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Pass-by noise source identification for railroad cars using array measurements

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ABSTRACT

The sound sources of innovative freight cars were investigated during pass-by measurements with a microphone array on a reference test track. The array consists of 112 microphones allocated in three interlaced helices. Delay & sum beamforming was implemented to provide an acoustic movie of the moving sources for the octaves 250 Hz … 8 kHz. The individual frames of the acoustic source maps were transformed to moving train coordinates and averaged to provide a static map of the sources moving with the train. The dominating sources are located within the bogie area, especially at the wheels. The effects of acoustic shielding and shrouds are demonstrated. From the source distribution, the sound pressure level during pass-by can be synthesized at specific microphone positions, e.g. at the standard position 7.5/1.2 m.

Keywords: Microphone Array, Source Identification

1. INTRODUCTION

Within the scope of an investigation of the noise reduction potential of innovative freight cars (1) the noise sources were characterized using a microphone array. The train consisting of a locomotive, a passenger coach for instrumentation, and two identical freight cars were operated on a test track. Several configurations of the test cars were investigated. The train passed at velocities of 80, 100 & 120 km/h in front of the array. The transit exposure level was measured with individual microphones according to EN ISO 3095 (2). The array measurements were used for additional details concerning the noise source distribution and transmission path.

With the highly transient passage of the train and limited spatial resolution of the array, the setup of the measurement and the method of signal processing must be configured carefully in order to achieve optimal results.

2. MEASUREMENT SETUP

2.1 Array System

A Bionic-L Array from CAE Systems was used, with 112 microphones, two trigger channels, and a sampling rate of 48 kHz. The microphones were arranged in spirals (helices) and an overall diameter of 1.7 m. Figure 1 shows the arrangement. In addition to the optical camera of the array system, a 2nd high resolution / high speed camera was used for improved optical images. The distance from the center of the track was 4 m. Two photo-electric triggers were installed at the rail to determine train position and velocity. The signals were recorded during pass-by for subsequent analysis.

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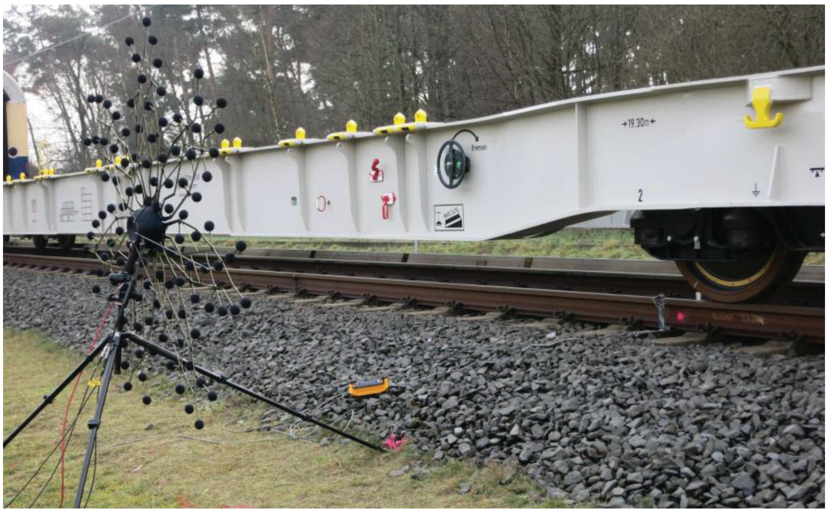

Figure 1 – Microphone array setup next to freight car

3. SIGNAL PROCESSING

3.1 Beamforming

The standard delay & sum algorithm of CAE was used for beamforming. Since the noise coming from the rail, wheels and bogies are dominant, the focal plane was set at the distance of 3.2 m, which is approximately the outer surface of the wheels.

In array signal processing, even ideal point sources do not appear as a single point but due to diffraction as a somewhat blurred image, characterized by the beam width, which is a function of wavelength, microphone arrangement, and the algorithm.

The resolution of the focus grid points was set to 1% of the focal distance, i.e. 0.032 m. This was set constant for all octaves. The region of interest for the horizontal direction was set to ±1.5× the focal distance. The beam width is accounted for, assuming a distribution of idealized uncorrelated point sources in the focal plane. The source distribution is normalized as "source intensity" with units W/m², i.e. the sound power radiated per unit area of the *radiating surface*; in the case of train noise, the source intensity can be interpreted as the acoustic power per unit area radiated to one side of the vehicle. In principle, this source intensity is independent of the distance between the sources and the array, beam width, and spatial resolution.

