Simplified wave signature extraction method for rail contribution estimations

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Summary
The present paper investigates a modified implementation of the wave signature extraction (WSE) method [1], whose aim is to separate the rail contribution to the pass-by noise of railway vehicles. The method requires a line microphone array parallel to the rail, and two accelerometers on the rail in the vertical and lateral direction. The motivation for this work is the need to separate the rail contribution to the pass-by noise of railway vehicles. The WSE method [1] is based on the wavenumber domain filtering of pass-by data measured with a microphone array located in the near-field of the rail. The filter design does not require a priori information of the structural properties of the rail, since the required information is obtained from array pressure data and rail vibration data before and after the train passes in front of the array. The filter is such that it extracts the dispersion plot branches of the first family of horizontal and vertical bending waves (moving band-pass filter). Although the comparison with TWINS simulation data provides very promising results, there are discrepancies at the higher frequencies, possibly due to the onset of new bending wave families. Therefore in the present paper we assess the performance of a simplified WSE method, where a moving low-pass filter is used instead, and the results are compared to the original WSE implementation and the TWINS simulation data. We show that the results in the higher frequency range are improved with respect to the original WSE implementation.

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1. Introduction

The pass-by noise radiated by European rail-bound vehicles is limited to specific sound levels by the technical specification for interoperability (TSI) NOISE [2]. Because the legislation requires the quantification of sound level spectra of the vehicle alone, the measurements are preferably performed on so-called "silent tracks", such that the noise radiated by the rail can be neglected. For arbitrary tracks, and for train speeds of up to 300 km/h, the rail can be the most dominant source of noise in the frequency range between 500 Hz and 1600 Hz [3, 4]. Thus, to the end of making the measurements on arbitrary tracks, the problem of separating vehicle and track noise contributions has become a subject of considerable inquiry.

For example, the TWINS method calculates these noise components by measuring track and wheel roughnesses as well as track decay rate [5, 6]. Beamforming arrays steered towards the rail radiation angles, with both one and two dimensional geometries, have been used to extract the rail contribution [7, 8, 3, 9], although typically underestimating the rail contribution by 10 dB or more. One more application of microphone arrays is the SWEAM method [10], which aims at finding the bending wavenumbers and decay rates of the propagating waves of the rail by means of solving an inverse problem via a least-squares criterion.

In addition to these applications, Zea *et al.* have recently introduced the wave signature extraction (WSE) method [1]. This method aims at separating the rail contribution to the pass-by via wavenumber filtering of microphone array data. WSE requires a linear microphone array and two accelerometers. However, the application of the WSE method is limited to identifying and separating *at most* one bending wave per excitation direction (vertical and lateral); thus, the rail contribution can be underestimated by almost 5 dB in the frequency range above which more than one wave per direction is excited –e.g. above 1.5 kHz in [1]. With the hope of improving the accuracy of the estimations, the central purpose of this paper is then to explore a different filtering procedure that potentially accounts for any arbitrary number of bending waves.

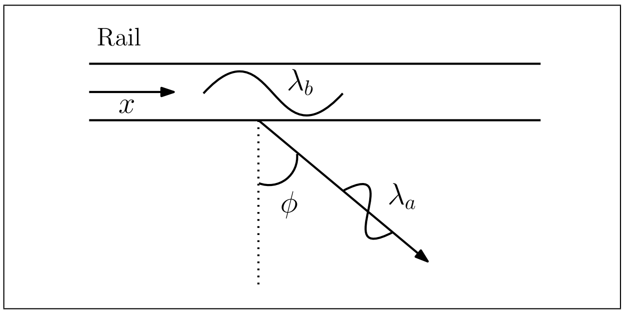

Figure 1. (Top view) Rail sound radiation. Plane waves are radiated with angle ϕ, determined by the ratio between the length of the acoustic wave and that of the bending wave, λ_a and λ_b respectively.

