27th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
12 – 16 July 2020, Prague

ICSV27 PRAGUE

Annual Congress of the International Institute of Acoustics and Vibration (IIAV)

VISUALISATION OF TRAIN NOISE WITH ACOUSTIC CAMERAS

Sebastian Kümmritz
gfai tech GmbH, Berlin, Germany
e-mail: kuemmritz@gfaitech.de
Ali Movahed
gfai tech GmbH, Berlin, Germany
email: movahed@gfaitech.de

Rail traffic noise is a nuisance for the residents affected and can have harmful consequences for their health. Therefore, a goal of the German government is to reduce rail traffic noise, mainly by a conversion of the existing freight wagon fleets to emission-reducing composite brake blocks. In order to monitor the long-term development of railway noise, the German Federal Railway Authority is setting up a nationwide monitoring system. The monitoring provides pass-by measurements with single microphones according to DIN EN ISO 3095:2014-07. This makes it possible to examine the noise emissions of trains as a whole, but provides only limited information about the origin of the individual sound-generating mechanisms.

Measurements with acoustic cameras are ideal for a precise investigation of the sources of noise in rail traffic. Therefore, we carried out extensive measurements with acoustic cameras on two measurement days. The aim was to get an overview of the typical sound sources in rail traffic and to develop a clear and simple representation for them.

The measurements took place on the main track between Hannover and Minden. A total of 157 trains were recorded with two acoustic cameras consisting of 120 spirally arranged microphones. One camera has an aperture size of 3.4 m and was used to determine the whole pass-by measurement and the other camera with an aperture size of 0.95 m was used for detailed analyses.

A special beamforming based pass-by algorithm was used in order to find the moving noise sources. The algorithm tracks a source for a certain period of time while passing by and compensates for the DOPPLER-effect that occurs during passing. The vertical arrangement of the individual pass-by images for different frequency bands provides a clear representation of all dominant sound sources at a glance. Furthermore, a beamforming level $L_{p,Beam}$ is introduced. This is comparable with a conventional sound pressure level but with strong directivity. It enables to determine the contribution of the single parts of the trains (e. g. the axes or the pantograph) to the overall sound emission more precisely.

The examples in this study represent a selection of the interesting effects that were observed during the evaluation of the two measurement campaigns. They show the potential of acoustic cameras for investigation and monitoring of railway noise.

Keywords: acoustic camera, pass-by, railway noise, sound source localisation

1. Introduction

The protection of the population from traffic noise is one of the core elements of a sustainable transport policy. The German government's goal is to reduce rail traffic noise by 10 dB(A) by the year 2020 - starting from 2008. The most important measure currently is a comprehensive, publicly funded conversion of the existing freight wagon fleets to emission-reducing composite brake blocks, so that in future no more wagons will be operated with grey cast iron brake blocks.

In order to record the long-term development of emissions from rail traffic, the Federal Railway Authority in Germany set up a nationwide noise monitoring system [1]. Within the framework of noise monitoring, sound measurement parameters are continuously collected at selected locations in the rail network, which are derived from the noise emissions of the overall system. A statistical analysis of the measured data makes it possible to draw conclusions about the development of noise emissions from the various trains.

The monitoring system enables trains as a whole to be compared in terms of sound emissions. However, it is of limited use for an analysis of the causes of noise. Supplementary measurements are necessary for a further specific assessment of the individual sound sources and for the observation of the causes of high sound pressure levels in rail transport. A suitable method is measuring with acoustic cameras.

The use of an acoustic camera, which is widespread in many industries, allows a fast and precise localisation of sound sources and an estimation of their intensity. Beamforming has also been used in the field of rail transport for many years ([2], [3], [4]). The method enables a precise and effective analysis of the frequency dependent sound emission of the individual wagons and components. This can be used to increase the understanding of noise generation mechanisms in rail transport.

During both measurement compaigns in May and September of 2019 a total of 157 trains were recorded with two acoustic cameras simultaneously. This paper presents and discusses some of the observations made.

