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IDENTIFICATION OF RAIL CONTRIBUTION TO PASS-BY NOISE BY A MODIFIED WAVE SIGNATURE EXTRACTION (WSE) METHOD

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ABSTRACT

The present paper explores a modified version the wave signature extraction (WSE) method \cite{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 \cite{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 propose a modified filtering procedure, where a bank of band-pass and low-pass filters are 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.

1 INTRODUCTION

The pass-by noise certification test for rail-bound vehicles in Europe requires the determination of the noise radiated by the vehicle, which, according to the technical specification for interoperability
(TSI) NOISE, shall not exceed the specified limit sound levels [2]. However, studies have found that a considerable part of the pass-by noise is radiated by the rail [3], which vibrates and generates sound due to the contact with the train’s wheels. Therefore, the need arises for separating the vehicle and rail contributions, such that the homologation test can be done independent of the track.

A number of studies have approached this problem in the past decades. Here we shall limit the survey slightly, and the reader is referred to [1] for a more comprehensive summary of studies. One of the most widely adopted methods is TWINS, which stands for Track-Wheel Interaction Noise Software, and it predicts the different noise contributions by means of roughness and track decay rate measurements [4, 5]. The predictions are such that the total sound pressure level is matched with that of a microphone measurement at 7.5 m away from the track center and 1.2 m high from the rail base –as in the ISO3095 [6]. As regards microphone array applications, beamforming arrays have been tested in one and two dimensional configurations [3, 7–9], leading to the conclusion that the rail noise can be underestimated by 10 dB or more in the frequency region between 500 Hz and 1.6 kHz. Another array application is the SWEAM method [10], standing for Structural Wavenumbers Estimation with an Array of Microphones, which solves an inverse problem using a least-squares criterion to jointly find the bending wavenumbers and the decay rates of the waves propagating in the rail.

As a part of the Roll2Rail project [11], the wave signature extraction (WSE) method has been developed and introduced by Zea et al. [1]. WSE requires a line microphone array and two acceleration sensors, and it aims at separating the rail contribution to pass-by noise by means of filtering the pressure wavenumber spectra per frequency band. WSE allows for the separation of the contributions of vertical and lateral rail vibrations to the pass-by noise, and also indirect estimation of the vehicle contribution. One of the drawbacks of the WSE method is, however, a consistent underestimation of the rail contribution at frequencies higher than 1.25 kHz, which has been attributed to the presence of new wave families that are not accounted for in the filters’ passbands [1]. It is then the central goal of this paper to explore a different filter design that does consider these new waves and seek for an accurate estimation of the rail contribution in a broader frequency range.

2 THEORETICAL BASIS

Below 500 Hz the rail behaves as a spatially compact source, with the radiation originated in the neighbourhood of the region in contact with the wheel [12]. In the range of frequencies between 500 Hz and 1600 Hz, and for train speeds of up to 300 km/h, the rail is likely the dominant source of noise [3, 13]. In such a frequency range, the rail behaves as a spatially distributed source (see Figure 1), and radiates plane waves at a certain angle $\phi$ to the normal of its longitudinal axis [12].

![Figure 1: (Top view) Sound radiation of the rail. Plane waves propagate at an angle $\phi$ that is determined by the ratio between the length of the acoustic wave and that of the bending wave, $\lambda_a$ and $\lambda_b$ respectively.](image)

As a consequence, the wavenumber spectrum of a collection of microphones located parallel to
the rail will likely exhibit narrowband peaks corresponding to these plane waves. A hypothetical situation is depicted in Figure 2, where the total pass-by noise captured with the array is shown. The narrowband peaks are situated at wavenumbers corresponding to bending modes of the rail,

$$p(k_L)$$

vertical $k_V$ and lateral $k_L$, while the broadband curve represents the noise due to the wheels, sleepers and other sources. Henceforth, wavenumber filters can in principle be designed and applied to the spectrum in Figure 2, to the end of separating the rail noise from the total pass-by noise.

3 WAVE SIGNATURE EXTRACTION

This section gives an overview of the original construction of the wave signature extraction (WSE) method, and the interested reader is referred to the work by Zea et al. [1] for further details. The WSE method makes use of measurements with a line microphone array located in the near-field of the rail, and two accelerometers mounted on the rail: one in the vertical and one in the lateral direction. The pressure measurements are then transformed into the wavenumber domain, and the rail noise is extracted by means of applying band-pass wavenumber filters tuned to the first-order vertical and lateral bending wavenumbers ($k_V$ and $k_L$ in Figure 2). The latter are estimated by means of recording pressure and vibration data before and after the pass-by event, thus circumventing the need for a priori knowledge of the rail properties [1]. A condensed diagram of the WSE method can be seen in Figure 3, where the input data from the array and the accelerometers is locally stationary, filtered at a given 1/3 octave band, and the process is iterated per time blocks until the desired time analysis window is completed [1].

