An investigation of a method for track decay rate measurement using train pass-bys

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ABSTRACT

The decay rate of rail vibration as a function of the distance from the excitation source is a key factor determining the general rolling noise contribution from the rail. A higher decay rate results in a shorter effective rail radiating length and therefore less noise emission from the rail. For the purpose of estimating rail noise radiation and evaluating the effectiveness of rail damping measures, the decay rate has to be determined accurately. The conventional impact hammer approach requires several hours of on-track time and normally manual data processing. An alternative method by using a passing train as the source of excitation requires track access to attach the sensors only and data processing can be automated. Results from the two methods have been compared for two elevated track situations. It was discovered that there was significant variation between the results obtained from the two methods. The reasons for the discrepancies may include the effect on the damping characteristics of the rail fastening system of the train's presence. The train pass-by method shows a good consistency over different train pass-bys.

INTRODUCTION

Railway noise is of concern to the rail industry world-wide. General rolling noise is reported by many, including Li et al. (2011), to be one of the significant railway noise sources requiring control. The rail's contribution has been acknowledged to be a significant component of rolling noise up to 1 kHz (Thompson, 1988; Thompson, Fodiman & Mahé, 1996; Thompson and Jones, 2000). One major factor affecting track noise performance has been identified by Jones et al. (2006) to be the attenuation rate of vibration on the rail as a function of the distance from the excitation point, usually referred to as track decay rate measured in dB/m. A higher decay rate often means less rail vibration and associated noise radiation. It has been used as an important input for theoretical track models to predict track radiation, such as by Thompson et al. (1996) and by Jones and Thompson (2003). Accurate track decay rate measurement is therefore required. Current methods include measuring the track frequency responses excited either by an instrumented hammer, such as the standard impact hammer method (EN 15461:2008) or excitation using a train passing over the site, such as used by Janssens et al. (2006). Those two methods will be referred to as 'impact hammer method' and 'pass-by method' respectively in this paper.

The set-up required for the pass-by method is significantly less than for the impact hammer method. The on-track instrumentation can be installed with a short track access time. The data can be gathered for numerous revenue-service train pass-bys with no disruption to traffic. In contrast, the impact hammer method requires significant time on track for the testing phase and therefore significant safe working implications for those on track. The impact test must be conducted with sufficient tests done at more than 20 positions within one site requiring perhaps 10 minutes per position. The post-processing of the data from the impact hammer test has to be done manually. This typically involves: averaging the vibration data over several samples per position for each frequency band from 100Hz to 5000 Hz and transferring the vibration data to decay rates. In comparison, the pass-by method can be completely automated so that the analysis can be completed off-track within several hours for one site. The pass-by method may also more accurately replicate the relevant track conditions, capturing any change in stiffness and damping in the rail fasteners associated with the presence of the train mass. The ease of use of the pass-by method has been suggested by a previous study (Kalivoda, 2005), which suggested that pass-by measurement is more accurate than impact hammer measurement due to this inclusion of the train loading. Interestingly that study indicated that the pass-by measurement can be 5 dB/m higher than the impact hammer test measurement for a ballasted track with mono-bloc concrete sleepers.

Many studies have been conducted in which the impact hammer method was applied to tune or evaluate predicted results (Thompson, 1997; Thompson et al., 1999; Jones et al., 2006; Kitagawa and Thompson, 2010). In comparison, the pass-by method has attracted less attention in the literature. Knowledge of the application of this method is therefore limited.

The work reported here concerns attempts to utilise the pass-by method to allow some comparisons to be drawn by an operating railway between possible track forms for an upgrade project. The forms to be compared were track with timber sleepers directly fixed to a concrete viaduct and track with resilient fasteners direct-fixed to a concrete bridge deck. Results from the impact hammer tests were used to compare with the results of the pass-by method. At each site, decay rates from several different train pass-bys were measured. Vertical and lateral decay rates were also compared over a typical range of frequencies. A trial of the pass-by method on the more typical ballasted track with existing data extracted from a previous noise study was also conducted. Unfortunately no impact hammer testing was undertaken at this site. The repeatability of the pass-by method is investigated based on the results from these three measurement sites.

