

Localizing Noise Sources on a Rail Vehicle during Pass-by

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Summary

This paper describes a pass-by measurement technique that has been developed for localization and visualization of noise sources on moving rail vehicles using beamforming. Based on measurements with an array of microphones, while also measuring the position of the vehicle, the technique calculates the contribution of noise, and visualizes it as a contour plot on top of a picture of the train. Deconvolution is applied in addition to traditional beamforming in order to get an improved spatial resolution in the noise map. A set of measurements was made on two different types of regional trains on the Danish railway: the Oresund trains and the IR4 trains. The speed of all the trains was approximately 120 km/h. The results show that deconvolution is efficient for identifying wind noise on the pantograph of the Oresund trains. The IR4 trains turned out to have a strong source at the very front part of the train for frequencies around 600 Hz - 800 Hz with a radiated sound power that was approximately 5 dB above the noise radiated by the noisiest bogies. The cause of this noise is yet unknown, but a potential explanation could be an aerodynamic phenomenon at the front.

1 Introduction

Delay-And-Sum (DAS) beamforming is a powerful method for understanding the sound radiation from acoustic noise sources. Often the method is used for localizing stationary (fixed) sources, but it can also be applied on moving sources such as for aircraft fly-over [1-3] or rotating blades on wind turbines [4, 5]. In Ref. 6 beamforming is applied on high speed train in a windtunnel to analyze the noise radiation from aerodynamic sources around the train, and in Ref. 7 and 8 beamforming is applied under real pass-by conditions to analyze also the wheel and rail induced noise.

During recent years, deconvolution techniques have been introduced as a post-processing after DAS to improve the resolution and reduce the level of ghost sources in the calculated noise maps [9]. The purpose of the paper is to describe a commercially available system that combines moving source DAS with deconvolution for applications on trains.

2 Theory

2.1 Delay-And-Sum (DAS) Beamforming

The idea in DAS is to measure the sound pressure simultaneously at a set of microphone positions, and focus the array at a specific location by delaying the measured signals in such a way that the delayed signals add up coherently if sound is approaching the array from that focus point. That is, for the j^{th} focus point on the source the beamformed signal is calculated as

$$b_j(t) = \frac{1}{M} \sum_{m=1}^M p_m \left(t + \frac{r_{mj}(t)}{c} \right), \quad (2.1)$$

where c is the speed of sound and r_{mj}/c is the time delay that ensures the coherent summation. Next, the same time signals are delayed differently corresponding to a new focus point to get the contribution from that point. Typically, the focus points are at fixed global positions, but for pass-by applications they are a function of time, and being fixed in the local coordinate system of the vehicle. As shown in Ref. **Error! Reference source not found.** this tracking automatically performs a de-dopplerization thereby providing the frequency content on the source rather than at the receiver position.

Once the beamformed time signals have been computed, averaging of autopower spectra (using FFT) is performed for each focus point in the time interval at which the point was inside the applied covering angle of the array (for instance up to $\pm 35^\circ$ off-axis). The fact that the focus points follows the movement of the source means that the averaging process will not smear out the resulting map of the sound field in contrast to the case with stationary focus points.

Beamforming maps will include both the sources as well as their reflections, which can for instance be introduced by the ground below the array. If the ground is flat and rigid, and if the position of the microphones with respect to the ground is known accurately, mirror ground conditions can be assumed. That is, the sources can be assumed to have a mirror source below the ground, and the array can be mirrored as well. For mirror ground conditions the array is often shaped as a half-wheel placed on the ground, which means that the effective array will be a full wheel. This gives a higher vertical spatial resolution in the maps than the half-wheel alone.

2.2 Deconvolution

The resolution of the DAS maps can be further improved by applying deconvolution [9]. For deconvolution it is assumed that the source can be represented as a set of incoherent monopole sources on the mapping surface. This is a reasonable assumption when dealing with aerodynamic noise due to the uncorrelated nature of turbulence excitation.

Ideally, DAS should represent each monopole as a delta function in the map, with the level of the peak representing the pressure contribution from that monopole. In practice, however, the beamformer will have a limited resolution, meaning that the ideal delta function will be spatially smeared. This can be seen as a 2D spatial impulse response (also called the Point Spread Function, PSF) introduced by the beamformer. The PSF can be predicted for a given array configuration and source position. The idea of deconvolution is to compute the PSF, and deconvolve it with the DAS map to get back to the real sources as illustrated in Fig.1.