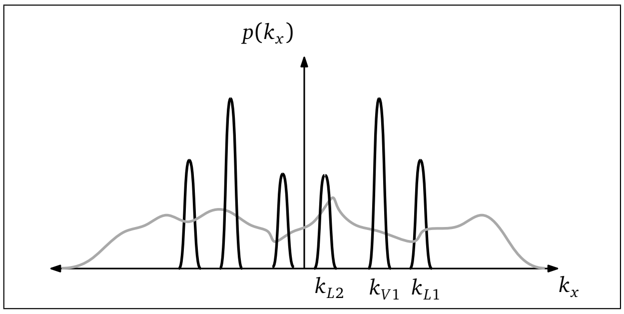

Figure 2. Illustration of pressure wavenumber spectrum of train pass-by noise at some frequency above 1.5 kHz.

2. Rail sound radiation

The cut-on of the waves that propagate freely in the rail determines its frequency-space radiation behaviour. Normally, the rail behaves as a compact source at frequencies below 500 Hz, and most of the radiation is concentrated in the contact region between the rail and the wheel [11]. Above 500 Hz the first wave families cut-on and the rail behaves as a spatially distributed source, radiating plane waves at an angle ϕ to the normal of the rail longitudinal axis [11]. This can be observed in Figure 1.

Due to the plane wave nature of the rail sound radiation, the wavenumber spectrum of a microphone array measurement is likely to show narrowband peaks situated at the bending wavenumbers of the aforementioned wave families. In Figure 2, a hypothetical illustration of this situation is shown, where k_{V1} is the wavenumber of the first-order vertical bending wave, k_{L1} and k_{L2} are the wavenumbers of the first- and second-order lateral bending waves, respectively. Particularly, it has been found in the study by Zea *et al.* that a lateral web bending mode k_{L2} cuts on at around 1.5 kHz [12, 1]. On the other hand, how broad these peaks are is related to the decay rate of the waves in the spatial domain: a high decay rate implies a broader peak.

The significance of the above statements is that band-pass filters can in principle be designed to extract the rail contribution, according to the bending wavenumbers of the rail k_{V1}, k_{L1} and k_{L2}. However, since the optimization problem of estimating the bending wavenumbers is convex *only if* there is at most one wave per excitation direction [1], there is no theoretical guarantee that the wavenumber k_{L2} can be estimated.

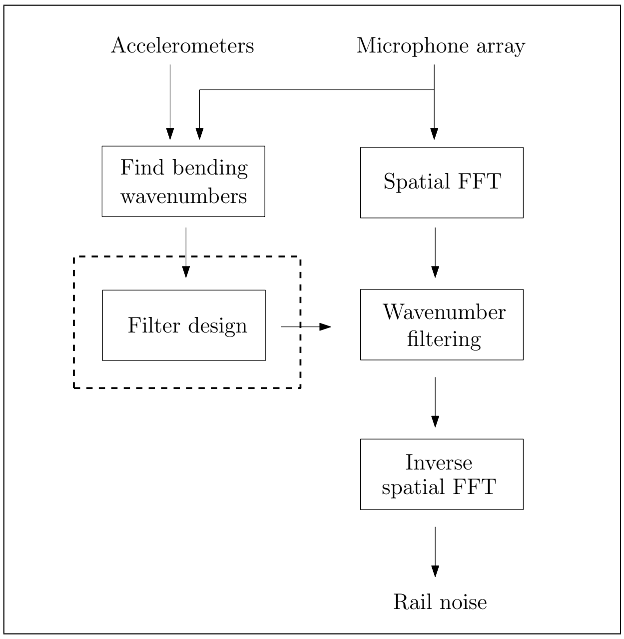

Figure 3. Block diagram of the WSE method at a given time iteration.