METHODS FOR MEASURING TRACK DECAY RATES

The impact hammer method uses the single impulse of the impact of an instrumented hammer to excite the unloaded rail at a series of points on the rail head at various distances from a fixed measurement site. By measuring the rail vertical or lateral vibration responses and the corresponding impact excitations in the same direction, the decay rate for the rail in that direction can be derived. Longitudinal rail vibration is not relevant to rail radiation and hence is not of interest to the track decay rates measurement. By further decomposing the measured rail responses into individual travelling waves through a wave-number decomposition method developed by Thompson (1997), the decay rates of each wave can be evaluated. Total rail responses have also been used directly to determine the 'total' track decay rate compounding the effects of all travelling waves. Typical application includes that used by Jones et al. (2006) and the standard impact hammer method (EN 15461:2008).

In contrast, the pass-by method uses the excitations from passing trains, while capturing the rail total vibration responses in both the vertical and lateral directions simultaneously to derive track decay rates. The typical application of this method is explored by Janssens et al. (2006).

DETAILED REVIEW OF THE PASS-BY METHOD

For the pass-by method as published by Janssens et al. (2006), the vibration of the rail is assumed to decay exponentially from the excitation point with a decaying parameter β. When a train passes across the measurement site the wheels of the train are assumed to represent independent and successive points of excitation all with similar characteristics. Track decay rates are derived based on the ratio of the vibration energy near the excitation sources, in this case the wheels, to the whole vibration energy transmitted in the rail excited by these wheels. The excitation vibration energy, denoted by A_1, is calculated by integrating the measured vibration over a finite and relatively short distance, L_1, of 1.8m centred at each wheel. The whole rail vibration energy excited by the wheels, denoted as A_2, can be calculated by integrating the measured vibration over a longer distance, L_2. The typical length L_2, corresponds to one vehicle length or possibly one train length. The positions of the wheels at a particular point in time must be known. This will typically be determined by using a wheel trigger signal. The vibration ratio is denoted as R, which is a function of β and can be expressed as:

$$R(f)=A_1/A_2=1-e^{-\beta L_1} \quad (1)$$

Where f is the central frequency of each one-third octave band. The decay rate, $D(f)$ also utilises the parameter β and is expressed as:

$$D(f)=20\, log_{10}(e^{-\beta}) \quad (2)$$

By combining Equations (1) and (2), $D(f)$ can be expressed in terms of $R(f)$ rather than β by

$$D(f)=-20/L_1\, log_{10}(1-R(f)) \quad (3)$$

It is noted that the constant of 20 in Equation 3 results from the combination of Equations 1 and 2, given the common logarithmic base (log_{10}). This is at odds with the constant of 8.686 published in error in the Janssens et al paper. That value of 8.686 may be obtained by assuming a natural logarithmic base which is clearly inconsistent with common logarithmic base (log_{10}) of the parent equations. It is not known and possibly unlikely that this error was carried through to the data analysis presented in that paper however if it is then it results in an estimation of the decay rate which is 2.3 times that using the correct value.

Decay rates are calculated for each nominal frequency band. Normally the vibration measured at a particular point on the rail will be the result of excitation by a number of wheels adjacent to that point. The influence of adjacent wheels, as suggested by Janssens et al. must be accounted for. For high decay rates, the rail vibration attenuates over a sufficiently short distance that the vibration excited by one wheel will have a negligible on the others. The effect is not negligible in the case of low decay rates. The effect is illustrated in Figure 1 where two adjacent wheels are shown. The very low decay rates lead to the vibration induced being contributed by the 2 wheels adjacent to the measurement point. Noting that decay rate is a function of vibration frequency, and denoting the measured vibration amplitude at the point when each of the adjacent wheels pass the measurement point as B_1, and B_2, and understanding that the decay rate does not vary with excitations for a site, then a value for the decay rate (β) can be obtained by iteration expressed in equations:

$$B_1' = B_1 - B_2\, e^{-\beta x} \quad (4)$$

$$B_2' = B_2 - B_1\, e^{-\beta x} \quad (5)$$

where x represents the distance between the adjacent wheels. Final values of B_1' and B_2' represent the rail vibrations excited by two independent wheels. Usually β will converge over several steps of iteration. Similarly, the effects of more than 2 wheels can also be taken into account. In this paper, four wheels on two adjacent bogies are considered except those at the head and tail of the train. For those bogies only the adjacent wheel in the bogie needs to be considered.