![Figure 3: Generalized block diagram of the wave signature extraction method at a given time iteration. The filter design block is where the filter functions are tuned to the bending wavenumbers.](image)

The key strength of employing band-pass filters is the possibility of separating not just the total rail contribution but also the individual contributions of vertical and lateral rail vibrations to the
pass-by. Nevertheless, as found in Reference 1, the presence of higher-order wave families in the wavenumber spectrum causes the rail contribution to be underestimated for frequencies above 1.25 kHz (see Figure 4). As frequency increases, the wavenumbers $k_V$ and $k_L$ also increase, and a new wave family appears \footnote{Reference 1} at a wavenumber in the region $|k_x| < k_V$ of the curve in Figure 2. (As frequency keeps increasing more families are likely to appear in the spectra.) In Reference 1, this type of wave has been identified and attributed to a lateral web bending mode that cuts on at around 1.5 kHz \footnote{References 1, 14}. Therefore, if we the goal is to capture this new wave in the filter passband, a low-pass filter with passband $k_c \in [-k_V, k_V]$ is more appropriate for frequencies greater than or equal to 1.25 kHz.

![Figure 4: Sound pressure level difference between the rail contribution estimated by the WSE method and the reference data from TWINS \cite{1}.](image)

### 3.1 Modified extraction

In the original construction of the WSE method there are two band-pass filters: one associated with the first-order lateral bending wave (L1), and another with the first-order vertical bending wave (V1). The modified WSE approach introduced in this paper preserves: (i) the band-pass filter for L1 within the whole frequency range, and (ii) the band-pass filter for V1 in the range of frequencies up to 1.25 kHz. Above this frequency a low-pass filter is instead applied in order to account for V1 and the second-order lateral wave (L2). Both the band-pass and low-pass functions are 4\textsuperscript{th}-order infinite impulse response (IIR) filters. Table 1 summarizes the filter functions designed for the WSE and modified WSE methods. The center wavenumbers $k_c$ are estimated by means of the optimization algorithm applied in Reference 1 (see Table 1 and Appendix B in \cite{1}). Note that $k_c$ is to be interpreted as the cut-off wavenumber of the low-pass filter function F (V1 & L2).

![Table 1: Summary of filters used in the WSE and modified WSE methods.](table)

<table>
<thead>
<tr>
<th>Method</th>
<th>Filter</th>
<th>Waves</th>
<th>Passband (rad/m)</th>
<th>Frequency range</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSE</td>
<td>F: Band-pass</td>
<td>V1</td>
<td>$k_c \pm 2.5$</td>
<td>Full range</td>
</tr>
<tr>
<td></td>
<td>G: Band-pass</td>
<td>L1</td>
<td>$k_c \pm 1.5$</td>
<td>Full range</td>
</tr>
<tr>
<td>Mod. WSE</td>
<td>F: Low-pass</td>
<td>V1 &amp; L2</td>
<td>$k_c + 1.25$</td>
<td>$f \geq 1.25$ kHz</td>
</tr>
<tr>
<td></td>
<td>G: Band-pass</td>
<td>L1</td>
<td>$k_c \pm 1.5$</td>
<td>Full range</td>
</tr>
</tbody>
</table>

Figure 5 shows the filter responses F (V1), F (V1 & L2) and G (L1) at 1600 Hz. The center wavenumbers are in this case $k_c = 7.11$ rad/m for V1 band-pass functions, $k_c = 10.29$ rad/m for L1 band-pass functions, and $k_c = 7.11$ rad/m for V1 & L2 low-pass functions.

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The main principle as regards the application of the filters F and G is similar to that in Reference 1. The difference in treatment here is that generalized filters F and G are used, and the notion of vertical and lateral rail filters is dropped. The root-mean-square outputs of these filters, evaluated at a given microphone position $x$ and a 1/3 octave band centered at $f_c$, follow:

$$p_{\text{rms}, F}(x, f_c) = \sqrt{\frac{\delta_f}{\pi B} \sum_{b=1}^{B} |p_F(x, \Upsilon_b)|^2}$$  \hspace{1cm} (1)$$

and

$$p_{\text{rms}, G}(x, f_c) = \sqrt{\frac{\delta_f}{\pi B} \sum_{b=1}^{B} |p_G(x, \Upsilon_b)|^2}$$  \hspace{1cm} (2)$$

where $\delta_f$ is the octave bandwidth per unit Hz, $B$ is the number of sub-frequencies in the band, and $\Upsilon_b$ is the $b$-th sub-frequency in the band. At this sub-frequency, the spatial sound pressure $p_F(x)$, and likewise $p_G(x)$, is the result of zero-phase filtering the measured sound field, where $x \in \mathbb{R}^M$ is the vector with the spatial positions of the $M$ microphones. For example, in the case of using the filter F, it follows that:

$$p_F(x, \Upsilon_b) = Q^H F^H F Q p_{\text{meas}}(x, \Upsilon_b),$$  \hspace{1cm} (3)$$