The output of DAS beamforming at a given frequency will be approximately equal to the true source power distribution convolved in 2D with a frequency-dependent PSF. Therefore the goal is to find the source strength vector, $\mathbf{A}$, in the following equation

$$\mathbf{DAS} \approx \mathbf{A} \otimes \mathbf{PSF}_0, \quad \text{with } \mathbf{A} = \{A_i\} \text{ and } A_i \geq 0 \quad (2.2)$$

where $\mathbf{DAS}$ is the Delay-And-Sum map and $\mathbf{PSF}_0$ is the PSF for a monopole on-axis in front of the array. The output from deconvolution basically is a map of the strengths, $\mathbf{A}$, of the monopoles, whereas DAS yields the pressure contribution from the source at the focus point. There are a wide range of deconvolution technique, but this paper considers only the Non-Negative Least Squares (NNLS) method based on Fast Fourier Transform (FFT) (see Ref. [9] for further details).

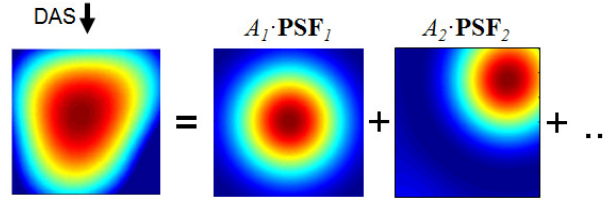


Fig. 1. Illustration of the idea behind deconvolution. The DAS map is assumed to consist of a linear combination of Point-Spread-Functions, $\mathbf{PSF}_i$ with individual amplitudes, A_i .

3 Measurement Results

In April 2013 array measurements were carried out at Skodsborg Station North of Copenhagen in Denmark on a set of regional trains. Four measurements were made: two passages of the Danish IR4 trains with four carriages, and two passages on the Swedish/Danish Oresund trains with six carriages. Both types of trains are electrical. Only trains driving north were considered, and they were all passing from left to right (seen from the array) at approximately 120 km/h. The platform is assumed to be acting as a mirror ground, which is why a half-wheel array was selected for the measurements (see Fig. 2).

3.2 Measurement Setup

The measurements were done with a 3 m diameter half-wheel array consisting of 7 arms with 6 microphones on each arm, and all microphones were fitted with wind shields. Two photocells – one on each side of the array – were pointing towards

reflectors on the opposite side of the tracks as shown in Fig. 2. The position of the train at given point in time is estimated using trigger pulses employed from the photocells. Assuming constant speed for the duration of the passage, the positions are estimated from the time difference between the trigger pulses. The array was positioned 6.29 m from the center of the track and 0.55 m above the tracks. The two photocells were at 8.55 m to the left of the array and 10.8 m to the right, respectively.



Fig. 2. Half-wheel microphone array (with 42 channels) on the platform at Skodsborg Station, Denmark. Two photo-cells were used for position calculation (indicated with red arrows).

3.2 Results – Oresund Train

Figure 3 shows the calculated pressure contribution using DAS on one of the Oresund trains at 448 Hz - 1088 Hz frequency. Note that the lowest 55 cm of the train is not included in the calculation, since this part was below the platform. Although the platform damps the sound radiation from the wheel/rails, high pressure contribution is still clearly seen at the locations of the wheels. This is due to the fact that the upper part of the wheels was above the ground, and also, the radiation from the wheel-rail contact point is likely to be transmitted due to reflections on the train. All bogies are seen to contribute more or less equally (with a pressure level of around 70 dB).

Although the wheels are dominating the maps in Fig.3, sound is also generated at the pantographs despite the relatively low train speed (120 km/h). Figure 4 shows a zoomed view on carriage 2 and 3 using DAS and deconvolution respectively. Higher resolution is clearly obtained around the wheels when applying deconvolution, even if the method is assuming the sound is emitted by a grid of incoherent point sources, which may not be the best assumption for vibrations in the wheels. The deconvolution maps also gives better results than DAS around the pantograph, where the ghost images are suppressed when comparing with the

DAS result. For this frequency band it is easy to see that noise comes from the top part of the unfolded pantograph as well as from the folded pantograph, which is exposed to a lot of wind because it is in front of the unfolded pantograph. Figure 5 shows a picture of the pantograph.