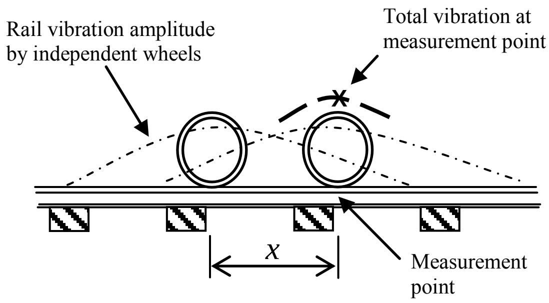

Figure 1 Illustration of the influence on rail vibration due to the interactions of adjacent wheels as one wheel passes the measurement point

A comparison between the independent wheel excitation assumption and the inclusion of adjacent wheel effects is possible using Figure 2. It indicates that for the case here the adjacent wheel contributions are significant across the frequency spectrum. The discrepancy varies between 1 and 1.5 dB/m. In the testing for the concrete viaduct (timber sleeper) site it is evident that adjacent wheels influence the result for decay rates below 5 dB/m.

MEASUREMENTS

Site description

In situ measurements of the decay rates on three forms of track were carried out. These include a normal ballasted track with concrete sleepers (rail pad stiffness approximately 1000

MN/m) on a curve of radius just below 300 m; a track with timber sleepers directly fixed to a concrete viaduct; and, a track with resilient fasteners direct-fixed to concrete slab on a continuous elastomeric bearing strip on steel girders of a bridge. Figure 3 presents the track conditions observed at the three sites. A comparison between the impact hammer and pass-by methods was made for the viaduct and bridge mounted forms only.

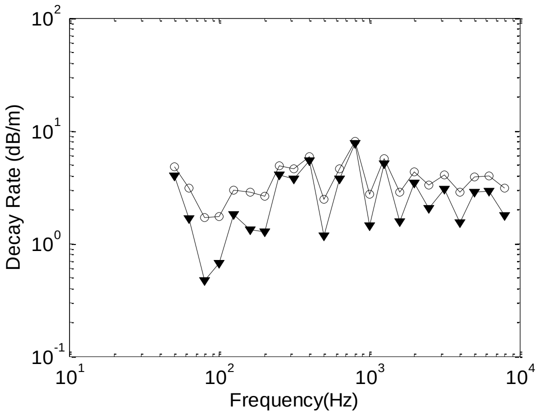

Figure 2 Comparison of indicated track decay rates for a concrete viaduct (timber sleeper) track site: (○—○) without consideration of adjacent wheels; (▼—▼) with of adjacent wheels.

(a) (b) (c)

Figure 3 Track conditions at three measurement sites (a) ballasted track on a curve (b) timber sleepers directly fixed to a concrete viaduct (c) track with resilient fasteners direct-fixed to a concrete bridge deck.

Measurement setup

To apply the impact hammer measurement technique as per EN15461:2008 vertical and lateral accelerations were measured at a fixed point on the rail while the rail was excited at more than 20 points in the range of 0 to at least 40 metres from that point. The lateral accelerations were measured on the rail head and the vertical accelerations were measured on the rail foot.

To apply the pass-by method for the viaduct and the bridge sites, accelerometers were positioned on the rail web to simultaneously measure both rail vertical and lateral vibrations. A wheel sensor was located adjacent to each accelerometer. Measurements were also made on the rail head (lateral vibration) and rail foot (vertical vibration) at one of the 3 positions and measured vibration was consistent with that measured in the rail web. This arrangement was applied at 3 locations approximately 5 metres apart, i.e. over a distance of 10 metres. This allowed the decay rate measured at these locations to be compared for each train pass-by. In the case of the ballasted track site, the data was extracted from a previous study of curving noise and only one position was measured at that time.