2. Theory

The theory of beamforming for sound source localisation is well known and extensively discussed in literature (e. g. [5], [6], [7]). The principle is based on a mathematical compensation of runtime differences of the noise signal from any point in an image plane to the single array microphones. A time waveform is calculated for each pixel and the rms or maximum value can be displayed as color coded levels. This representation is typically referred to as an acoustic map. The superposition with a photographic image displays the position of dominant sound sources and is called acoustic photo.

Conventional beamforming algorithms work good for the localisation of stationary sources but they have a significant drawbacks with moving sources. To get a good localisation a short integration time is needed. The integration time is the time range for that the beamforming algorithm is appplied. It can be compared with the exposure time of a conventional camera. Like long exposure times with moving objects lead to a blurred optical photo, long integration times lead to a blurred acoustic image. The solution might be to use small integration times, but as well as small exposure times in optical imaging lead to a dark picture with low contrast, small integration times cause a poor frequency resolution.

To determine the origin of moving sources with a good resolution the trajectory of the object under test has to be known. This allows to track a moving acoustic source for a longer time period. For rotating objects like fans, turbines, wheels etc. rotational beamforming can be used [8]. For pass-by measurements the "Society for the Advancement of Applied Computer Science", in german "Gesellschaft zur Föerderung angewandter Informatik" (GFaI), developed a special pass-by algorithm, which is able to compensate the frequency shift caused by the DOPPLER-effect [9]. The results are drawn in a stitched picture of the whole pass-by measurement which allows to visualise all dominant sound sources of the moving object. Figure 1 shows as an example the result of the algorithm applied on the pass-by measurement of a regional train.

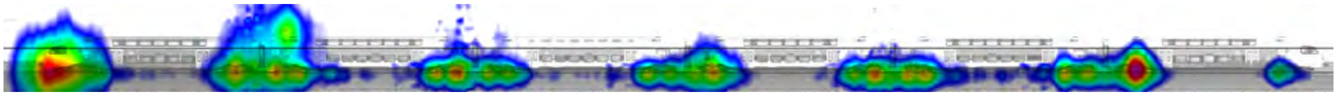

Figure 1: Example for the pass-by algorithm applied on the passing by of a regional train

3. Methods

3.1 Equipment

The measurements were performed with two microphone arrays of the company gfai tech, called FlexStar and Fibonacci. Both arrays consist of 120 microphones arranged in a spiral configuration. The FlexStar is designed for outdoor applications and has an aperture size of 3.4 meters, making it suitable for the localisation of sound sources with frequencies above 86 Hz. While the majority of testing were carried out using the FlexStar, the Fibonacci array was used for detail analyses of the wheel-rail-contact. The Fibonacci has an aperture size of 0.95 m, making it suitable for the localisation of sound sources for frequencies above 262 Hz. The data acquisition was achieved with the data recorder "mcdRec" of the gfai tech. It is able to sample data at rates up to 192 kS/s with a resolution of 32 bit.

3.2 Setup

Two measurement campaigns were carried out on the main line 1700 between Minden and Hanover at route kilometre 37.8. The arrays "FlexStar" and "Fibonacci" from gfai tech recorded the passes synchronously. The "FlexStar" array is used for acoustic source mapping of the entire train. It was installed at a distance of 13.2 m to the middle of the front track. The "Fibonacci" array was used for a detailed evaluation of the sound radiation at the wheel-rail-contact. It was positioned at a distance of 7.5 m to the centre of the front track. The array was placed 10 m away from the FlexStar along the track. One microphone of the Fibonacci Array, located at a height of 1.2 m above the top of the rail, was used to record the pass-by level. This position corresponds to measuring position A for train passing measurements according to ISO 3095:2013. The setup of the measurement is shown schematically in figure 2.