3.2 Acoustic Movie

Since the train with the noise sources is passing in front of the array, the analysis is performed in short time segments resulting in individual frames of an acoustic movie. A typical still frame of the acoustic movie is shown in Figure 2.

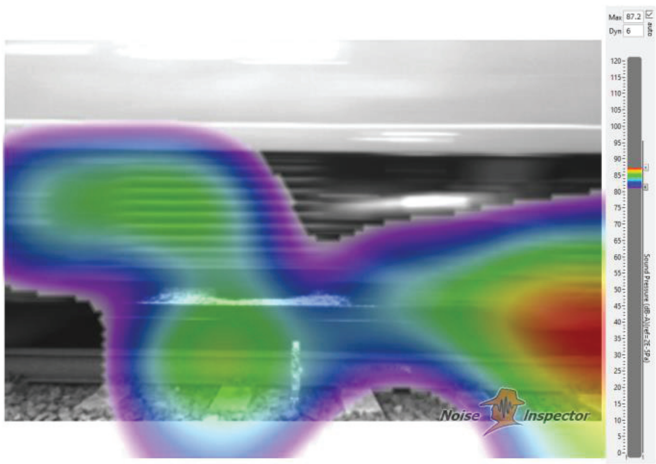

Figure 2 – Example of instantaneous source distribution superimposed on the optical image of a bogie.

In order to avoid excessive blurring, the distance of train travel during a single movie frame should be less than the width of the beam. Note that the beam width is approximately proportional to the acoustic wavelength. The duration of each time segment was defined as 0.018 s. i.e. at a train velocity of 80 km/h the train travels 0.4 m. For adequate accuracy of the sound level, the duration of averaging must be sufficient, i.e. for accuracy of 3 dB with confidence level of 95% the Bandwidth-Time product (BT-Product) must be >12, see Kleiner (3). This requirement is satisfied at the 1 kHz octave with bandwidth 707 Hz. However, for octaves below 1 kHz averaging time is not sufficient and therefore, level accuracy is affected. In the movies travelling blobs of acoustic sources are discernible as in Figure 2. However, they do not match well with actual sources at the wheels. Due to insufficient averaging (BT-product), the result is rather "noisy".

Before and after the train transit, radiation of the rails is expected to be the dominant source. Structure borne sound is transmitted by bending waves along the rails. These radiate airborne sound at a characteristic angle (Figure 3). According to (4) this angle is 15° at 1 kHz. This effect can be seen in Figure 4. Here the angle is ≈20°. At 500 Hz the measured angle is ≈30°; at 4 kHz it is ≈10°.

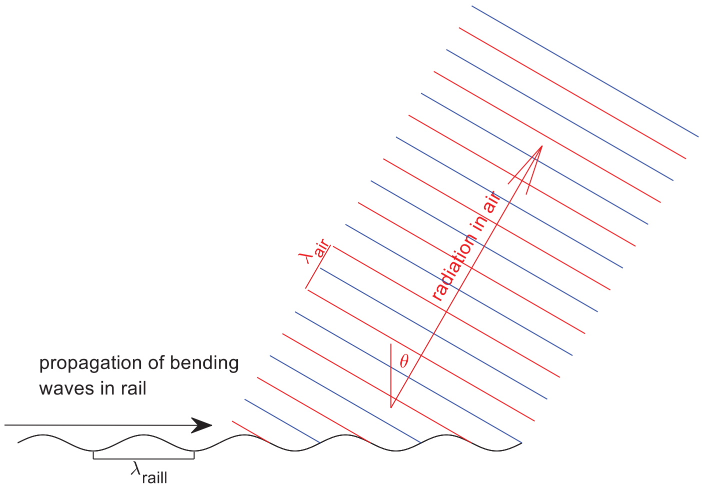

Figure 3 – Coincidence effect: bending waves in the rail with wavelength λ_{rail} radiate acoustic waves in air at a characteristic angle θ

