Noise and Vibration Spectrum of Structure-borne Noise from Railway System

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In this study, the spectrum and resonance frequencies of the structure-borne noise and vibration excited by the train traffic on concrete viaduct structure are examined. Comparisons of air- and structure-borne noise spectrum between local and overseas trains are taken. Real-time octave band and FFT (Fast Fourier Transform) mode are used to analyze structure-borne noise spectra in details.

Based on the spectrum results of the structure-borne noise, air-borne noise lies on high frequency component and structure-borne noise lies between 20 Hz and 200 Hz, which is a tonal noise. From the FFT analysis, the vibration resonance frequencies are 43 Hz and 54 Hz and acoustics coincidence are 121.5 Hz and 128.5 Hz. The theoretical relationships between sound and vibration are in agreement with the experimental results. The results will be useful for the prediction of structure-borne noise from railways.

Keywords: *Structure-borne Noise, Concrete Bridge/Viaduct, Fast Fourier Transformation, Resonance Frequency*

Introduction

The extension of the railway system become one of the major transport system to cope with the growing demand for public transportation, significantly reducing vehicle exhaust emissions and stimulating extensive land development. Currently, the projects of railway extension in Hong Kong include KCRC West Rail, Lok Ma Chau spur line, Ma On Shan, and Tsim Sha Tsui extension and MTRC Tseung Kwan O extension. It is inevitable that the speed of trains and number of viaduct through residential area will be increased. The nearly residents along the railway system will be exposed to the noise nuisance due to the air- and structure-borne noise radiated from train system. Air-borne noise is well established but structure-borne noise radiated from concrete viaduct is a new concern for the railway noise nuisance.

In different publications, most of the studies [1-8] were concerning the structure-borne or ground-borne noise created by the underground train, that characteristics were very familiar to that from the concrete viaduct. The difference between them is structure-borne noise exposed to the air immediately while ground-borne noise transmitted through soil or ground. All of these researches showed that the structure-borne noise is mainly consist of low frequency components. Y Moritoh, Y Zenda and K Nagakura [1] undertook a site measurement of concrete bridge structure noise below the bridge structure. They showed that the spectra had marked peaks at frequencies around 50 Hz as train speed was 240 km/h.

M Heckl, G Hauck and R Wettschureck [2] used an in -situ measurement to show that the dominant frequency range of wheel/track resonance lies between 40 Hz and 100 Hz. They concluded that vibration transmission caused by rail traffic was found to be a low frequency problem. An measurement for suburban trains running at 60 km/h in a tunnel indicated that the peaks of vibration was found at 40 Hz while the peak noise level at 50 Hz. Takaashi Morii [3] investigated the vibration-isolation techniques of Shinkansen and focused on the control of the magnitude of the vibration. His paper showed that the peak vibration of the viaduct girder without ballast mat was in the range between 40 Hz and 60 Hz.

In the past, most of the investigations were studied about the resonance frequencies of the metal box structures, beams and panels, etc. Some investigations of structure-borne sound from rail traffic, both theoretical and experimental, were also found in the literature. A number of research papers have only examined the effect of the structure-borne noise and vibration separately. Although there are a considerable number of studies have been made in the structure-borne noise of railway systems, there is a lack of detailed investigation about the noise and vibration correlation for concrete box structure. E C Bovey [9] only had determined the vibration transfer characteristics of railway installations. An impact method was developed to determine the vibration transfer characteristics of railway installations. He concluded that this technique has been shown to be a reliable, controlled method for providing quantitative data. For frequencies at which coherence had been depressed indicate variability in track parameters for nominally the same form of track. Several track forms were examined in transfer functions and showed that poor coherence indicated uncertainty in the values at certain frequencies particularly in the range 200 - 500 Hz where the frequency content of the hammer input was very low. In his paper, the underground concrete viaduct was analyzed but there was no discussion about the resonance frequencies produced by concrete structure.

In fact, the structure-borne noise is due to the vibration of concrete viaduct. Vibration and noise are interrelated, so the correlation of noise and vibration is an important parameter for analyzing the characteristics of structure-borne noise. In this paper a detailed study to compare the noise and vibration characteristics of local and oversea viaducts is carried out under same corrected distance pattern.

Results of Site Measurement Setup of the Railway System

Methodology

Train noise spectra measured in Lyon, Switzerland and Hong Kong are recorded and compared by Real-Time Frequency Analyzer. For the concrete railway viaduct in Hong Kong, the FFT (Fast Fourier Transform) is carried out to determine the frequency response of sound and vibration generated by running trains. All of the measurement data are measured by the Real-time Frequency Analyzer simultaneously where the measurement set-up is shown in Figure 1. All measurement points were taken under the viaduct in order to determine the contribution from the bridge itself (ie structure-borne sound of the viaduct).

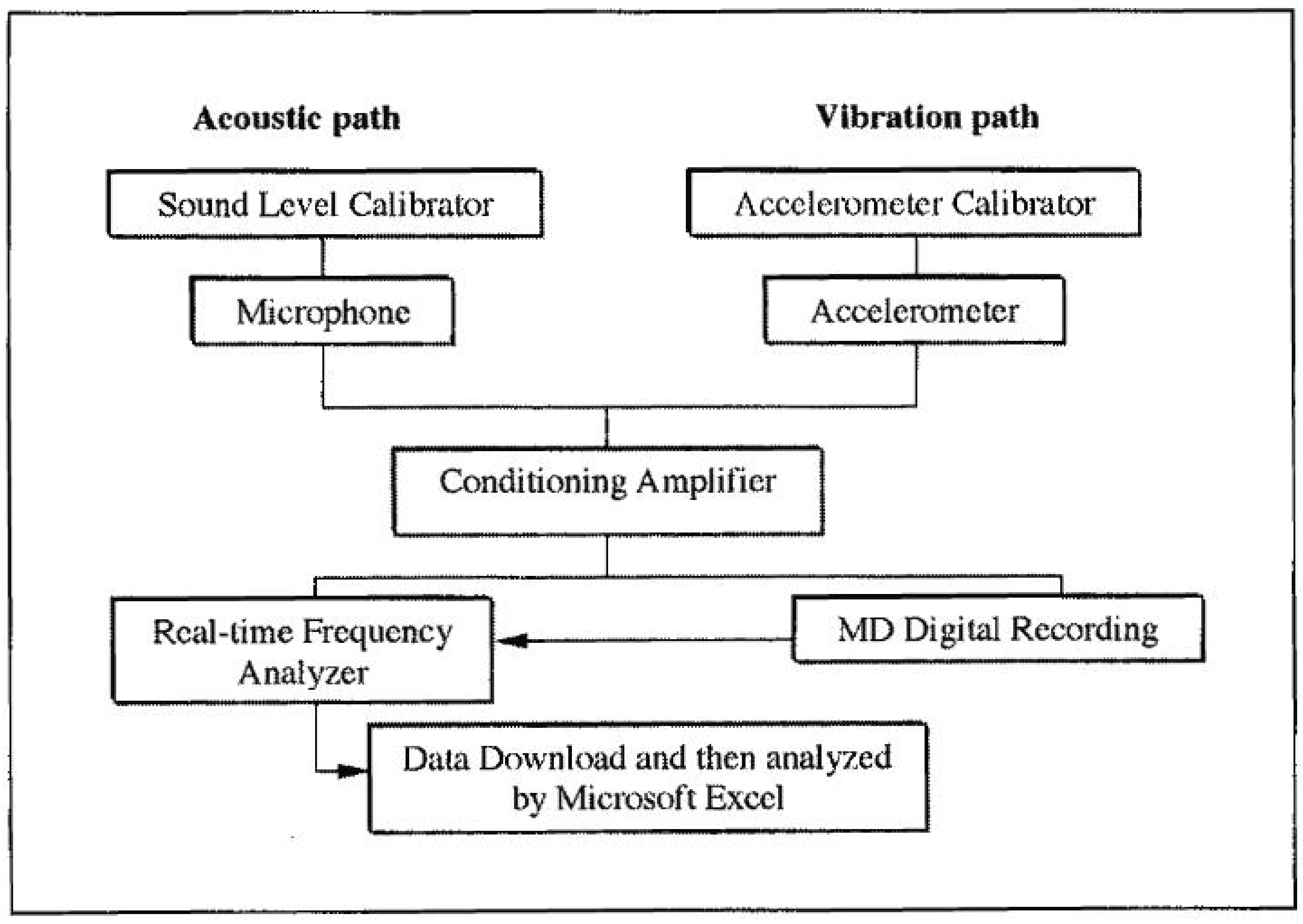

Figure 1 – Diagram of the Measurement Set-up for Simultaneous Recording of Vibrations and Noise for Viaduct Measurement

Air-borne Noise Spectrum

In France, TGV (Train Grande Vitesse) (see Figure 2) is a high-speed train, which is a system comprises train, track, and signaling technologies that when combined make high speed possible. For dedicated TGV lines, welded rails laid on hybrid steel and concrete ties, over a thicker than usual bed of ballast. The track centers are spaced further apart than usual, to reduce the blast of two crossing trains. When a TGV moves over a ballast track at the tope of embankment, vibration stimulated in the rail is transmitted to the soil producing ground-borne noise, and from there it is radiated as irritating air-borne noise to the neighborhood. The noise spectrum was recorded at 5 m below and 25 m away track, and measurement point is shown in Figure 2. For the comparisons, the local and overseas train data has been adjusted to a lateral distance of 25 m away the track by assuming train noise as a line source. The TGV spectrum shows the combination of ground-borne and air-borne radiated from the railway system, two noise peaks are found, one is at 80 Hz and the other is 2500 Hz (shown in Figure 3). The 80 Hz should be ground-borne noise and 2500 Hz represents the air-borne noise part. The dominant frequency is the highest for TGV train, which is at 2500 Hz, the low frequency sound is relatively low.