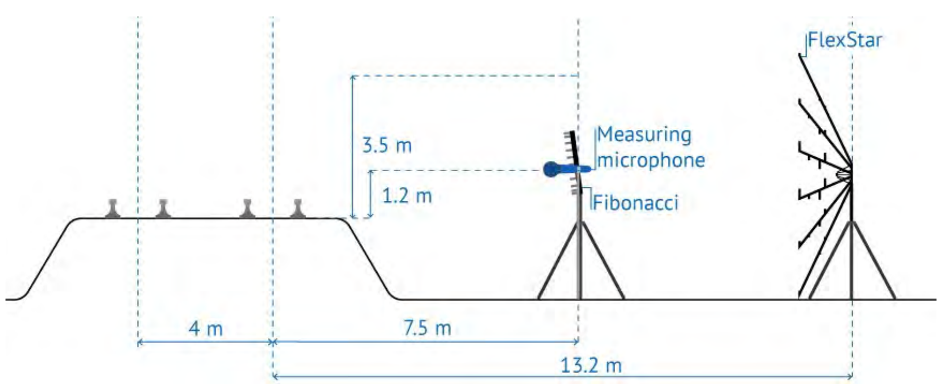

Figure 2: Measurement set-up; the "Fibonacci" array was placed 10 m away from the "FlexStar" array along the track

4. Results and discussion

4.1 Overview

During both measurement campaigns a total of 157 trains were recorded, including regional trains, express trains and freight trains. Figure 3 shows the average pass-by levels of all train passages measured on the front track. The freight trains are marked by crosses and the passenger trains by circles in the diagram.

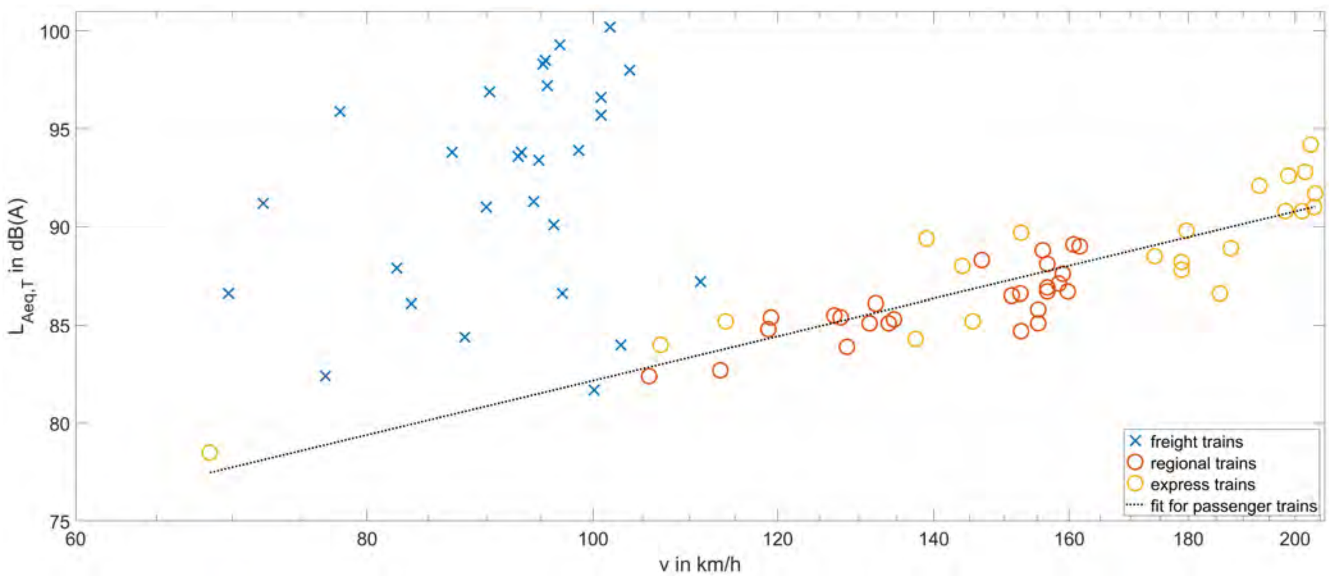

Figure 3: Total pass-by level $L_{Aeq,T}$ as a function of the average pass-by speed

For passenger trains, the correlation can be seen that the overall pass-by level increases with speed. The relationship between sound emission and pass-by speed can be described by

$$L = L(v_0) + n \cdot \log\left(\frac{v}{v_0}\right) \tag{1}$$

where the velocity coefficient n is an empirical value. Values for are usually found to be between about 25 and 35 [10]. In the 2nd annex to the 16th BImSchV (Germany), which is decisive for legal sound calculations, different parameters are used for different sound sources and different frequencies . The fit in the measurements shows a velocity coefficient of 28.6.