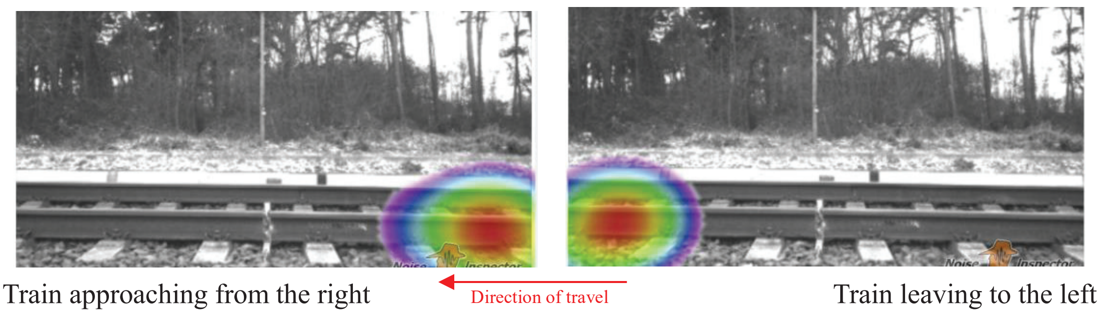

Figure 4 – Radiation pattern of rail before and after train passing. 1 kHz octave. The radiation angle is ≈20°

3.3 Averaging

Averaging of the source distribution during the passage of the train in front of the array can substantially increase the accuracy of the source map. Movie frames based on the fixed coordinate system are mapped to a coordinate system which moves with the train. The partly overlapping frames are then averaged. To avoid artefacts at the edges of individual frames the source distributions of the individual frames are weighted along the horizontal direction before averaging, similar to a hanning window. Effectively, the averaging time is increased from a single movie frame of 0.018 s duration to the passage of the source across the field of "view", i.e. 0.2 s at 80 km/h. By this averaging process the acoustic movie consisting of many individual frames showing a small section of the train are converted to a single picture of averaged source distribution of the complete train. The frames of the optical movie are assembled with the same averaging process to obtain an image of the complete train. Figure 6 shows a typical example of averaged source distribution. Typically, in presentations of array results, only a very limited range of 3 … 10 dB of sound levels is displayed, which nicely shows the dominant source. Weaker sources are below the displayed range are not shown. Note that in Figure 6 an extended range of sound levels is displayed, covering more than 50 dB in order to reveal also weaker sources. As a disadvantage of this extended range, artefacts of beamforming sidelobes appear in the octave bands 4 & 8 kHz.

Multiple pass-by measurements with identical parameters could be averaged in order to further increase total averaging time. Spatial resolution however is limited by diffraction effects and cannot be improved by averaging. Finer resolution could be achieved by optimized beamforming or deconvolution techniques (5).

3.4 Sound power of individual components

In order to evaluate the sound power emitted by components such as rail, wheels or complete bogies, the source intensity of such areas of interest can be integrated over defined rectangles. Figure 6 shows small boxes around each wheel, with numbers 1 … 10 in the upper left corner. The corresponding sound power level of these boxes are listed at the top of each diagram. These values of sound power level can easily be compared for different test configurations.

In a similar manner, the sound pressure level due to a selected range of sources can be computed at a specified microphone position, e.g. at 7.5/1.2 m (see Figure 9 for illustration).

4. Results

In Figure 6 the train runs from right to left. On the left, the 2nd bogie of a passenger coach is displayed, followed by two freight cars for carrying ISO-containers. The top diagram shows the optical image of the train; below are the acoustic noise maps in the octave bands 8 kHz down to 250 Hz. For high frequencies, the resolution is quite good. Individual wheels can be discriminated down to approx. 1 kHz. At lower frequencies the resolution is diminished and at 250 Hz hardly any details can be recognized. The dominant sources are at and below the wheels. The wheels of the freight cars are partly covered by the railcar body which acts as a partial noise shield. This can best be observed in octaves 2 kHz & 4 kHz. The wheels of the passenger coach are not covered, and the noise sources extend over the complete wheels. Additional noise sources are apparent at the rail sections between the bogies; the level of the rail noise decreases with distance from the wheels. The acoustic resolution is not so detailed as to discriminate between the wheels and the rail section directly under the wheels.

