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AN EXPERIMENTAL INVESTIGATION INTO THE INFLUENCE OF TRACK CROSSOVERS ON TRAM-GENERATED GROUND-BORNE VIBRATION AND RE-RADIATED NOISE

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Abstract

The operation of tramways close to sensitive buildings can lead to concerns over ground-borne vibration and re-radiated noise. Vibration generated at the wheel-rail interface propagates through the track structure, through the ground and into buildings, where it may cause disturbance as perceptible vibration and/or re-radiated noise. There are primarily two potential sources of vibration: the inherent roughness of the wheels and rails; and discontinuities in the rails, such as those found at track crossovers.

This paper presents an experimental investigation into the source of re-radiated noise within a UK concert hall. The hall in question is situated alongside a tramway that includes a crossover between two rail tracks. A particular objective of this investigation was to establish the relative significance of the impulsive vibration generated at the rail breaks of the crossover compared with the essentially continuous vibration due to wheel/rail roughness. The paper includes a description of the method used to make simultaneous noise and vibration measurements, together with the necessary data processing and a discussion of the results. It is concluded that, while plain line track may be acceptable in a given location, the presence of a crossover can lead to significantly higher levels of noise and vibration. Special consideration should therefore be given to the location and vibration isolation of crossovers in an urban environment.

INTRODUCTION

Tramways are one of the most significant sources of ground-borne vibration in our cities [1, 3]. Vibration generated at the wheel-rail interface propagates through the track structure, through the ground and into buildings, where it may cause elements of the building structure to vibrate. This vibration can be felt by a building's occupants and is known as *perceptible vibration* when the level is such that the comfort of the occupants is adversely affected.

Structural vibration also radiates sound and this can be significant within the audio frequency range, approximately 25 Hz and above. *Re-radiated noise* (also termed *structure-borne* or *ground-borne noise*) describes vibration, originally radiated through the ground and into a building, which is then re-radiated as audible, airborne noise [2]. The result is an audible low-frequency 'rumble' which, depending on the radiation efficiency of the particular structure, is usually most noticeable in the frequency range from 50 Hz to 125 Hz.

This paper is concerned with diagnosing the source of intrusive re-radiated noise within the auditorium of a UK concert hall.

OVERVIEW OF THE PROBLEM

The concert hall in question is situated alongside a tramway that includes a crossover between two rail tracks. The crossover lies approximately 8 m away from the rear façade of the concert hall, which separates the tramway from the back-stage space of the auditorium, as illustrated in Figure 1.