Two types of viaduct section (I and II) are investigated, the configuration and dimensions of cross-section are indicated in Figure 4 and Figure 7. For the MTR train running at section I viaduct in Hong Kong, the noise spectrum is shown in Figure 3. The dominant frequency range of this system is between 200 Hz and 1250 Hz, which may represent the air-borne noise component of the system. The high frequency component of above 1250 Hz is decreased gradually because there is a parapet unit shielding the emission from the wheel and rail parts (cross-section shown in Figure 4).

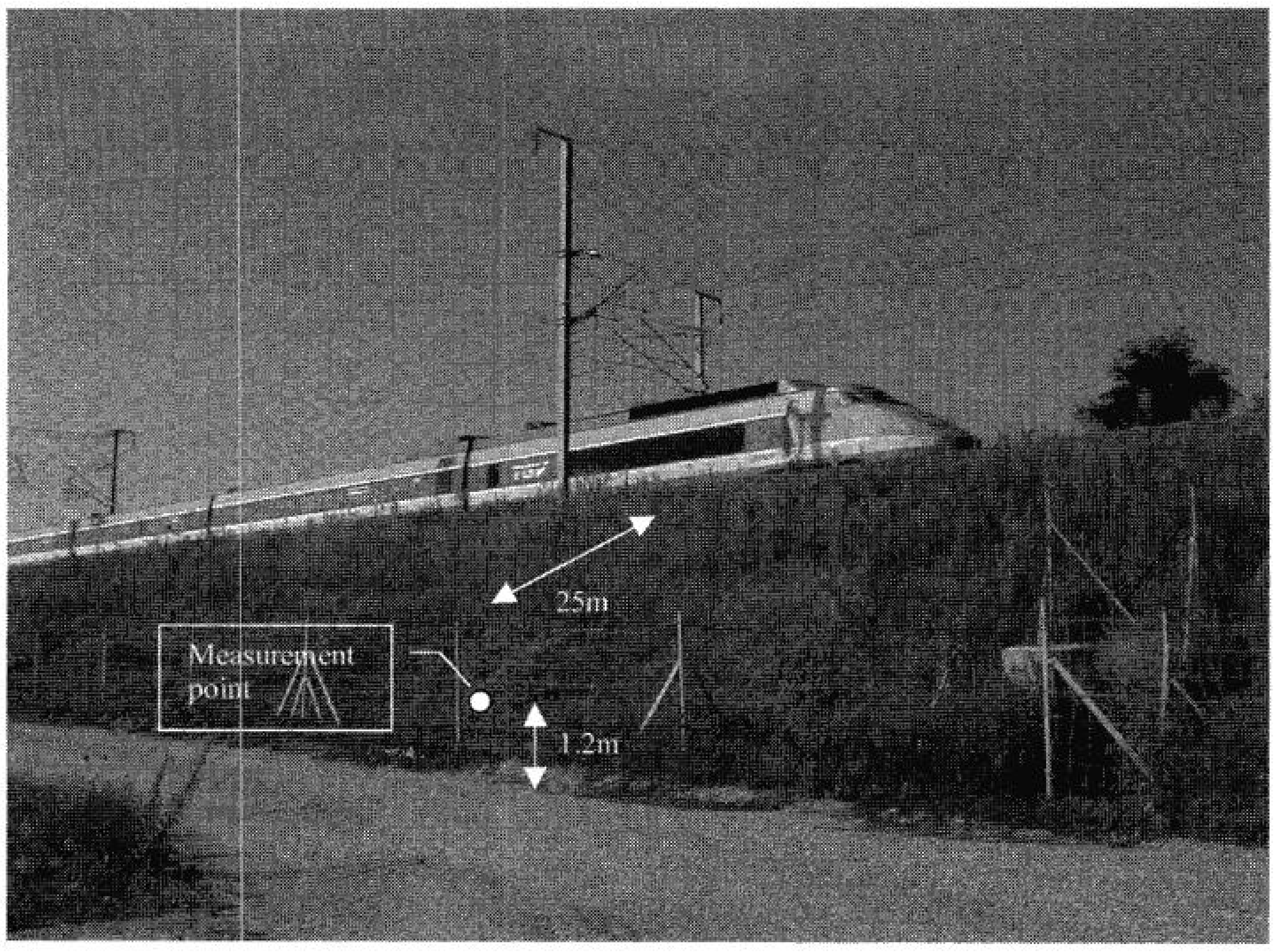

Figure 2 – TGV (Train Grande Vitesse) Moves Over Railway Track at the Tope of an Embankment

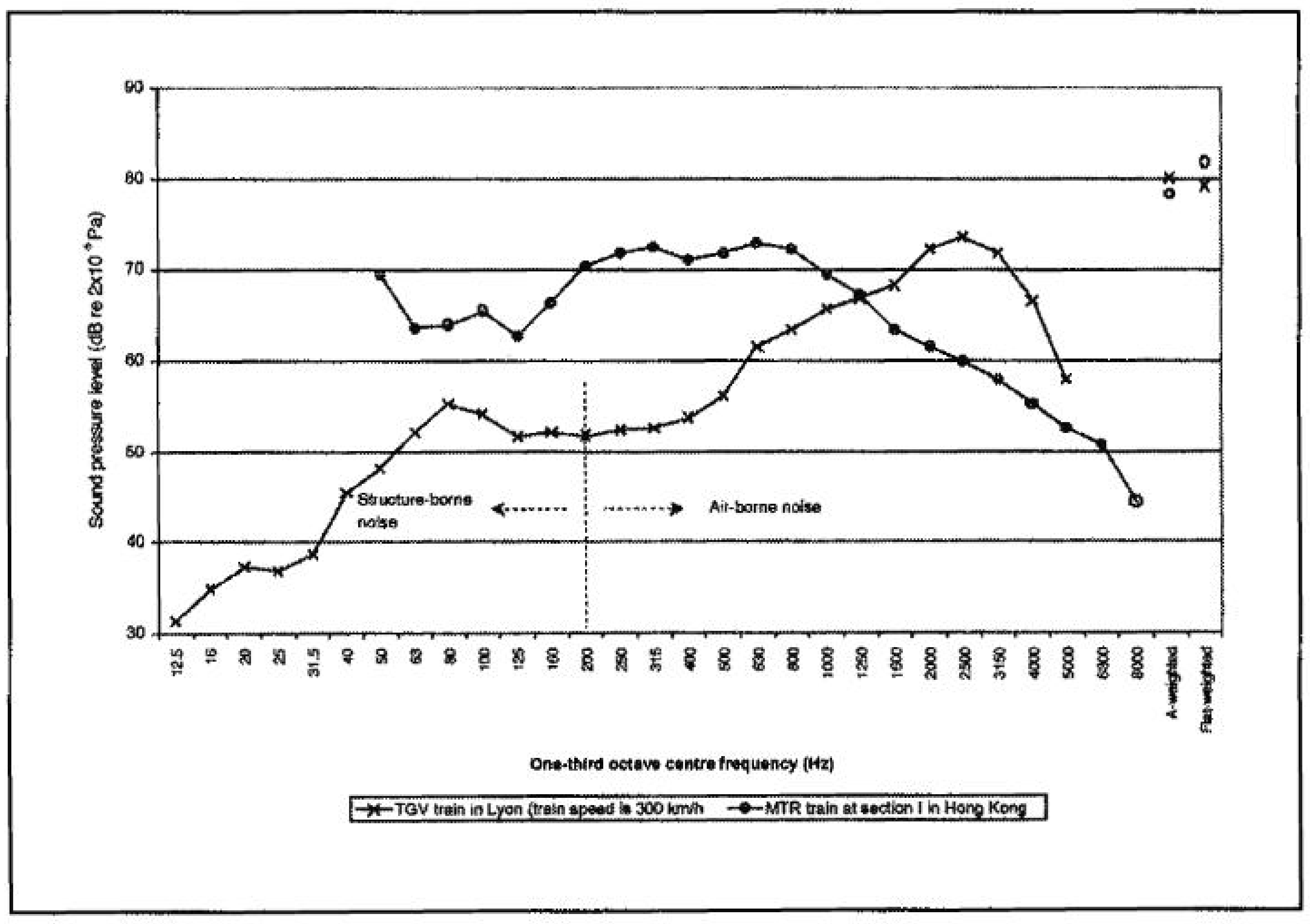

Figure 3 – Air Borne Noise Radiated from Railway System for TGV and MTR Train at 25m Away the Track

Structure-borne Noise Spectrum under the Concrete Bridge/Viaduct Structure

The structure noise is generated when trains excite rails, the vibrating motion of the rails is related to the supporting structures such as tracks and concrete structure (bridges/viaduct), then sound is radiated by the vibration of the concrete bridges/viaduct. The measurement of structure-borne noise should be at the bottom of the concrete structure since the bridge/viaduct acts as a barrier to reduce the air-borne noise radiated to the bottom.