Figures 5 & 7 depict an investigation of the effect of bogie shrouds covering parts of the wheels. In octaves 2 kHz & 4 kHz the shielding effect of the shrouds can clearly be recognized, in comparison to the bogies without shrouds. Some noise is radiated upwards and reflected by the cylindrical surface of the tank. This reflected noise can be recognized as mirror sources at the tank, directly above the wheels.

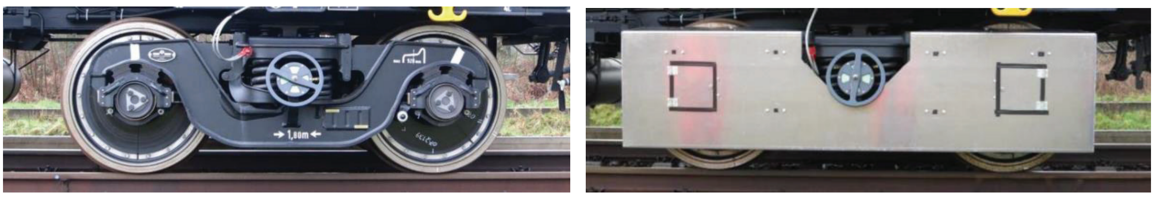

Figure 5 – Standard bogie and modification with acoustic shroud

Figures 8 depicts an example of one defective wheel. Two freight cars for transporting automobiles are measured. Wheel number 6 is exceptionally loud in the octaves 250 Hz … 2 kHz.

