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Assessment of measurement-based methods for separating wheel and track contributions to railway rolling noise

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ABSTRACT

The noise produced during a train pass-by originates from several different sources such as propulsion noise, noise from auxiliary equipment, aerodynamic noise and rolling noise. The rolling noise is radiated by the wheels and the track and is excited by the wheel and rail unevenness, usually referred to as roughness. The current TSI Noise certification method, which must be satisfied by all new mainline trains in Europe, relies on the use of a reference track to quantify the noise from new vehicles. The reference track is defined by an upper limit of the rail roughness and a lower limit of the track decay rate (TDR). However, since neither the rail roughness nor the track radiation can be completely neglected, the result cannot be taken as representing only the vehicle noise and the measurement does not allow separate identification of the noise radiated by wheel and track. It is even likely that further reductions in the limit values for new rolling stock cannot be achieved on current tracks. There is therefore a need for a method to separate the noise into these two components reliably and cheaply. The purpose of the current study is to assess existing and new methods for rolling noise separation. Field tests have been carried out under controlled conditions, allowing the different methods to be compared. The TWINS model is used with measured vibration data to give reference estimates of the wheel and track noise components. Six different methods are then considered that can be used to estimate the track component. It is found that most of these methods can obtain the track component of noise with acceptable accuracy. However, apart from the TWINS model, the wheel noise component could only be estimated directly using three methods and unfortunately these did not give satisfactory results in the current tests.

1. Introduction

Railway noise originates from several different sources such as propulsion noise, noise from auxiliary equipment, aerodynamic noise at high speeds and rolling noise. The rolling noise is radiated by the vibration of the wheels and the track and is excited by the combined wheel and rail unevenness, usually referred to as roughness [1]. A high level of roughness in combination with low damping of wheel and rail leads to high levels of rolling noise. This noise source is considered to be dominant for train speeds up to more than 300 km/h [2]. In efforts to reduce rolling noise by improved design and to quantify it in relation to vehicle certification, a key question is related to the separation of the noise radiated by the wheel from that radiated by the track. Without such a separation, certification tests can be influenced by the track

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properties and do not only measure the vehicle noise. Moreover, improved designs of vehicle or track may not be properly assessed if the vehicle contribution to the noise is masked by the track.

The current certification tests defined in the Technical Specification for Interoperability (TSI) Noise [3] and ISO 3095 [4], which must be satisfied by all new mainline trains in Europe, rely on the use of a reference track to quantify the noise from new vehicles. The reference track is defined by an upper limit of the rail roughness and a lower limit of the track decay rate (TDR) which are intended to minimise the influence of the track on the measurement. However, since neither influence of the rail roughness nor the contribution from the track radiation can be completely neglected in such a test, the result cannot be taken as representing only the vehicle noise and the measurement does not allow separate identification of wheel and track noise contributions.

Current understanding of railway rolling noise is largely based on the theoretical work of Remington [5,6] and Thompson [1,7]. This has been implemented in the TWINS model [8], which is a prediction tool, developed on behalf of the European railways (ERRI) in the 1990s. It takes a roughness spectrum as the input and uses the dynamic properties of the wheel (from a finite element model) and the track (from an analytical model) to calculate their dynamic interaction. Sound radiation is calculated from the vibration of wheel, rail and sleeper. Validation measurements [8–10] have shown that the model can predict the overall noise level to within ± 2 dB and the result in any one-third octave band to within about ± 5 dB. However, this uncertainty was largely attributed to uncertainty in the inputs, particularly the roughness. The division into wheel and track components was also verified by means of intermediate vibration measurements. The estimates of radiated sound due to wheel and track vibration were found to be reliable to within about ± 2 dB in any one-third octave band provided that wheel and rail vibration measurements are available. Although TWINS can be considered to be an accurate separation method, the emphasis in the present work is on developing a method that is experimentally based and therefore less reliant on expertise in using the models. Moreover, it should not require measurements on the vehicle such as wheel vibration but should be possible to execute from the trackside.

The roughness of the wheels and rails can be measured directly [11,12]. For the TSI and ISO test procedure [3,4] it is required to measure the rail roughness of the test site. However, measurements of wheel roughness are not required and would add considerable extra effort. An alternative is provided by the Pass-by Analysis method (PBA) which uses rail vibration measurements to extract the track decay rate, the combined effective roughness and the total transfer function from roughness to noise [13–15]. The PBA method does not directly separate wheel and track contributions although it can form the basis for separation methods, as described later in this paper.

