Improved methods for the separation of track and wheel noise components during a train pass-by

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Abstract. Experimental techniques are described that aim to allow the wheel and track components of rolling noise to be separated from pass-by measurements. These are based on Advanced Transfer Path Analysis, Pass-by Analysis, and a method based on the TWINS model. Improvements to these methods and their experimental validation using field tests are described. Initial comparisons are made for two test cases, a metro train running at 60 km/h and a regional train running at 80 km/h. The three methods agree reasonably well in terms of overall trends. The largest differences are found at low frequencies where the two experimental methods give similar levels for sleeper and rail vertical components whereas the TWINS model gives a larger distinction between them.

Keywords: Rolling Noise, Source Separation, Pass-by Tests.

1 Introduction

Mainline trains in Europe must satisfy noise certification tests defined in the Technical Specification for Interoperability (TSI) Noise [1] and ISO 3095 [2]. The need to carry out the tests on a compliant track (with low roughness and high track decay rate) poses very restrictive limitations on the tracks that can be used, complicating the certification process in terms of time and costs. This requirement could be relaxed or even eliminated if the track and vehicle contributions could be identified separately.

In the previous project Roll2Rail, experimental techniques to obtain the contributions of vehicle and track to rolling noise were developed and assessed [3]. The most promising techniques for quantifying the track component were Advanced Transfer Path Analysis (ATPA), Pass-by Analysis (PBA), and a method based on the TWINS model. For the wheel component, however, none of the methods tested (PBA-based methods or beamforming) achieved sufficient accuracy compared with a TWINS-based method. This paper describes improvements to these methods and their experimental validation using field tests. The aim is to separate the track from the wheel contributions, and if possible to separate the track into rail vertical, rail lateral and sleeper components. The frequency range should be extended to cover 100-8000 Hz.

2 Separation methods

2.1 Method based on Pass-by Analysis

The PBA method [4] uses accelerometers on the rail and a microphone at the trackside to separate the total equivalent roughness excitation from the roughness-to-noise transfer function. Track decay rates are also extracted. This method is enhanced in the current work by the addition of measurements of static vehicle and track transfer functions. For these, reciprocal measurements are preferred. Whereas in the direct method, the track or wheel is excited by an impact hammer and the pressure at the wayside microphone position is measured together with the force (see Fig. 1(a)), in the reciprocal method a sound source of known volume velocity is placed at the microphone position (see Fig. 1(b)) and the resulting vibration is measured. Both methods yield a transfer function of the form p/F, where p is pressure at the receiver and F is force. They are then converted to the form p/r, where r is the roughness spectrum and the index i indicates vertical or lateral directions:

$$\left(\frac{p}{r}\right)_i = \left(\frac{p}{F}\right)_i \times \frac{F_i}{r} \tag{1}$$

(a)

(b)

Fig. 1. Experimental set-up. (a) Impact measurements on the track; (b) sound sources used for reciprocal measurements.

where the force per unit roughness F/r is obtained from a TWINS model. The vertical and lateral interaction forces are obtained separately and applied to the corresponding p/F transfer functions. An estimate of the force acting on the sleeper is derived from the ratio of the response of the sleeper and the rail to a force acting on the rail. More details are given in [5]. Both wheel and track radiation can be estimated if their p/F transfer functions have been measured; however, for the wheel it is important that the damping is at a similar level to a rolling wheel, as the use of undamped transfer functions would lead to an overestimate. Ideally, the transfer functions should be measured with the wheel lifted slightly so it is not in contact with the rail.

2.2 Advanced Transfer Path Analysis method

The ATPA method [6] is based on extensive transfer function measurements of the track, preferably with the vehicle present; these are combined with operational measurements of noise and track accelerations. The transfer functions take the form of transmissibilities (ratios of acceleration at different points) so there is no need to measure the applied force. A matrix operation allows the 'direct transfer functions' $T^D_{k\to M}$ to be obtained which express the sound pressure at a receiver point M due to vibration in one 'sub-system' k when the response of all other 'sub-systems' is blocked [6]. There is no need to lift the wheel from the track. By combining these direct transfer functions with the measured acceleration spectra during the train passage a_k, the total noise at location M can be decomposed into the components associated with each sub-system

$$p_M = \sum_{k=1}^{N} a_k T^D_{k\to M} \tag{2}$$

2.3 TWINS-based method

The TWINS model [7] is a series of engineering models for rolling noise that has been validated against extensive field experiments. It can be used to identify the separate wheel and track components. Moreover, as the parts of the model used to calculate the noise radiation are considered to be more reliable than the vibration prediction [8], the uncertainty in the estimates can be reduced by combining the model with vibration measurements obtained during a train pass-by. In the present work, updated models of the track radiation have also been introduced [9] and the effect of the vehicle on the sound radiation from the rail is included using boundary element models [5,10].