3. WSE

This section provides an overview of the WSE method with emphasis on the filter design (see Figure 3). The interested reader is encouraged to inquire further details in the reference [1]. The WSE method applies filters to wavenumber spectra of line microphone array measurements of a pass-by event. These filters are tuned to the bending wavenumbers of the first-order vertical and lateral bending wave (k_{V1} and k_{L1} in Figure 2), where the latter are estimated by means of recording the array pressure and vibration data from two accelerometers before and after the pass-by [1]. The input data in Figure 3 is locally stationary, filtered in 1/3 octave bands, and the analysis is iterated in overlapping time blocks until the desired analysis time window is completed [1].

3.1. Modified filtering

Instead of the two band-pass filters applied in the WSE method [1], this paper investigates the application of a single low-pass filter, with a bandwidth related to the largest bending wavenumber of the rail: first-order lateral wave (L1). The filter family adopted is that of infinite impulse responses, of order 30, and with a cut-off wavenumber defined as $k_{co} = k_{L1} + \zeta$ rad/m, where the value $\zeta = 3.5$ rad/m has been found empirically. This value might be understood as half the bandwidth of the peak situated at k_{L1}. (C.f. with the filters' order of four and pass-bands $2\zeta = 1.5$ and 2.5 rad/m in [1].) Figure 4 shows the power in dB of the WSE and modified WSE filters. The band-pass functions V1 and L1 are applied in the original WSE construction, whilst the low-pass is applied in the modified WSE approach.

Zero-phase filtering is performed such that the spatial phase of the measured sound field is preserved. In mathematical terms, the filter output at a given sub-frequency Υ_b in the 1/3 octave band reads

$$\mathbf{p}_{\mathrm{F}}(\mathbf{x}, \Upsilon_b) = \mathbf{Q}^H \mathbf{F}^H \mathbf{F} \mathbf{Q} \mathbf{W} \mathbf{p}_{\mathrm{meas}}(\mathbf{x}, \Upsilon_b), \qquad (1)$$

where $\mathbf{x} \in \mathbb{R}^M$ is the vector containing the spatial positions of the M microphones, $\mathbf{Q} \in \mathbb{C}^{M\mathrm{x}M}$ is the 1D discrete Fourier transform matrix, $\mathbf{F} \in \mathbb{C}^{M\mathrm{x}M}$ is a diagonal matrix with the wavenumber–domain coefficients of the low-pass filter, $\mathbf{W} \in \mathbb{R}^{M\mathrm{x}M}$ is a diagonal matrix with a Tukey window in its elements, and superscript H denotes the Hermitian matrix transpose. The column vector $\mathbf{p}_{\mathrm{meas}}(\mathbf{x}, \Upsilon_b) \in \mathbb{C}^M$ contains the measured sound field at the sub-frequency Υ_b. Do note that, in general, this sound field is first extrapolated from N to $M > N$ positions with the aim of having a finer wavenumber spacing.

Then, the rail contribution to the sound pressure level, in the full 1/3 octave band $\boldsymbol{\Upsilon} \in \mathbb{R}^B$ centered at f_c, and at a given microphone position $x \subset \mathbf{x}$, gives

$$\mathrm{SPL}_{\mathrm{rail}}(x, f_c) = 20\log_{10}\left[\frac{\|\mathbf{p}_{\mathrm{F}}(x, \boldsymbol{\Upsilon})\|}{\mathrm{p}_{\mathrm{ref}}}\right] + \\ + 20\log_{10}\frac{\delta_f}{\pi B} + A(f_c), \qquad (2)$$

where δ_f is the octave bandwidth per unit Hz, B is the number of sub-frequencies in the band, $\|\cdot\|$ denotes the ℓ_2 norm, $\mathrm{p}_{\mathrm{ref}} = 20\mu\mathrm{Pa}$, and $A(f_c)$ is the A-weighting filter coefficient at f_c.

It is worth mentioning that only one accelerometer sensor needs to be mounted on the rail in the lateral direction, since the cut-off wavenumber of the low-pass filter is fully determined by L1.