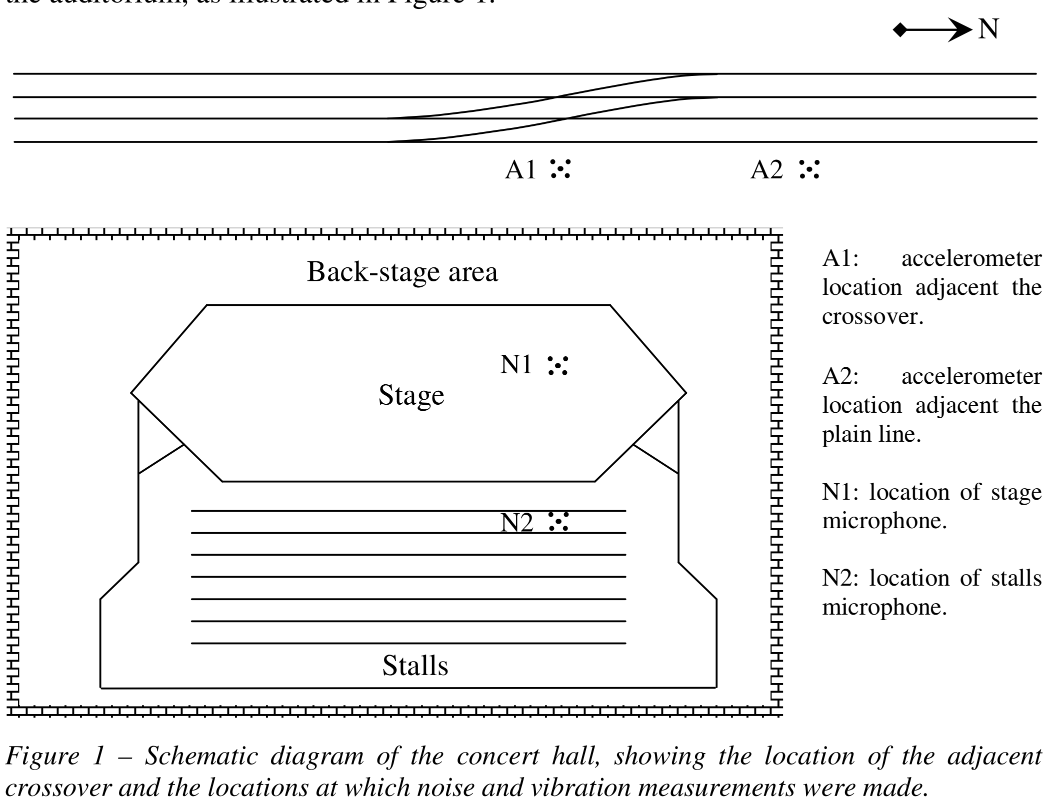

Figure 1 – Schematic diagram of the concert hall, showing the location of the adjacent crossover and the locations at which noise and vibration measurements were made.

The concert hall was built to a high standard approximately 20 years ago but this was before the tramway was conceived and no special measures were taken to limit the effects of ground-borne vibration. Since the construction of the tramway, the hall has suffered significant disturbance due to the operation of the trams. The auditorium is well isolated acoustically and the level of airborne noise from the trams is insignificant. However, although the level of perceptible vibration is low, the level of re-radiated noise is significant. The individual tram pass-bys are clearly perceptible as low-frequency 'rumbles', both on the stage and in the auditorium, and the noise is intrusive for both the orchestra and the audience.

There are primarily two sources of ground-borne vibration, and hence re-radiated noise, associated with tramways: the inherent roughness of the wheels and rails; and discontinuities in the rails, such as those found at track crossovers. A particular objective of this investigation is to establish the relative significance of the impulsive vibration generated at the rail breaks of the crossover compared with the essentially continuous vibration due to wheel/rail roughness. The aim is to estimate the likely reduction in re-radiated noise levels within the concert hall in the event that the crossover is removed and replaced with plain line.

DESCRIPTION OF MEASUREMENTS

The purpose of the measurements was to record a series of continuous noise and vibration time-histories as trams made controlled pass-bys from the nominally straight section of plain line, over the crossover and beyond. Only southbound trams were monitored as these operate closest to the concert hall. The measurements avoided the occasional periods when a northbound tram was also passing.

Tram speeds of 10 kph and 20 kph (the typical service speed) were considered and these were held constant over both the plain line and the crossover. Measurements of average speed over the monitored track indicate that the level of control was good: only 2 pass-bys, out of a total of 25, were rejected due to speed deviations of more than ± 10 %.

Noise and Vibration Measurements

Vibration measurement locations were established by the side of the concert hall, adjacent to the centre of the crossover and adjacent to the preceding section of plain line. See Figure 1. In both cases, the stand-off distance of the measurement location from the centre of the southbound track was 3 m.

The same type of accelerometer was used to measure the vertical vibration of the ground at both locations. The accelerometers were mounted on heavy steel blocks, which provided adequate coupling to the ground over the frequency range of interest.

Noise measurement locations were established inside the concert hall, on the stage and in the front seats of the stalls. See Figure 1. These are the closest locations to the trams at which a musician and member of the audience may be seated. In both cases, the microphone was positioned approximately at the head-height of a seated person. The same type of sound level meter was used for both locations.

The output signals from the accelerometers, along with the linear outputs of the sound level meters, were recorded simultaneously by a common data acquisition unit located adjacent to the tramway. The power and microphone cables were routed without introducing any significant paths for airborne noise into the auditorium.

Marker Signal

A fifth channel on the data acquisition unit was used to record a manually switched voltage input. This enabled salient moments during a tram pass-by to be marked on the recorded time-histories by visually monitoring the progress of a tram. Moments of particular interest are when the first wheel of a tram reaches the start of the crossover, and when the last wheel of a tram leaves the start of the crossover.