RESULTS AND DISCUSSION

Repeatability over different train pass-bys

One method of investigating the accuracy of the measurement system is to determine its repeatability. In this case the repeatability of the pass-by method is illustrated by comparing decay rates measured for different train pass-bys across all frequency bands. This is depicted in Figure 4 for the 3 track forms investigated. The arithmetic average value and +/- standard deviation are depicted. These were obtained from: 5 pass-bys for the viaduct, Figure 4a; 5 pass-bys for the bridge, Figure 4b; and, 4 pass-bys on the ballasted track on a curve, Figure 4c.

Overall the pass-by method is considered to have a reasonable repeatability given a standard deviation of less than 3 dB/m. However numerous one pass-bys must be measured in order to verify the result. Decay rates of the ballasted track exhibited the lowest variation for most frequencies, being less than 1 dB/m. The variation for the viaduct and bridge are higher: about 2 dB/m at 800 Hz for the viaduct and at 1600 Hz for the bridge.

Varying load conditions from train to train may explain the differences between measured decay rates. The effect of different load conditions may be significant at low frequencies according to Wu and Thompson (2000). It is likely that the damping of the rail afforded by the track support system will depend on the load applied by the train. In the case of the viaduct site, clearance between elements of the fastening system in the absence of a train was noticed. In the case of the bridge site, movement in the fastening base-plate connections to the structure was apparent when the train traversed the test section.

It is noted that at low-frequencies a decay rate of 10 dB/m is commonly found in practice for conventional ballasted track (Thompson, 2009). This results from the support stiffness at low frequencies being significantly contributed by the ballast. At relatively high frequencies the rail vibration is decoupled from that of the track support resulting in vibration propagating along the rail: i.e. resulting in lower decay rates. In contrast, the tests reported here do not exhibit this pattern. Figure 4 shows that the decay rates are unusually high at higher frequencies. There has been no measurement error identified that would result in such an apparent anomaly but of course this remains a possibility. The result may be due to the non-ballasted track structures used for the first two cases and the stiff rail pads used at the third site. Stiff pads can strengthen the coupling between the rail and the sleeper over a wide frequency range. In other words, more rail vibration energy will be dissipated to the sleeper and other support structures which will induce a higher decay rate compared with that of a rail supported on soft rail pads.

It has also been found that certain behaviours of the wheels during curving: i.e. flange contact and wheel squeal, impact on pass-by measurement accuracy. One example is shown in Figure 4c for which the data was collected in the presence of flanging or squeal. The occurrences of these events were identified manually. Underestimation of decay rates by more than 4 dB/m are evident between 250 and 800 Hz relative to the values obtained in their absence. As such, data containing such events should be ignored.