4. Experimental analysis

The experimental data has been recorded on a track near Munich in 2016, as a part of the Roll2Rail project [13]. A photograph of the setup is shown in Figure 5. The microphone array consists of $N = 42$ microphones, spaced by 8 cm, and located 1.2 m away from the nearest rail and at half the rail web in height. The extrapolation algorithm applied here is the linear predictive border padding [14], with order 10, and the extrapolated space domain consists of $M = 210$ positions. The array has been calibrated in free-field in

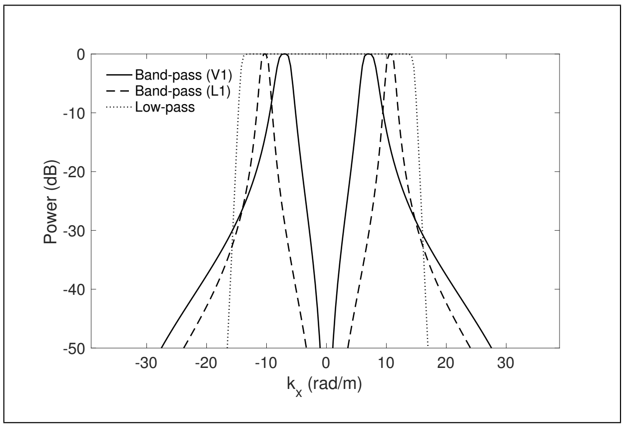

Figure 4. Power of the WSE and modified WSE filters.

Figure 5. Photograph of experimental setup in Germany.

the anechoic room at the Marcus Wallenberg Laboratory in KTH, in order to minimize potential scattering from the array structure and the sensors.

Measurements of two pass-by events are investigated: one train running at 80 km/h and another running at 160 km/h. The analysis time window from the entire event corresponds to two bogies. The reference data is provided from TWINS, and the details concerning the calculations can be found in Section 5.4 of [1]. The separation results are calculated at the center-most microphone in the array.

4.1. Separation results

Figures 6(a) and 7(a) show the SPL spectra for the trains running at 80 km/h and 160 km/h respectively. The SPL difference between the WSE methods and TWINS are shown in Figures 6(b) and 7(b) for the aforementioned train speeds. Within the whole frequency range examined, there appears to be a better estimation with the modified WSE method, except at 800 Hz where the separation results with the WSE method are closer to TWINS predictions.

In particular, the separation results for the train running at 160 km/h indicate a greater improvement from WSE to modified WSE, than those for the train

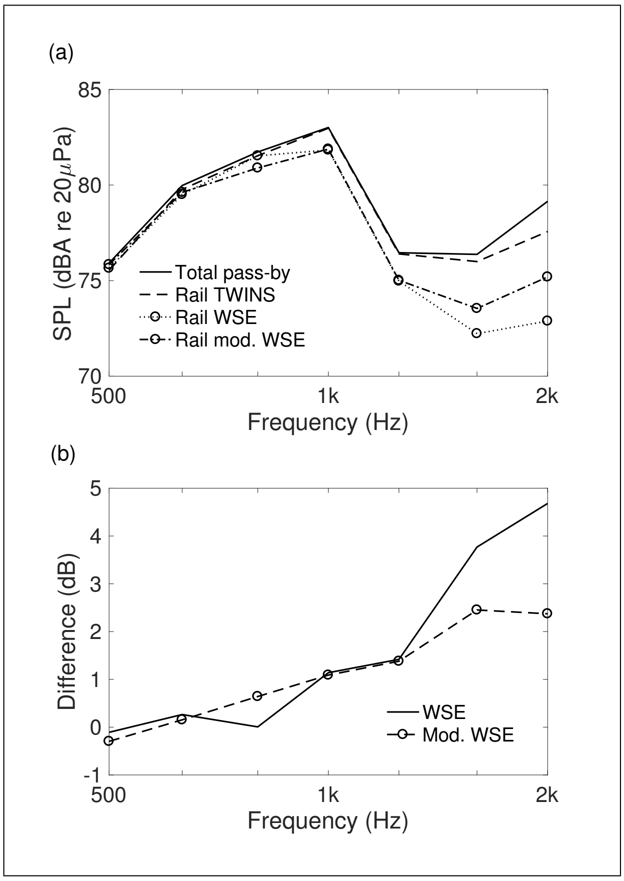

Figure 6. (a) Sound pressure level spectra in dBA re 20 μPa for the train running at 80 km/h. (b) Difference in dB between sound levels obtained with WSE (and modified WSE), and the reference levels obtained with TWINS.