Several experimental methods for performing this separation have been proposed and tested in previous work with varying results. Different levels of rolling noise separation were defined within the STAIRRS project [13]. Level 0 indicates that no separation is achieved; only overall noise levels are obtained. Level 1 separation provides the wheel and track sound pressure levels in a given situation. Level 2 separation provides the wheel and rail roughness as well as the vehicle and track transfer functions. Level 3 separation is intended to provide all necessary data to assess the complete vehicle and track interactions. This would normally only be required if the vehicle or track are non-standard, for example with resilient wheels.

Various types of acoustic transfer functions can be determined for the track and the vehicle separately by using measurements on a stationary vehicle and track. In particular, transfer functions from contact force to sound pressure can be measured directly using an instrumented hammer impacting on the wheel or rail surface or reciprocally by using a loudspeaker near the track [16]. The latter is preferred as it can overcome potential problems of poor coherence in direct measurements using an impact hammer. For the track transfer function, ideally the vehicle should be present but dynamically decoupled from the track, which is difficult to achieve. For the wheel measurement the vehicle should again be decoupled from the track but some artificial damping should be introduced to simulate the ‘rolling damping’ present during running. In order to use these transfer functions to obtain the vehicle and track noise contributions from a moving vehicle, they have to be converted into transfer functions from combined roughness to sound pressure. To achieve this some correction functions were derived in the STAIRRS project based on the TWINS model [13]. The results are used with measurements of the combined wheel and rail roughness to determine the track and vehicle contributions to the rolling noise.

Another method developed in the STAIRRS project is called the MISO method (Multiple Input Single Output separation method) [17]. This was based on simultaneous measurements of the sound pressure and track vibration during the train pass-by. The vibroacoustic Frequency Response Functions (FRFs) between the track vibration signals and the sound pressure at a close microphone were determined using the parts of the signals corresponding to the middle of the vehicles. These were combined with the vibration measured over the whole pass-by to estimate the track contribution. The result could then be transposed to the standard microphone position using geometrical attenuation.

A ‘reference vehicle’ method was proposed and tested in the METARAIL project [18,19] and further investigated in the STAIRRS project [13]. The principle was to measure the sound pressure level and rail vertical vibration level during the passage of a quiet vehicle with only rolling noise sources and relatively quiet wheels. These measurements were used to estimate a transfer function for the track by assuming that the vehicle contribution is negligible. The test vehicle was then measured in the same way. The track contribution was determined from the rail vibration during the passage of the test vehicle and the previously determined track transfer function. Some experience was gained with this method using wagons with bogie-mounted shields [18]. These reference vehicles were not ideal, however, as the shielding also reduced the track noise contribution. Vehicles with small wheels were used in Ref. [13].

In a similar way, the use of a reference track method could be envisaged to determine the vehicle contribution. However, even for a quiet TSI-compliant track, the track contribution usually exceeds the vehicle one over a large part of the frequency range. No current track design is known that would be suitable for such a method.

Microphone arrays with beamforming [20] have been used since the 1980s to locate sources on a moving train, with the main application being aerodynamic sources [21,22]. The steering of the array should follow the moving source and the Doppler shift should be removed from the signals, for example by resampling [23]. The spatial resolution depends on the frequency, with the width (aperture) of the main lobe in the array pattern depending on the ratio of the acoustic wavelength to the array size. Thus at low frequencies large arrays are required and it becomes difficult to separate sources that are close together. Conversely at high frequencies the results can be subject to spatial aliasing leading to ghost images.

Some attempts have been made to use microphone arrays to study rolling noise [24,25]. However, a common feature of these measurements is that the wheel noise is found to be prominent. Although this may be the case in the situations considered, Kitagawa and Thompson [26] indicated that the assumption of a distribution of uncorrelated point sources in beamforming processing is not appropriate for the rail, which is a distributed source radiating at a certain angle with respect to the normal. If the array is focused mainly in a direction normal to the rail it is expected that this will suppress the rail contribution [26]. This is considered in the present paper as the basis of a new method to identify the wheel contribution.

The purpose of the study presented here is to assess existing and new methods for rolling noise separation. Dedicated field tests have been carried out under controlled conditions allowing the different methods to be compared. The principle of wheel and track separation is