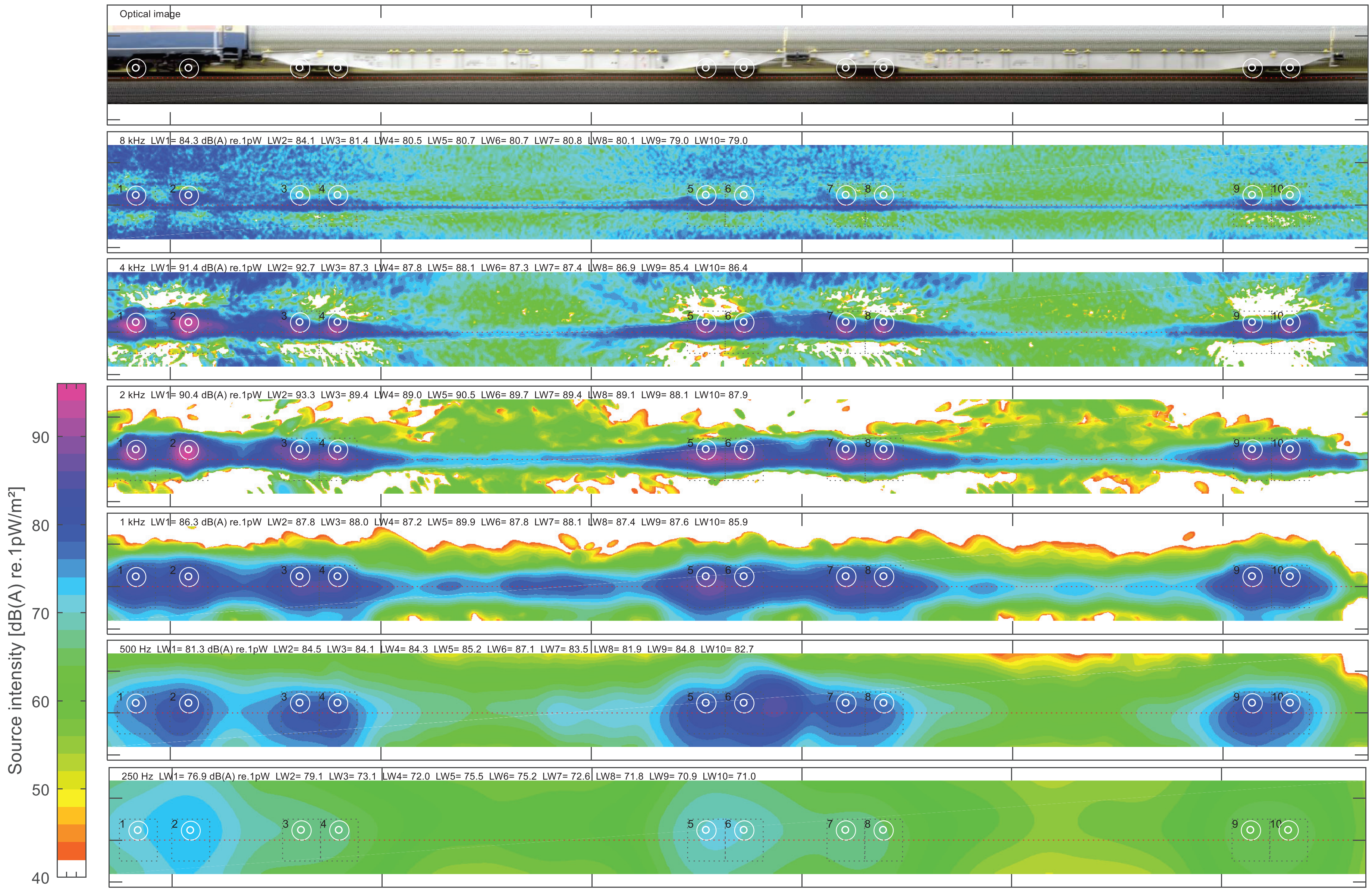

Figure 6 - Noise sources of freight cars for carrying ISO-containers