Significantly higher pass-by levels were measured for freight trains even at low speeds. For freight trains, the pass-by levels scatter so strongly that no proportionality to the speed can be discerned.

4.2 Emission of the bending wave

An essential aspect regarding the sound emission of the rails is the radiation of the bending wave. Bending waves can propagate in structures whose dimensions are smaller than the wavelength of the sound, which is true in the audible frequency range on rails. If the wavelength of the bending wave λ_B is greater than the wavelength of the airborne sound λ_L, sound radiation from the structure-borne sound field of the rail is emitted at the angle

$$\vartheta = \arcsin\left(\frac{\lambda_L}{\lambda_B}\right) \tag{2}$$

into the adjacent airborne sound field. Like fig 4 (left and right) shows, the radiation of the bending wave is dominant especially before the train entry and after the train exit. The bending wave can, however, also be identified by the acoustic camera at times during the passage of the train, as can be seen in the picture in the middle of fig 4. The amplitude of the rail emission by the bending wave during the pass-by can reach the same order of magnitude like the emission from the adjacent wheel-rail-contact.

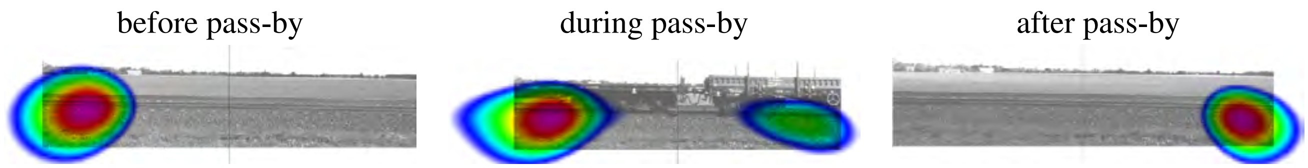

Figure 4: Sound emission of the bending wave

4.3 Wheel flats

A typical rolling noise, which frequently occurs in rail traffic, is caused by so-called wheel flats. These are unwanted wear and tear on the wheel tread. The result is a periodically occurring impact noise, which is perceived as "rattling".

Wheel flats can be identified in the time signal as periodically occurring peaks, as can be seen in fig 5 above. The time signal here indicates one wheel flat. However, the evaluation with the acoustic camera shows that these are two different wheel flat on different wagons.

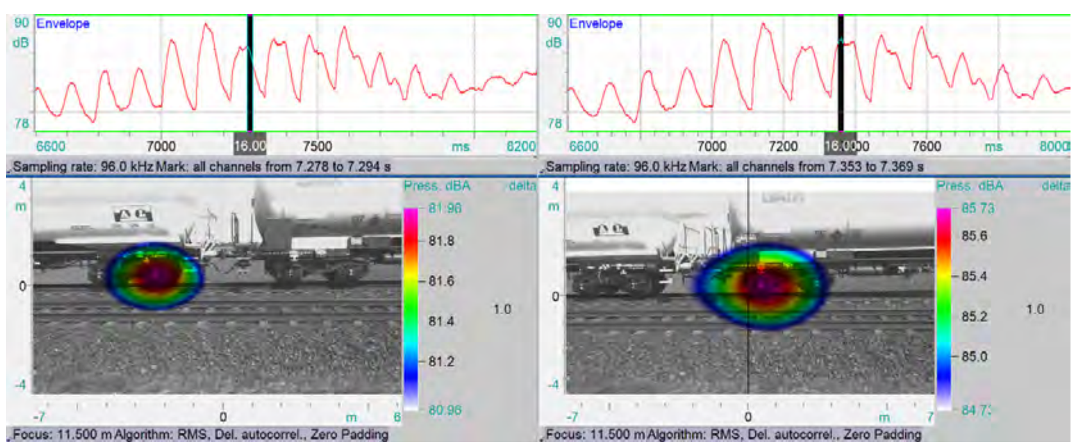

Figure 5: Examples of sound radiation of two closely spaced wheel flats of a freight train

Wheel flats on individual wagons could be observed in about 17 percent of the measured pass-by. Sometimes the typical periodic noise of a wheel flat is only perceptible after the train has passed. This could be explained by the fact that other sound sources masking the noise emission of the wheel flats while passing by. The transient sounds of the wheel flats spread out along the rail and can be heard after passing by as soon as the previously masking sources disappear.