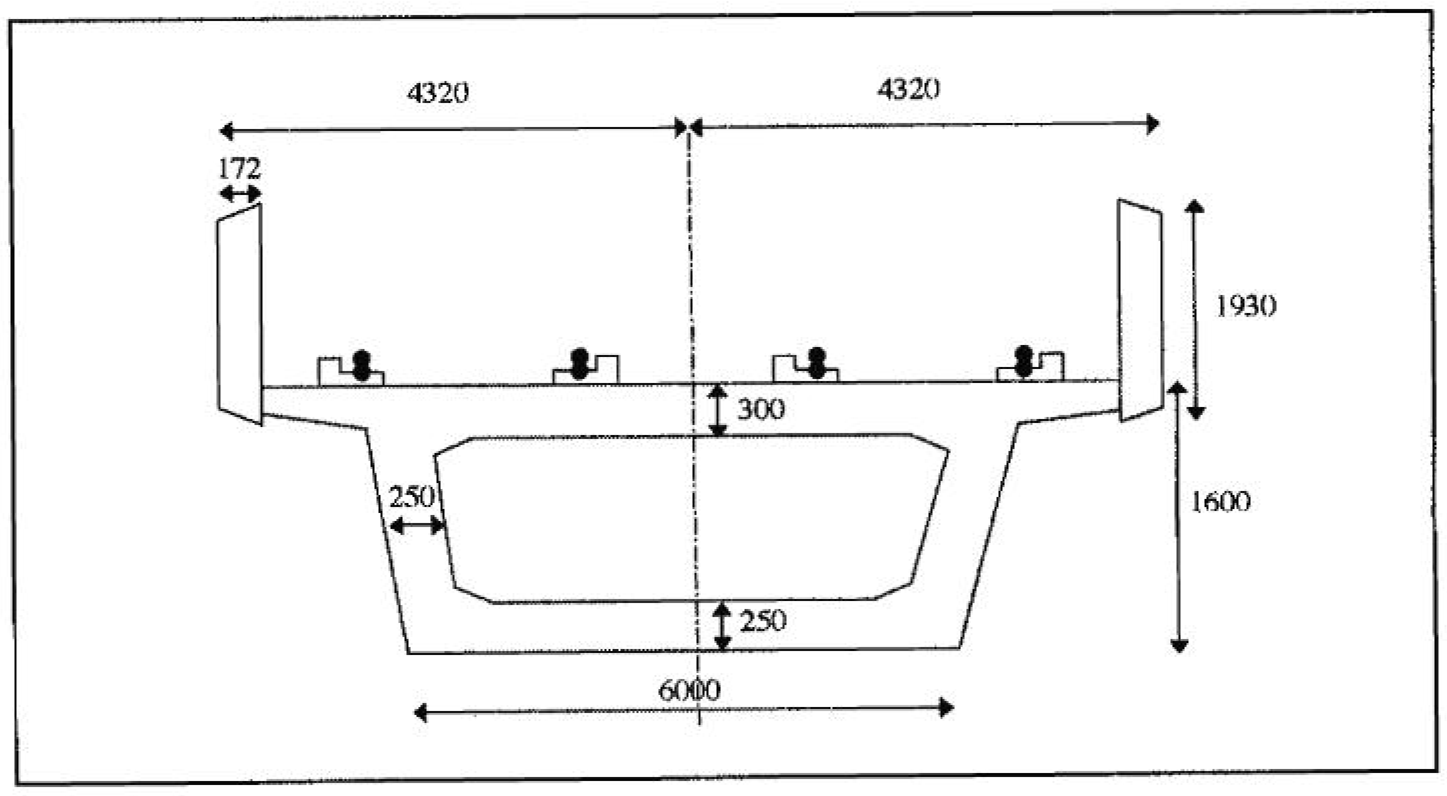

Figure 4 – Cross-section of the Concrete Viaduct for MTR Train at Section I in Hong Kong (Not in Scale and Unit is mm)

As stated in the Swiss Environmental Report 1999 [10], awareness of rail noise was increasing in Switzerland as the adverse effects on health and quality of life were being recognized. However, they didn't concern structure-borne noise radiated from the concrete viaduct along, they take it as part of air-borne noise component. In Switzerland, there are many concrete bridge structures, which generate noise nuisance to the nearby residents. One of concrete bridge structures was selected and measurement point and concrete bridge structure's cross-section are shown in Figure 5 and 6 respectively. The cross-section of the concrete bridge is different from that in Hong Kong (shown in Figure 7), there are 5 circle holes for Switzerland and 2 rectangular holes for Hong Kong in two track structures. From the train noise spectrum, 50 Hz, 400 Hz are peaks for Switzerland's bridge (shown in Figure 8) and 63 Hz and 630 Hz are peak frequencies for Hong Kong's viaduct II (shown in Figure 9). Both local peaks for low frequencies are around 60, but 63 Hz is higher than 630 Hz for that in Hong Kong, while the Switzerland's one is reverse. This is because precast

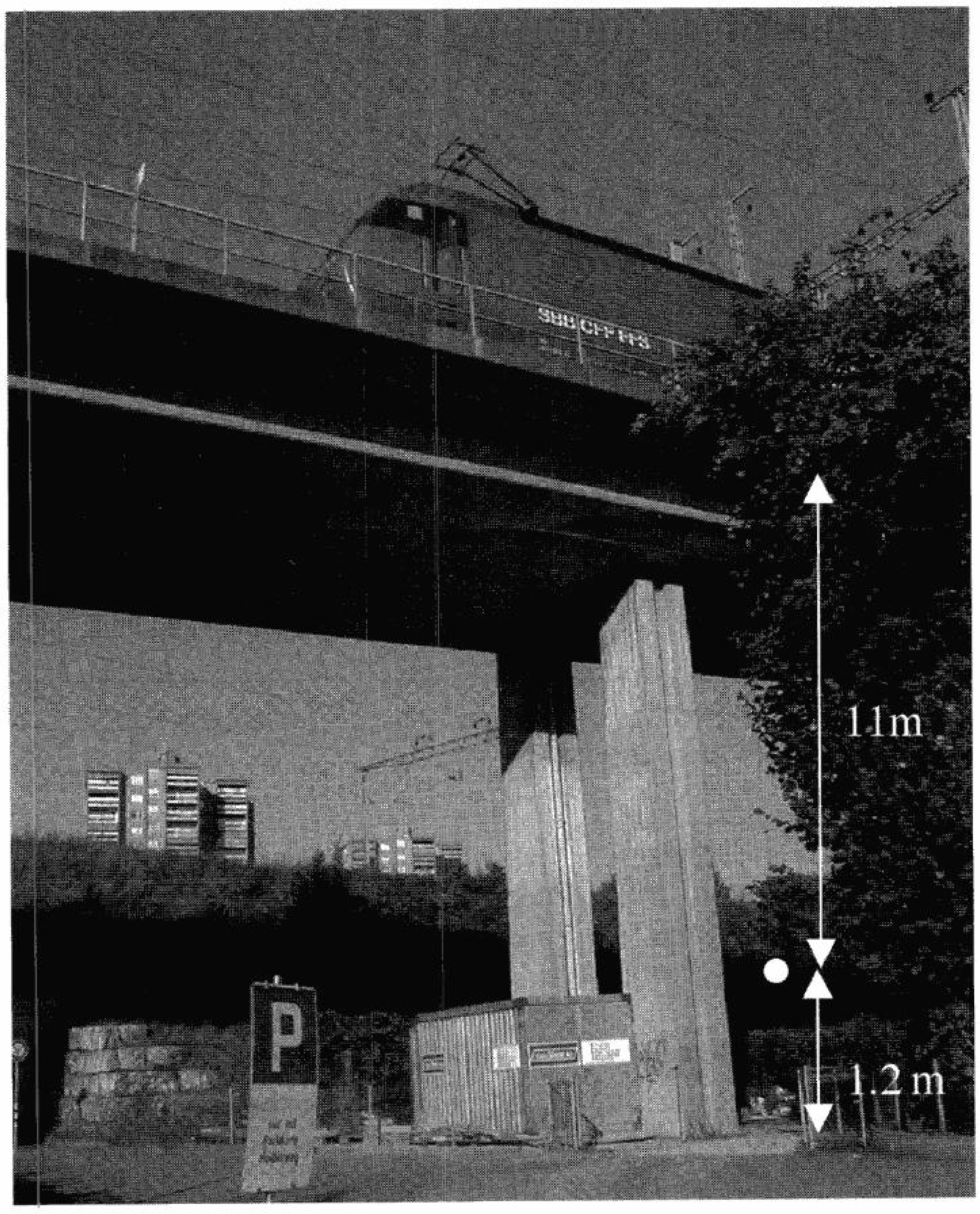

Figure 5 – Passenger Train Runs over the Concrete Bridge Structure in Switzerland