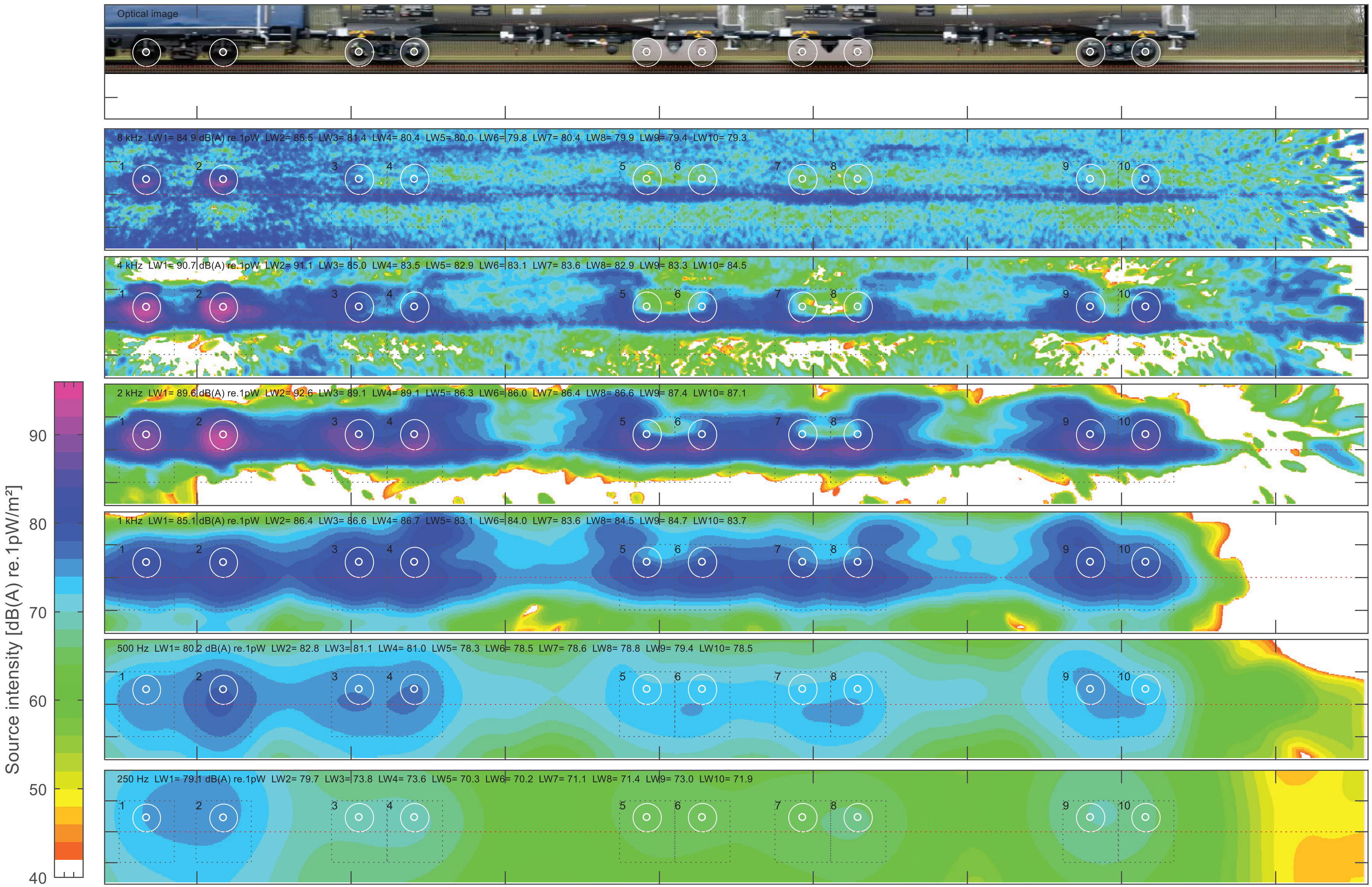

Figure 7 – Noise sources of freight cars for liquid goods, two bogies with acoustic shrouds