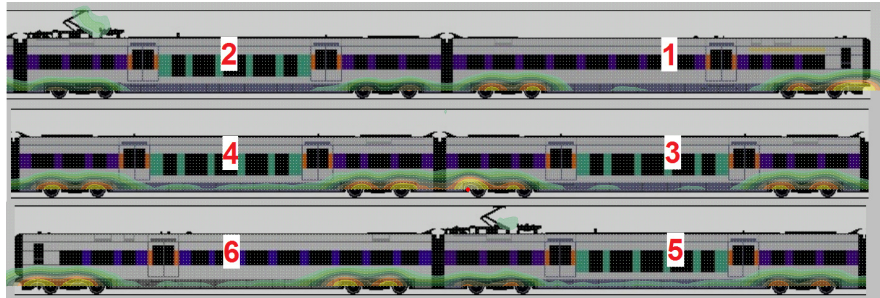


Fig. 3. A-weighted DAS pressure contribution on an Oresund train driving to the right. The carriage numbers are indicated on the map. Display range: 15 dB. Max. level: 70 dB. 448 Hz - 1088 Hz.

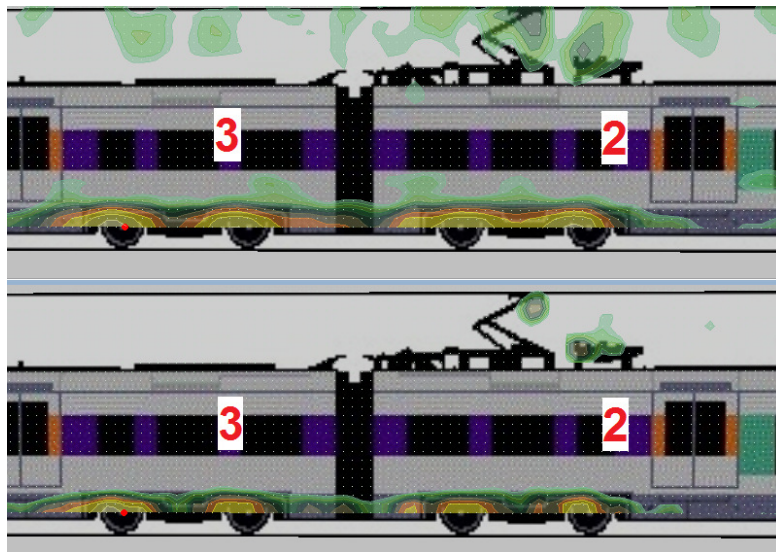


Fig. 4. A-weighted pressure contribution level from wheels and pantograph for an Oresund train at 864Hz-1120 Hz. Display range: 15 dB. Upper: DAS pressure contribution, max. level 62 dB. Lower: Deconvolution pressure contribution density, max. level 68 dB.



Fig. 5. Picture of pantograph on Oresund train. The train is driving to the right, and the front pantograph is folded

3.3 Results – IR4 Train

Next, calculations are shown for the IR4 train. Figure 6 shows the DAS maps at two different frequency bands. For the lower frequency band (448 Hz-1088 Hz) there is a significant source at the front of the train. This source is not present at the higher frequency band in Fig. 6. Notice also that the maximum level in the map is 82 dB, which is significantly higher than from any of the wheels. The source is not located at the front wheel but approximately 1 m in front of the wheel. The explanation for this source remains unknown, but a potential explanation could be that the train generates some aerodynamic noise on the front of the train. Alternatively, it could be noise from the rails, but the round shape of the hotspot in Fig. 5 indicates that the noise is very localized at a specific point. By playback of the array microphone signals, an audible noise component is clearly identified with a frequency around 600 Hz - 800 Hz. The same phenomenon was found in the measurements on another IR4 train. It was not identified for any of the Oresund trains.

The maps from deconvolution can be scaled so that it represents the intensities from the assumed monopoles. Hence by integrating these intensity maps over selected areas, the radiated sound power can be computed. Figure 7 shows the calculated sound power for the front of the train and for the bogies. The front has a peak at the 574 Hz and 640 Hz bands, with a level that is about 5 dB higher than the most radiating bogie. At other frequency the level from that area is lower than the bogies. The overall highest level of radiation happens around 1408 Hz by bogie 2 and bogie 4, which are the only bogies with traction.