4.4 Beamforming level

Conventional pass-by measurements are performed with single microphones. They give information about the overall sound emission or about the duration of the pass-by. However, single microphones measure only an integral sound emission. If there is an interest in determining the number of noisy wagons, these measurements are of limited use. Due to the auditory masking a quite wagon between two loud wagons also appears to be loud. With beamforming, the contribution of the individual wagons to the overall noise emission can be determined more accurately.

In order to visualise the sound emission determined by beamforming the pass-by-level $L_{p,Beam}$ is defined. The beamforming levels are determined from the acoustic map of the complete train by averaging each position x along the y axis.

Figure 6 shows the comparison of $L_{p,Beam}$ with the conventional sound pressure level measurement. $L_{p,Beam}$ allows to determine the contribution of the sound emission of the single axes of the train. The above mentioned masking effect of the single microphone measurement can be seen in 6, for example, for the fourth wagon (transitions between the wagons marked by black dotted lines; locomotive on the left). While the conventional microphone level shows a continuous increase of the sound pressure level, the beamforming level shows that this is a quieter wagon.

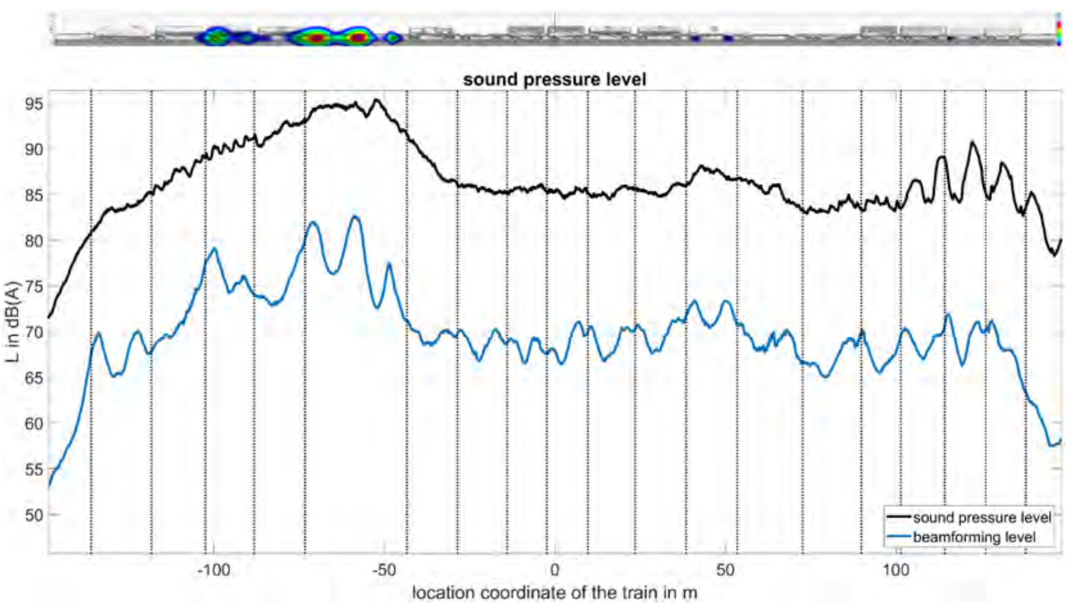

Figure 6: Comparison between sound pressure level and beamforming level of a freight train

4.5 Frequency dependant sound source representaion

For the frequency-dependent analysis of all sound sources of a train in one image, a vertical arrangement of the pass-by evaluations for the individual one-third octave or octave bands is useful. In fig. 7 such a representation for the octave bands is shown using a section of a freight train. This representation shows the dominant, A-weighted sound sources at a glance and can be, therefore, called the acoustic fingerprint of the train.