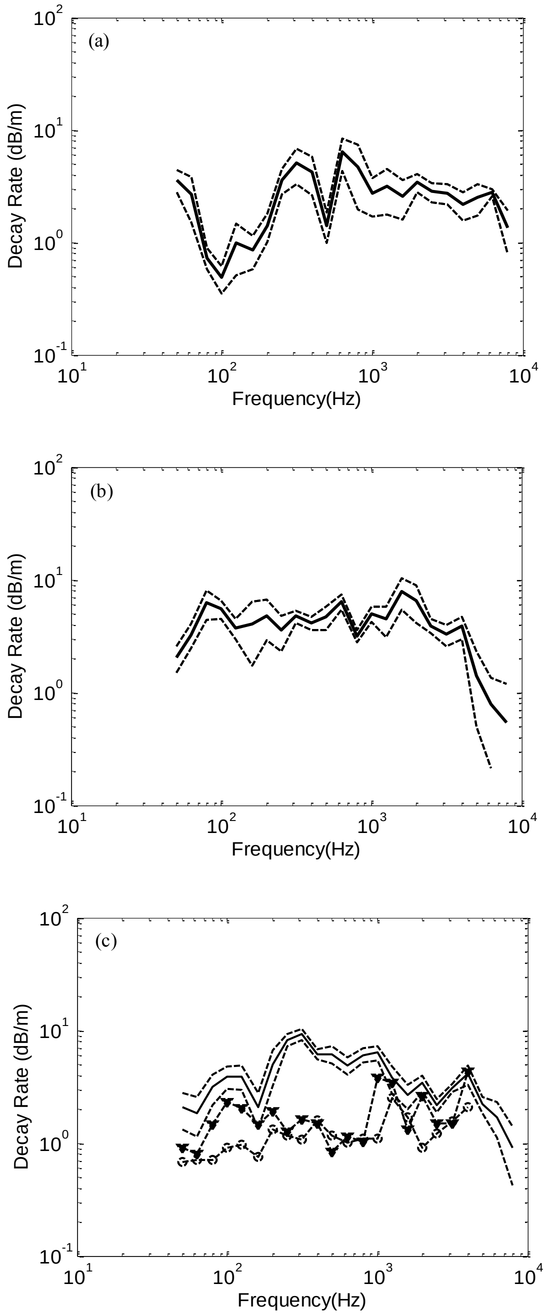

Figure 4 Vertical track decay rates measured at 3 different sites using pass-by method (a) a concrete viaduct (timber sleepers) (b) a bridge (resilient fasteners) (c) a ballast track (concrete sleepers), (——) mean; (– – –) standard deviation range. (○—○) Decay rates measured from a single passing train with flanging noise; (▼—▼) Decay rates measured from a single passing train with wheel squeal. Each mean value in (a) and (b) is averaged over 5 different train pass-bys, in (c) is averaged over 4 pass-bys.

Comparison of decay rates at a particular site

An investigation to determine the variation of decay rates measured at different positions over the same site was possible. This to some extent allows further consideration of the repeatability of the pass-by method. It does provide some evidence of the variation in measured decay rates that may be expected within the one site, depending on the extent of the consistency of the track properties at that site. It is also expected that measurement error may also account for the vibration presented in the final results.

Figure 5 shows the decay rates of a track measured at the viaduct site, Figure 5a, and at the bridge site, Figure 5b. It is evident that the decay rates measured at different positions of the same track were significantly different. This was particularly evident in the case of the bridge site. There are two basic reasons for the result: actual non-uniformity of the track properties as previously noted for the fastening system for both cases; or, a measurement error resulting in an inability to identify the vibration peaks. These peaks may be expected to occur as the wheel passes over the measurement position. However during the tests peaks sometimes occurred either between wheels or ahead of the time when the wheel passed over the accelerometer position. This uncertainty in detecting the wheel positions can significantly influence the wheel excitation energy. With the total vibration energy integrated over a distance of a whole train length unchanged, the ratio between the two energy values can vary significantly and hence the calculated decay rates. These events occurred often for measurements at the bridge site position B and C. This may account for the larger variation as shown in Figure 5b than Figure 5a. It can be inferred from Figure 5a that the track decay rates are sensitive to properties at different positions. Such variation, where it results from stiffness and damping characteristics impacted on by the presence of a train may only be observable using the pass-by method. Figure 5b may indicate the importance of accurate detections of wheel positions in the rail vibration data or the importance of an accurate alignment of a wheel sensor with the accelerometers installed at the same measurement site.