To apply TWINS to source separation involves the following steps [3]: (1) The input parameters for the track are chosen to give the best possible fit to static measurements of track mobility and decay rate; the natural frequencies and damping of the wheels are measured and used to ensure good agreement with a finite element model of the wheel. The wheel and rail roughness spectra are also measured directly. Measured decay rates are used in the predictions. (2) The predicted rail and sleeper vibration is compared with measurements during train passages and the predicted noise from each component is adjusted in accordance with the difference between them. It is important that none of these adjustments is too large, i.e. that the TWINS model gives as good an agreement as possible with the measurements of vibration and noise before applying any adjustments. This requires experience and engineering judgement.

As both test sites (see below) were fitted with stiff rail pads it was found to be necessary to use a discretely supported track model in the TWINS calculations. The average over five contact positions within half a sleeper span is used to estimate the noise during the train passage.

3 Field tests

Field measurements are used to verify and compare the methods. Selected results are presented here from two campaigns. The first is on a metro train running at 60 km/h on a metre gauge line in Northern Spain. The second is on a regional train running at 80 km/h at a test site at Velim in the Czech Republic; this site was fitted with rail dampers, visible in Fig. 1. In both cases the measurements focus on unpowered bogies for which the noise was dominated by rolling noise. Results are determined as the average over the passage of two half-vehicles with the test bogies at the centre.

Rail roughness and track decay rates were measured at each test site using standard direct methods. Wheel roughness of the test bogies was also measured and modal identification of the wheels was carried out to verify the finite element modelling used in TWINS. Rail and sleeper accelerations and pass-by noise were measured during train passages. The various transfer functions described above were obtained, both with and without the train present. Wheel and track transfer functions were obtained with the wheels resting on the track as it was not permitted to jack the vehicle up on site. This had an adverse effect on the PBA wheel estimates.

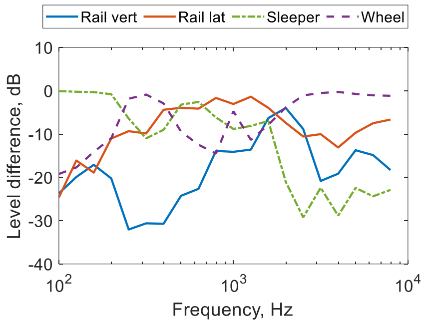
4 Results

The results are presented in the form of the components of noise from the track and wheel vibration relative to the total noise. In most cases the microphone position was at 7.5 m from the track centre and 1.2 m above the rail head. However, for the ATPA method the estimates are based on measurements at 3.5 m from the track and 0.5 m above the rail head as the transfer functions at 7.5 m were affected by background noise especially at low frequency.

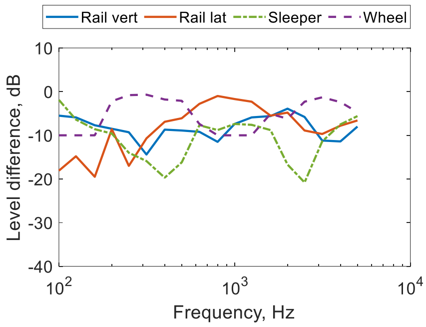
4.1 Site 1: metro train at 60 km/h

At the first test site, the transfer function measurements required for PBA separation were not carried out, so results are only shown here for ATPA and TWINS. Moreover, the instrumentation used for ATPA only allowed a maximum frequency of 5000 Hz at this site. Fig. 2 shows the contributions of each component (rail vertical, lateral, sleeper and wheel) relative to the overall noise spectrum obtained from these two methods.

As typically found [7,8], the TWINS results indicate that the noise is dominated by the sleepers at low frequencies, the rail in the mid-frequency region and the wheel at high frequencies. Due to the stiff rail pads, the vertical track decay rate is high and consequently the contribution from the vertical vibration is small below 1000 Hz; the lateral contribution is larger for frequencies up to 1600 Hz. The stiff pads also mean that the sleeper is strongly coupled to the rail over a wide frequency range and, due to its larger area, it radiates significant noise up to 1600 Hz.



