$

Note that although the vertical surface is nominally 3m in height, the under-girder is recessed from the parapet by about 1.3m.

$$R = 93.5 + 10 \log (\{\cos(73)+\cos(63)\}/2) = 93.5 - 4.3 \text{ dB} = 89.2\text{dB}$$

A separate calculation shows that the airborne component at this location is 86.6 dB. Therefore the total level at the control mic is 89.2 ⊕ 86.6 = 91.1 dB. (where ⊕ signifies logarithmic addition.) This compares well with the measured value of 91.0 dB, and gives confidence in the procedure.

5.2.1 Application of Procedure to the Depot Measurements

The analysis of the source measurements in the depot showed that the viaduct measurement was 77.8 dB, whereas the level expected from airborne noise alone was 71.2 dB. This indicates that the sound level from viaduct re-radiation was 77.8 (-) 71.2 = 76.7 dB(A), where (-) signifies logarithmic subtraction.

Considering the whole structure, rather than just the parapet, α = 72.9°, and β = 102°.
Thus,

$$K = 76.7 - 10 \log (\{\cos (72.9) + \cos(102)\}/2) = 90.4 \text{ dB(A)}$$

This is for half the train speed, 30 km/h, than for the close microphone measurement location, and implies a rate of increase of viaduct re-radiation of 3 dB(A) per doubling of train speed. The literature (Transportation Noise Reference Book) indicates that this is within the range of experience, but at the lower end.

5.3 Comparison in the Study Area.

To give further confidence in the procedure, two sets measurements of were taken in the study area. The first set consisted of measuring train pass-bys at three different heights at a building adjacent to the viaduct track. The second set of measurements consisted of taking samples of the train noise at locations further back from the viaduct. Comparisons of the structure re-radiation procedure with measurements in the study area is complicated by the level of traffic noise.

5.3.1 Pass-by Measurements

At the selected location, the viaduct is also directly above a major road, and is therefore affected by road traffic noise at all times of the day, but was the only location where measurements could be made close to the viaduct at a range of heights without considerable difficulty in obtaining access. However, this meant that it was necessary to model all three noise sources: road traffic noise, airborne rail noise and structure re-radiated noise. At this location, the viaduct is double track. Measurements were taken 12.3m horizontally from the parapet face, and at each height, between 8 and 12 pass-bys were measured on both the near and far tracks.

Predictions were undertaken of the traffic noise using the CTRN procedures, airborne rail noise using the CRN procedures and structure re-radiated noise using the formula derived from the close microphone measurements.

The three predicted L_{eq} levels were added together to give a total noise level at each elevation. Predictions are carried out separately for the near and far tracks. These were compared with the measured values, and are detailed in the table below.

Table 5.1 Pass-by Measurements

	Near Side			Far Side	
Highest Prediction Point (27.9m above track level)					
	Prediction	Measurement		Prediction	Measurement
Road	71.6		Road	71.6	
Airborne rail	75.3		Airborne rail	75.2	
Structure	58.9		Structure	58.9	
Total	76.9	75.4	Total	76.8	75.8
Middle Prediction Point (16m above track level)					
	Prediction	Measurement		Prediction	Measurement
Road	73.1		Road	73.1	
Airborne rail	76.2		Airborne rail	76.3	
Structure	64.2		Structure	64.2	
Total	78.1	78.3	Total	78.2	78.2
Lowest Prediction Point (0.9m above track level)					
	Prediction	Measurement		Prediction	Measurement
Road	77.0		Road	77.0	
Airborne rail	69.1		Airborne rail	70.8	
Structure	70.7		Structure	70.7	
Total	78.5	77.9	Total	78.7	78.1

All Values are $L_{eq,40s}$ dB(A)

It can be seen that at the lowest height, about track level, road traffic noise is dominant, but the structure contributes about the same railway noise than the airborne component. At the middle point, airborne railway noise is dominant, followed by road, and then by the structure. At the top point, airborne railway noise is most significant, road is 2 to 3 dB less, and structure re-radiated noise is insignificant by comparison.