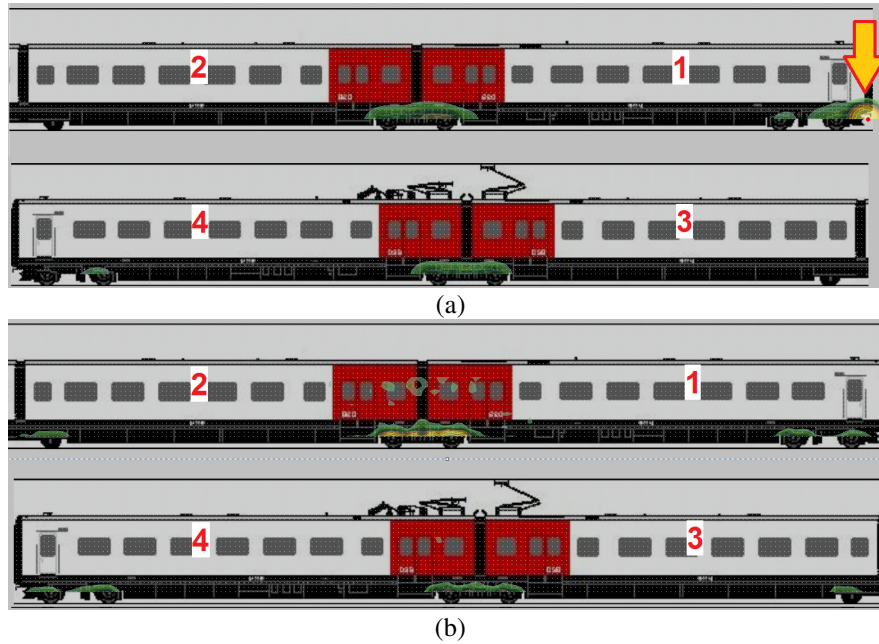


Fig. 6. DAS pressure contribution (A-weighted) on an IR4 train driving to the right. The carriage numbers are indicated on the map. Colors of the trains do not resemble the actual colors. Display range: 15 dB. (a) 448 Hz - 1088 Hz, max. level: 82 dB. (b) 1088 Hz - 2496 Hz, max. level: 79 dB.

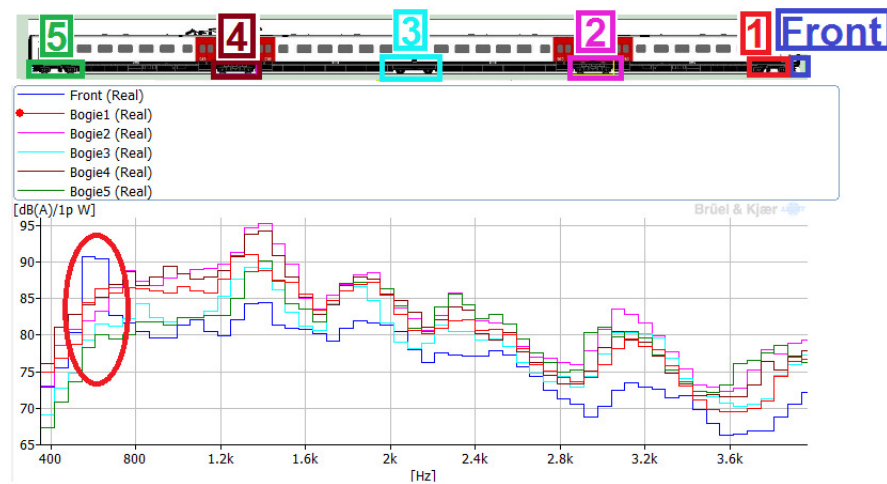


Fig. 7. Sound power (based on intensity maps) as a function of frequency (64 Hz bands) for different areas on the IR4 train. A peak is seen around 600 Hz from the front area of the train.

3 Conclusions

This paper describes a measurement system for mapping of noise sources on rail vehicles during pass-by. The system uses an array of microphones together with the measured position of the train as a function of time to calculate and visualize the sound field on the surface of the vehicle. The data is processed using a moving source Delay-And-sum approach, and deconvolution for improving the resolution even further. The presented results are based on a measurements made on Danish regional electrical trains (Oresund trains and IR4 trains) driving at about 120 km/h. Noise from the pantographs was clearly identified despite the relatively low speed of the train. Especially, deconvolution was efficient at pinpointing the position of those aerodynamic sources on the Oresund trains. It was seen that the IR4 trains had a strong noise source at the very front of the train around 600 Hz - 800 Hz. The reason for this is yet unknown. However, since the engines and traction are not located at the front bogie, and since the sound did not appear at the wheel location, a potential cause could be an aerodynamic phenomenon.

References

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