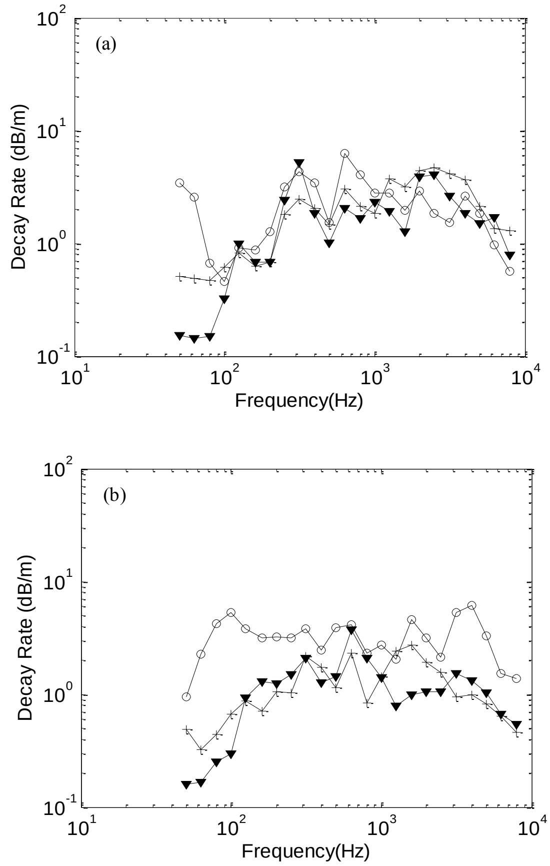

Figure 5 Vertical track decay rates measured by pass-by method at three positions on rail web with 5m spacing at the viaduct site (figure a) and the bridge site (figure b). (○—○) position A; (+—+) position B; (▼—▼) position C.

Vertical and lateral track decay rates

By measuring vertical and lateral decay rates, noise performance of the rail in those two directions can be evaluated. Figure 6 shows the vertical and lateral decay rates measured for the viaduct site averaged over 5 different train pass-bys. The web lateral vibration is used to calculate the lateral track decay rates and the rail foot vertical vibration is used to calculate the vertical track decay rates. The decay rates for the two directions are similar at low frequency: below 500 Hz. Between 500 and 8000 Hz the lateral decay rates are lower than the vertical decay rates. This indicates that rail lateral vibration may radiate more noise than vertical vibration at high frequencies.

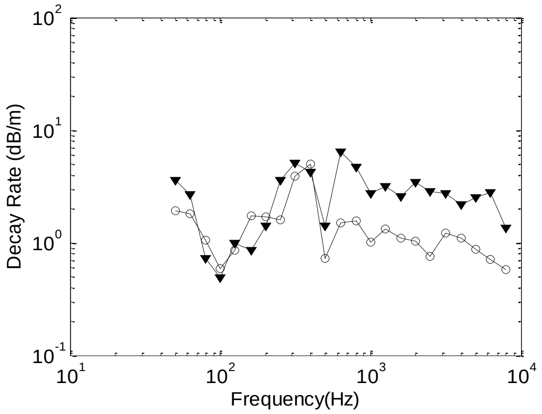

Figure 6 Vertical and lateral track decay rates measured at the viaduct site by pass-by method. (○—○) lateral decay rate; (▼—▼) vertical decay rate.

Comparison of impact hammer and pass-by methods

It is noted that the track conditions for the viaduct and bridge sites are not among those suggested by EN 15461:2008 for the application of impact hammer method. According to that standard tracks with the load-bearing structures should be avoided when measuring track decay rate. Nevertheless the impact hammer test would appear to offer a more controlled and accurately known excitation source, providing a source of calibration for the pass-by method. One significant difference in the two tests, as previously noted, is the absence of a load on the track in the case of the standard impact hammer test procedure.

Figure 7a shows the results for the viaduct site, and Figure 7b the results for the bridge site. The measurements are averaged over 5 train pass-bys from the same pass-bys used for the results presented in Figure 4. In Figure 7, results from the two methods for both sites have a large variation for most of the frequencies. For the viaduct site, Figure 7a, decay rates measured using the impact hammer method exceed the pass-by measurement below 200Hz and between 2000 and 3000 Hz. In the case of the bridge, Figure 7b, this occurs from 1500 Hz and upwards. A significant divergence can be noticed at 5000 Hz, Figure 7b, which is unusual as waves normally propagate freely at this frequency: i.e. lower decay rates are expected. There is some evidence that this may be due to the resonance of the accelerometer on the large magnet used for the experiment. The observations for the viaduct may be indicative of the large variability in how well the rail is fastened to the timber sleeper as previously noted. The non-uniformity of rail contact with the fastenings may have significantly influenced the measurements of impact hammer tests relative to the pass-by method, specifically due to the influence of the train's load on the contact between the fastening elements. Janssens et al. (2006) found consistency between the two methods, less than 2 dB/m variation, with the pass-by measurement tending to give higher indicated decay rates at frequency from 200 to 800 Hz. This is apparently not the case for the results presented here.