It is clear that (in the absence of road traffic noise) the structural re-radiation effect is most important at receivers on axis to the viaduct, and at low positions where airborne noise is well screened. At locations elevated above the viaduct, which have a small angle of view of the parapet structure, the structure contribution is insignificant, confirming the expected directivity pattern.

5.3.2 Sample Measurements

At five locations along the route samples of noise were taken. The locations were generally about 30-50m from the viaduct, elevated 2-6m above the viaduct level and had a clear view of the structure. The samples resulted in the derivation of a five minute continuous train noise level. To enable comparisons with predictions this level can be converted into a period Leq with a knowledge of the train flow. Table 7.2 below shows the differences between measurements and predictions.

Table 5.2 Sample Measurements

Predicted Airborne Noise	Predicted Structure re-radiated	Total Predicted Train Noise	Period L_{eq} derived from Measurements	Prediction to Measurement Difference
56.6	47.7	57.1	56.0	1.1
51.8	48.0	53.3	50.1	3.2
55.8	50.5	56.9	56.6	0.3
63.6	47.2	63.7	61.9	1.8
63.4	50.4	63.6	62.6	1.0

The locations where these comparisons have been made are elevated above structure level, and have a restricted view of the under-girder support. The structure re-radiation is contributing a small amount to the total rail noise level. This confirms that the contribution from the structure becomes less important as distance from, and elevation above, the viaduct are increased.

5.4 Conclusions for Structure Re-Radiation Procedure

It has been shown that the various parts of the structure contribute in roughly equal amounts to the re-radiated noise for locations at around the same elevation as the viaduct structure. Locations significantly above the viaduct structure are unable to see the box-girder support, the angle of view of the parapet surface is small, and consequently the contribution from the structure re-radiation is less.

The re-radiation correction factor has been confirmed as K = 93.5 at the running speed of the track. The directivity/distance adjustment formula has been confirmed, by comparison of measurements at the close microphone location, the pass-by measurements, the sample measurements, and the source measurements at the depot.

Re-radiation from the box under-girder support will be the limiting factor for mitigation options at locations close to the viaduct and at about the same elevation. Indeed, since this is of similar size to the parapet, then totally quietening the parapet will only reduce the re-radiated noise by about 3 dB.

It is clear that (in the absence of road traffic noise) the structural re-radiation effect is important at locations on-axis to the viaduct, and at low positions where airborne noise is well screened.

6. TOTAL NOISE LEVEL PREDICTIONS

Using CRTN, CRN and the derived structural re-radiation radiation procedure, we are then able to predict the total noise level at any location of interest. We are also able to identify the relative contributions from the three sources and determine which is dominant.

A background noise measurement program was undertaken at locations through the study area. These measurements were then compared with the results from the prediction model and were found to be within expected tolerances.

The Hong Kong EPD's Acceptable noise limits are applicable over any 30 minute period throughout the day. To assess exceedances of the ANL it is necessary to look at the diurnal variations in road and rail traffic flows. Examination of train time-table information and traffic flow statistics, it was discovered that the road and rail diurnal variations were different. The study then became a four-dimensional study.

From the diurnal variation data it was possible to use the prediction model to assess both the total noise level and dominant sources over any 30 minute period during the day. This allows any exceedances of the ANL to be identified, along with the dominant noise source at that location.

When assessing any rail mitigation options, greatest benefit will obtained at the times of day when the rail noise is dominant over the road traffic noise, even if this does not correspond to the highest noise level. The model was able to identify, and predict for, this period of the day. These results were used to assess each of the mitigation options.

7. CONCLUSIONS

This paper has reported a prediction method for evaluating the structure radiated noise from a concrete box-girder type viaduct with solid concrete panel-style parapets. The prediction methodology has been derived from cosine directivity theory for an incoherent panel source. Close microphone measurements were taken to establish the source level of the radiating structure.

Predictions and measurements have been compared at 10 locations. Predictions have been shown to agree well with measured data.

The directivity effect of the structural re-radiation shows that the contribution from the structure is most important at locations below the structure, where the airborne noise is well screened, and also at locations perpendicular to the structure.

The approach used differs from that given in CRN. Methods of mitigating airborne noise and structure re-radiated noise are different, defining a need to predict these components separately.

8. ACKNOWLEDGEMENT

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