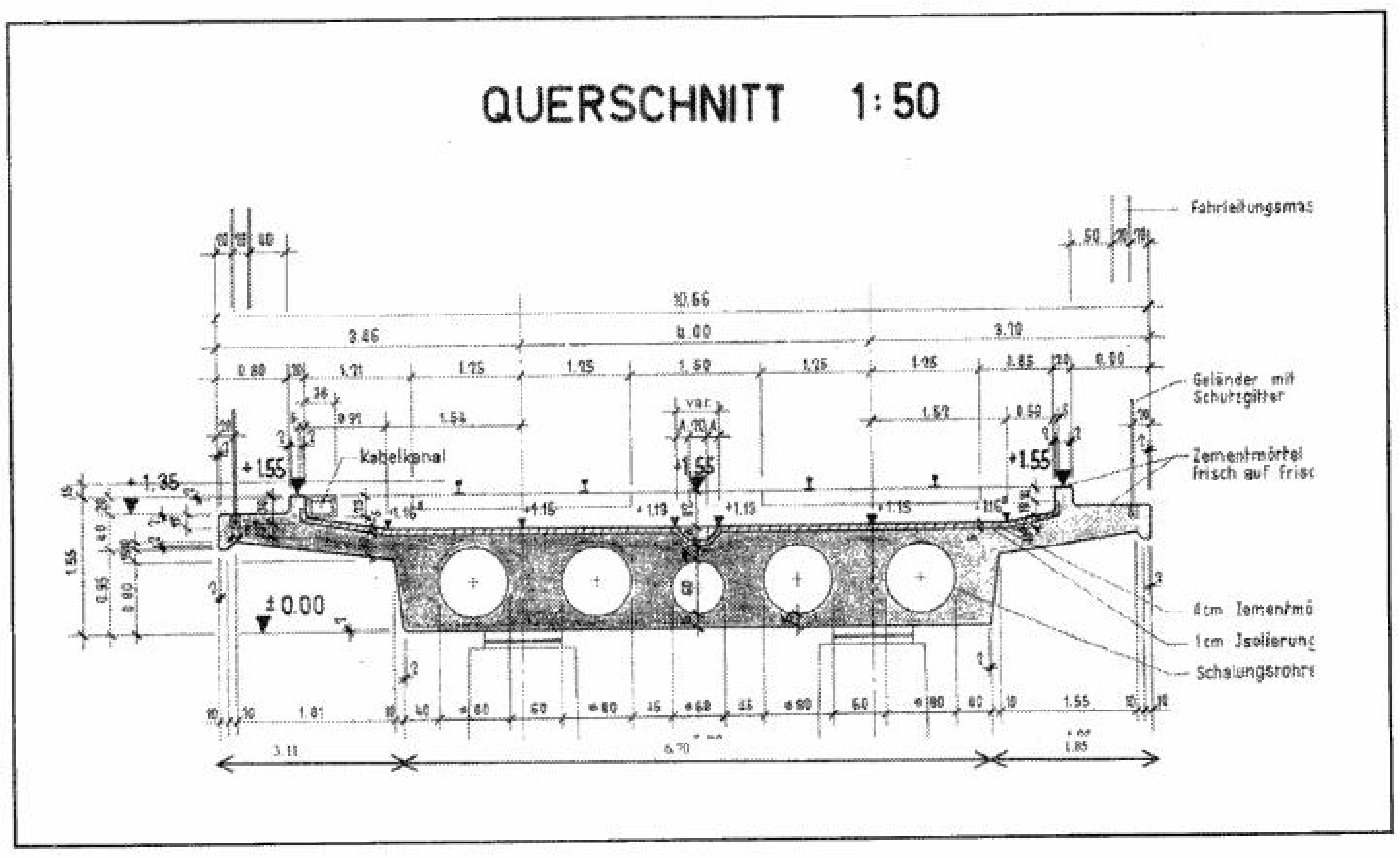

Figure 6 – Cross-section of Concrete Bridge in Switzerland

parapet unit reduces high components for local concrete viaduct design where Switzerland's bridge doesn't has a shielded design.

In the Shinkansen system [1], there were many concrete bridge structures. Steel bridges were used on very few sections, the bridge was shielded on the underside and damping to the steel members, resilient methods and rail smoothing, etc, were applied. They concluded that the noise was almost the same as that of the concrete bridges. For the concrete structure of high speed Shinkansen, measurement points were shown in Figure 10. The noise spectrum of Shinkansen and MTR train at section II viaduct are quite similar, as the air-borne noise were suppressed by the precast parapet unit in both cases. According to the noise spectrum in Figure 9, the structure-borne noise for section II viaduct in Hong Kong is between 40 Hz and 200 Hz and peak at 63 Hz. The peak frequency of Shinkansen is 100 Hz, which is a little bit higher than that for section II viaduct in Hong Kong. The reasons may be due to the different in the speed of trains, dimensions and design of concrete viaduct system.

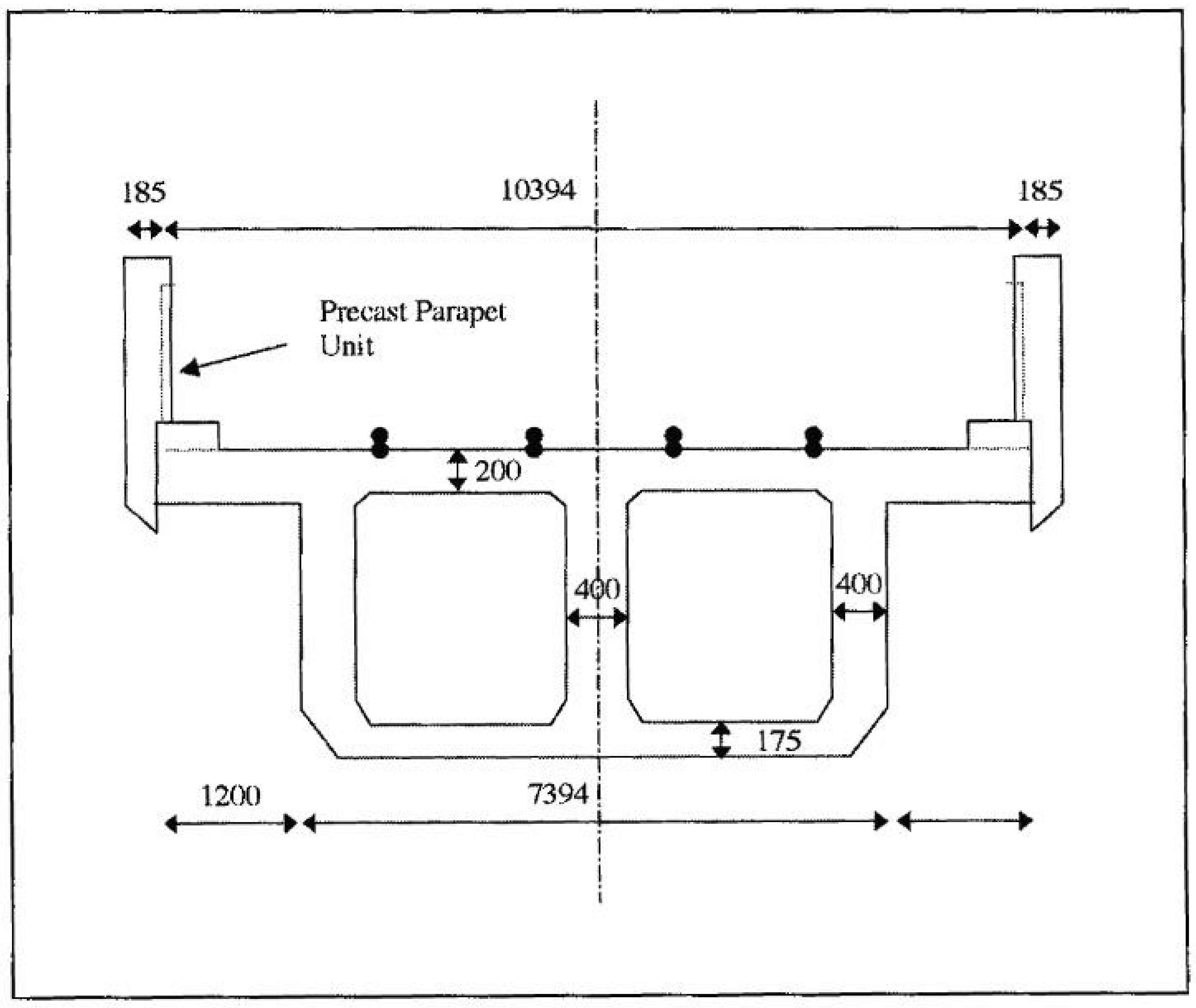

Figure 7 – Cross-section of the Concrete Viaduct for MTR Train at Section II in Hong Kong (Not in Scale and Unit is mm)

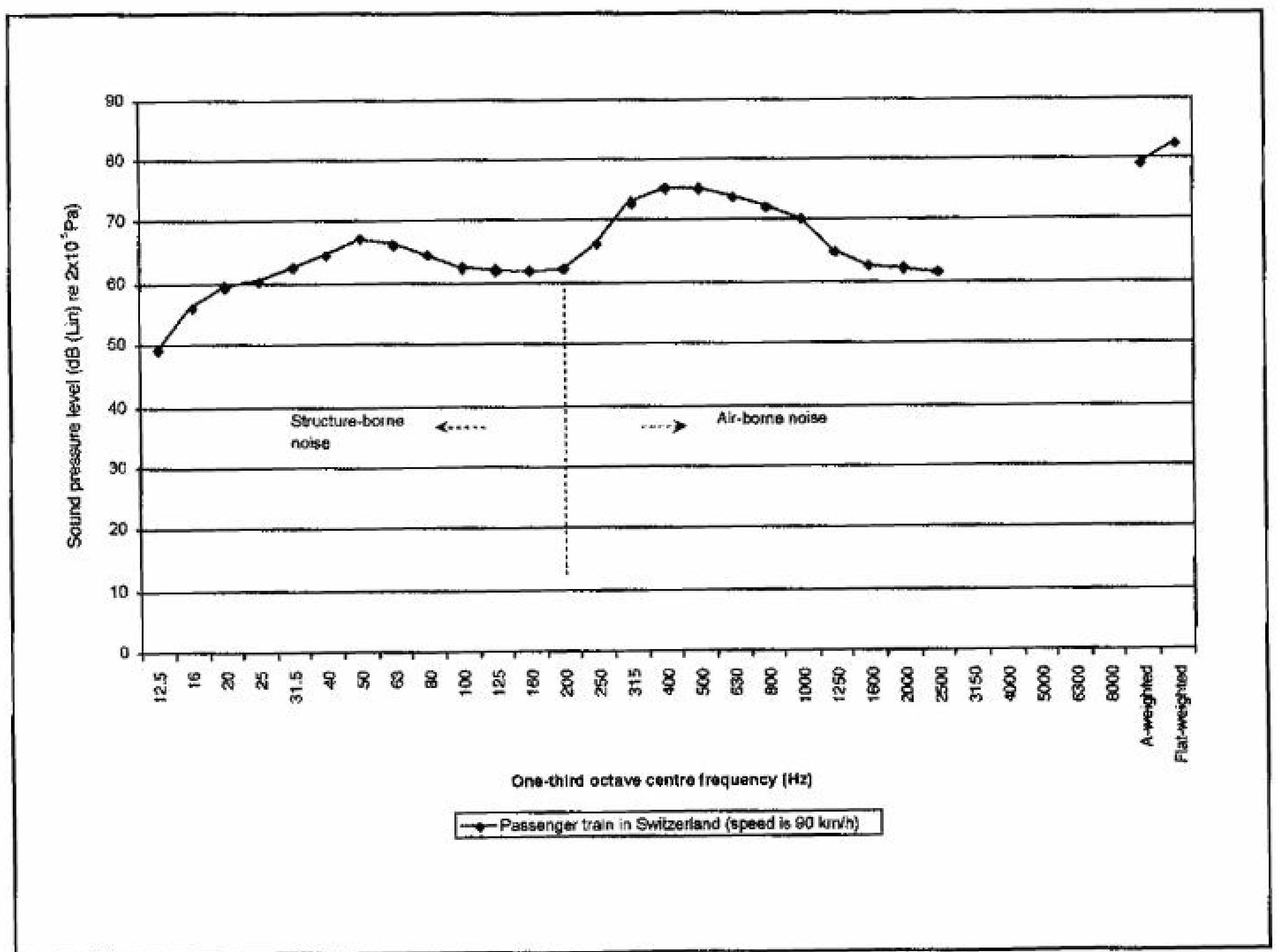

Figure 8 – Noise Spectra at 25 m away from the Track for Passenger Trains in Switzerland