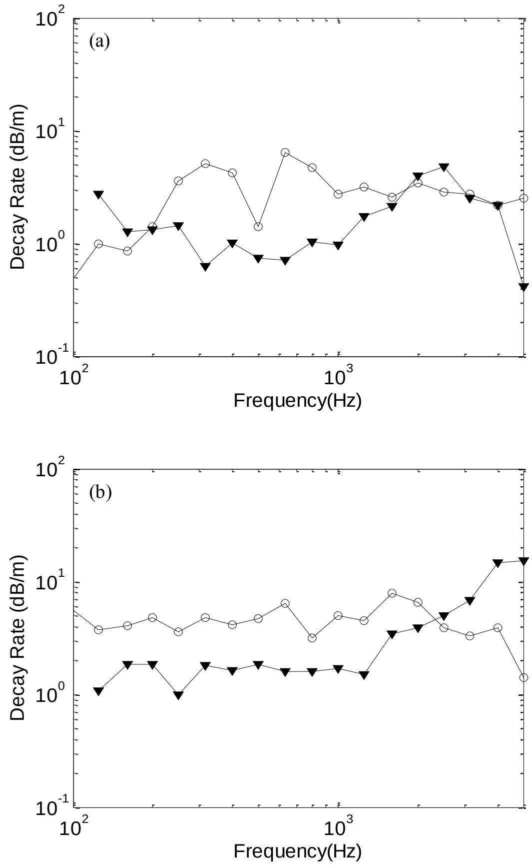

Figure 7 Vertical track decay rates measured from the viaduct site (figure a) and the bridge site (figure b). (○—○) by pass-by method; (▼——▼) by impact hammer method.

CONCLUSION

The general finding from the application of the pass-by method are:

1. Relative to the impact hammer method, the application of the pass-by method requires less time on track and the data processing can be automated and therefore very effective.

2. The pass-by method provided reasonably consistent results over different train pass-bys. A standard deviation of less than 3 dB/m in each frequency band was achieved for these tests.

3. The influence of adjacent wheels should be taken into account when the pass-by method is to be used. If this is done then accurate results can be obtained. Despite this, some averaging of results over several train pass-bys may be necessary to improve the result.

4. Decay rates may vary significantly depending on the exact measurement position within one apparently homogenous site having a consistent track configuration. This may be correlated with the consistency of the track condition at that site. Other influences such as meas-

urement error may also account for the variations of the measured decay rates at different positions.

5. Track decay rates measured using the pass-by method when flange contact and wheel squeal occurs may not be accurate. The data are not suitable for determining track decay rates.

6. The pass-by method relies on the accurate detection of rail vibration peaks corresponding to the moment when each wheel passes the measurement point. It was found that the peak may not always correspond to the instant the wheel passes the measurement site. Careful installation of the wheel sensors to ensure a good alignment with the accelerometers at a measurement position is required.

7. In addition to the cost, the application of the impact hammer method on tracks without uniform properties along the test section may not provide accurate results. The pass-by method may better allow this variation to be detected.

Future work required includes:

1. Verification of the effect of the presence of a train on the impact hammer test results and more importantly on the actual track decay rate is required.

2. A further comparison of the impact hammer and pass-by methods on more conventional track forms in standard condition is required.

ACKNOWLEDGEMENTS

This work is being conducted under CRC for Rail Innovations Project R1-128 Improved Rail Noise Management. The authors are grateful to the CRC for Rail Innovation (established and supported under the Australian Government's Cooperative Research Centres program) for the funding of the research. Thanks are also given to RailCorp for collaborating in the field trials and approving the use of the data to publish this paper. The first author also gives thanks to AAS NSW Division for supporting his travelling fees.

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