The analysis of the frequency content of the sound sources on the most trains showed that the noise emissions mainly occour in the frequency range between 500 Hz and 2 kHz and originates from wheel-rail-contact. Above 2.5 kHz significant sound emissions were rarely observed. Also in fig. 7 no sound emission in the given dynamic range in the 4 kHz octave band can be observed.

The example in Figure 8 shows rather an exception with the distinct sound emission in the 250 Hz octave band. In this case a wheel flat was identified. It is assumed that this wheel flat causes a broadband excitation of natural frequencies in the boiler wall, which leads to the low-frequency sound emission.

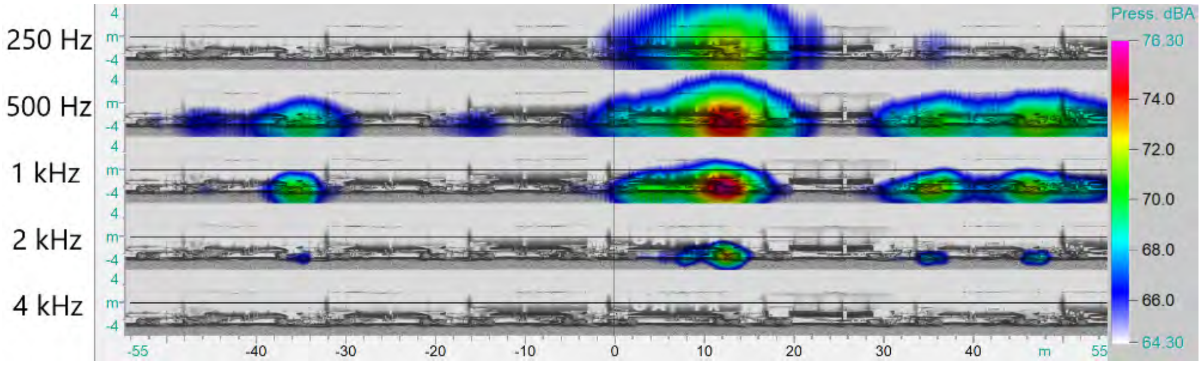

Figure 7: Pass-by evaluation of a section of a freight train for different octave bands with the same dynamic range

Figure 8 shows a detail analysis with the Fibonacci Array. The time signal can be seen in the picture above right. It shows the typical pattern of a wheel flat. The amplitude frequency response for the range marked black in the time signal is shown in the top right. In the bottom of the picture the acoustic photo is shown which was calculated from the black marked area in the amplitude frequency response (26 - 404 Hz). In the acoustic photo four sources can be seen: two sources on the tank wall (1.1 and 1.2), one source on the wheel (2) and one source on the ground. The source on the wheel is most likely from the wheel flat and the source on the ground is probably a reflection.