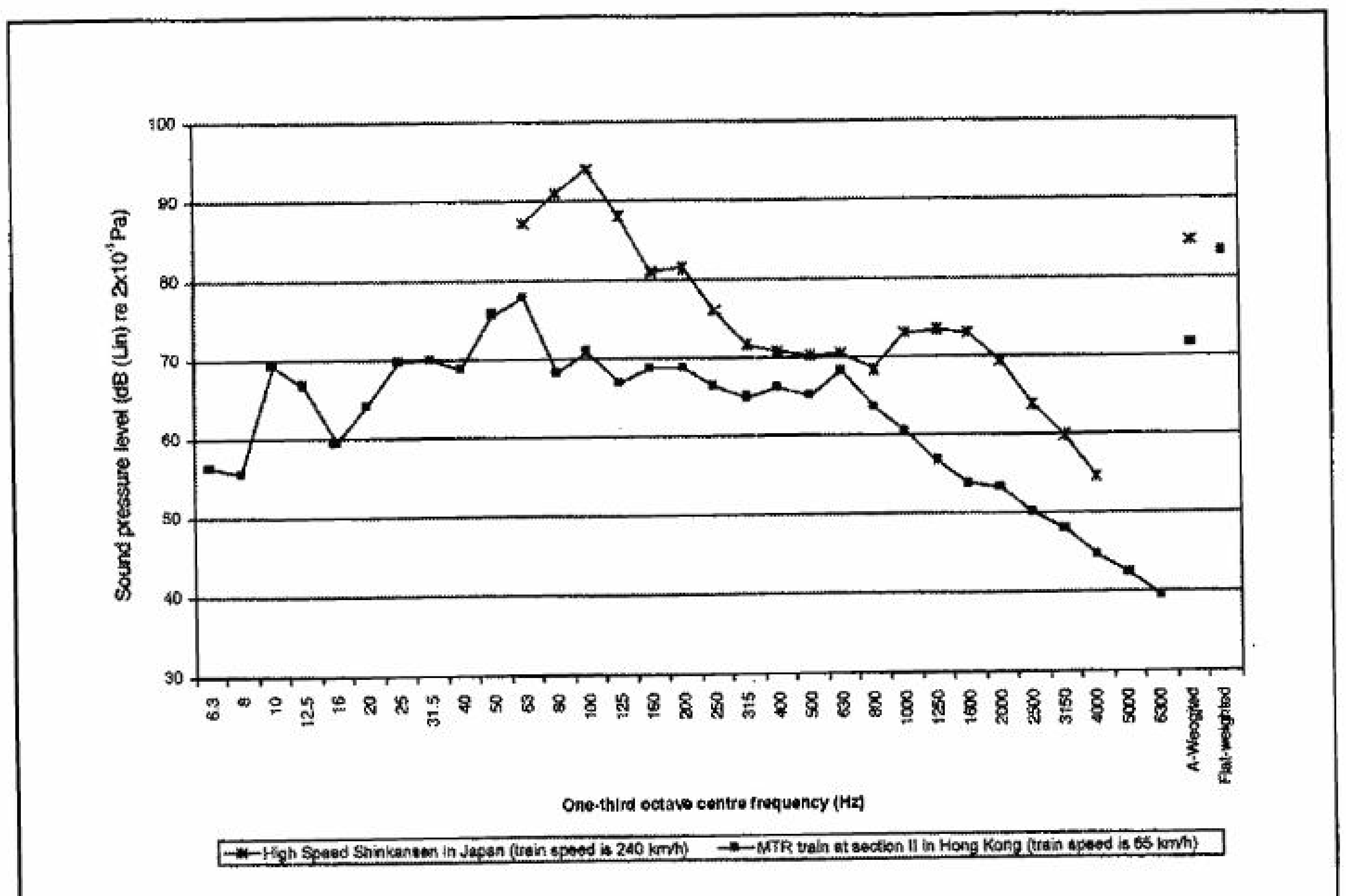

Figure 9 – Structure-borne Noise Spectrum Measured at 10 m below the Concrete Bridge/Viaduct

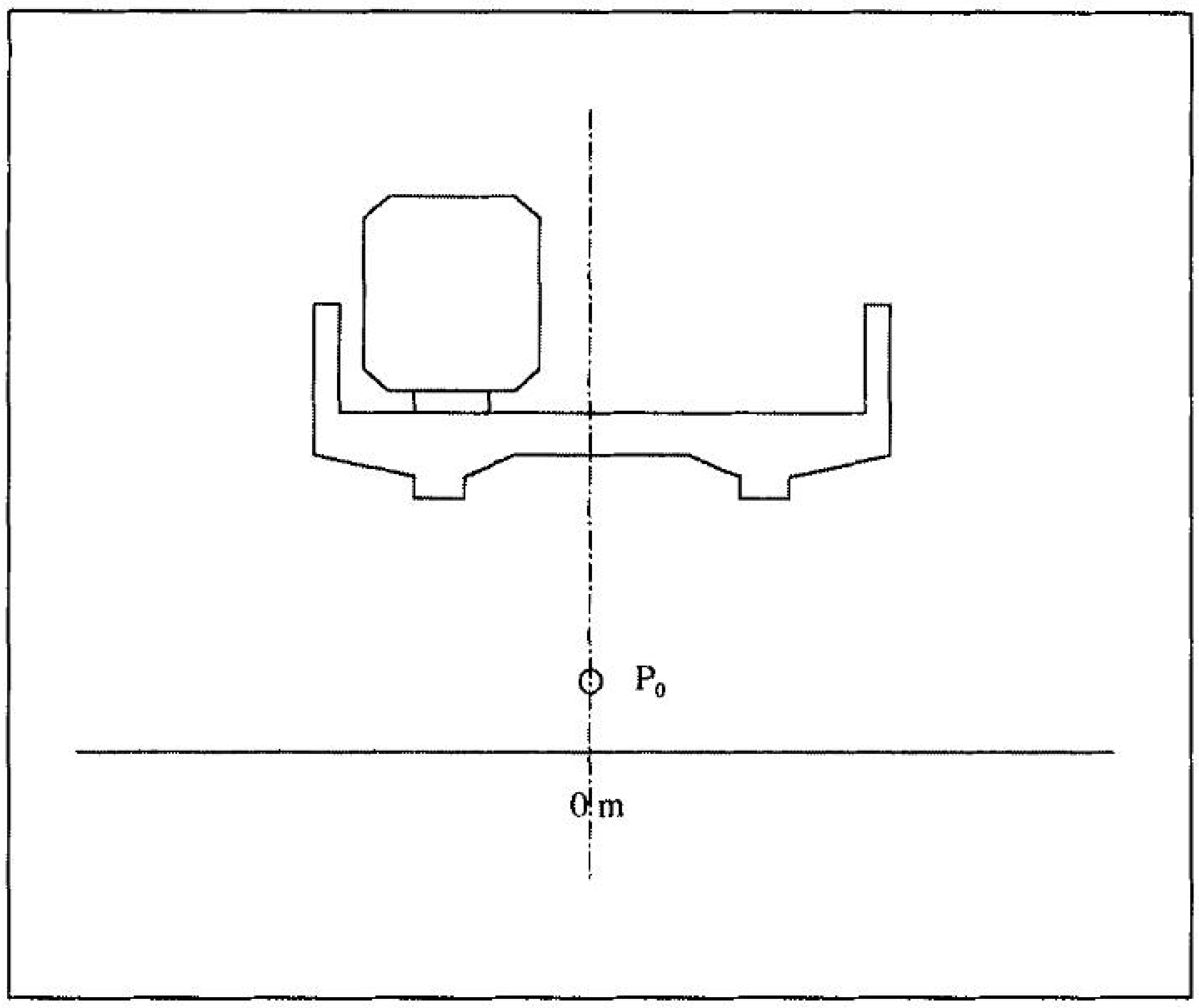

Figure 10 – Concrete Structure Sketch and Measurement Locations of High Speed Shinkansen System in Japan (Not in Scale)