RESULTS

Figure 2 (a) illustrates the nature of a typical vibration time-history measured adjacent to the crossover with a tram speed of 20 kph.

(a)

(b)

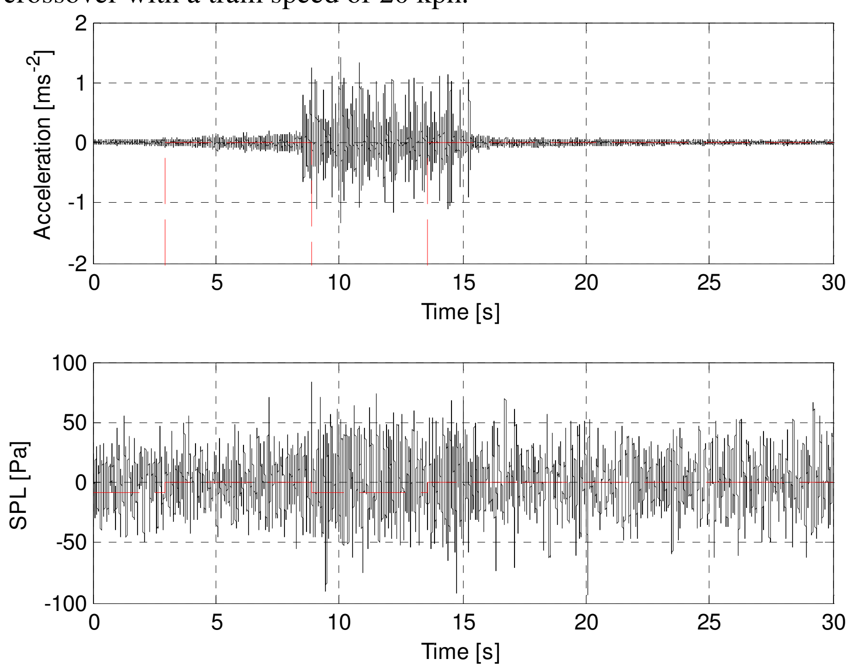

Figure 2 – Typical time-histories of (a) ground vibration adjacent the crossover and (b) the associated re-radiated noise on the concert hall stage. The dashed vertical lines correspond to the marker signal, which provides confirmation of the tram location. Tram speed = 20 kph.

The ground-borne vibration level gradually increases as a tram approaches the crossover. The transition from the essentially continuous roughness-induced vibration to the impulsive vibration generated at the rail breaks is clear. Once on the crossover, the individual wheel impacts are clearly visible.

The vibration time-histories provide clear evidence that the crossover leads to a significant increase in peak vibration levels adjacent to the track. The associated re-radiated noise time-histories, such as that plotted in Figure 2(b) do not provide such clear evidence of the effect of the crossover. To establish this, the raw sound pressure data must be processed into more familiar forms.

Noise Spectra for the Crossover and Plain Line Sections

Figure 3 compares the mean spectrum of the re-radiated noise due to trams travelling at 20 kph on the crossover with that due to trams on the plain line. The spectra are calculated by sectioning the noise time history and applying the Fast Fourier transform to the data acquired with the tram on the crossover and that acquired with the tram on the plain line immediately preceding the crossover. The conventional A-weighting is applied.