(a)



(b)

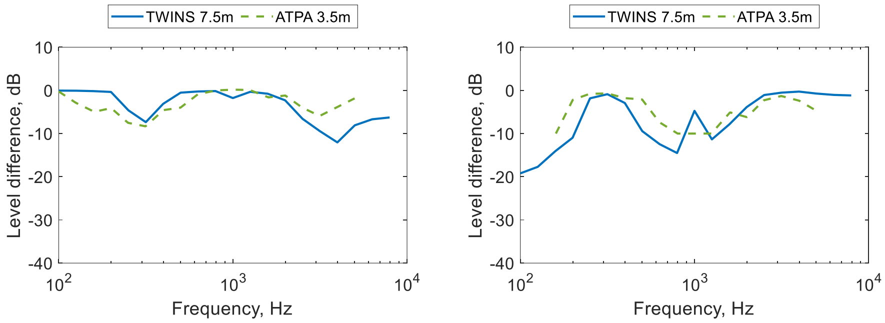
Fig. 2. Source contributions for site 1. (a) TWINS-based method; (b) ATPA method.

The ATPA results show similar trends, especially for the lateral rail contribution. The wheel contribution is estimated by ‘subtraction’ (the difference between the measured total and the sum of the reconstructed components) which is known to be a less reliable method; nevertheless, it agrees reasonably well with the TWINS estimate. Results below -10 dB have been capped at this level. The main difference compared with TWINS is seen at low frequencies, where the sleeper contribution is up to 10 dB smaller than the TWINS estimate and the rail vertical contribution is 15-20 dB larger than that from TWINS. These two components are strongly coupled together by the stiff rail pads and it appears that the experimental method cannot easily separate them with the current test setup. At high frequencies both rail components are larger than the results from TWINS. The larger contribution from the rail was also found in [3] and is believed to be due to the neglect of rail cross-sectional deformation in the TWINS model.

The estimates of the total noise contributions radiated by the track and wheel are compared in Fig. 3. Generally good agreement is seen between the two methods.

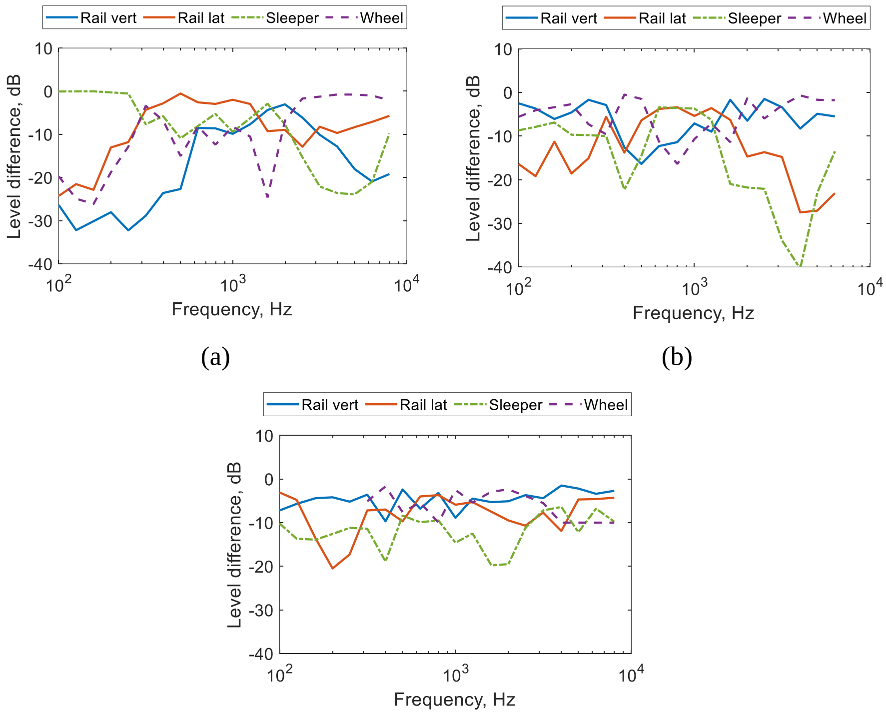
4.2 Site 2: regional train at 80 km/h

For test site 2, Fig. 4 shows the contributions of each component relative to the overall noise spectrum. The overall trends from the TWINS model in Fig. 4(a) are similar to those in Fig. 2(a) for the first site. This site again has stiff rail pads and additionally is fitted with rail dampers. The sleeper noise is dominant up to 250 Hz and remains important up to 2 kHz. Of the rail components, the lateral direction is more important up to 1250 Hz and the vertical direction for 1600-2500 Hz. The wheel is mainly important above 2 kHz.