FFT Measurement Results of Viaduct

For the better identification of resonance frequency of the concrete viaduct structure, FFT analysis technique is used. This frequency response analysis reveals the narrow band amplitude and coherence between input and output signals. Several site surveys on viaduct with train traffic were conducted by FFT analysis in Hong Kong. Relationship of the structure-borne noise and vibration in terms of transfer function and coherence frequency were evaluated at measurement point shown in Figure 11-14. As the train travels at 140 km/h, the dominant frequency of both noise and vibration is between 40 Hz and 120 Hz that contains significant tonal noise characteristics. From Figure 13 and 14, the acoustics coincidence phenomena should be occurred at 121.5 Hz, 128.5 Hz, whose frequency response is local peaks and its coherence is 0.84 and 0.96 respectively. According to the equation 1 [11], the calculated coincidence frequency is 107 Hz for 175 mm thick concrete plate. Then it is more confidence that 121.5 Hz and 128.5 Hz should be coincidence frequency for section II concrete viaduct.

$$f_c = 0.55c^2\sqrt{\frac{\rho_m}{E}\,\frac{1}{h}} \tag{1}$$

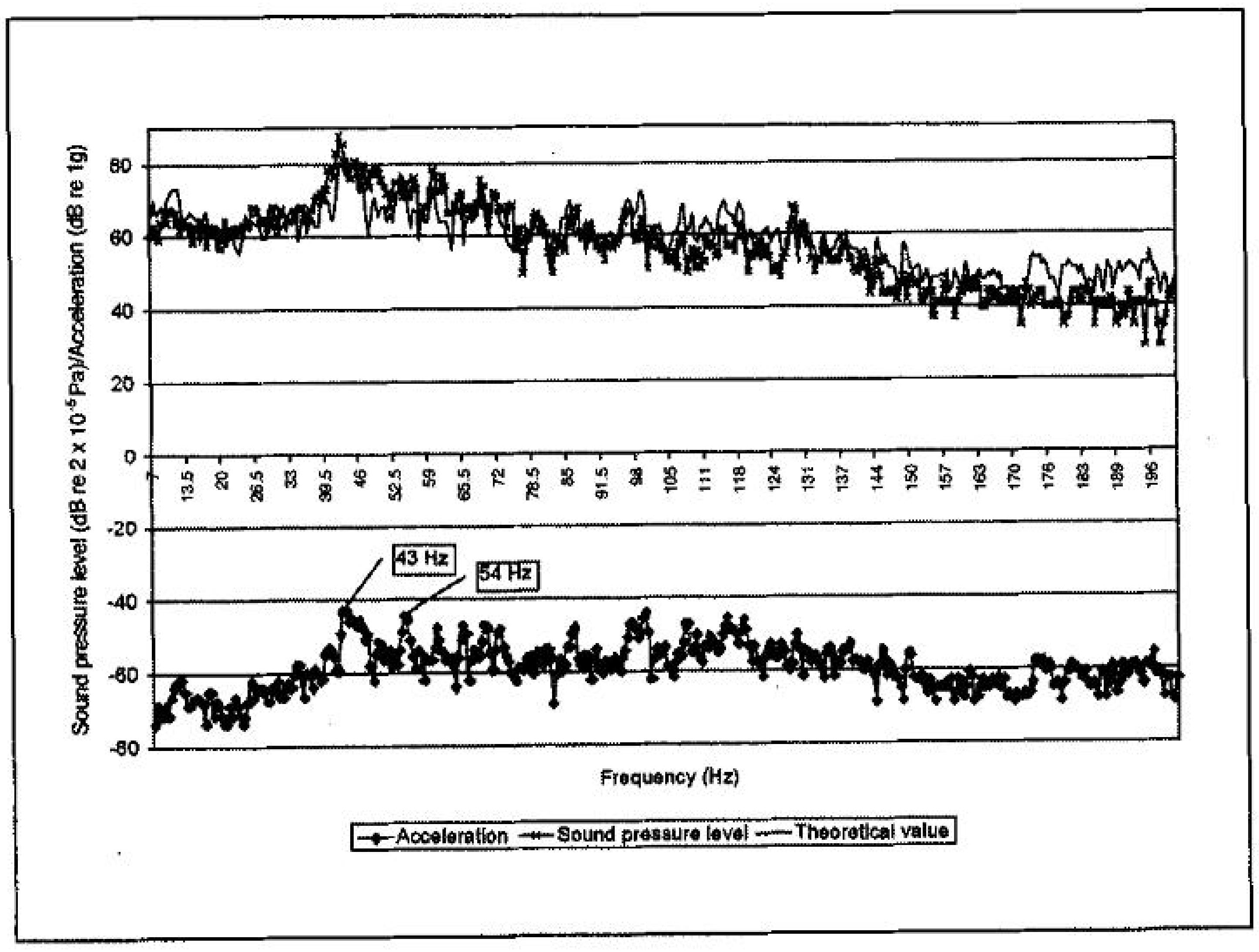

Figure 11 – Magnitude of Sound Pressure Level, Theoretical Value and Acceleration for Section II Concrete Viaduct in Hong Kong

Where c = speed of sound in air (m/s)

ρ_m is the material density (kg/m^3)

E = Young's modulus (10^9 N/m^2)

h is the panel thickness (m)

Vibration resonances of the viaduct are found to be 43 Hz and 54 Hz, they can be observed in the peak responses of acceleration vibration (Figure 11) and velocity vibration (Figure 12). Accordingly, the amplification of the vibration at 43 Hz and 54 Hz band is influenced by resonance of the combination of viaduct and train, and the vibration response can be caused by wave motion propagating upon the concrete elevated structure. In addition, the magnitude of sound pressure level at structure resonance of 43 Hz is 23 dB higher that at the acoustic coincidence of 121.5 Hz. This may implies that the structure resonance is more significant than acoustic coincidence.

Theoretically, the average relationship of simultaneous measurements of vibration and noise level during train passes is [12]:

$$L_p = L_a - 20\log(f) + 36 \tag{2}$$

Where L_p = sound pressure level, dB

La = rms vibration acceleration level for the floor, (dB re 10^{-6}g)