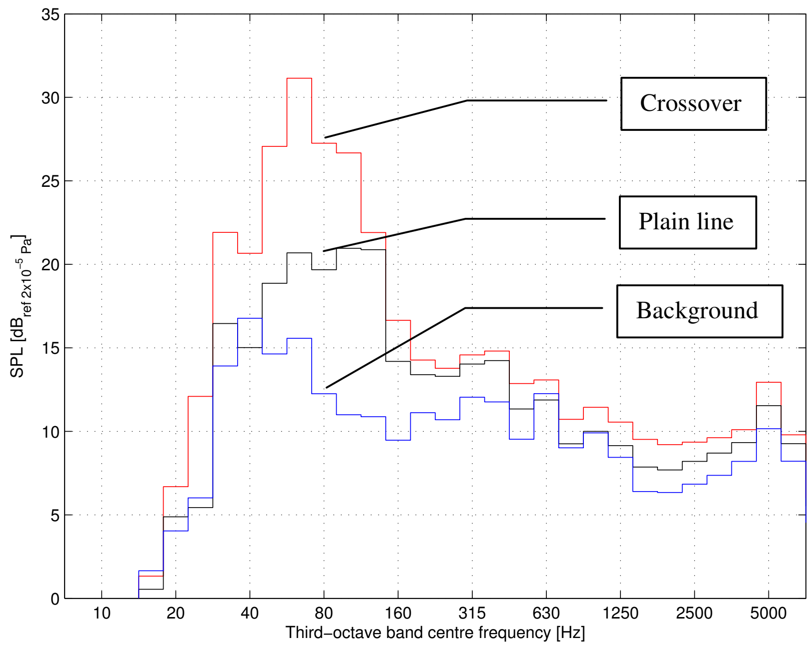

Figure 3 – Comparison of the mean A-weighted noise spectrum due to trams travelling on the crossover with that due to trams on the plain line. The background spectrum (in the absence of any trams) is also plotted. Stage measurement location; tram speed = 20 kph.

At a tram speed of 20 kph, the re-radiated noise levels on the stage due to trams travelling on the straight track exceed the background level by up to 10 dB in any one third-octave band. In contrast, the levels due to trams traversing the crossover exceed the background by up to 16 dB. In general, the noise levels significantly exceed the background level over the frequency range from approximately 25 Hz to 160 Hz. The peak noise level occurs in either the 63 Hz or 80 Hz bands. This is a characteristic of vibration from light rail systems and is often attributable to a vibration resonance of the wheels on their axles. It is this peak in the noise spectrum that enables the trams to be heard in the concert hall.

Overall Noise Levels

Figure 4 plots the typical variation in the time-weighted re-radiated noise levels ($L_{A,\ slow}$) with time. $L_{A,\ slow}$ is an overall measure of noise level across the whole of the audible frequency range. Independent measurements of the background level, in the absence of any trams, indicate equivalent levels of 25.7 dB on the stage and 25.2 dB in the stalls

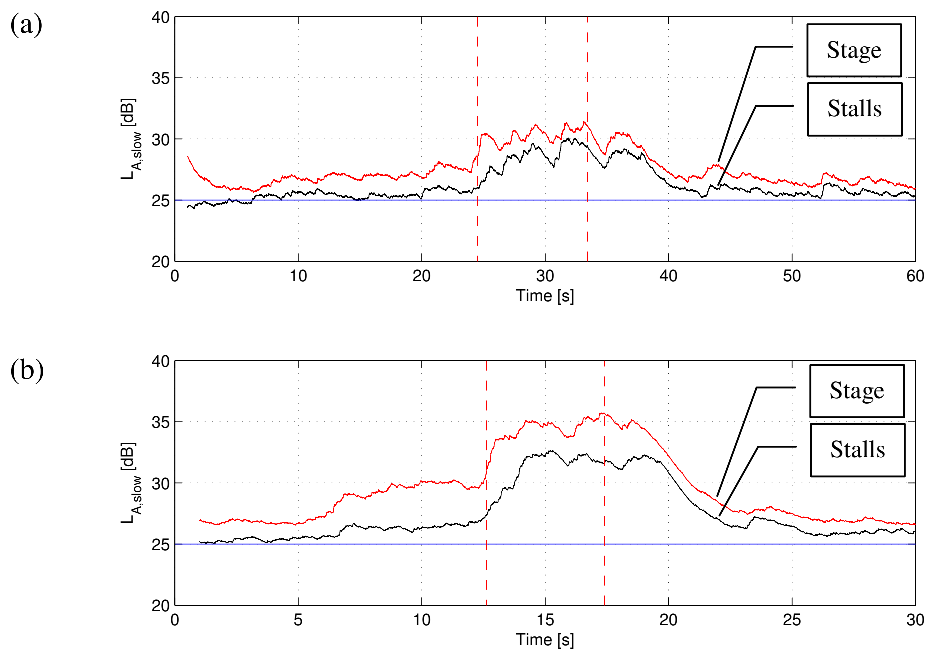

Figure 4 – Typical time-weighted re-radiated noise levels recorded with tram speeds of (a) 10 kph and (b) 20 kph. The dashed vertical lines correspond to the marker signal.