(a) (b)

Fig. 3. Source contributions for site 1. (a) Track component; (b) wheel component.



(c)

Fig. 4. Source contributions for site 2. (a) TWINS-based method; (b) PBA method; (c) ATPA method.

The PBA method gives similar trends except that the sleeper component is lower at low frequency and the rail vertical component is higher at both low and high frequencies. As for site 1 these trends are also found with the ATPA method. The wheel noise estimate from ATPA is not shown below 250 Hz as the transfer function measurements were less reliable at these frequencies due to low signal to noise ratio.

The total noise spectra for the track are compared in Fig. 5(a) and for the wheel in Fig. 5(b). These show generally good agreement apart from below 250 Hz, where the wheel contribution predicted by TWINS is much lower than PBA (possibly because the wheel could not be lifted). Above 4 kHz the ATPA method gives a much higher track noise estimate and hence a lower wheel noise estimate than the other methods.

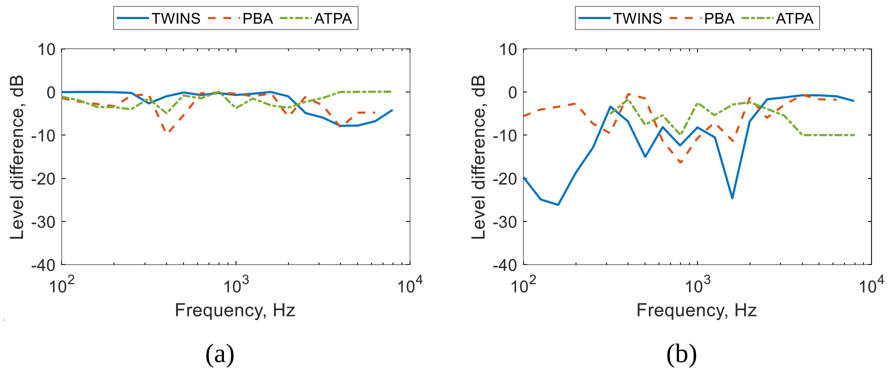


Fig. 5. Source contributions for site 2. (a) Track component; (b) Wheel component.

The contributions of each source to the overall A-weighted sound level are shown in Fig. 6. The two methods used at site 1, TWINS and ATPA, agree well apart from the higher rail vertical and lower sleeper found by ATPA. This trend is found again for site 2 but with larger differences. PBA and TWINS results mostly agree quite well.

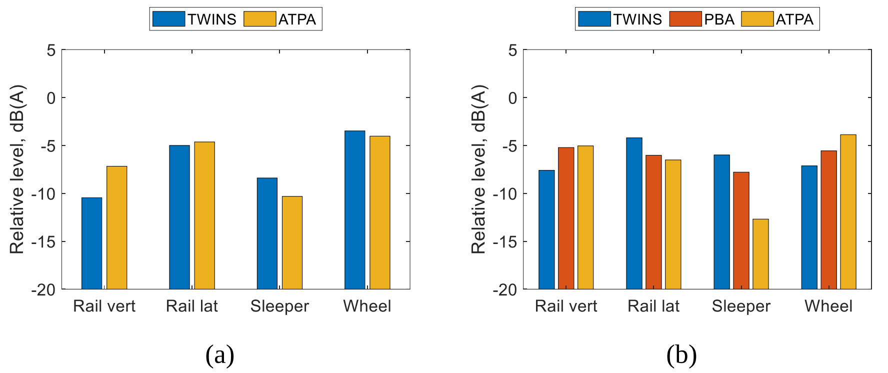


Fig. 6. Source contributions in terms of overall A-weighted level. (a) For site 1; (b) for site 2.

5 Discussion and conclusions

Three methods for separating components of rolling noise during train pass-bys have been compared. ATPA is a purely experimental method, the TWINS-based method is based on theoretical models and the PBA-method, although experimental, relies on the TWINS framework to some extent. The three methods agree reasonably well in terms of overall trends. The largest differences are found at low frequencies where the two experimental methods give similar levels for sleeper and rail vertical components whereas the TWINS model gives a larger distinction between them.

Further development and analysis are continuing to understand reasons for differences. Various possible simplifications will be considered, e.g. in the numbers of measurement transducers and static measurements required for the ATPA method.

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