F = frequency, either octave band or 1/3 octave band center frequency, Hz

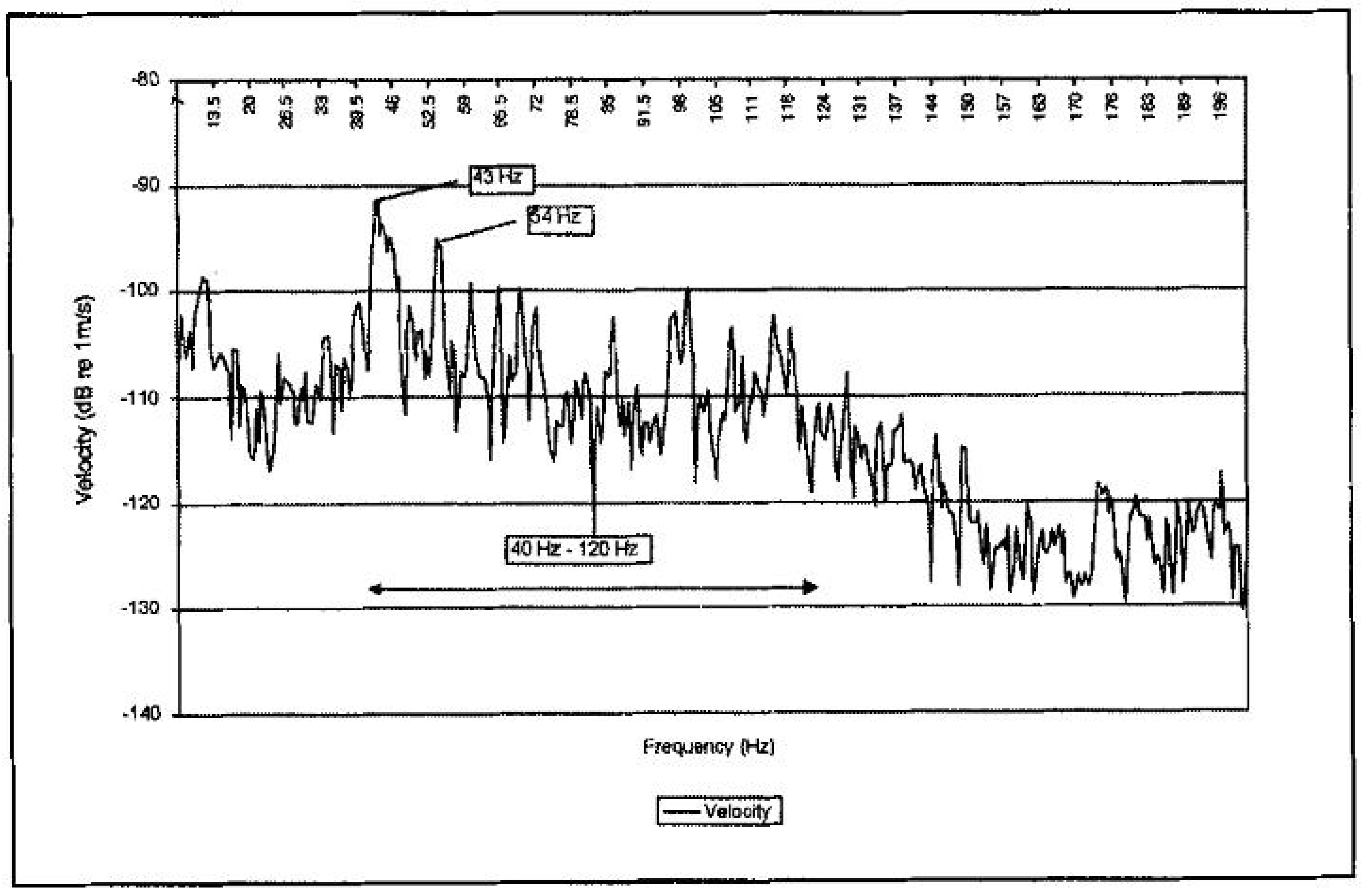

Figure 12 – Velocity for Section II Concrete Viaduct in Hong Kong

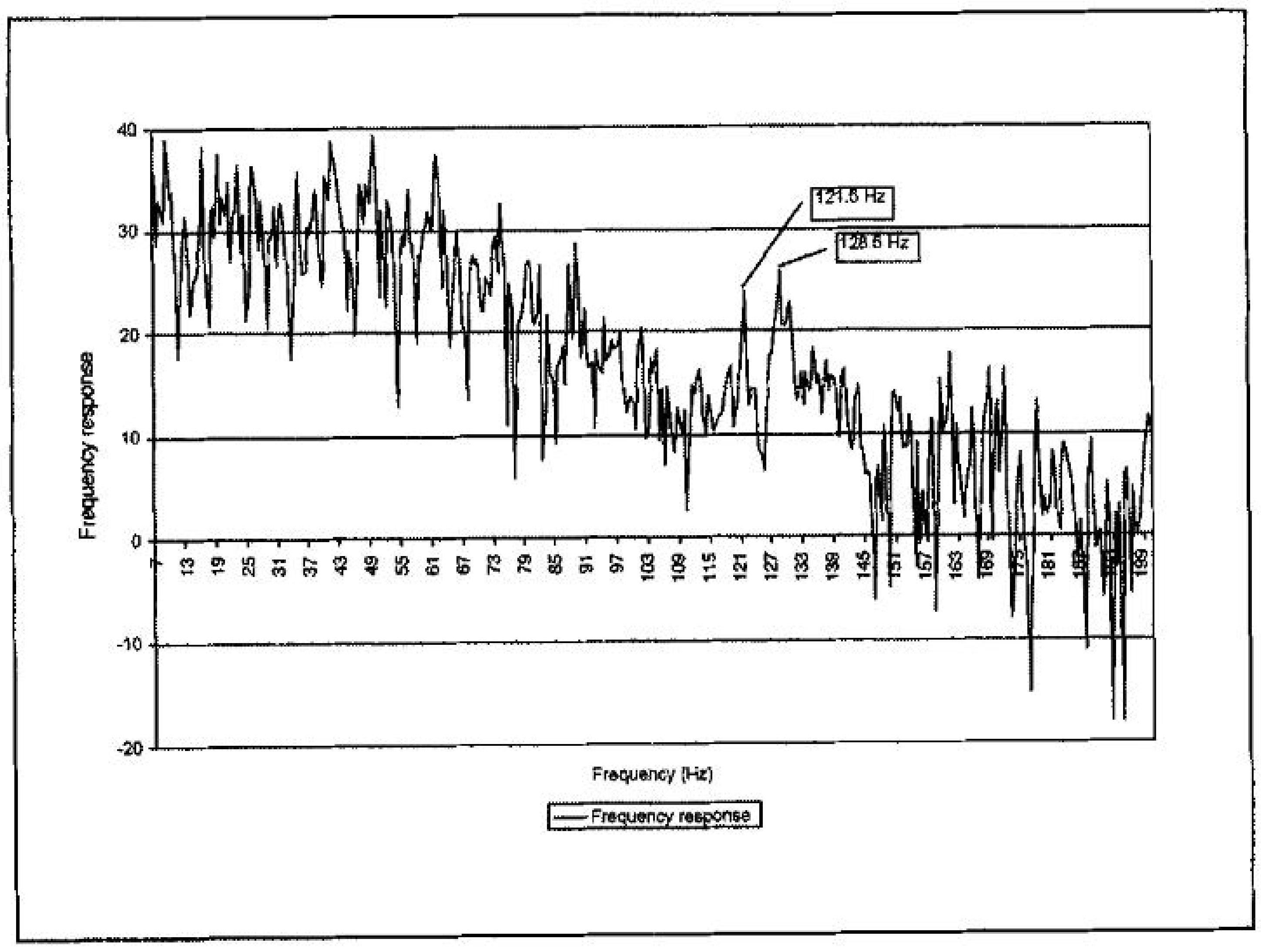

Figure 13 – Magnitude of Frequency Response (Acoustic/Vibration) for Section II Concrete Viaduct in Hong Kong

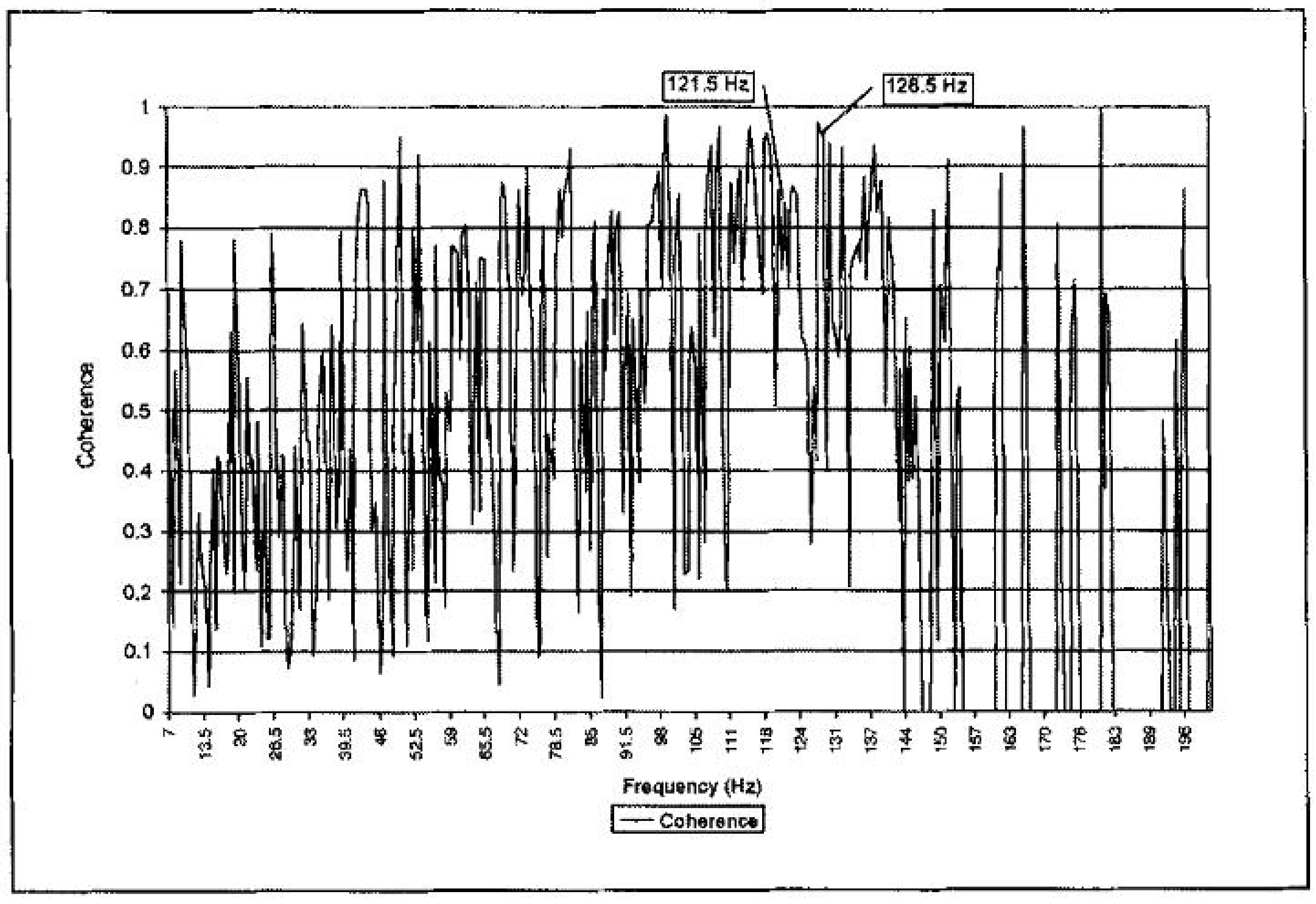

Figure 14 – Coherence (Acoustic/Vibration) for Section II Concrete Viaduct in Hong Kong

To validate the experiment data, the equation (2) is used for comparison, which is shown in Figure 11. The measured results has a good agreement with theoretical one, this shows the measurement method is quite reliable and acceptable.

Comparison between Air-borne and Structure-borne Noise Radiated from Viaduct

From the above results, it can be seen the characteristic of structure-borne noise is very different from those of airborne noise. Since, train operations on elevated structures radiate four basic sources of community noise, they are:

1. Noise radiated from on-car equipment such as traction motors, compressors, and motor generators.
2. Wheel/rail noise radiated directly from the vibration of the wheels and rails. Wheel/rail noise includes impacts at rail joints, squeal noise on curves, and normal rolling noise.
3. Noise radiated from the vibrating components of the structures.
4. Groundborne noise transmitted through the support columns to nearby buildings.

The first two sources can be counted as air-borne noises and the following two are called structure-borne noises. At speeds up to approximately 50 km/h, wheel/rail noise predominates, while at speeds greater than 50 km/h, the propulsion equipment noise predominates [13]. There is a great different in frequency domain for air- and structure-borne noise, air-borne components consists of high frequency components (500 Hz to 4K Hz) and low frequency range for structure-borne noise. According to Figure 15, 20 Hz to 200 Hz (low frequency) is the higher for structure-borne noise and there is 12 dB(Lin) higher begin at 630 Hz for air-borne noise components. In this railway system, wheel/rail noise is reduced by the reinforced parapet unit, so the high frequency components is not so high as normal.