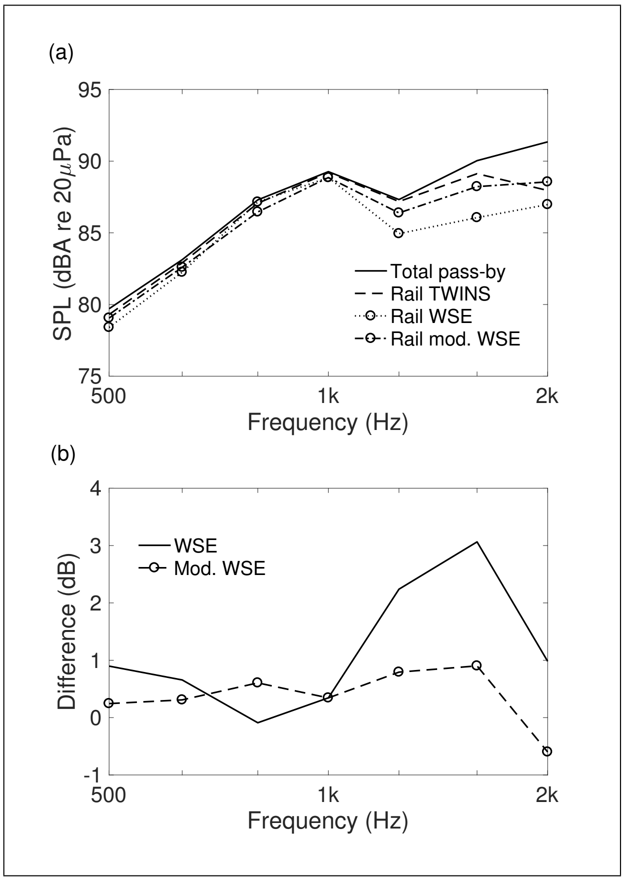

Figure 7. (a) Sound pressure level spectra in dBA re 20 μPa for the train running at 160 km/h. (b) Difference in dB between sound levels obtained with WSE (and modified WSE), and the reference levels obtained with TWINS.

running at 80 km/h. For example, the SPL differences for the train speed of 80 km/h are within ±2.5 dB, whereas for the train speed of 160 km/h these differences are within ±1 dB.

Overall it can be stated that the modified filters provide closer results to those calculated with TWINS than the original WSE filters do [1]. The discrepancies have decreased from ±5 dB to ±2.5 dB in the frequency range and the two pass-bys examined. Further investigation of this method is strongly encouraged, specially at higher frequency bands where more bending waves are excited in the rail.

5. Conclusions

This paper explores a modified filter approach for separating the rail contribution to pass-by noise, based on the wave signature extraction (WSE) method [1]. The original application of the WSE makes use of band-pass filters to extract one bending wave per excitation direction from microphone array spectra. Therefore the presence of additional wave families in the spectra causes the rail contribution to be underestimated, sometimes by almost 5 dB [1].

In this occasion low-pass filters are used instead, aiming to extract any arbitrary number of wave families within the rail wavenumber bandwidth –i.e. up to the first-order lateral bending wavenumber. It can then be shown that the rail contribution is no longer as underestimated as in the application of the original WSE construction. For the two pass-by events examined, the sound pressure level differences between the modified WSE method and TWINS predictions are within ± 2.5 dB.

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