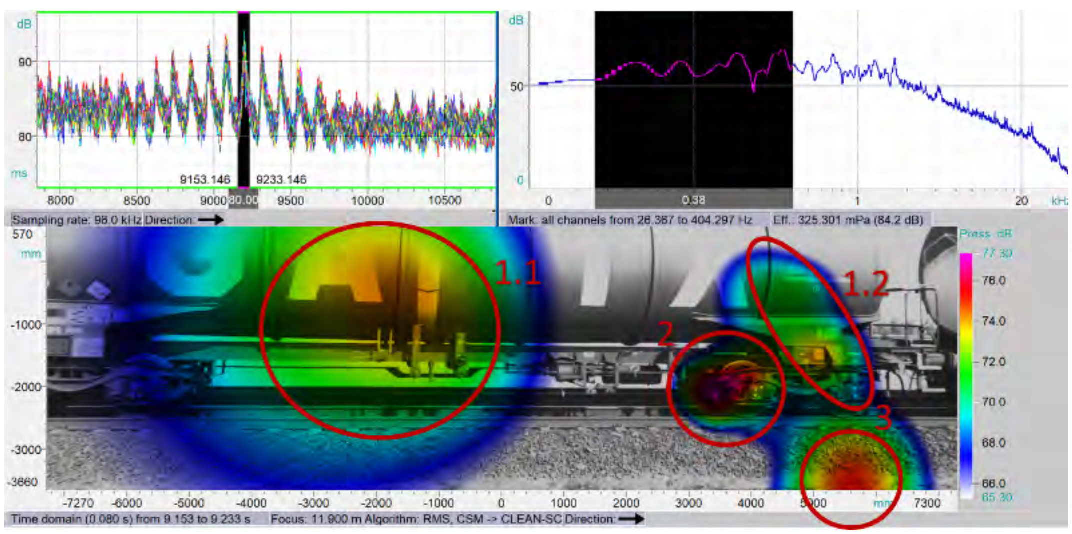

Figure 8: Low frequency sound emission on a tank wagon near an axle with a wheel flat

5. Conclusion

During the two measurement campaigns a total of 157 trains were measured with two acoustic cameras. The passes were evaluated with a special pass-by algorithm developped by the GFaI. The algorithm tracks a source for a specific period during the pass-by of the train and draws the amplitude of this source on an image composition of the whole train, which is created from the single frames of the optical camera.

The large number of measurements and results obtained exceeds the scope of this paper. Therefore, it was only possible to present a small selection of promising results. The following effects were analysed:

- **Pass-by noise vs. velocity** This analysis does not require an acoustic camera, but it was shown since it gives a good overview about the kinds and velocities of the investigated trains. The observed velocity coefficient of about 28.6 is in good accordance with the literature.
- **Bending wave emission** The radiation of the bending wave can be seen not only before and after passing by, but often also during this time. In fact, the influence of the bending wave is underestimated when evaluating with the pass-by algorithm. The algorithm looks for moving sources, but the location of the bending wave emission is always observed at a fixed position due to its directional sound radiation.
- **Wheel flats** Wheel flats can be precisely located with acoustic cameras.
- **Beamforming level** This beamforming level is determined from the acoustic map of the complete train by averaging each position x along the y axis. It allows to determine the contribution of the sound emission of the single regions of the train (e. g. axles or pantograph).
- **Frequency dependant sound source representaion** A vertical arrangement of the pass-by evaluations for the individual one-third octave or octave bands shows the dominant sound sources at a glance.

These evaluations demonstrate the usability of acoustic cameras for the investigation of railway noise. A precise localisation of wheel flats can help to identify and report their origin for a better maintance. Also the frequency dependant sound source representaion can be used for maintance purposes. It enables the localisation of undesired sound events such as droning or hissing. Such noises are usually indicators of defective components.

REFERENCES

1. *Lärm-Monitoring - Schallmessungen im Schienenverkehr*. https://www.laerm-monitoring.de, accessed: 2020-03-31.
2. Barsikov, B., King, W. F. and Pfizenmeier, E. Wheel/rail noise generated by a high-speed train investigated with a line array of microphones, *J SOUND VIB*, **118**, 99–122, (1987).
3. Brühl, S. and Schmitz, K.-P. Noise source localization on high-speed trains using different array types, *Proc. of InterNoise 1993*, pp. 1311–1314, (1993).
4. Dinhobl, G., Petz, M., Kümmritz, S. and Hutterer, H. On measurement of railway noise: usability of acoustic camera, *Proc. 13th International Workshop on Railway Noise*, (2019).
5. Johnson, D. H., *Array Signal Processing: Concepts and Techniques (Prentice-hall Signal Processing Series)*, Pearson Education (US) (1993).
6. Dougherty, R. Advanced time-domain beamforming techniques, 05, vol. 2, (2004).
7. Heilmann, G. and Böck, M. Exploring the limitations and expectations of sound source localization and visualization techniques, *Proc. of InternNoise 2014*, (2014).
8. Kerscher, M., Heilmann, G., Puhle, C., Krause, R. and Friebe, C. Sound source localization on a fast rotating fan using rotational beamforming, *Proc. of InterNoise 2017*, (2017).
9. Meyer, A., Döbler, D. and Gräser, M. Efficient methods for the analysis of moving sound sources with high channel microphone arrays, *Proc. of BeBeC 2014*, (2014).
10. Thompson, D., *Railway Noise and Vibration*, Elsevier (2008).