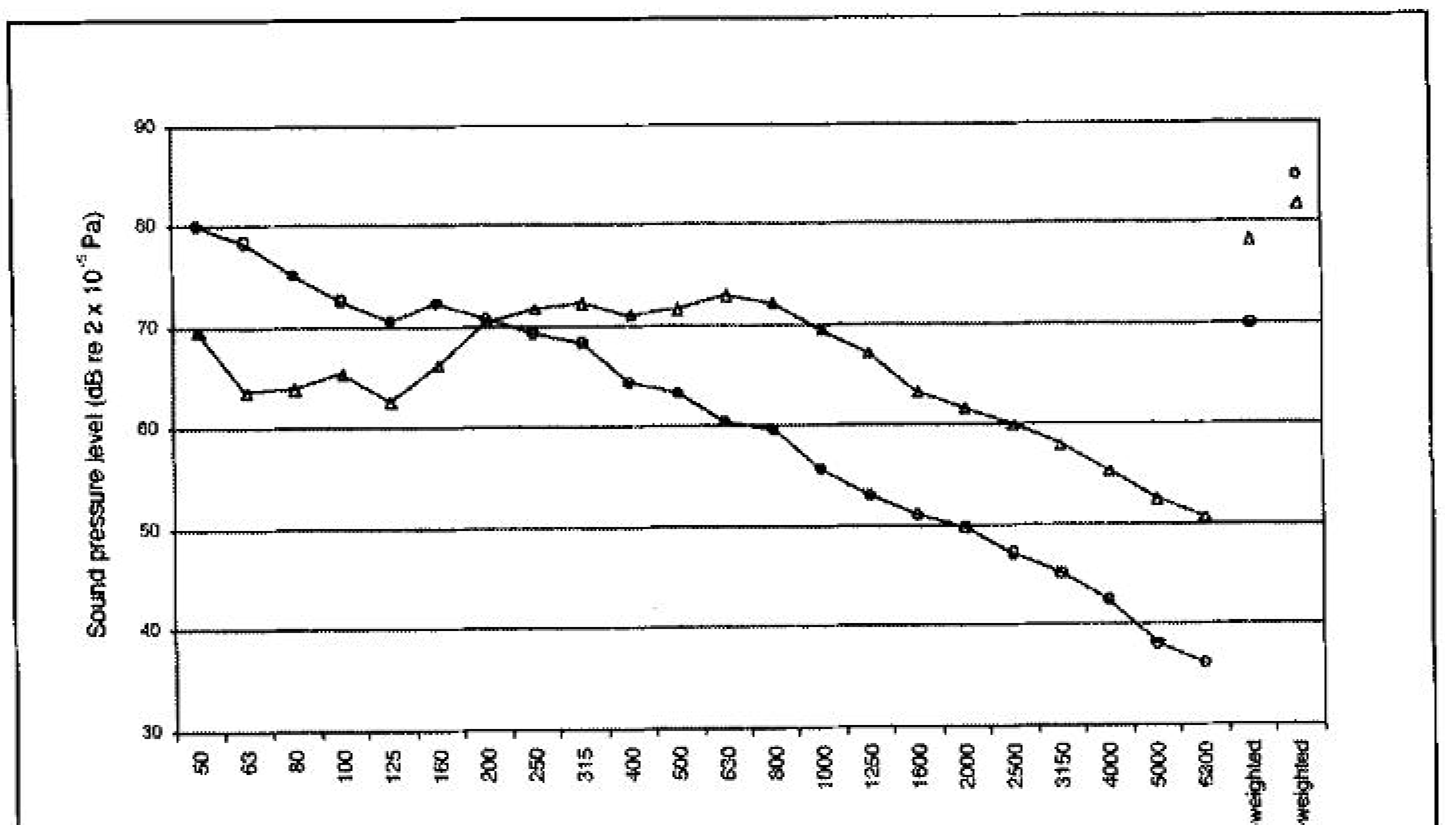

Figure 15 – Air- and Structure-borne Noise Spectra at Section I Viaduct in Hong Kong (Train Speed is 60 km/h)

For the wheel truing and grinding can reduce the wheel/rail forces, so it also gives help to reduce the vibration and structure-borne noise. The other measures to deal with the re-radiated noise:

1. To use vibration isolation to reduce energy flow into the structure.
2. To apply vibration damping to major structural components to reduce the magnitude of vibration, eg floating slab.
3. To stiffen the viaduct, effective for low frequencies, and make the viaduct more massive, which is effective at high frequencies as power input reduce.
4. Provide a full, resiliently hung absorptive shield covering the noise-radiating area.
5. To place closer web panels beneath the rail support, the greater mechanical impedance of the structure at that point and the less resonant vibration response from the deck.

The structure-borne noise measures must be applied during the design stage because the structure cannot be modified. The comparison between air- and structure-borne noise has been summarized in Table 1. It can be seen that prediction of structural vibration is required for prediction and control of structure-borne noise.

Parameters	Air-borne Noise	Structure-borne Noise
Sources	• On-car Equipment • Wheel/Rail Noise	• Radiated from Structural components • Ground-Borne Noise
Subjective Response/ Frequency Character	• High Frequency (500 - 4K Hz)	• Low Frequency (20 - 200 Hz)
Prediction Methods	• Noise Prediction Models by considering a train as discrete sources (wheels) or a single source	Structural vibration by • Finite Element (FE)
Control Measures	• Screening Skirt • Wayside Noise Barrier • Enclosure	• Vibration Isolation and Damping • Increase stiffness and mass of viaduct • Full, Resiliently Hung Absorptive Shield • Place Closer Web Panels Beneath the Rails

Table 1 – Comparisons between Air- and Structure-borne Noise

Conclusions

The analysis of correlation of noise and vibration indicated that the peak level of structure-borne noise was due to the vibration resonance of concrete viaduct structure. The frequency spectrum, magnitude and phase angle of frequency response and coherence function are the important parameters of resonance frequencies analysis, FFT measurement technique is particularly good for correlation with spectrum analysis for identifying vibration resonance and coincidence behaviour created by the viaduct.

The dominant range of structure-borne noise radiated concrete viaduct structure is between 20 Hz and 200 Hz. It is evident that vibration resonance effect is more significant than acoustic resonance. Therefore the structural vibration resonance is one of the important parameter to be analyzed to reduce the structure-borne noise problem in viaduct. Accurate prediction of this structural resonance can help the design of a quiet railway viaduct.

Acknowledgement

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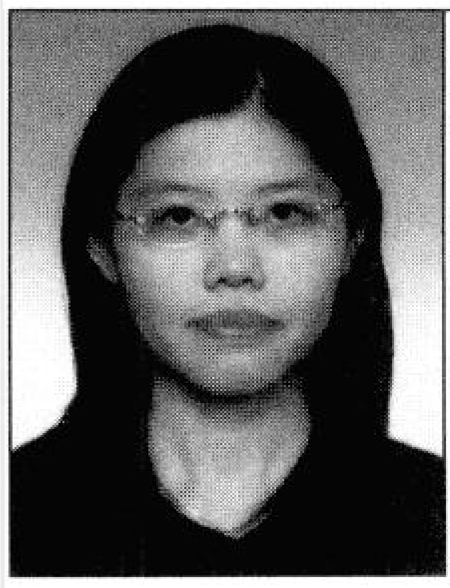
References

1. Y. Moritoh, Y. Zenda and K. Nagakura (1996). Noise Control of High Speed Shinkansen. *Journal of Sound and Vibration*, 193(1), 319- 334.
2. M. Heckl, G.Hauck, R. Wettschureck (1996). Structure-borne Sound and Vibration from Rail Traffic. *Journal of Sound and Vibration*, 193(1), 175-184.
3. Takashi Morii (1975). Development of Shinkansen Vibration-isolation Techniques. Structure Laboratory, Railway, Technical Research Institutes J.N.R.
4. C. Stber (1975). Air- and Structure-Borne Railway Noise. *Journal of Sound and Vibration*, 43(2), 281-289.
5. R J Greer and K M Collins (1996). Groundborne Noise and Vibration from Railways: The Pitfalls. *Proceeding of Internoise.*
6. J T Nelson (1996). Recent Developments in Ground-borne Noise and Vibration Control. *Journal of Sound and Vibration* 193(1), 367-376.
7. E J Rathe (1977). Railway Noise Propagation. *Journal of Sound and Vibration* 51(3), 371-388.
8. U J Kurze (1996). Tools for Measuring, Predicting and Reducing the Environmental Impact from Railway Noise and Vibration. *Journal of Sound and Vibration* 193(1), 237-251.
9. E. C. Bovey (1983). Development of an Impact Method to Determine the Vibration Transfer Characteristics of Railway Installations. *Journal of Sound and Vibration*, 87(2), 357-370.
10. *Environmental Report 1999* (1999). Swiss Federal Railways (SBB AG).
11. David A. Bies and Colin H. Hansen (1996). *Engineering Noise Control-Theory and Practice* (Second Edition). E&FN SPON
12. H.J. Saurenman, J.T.Nelson, G.P. Wilson (1982). *Handbook of Urban Rail Noise and Vibration Control.* Prepared under contract to US DOT/Transportation Systems Center, Report UMTA-MA-06-0099-82-2.
13. P. M. Nelson (1987). *Transportation Noise Reference Book.* Butterworths.



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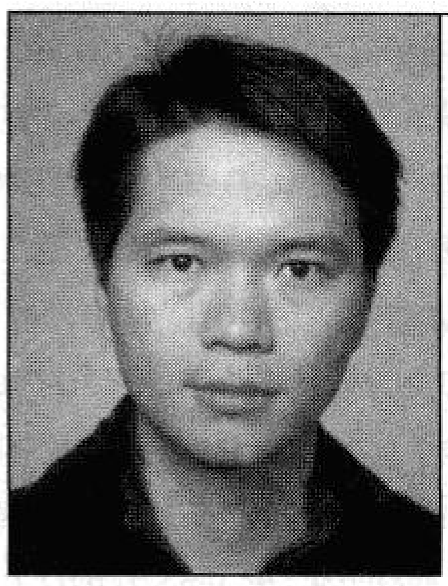

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