where superscript $H$ denotes Hermitian transpose of the matrix, $Q \in \mathbb{C}^{M \times M}$ is the 1D spatial discrete Fourier transform matrix, $W \in \mathbb{R}^{M \times M}$ is a diagonal matrix whose elements are a Tukey window, $F$ is a diagonal matrix containing a band-pass or low-pass filter function (see frequency-dependence in Table 1), and $p_{\text{meas}}(x, \Upsilon_b) \in \mathbb{C}^M$ is the measured pressure field at the $b$-th sub-frequency in the band. Generally, $p_{\text{meas}}(x, \Upsilon_b)$ is a spatially extrapolated version of the actual measured field from $N$ to $M > N$ positions, in order to have a finer wavenumber spacing [1].

Then, the rail contribution to the sound pressure level (SPL) is calculated in dBA as:

$$\text{SPL}_{\text{rail}}(x, f_c) = 20 \log_{10} \left[ \frac{p_{\text{rms}, F}(x, f_c) + p_{\text{rms}, G}(x, f_c)}{p_{\text{ref}}} \right] + A(f_c),$$  \hspace{1cm} (4)$$

where $p_{\text{ref}} = 20 \mu\text{Pa}$ and $A(f_c)$ is the A-weighting filter coefficient at $f_c$.

## 4 EXPERIMENTAL INVESTIGATION

The experimental data was recorded during a measurement campaign in Germany in 2016, as a part of the Roll2Rail project [11]. A photograph of the experimental setup is shown in Figure 6.
The microphone array consists of 42 microphones spaced by 8 cm, and it is located 1.2 m away from the closest rail and at half the rail web in height. The two accelerometers are located in front of the left-most microphone of the array. In order to minimize scattering from the holder and the sensors, the array is calibrated in an anechoic room at the Marcus Wallenberg Laboratory for Sound and Vibration Research in KTH. The extrapolation method adopted is a 10th-order linear predictive border padding filter [15], and the extrapolated space consists of $M = 210$ positions.

![Pass-by measurement setup in Germany (2016).](image)

Two train speeds are investigated: 80 km/h and 160 km/h. Sound recordings of two boogies are taken from the full pass-by event. The reference data used for comparisons is produced by TWINS. (Details concerning TWINS predictions can be found in Section 5.4 of Reference 1.) The rail sound pressure level (SPL) at the center-most microphone is taken for the comparisons.

### 4.1 Separation results

Figure 7 shows the SPL results for the train running at 80 km/h. It can be seen in Figure 7(b) that the SPL difference with the modified WSE method is smaller in the frequency bands above 1.25 kHz, compared to the SPL difference obtained with the original WSE method. Overall, the SPL results with the modified WSE method are now within 2 dB from the TWINS predictions in the whole frequency range.

![Figure 7: (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.](image)
Likewise, as it can be seen in Figure 8(b) for the train running at 160 km/h, there is a significant difference from the original WSE to the modified WSE method, most noticeably in the bands centered at 1.25 kHz and 1.6 kHz. At 2 kHz the modified WSE method overestimates TWINS predictions by about 1.5 dB. Overall, and in a similar way as for the train running at 80 km/h, the SPL difference between the modified WSE results and TWINS predictions is bounded to ± 1.5 dB in the frequency range investigated.

In general, for both train speeds examined, the SPL differences between the modified WSE method and TWINS are much smaller than those with the original WSE construction, which can be attributed to the presence, as well as the extraction of the secondary lateral wave family.

5 CONCLUDING REMARKS

Current pass-by noise certification tests of railway vehicles require the determination of the vehicle noise alone, preferably independent of the track on which the test is performed [2]. To the end of extracting the rail contribution to pass-by noise, the wave signature extraction (WSE) method has been introduced by Zea et al. [1]. However, since the extraction is performed with a bank of two band-pass wavenumber filters –tuned to one vertical and one lateral bending wavenumber of the rail, the WSE method cannot account for the presence of more than one bending mode per excitation direction. As a consequence, for frequencies above 1.25 kHz, the WSE method can underestimate the rail contribution by almost 4-5 dB [1].

This paper explores a modification of the WSE method, in which a frequency-dependent filter choice is introduced, in order to account for the sound field due to not only the first vertical bending wave, but also due to a secondary lateral wave that cuts on at about 1.5 kHz. The first lateral wave is filtered the same way as in the original WSE method. In order to extract the first vertical wave below 1.25 kHz, the modified method applies the same band-pass filter as the original method; and above 1.25 kHz a low-pass filter function to also extract the second lateral wave. It can be confirmed that the application of the modified WSE method yields closer results to TWINS predictions for the two pass-bys examined in this paper, in comparison with the results obtained with the original WSE method. Overall, the sound level differences have decreased from ±4 dB to ±2 dB in the whole frequency range.
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