Re-radiated noise levels gradually rise as a tram approaches the crossover, before rising sharply as the first wheel impact occurs. It is clear that the peak noise levels are due to the trams traversing the crossover.

By comparing the peak levels in Figure 4 with those acquired with the tram on the plain line, just before the first wheel impacts, it is possible to estimate the expected reduction in re-radiated noise in the event that the crossover is removed. These levels are summarised in Table 1.

Tram speed [kph]	**Peak level (crossover) [dB]**		**Level on plain line [dB]**		**Difference [dB]**	
	Stage	Stalls	Stage	Stalls	Stage	Stalls
10	31.4	30.1	27.6	26.0	3.8	4.1
20	35.7	32.6	30.1	26.6	5.6	6.0

Table 1 – Comparison of peak noise levels ($L_{Amax,\ slow}$) associated with trams traversing the crossover with those due to trams travelling on the preceding plain line.

Note that the noise levels recorded at the stage measurement location are greater than those recorded in the stalls. This is most likely due to amplification in the elevated stage structure.

For trams travelling at 20 kph, the data indicate that removal of the crossover would result in a reduction in overall noise levels of approximately 6 dB. At 10 kph the reduction is approximately 4 dB. Both reductions are significant in that they would be clearly noticeable – changes in level of over 3 dB are typically discernible by the human ear. In addition, they bring the noise level to within approximately 3 dB and 1 dB of the background level at 20 kph and 10 kph respectively.

In judging the significance of this reduction it is worth considering the subjective assessments made in the concert hall during the measurements. The engineer attending the microphones noted the times of all audible tram pass-bys, in terms of the when the noise was judged to rise above and fall below the background level.

At 20 kph the durations of the perceived pass-bys were consistently repeatable at between 8 s and 10 s long. These correspond to the periods when the trams traverse the crossover. The tram noise was imperceptible in the time periods before and after the crossover. At 10 kph, it was more difficult to perceive the trams. The pass-bys were recorded as being between 12 s and 16 s long and described as ‘faint tram rumble?’, ‘possible tram’, etc.

CONCLUSIONS

A series measurements has been made to diagnose the source of intrusive re-radiated noise inside a concert hall auditorium adjacent to a tramway. The measurement of sound pressure time-histories, and the simultaneous measurement of the associated ground-borne vibration, has helped considerably to demonstrate that the crossover in the rail tracks is the dominant source of re-radiated noise.

The following conclusions may be drawn from the measurements.

1) In general, tram pass-by noise levels are greater than the background level over the frequency range from approximately 25 Hz to 160 Hz. The peak noise levels occur in either the 63 Hz or 80 Hz bands. It is this peak, which exceeds the background level by up to 13 dB in any one third-octave band, that enables the trams to be heard in the auditorium.

2) At a tram speed of 20 kph, the noise levels due to trams travelling on the plain line exceed the background level by up to 10 dB in any one third-octave band. Those due to trams traversing the crossover exceed the background by up to 16 dB.

3) At a speed of 10 kph, the significance of the crossover is less. Noise levels due to the plain line exceed the background level by up to 8 dB in any one third-octave band. Those due to the crossover exceed the background by up to 11 dB.

4) It is clear that the peak noise levels are due to impacts between the wheels and the rails as trams traverse the crossover. It is estimated that, if the crossover was removed and replaced with plain line, this would lead to reductions in the overall re-radiated noise levels of approximately 6 dB and 4 dB for trams travelling at 20 kph and 10 kph respectively. This would bring the noise level to within approximately 3 dB and 1 dB of the background level. Trams travelling at 20 kph are therefore not expected to be noticed as intrusive above the background noise by the majority of people. For trams travelling at 10 kph, the reduction in noise to within 1 dB of the background, together with a broadening of the spectral peak, suggests that the residual noise levels would be imperceptible.

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