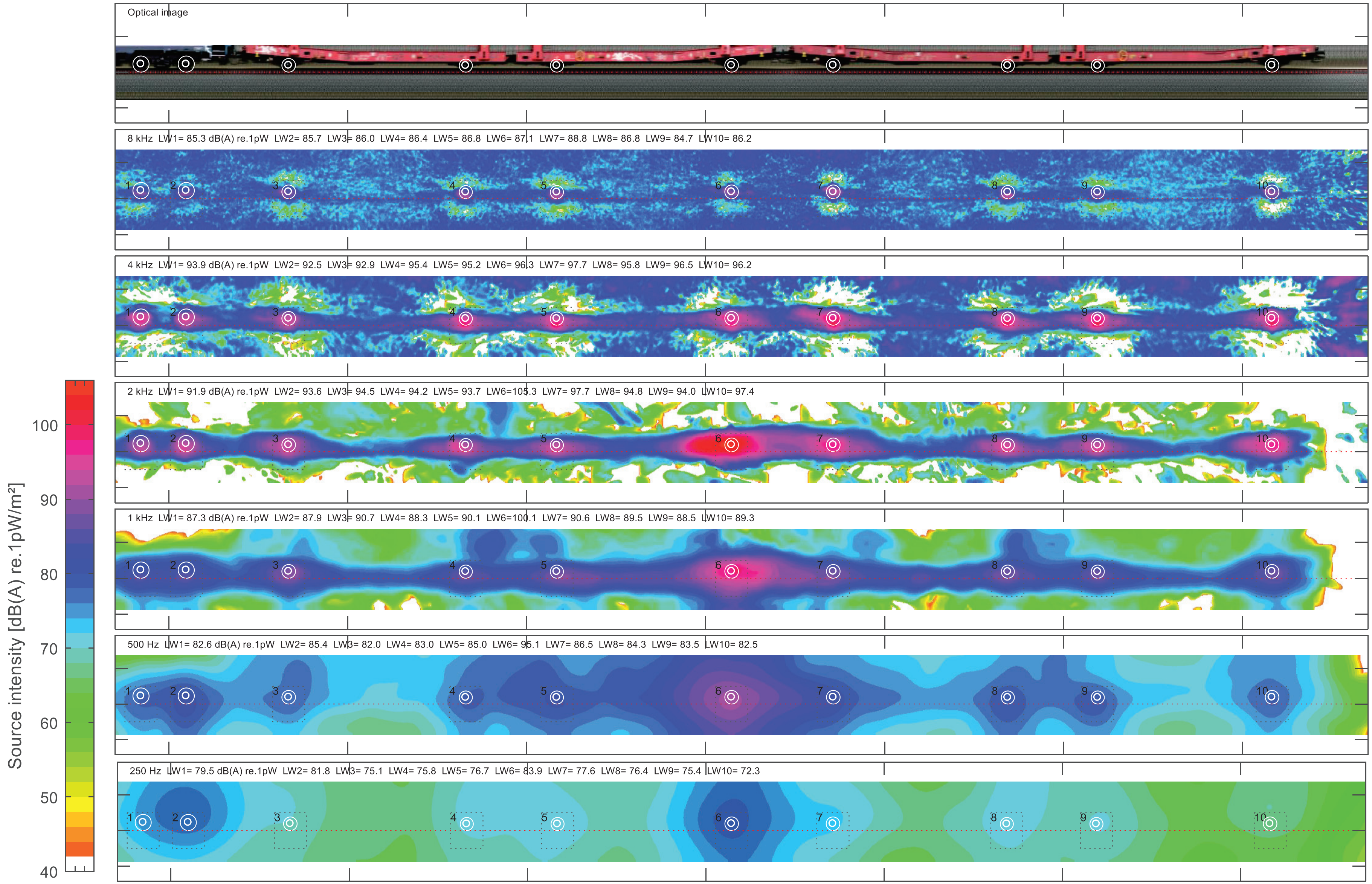

Figure 8 – Noise sources of automobile transporter, one wheel is exceptionally loud

In Figure 9 the source intensity of a train with two automobile carriers (with good wheels) is used to predict the resulting sound pressure at the standard microphone position 7.5/1.2 m. The prediction is compared with the sound pressure measured at the same position. The contributions of the individual wheels (sources inside each of the numbered boxes as in Figure 8) are shown as dashed lines.

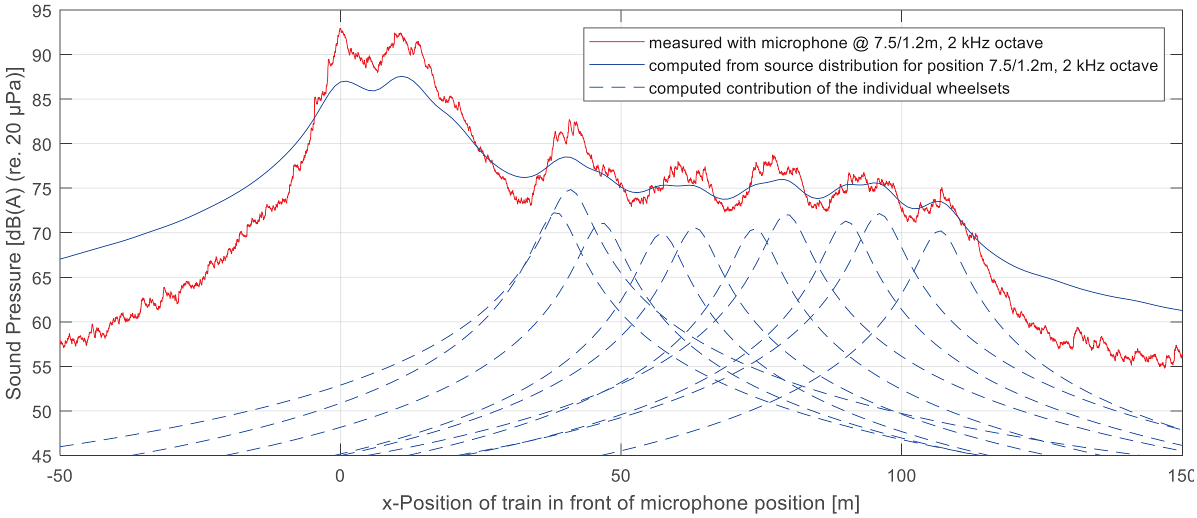

Figure 9– Comparison of sound pressure level measured at 7.5/1.2m with computed sound pressure at this point based on source distribution. 2 kHz octave

The SPL measured by the microphone (time constant "Fast") appears somewhat stochastic due to random noise and the single measurement position. The computed SPL is based on a fixed source distribution which passes by in front of the microphone position, therefore, it appears much smoother.

5. CONCLUSIONS

In an acoustic movie of the travelling train the available averaging time is very short, which results in substantial uncertainty of the resulting source distribution. With additional averaging of the source distribution in the frame of reference moving with the train, the accuracy can be substantially improved. Compared to standard pass-by noise measurements according to EN ISO 3095, the maps of the noise sources achievable with an array system provides much more details. Such details are particularly helpful to assess the effect of innovative noise reduction measures. For freight vehicles travelling between 80 and 120 km/h the array measuring distance of 4m from the center of the track leads to optimal results regarding sound level and source separation accuracy. This may not be the case for array investigations on railways traveling with over 120 km/h due to bow waves and slipstream.

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