Microphone array measurements on high-speed trains in wind tunnels

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The present study evaluates the capabilities of the phased microphone array technique for the localisation and quantification of aeroacoustic sound sources of high speed trains in wind tunnels. The major challenge is to obtain a sufficient resolution of the sources with low source strength. The experiments were carried out using 1:25 models in the Aeroacoustic Wind Tunnel Brunswick (AWB) of the German Aerospace Center (DLR). This Göttingen – type wind tunnel has an open test section which is surrounded by an anechoic chamber. The microphone array consists of 143 microphones and is positioned outside the flow. In order to achieve reasonable results a shear layer correction is applied. Performing a phase-calibration can increase the signal-to-noise ratio, especially for higher frequencies. This procedure will be presented als well.

1 INTRODUCTION

Airplanes as well as any kind of ground vehicles produce aerodynamic noise which depends on the velocity. Especially trains became faster in the last few decades. Modern High-speed trains reach velocities up to 350 kilometres per hour. For this range of velocities aerodynamic noise is dominating and exceeds all other sources of sound like engine / gearbox noise, noise from aggregates like engine cooling, general noise from the bogies and interaction between wheel and rail. Figure 1 (from: [13]) depicts the relations between sound pressure levels of different sources of sound and the velocity of the train. In general, traffic noise is a problem for the residents which live beside the traffic route and decrease the comfort for the passengers inside the vehicle. For the reduction of the noise a detailed knowledge of the distribution and the properties of the sound sources is necessary. In the field of acoustics of high-speed trains both, investigations of the full-scale vehicle as well as testings in wind tunnels on models has been performed. Full-scale tests have the advantage, that the measurement takes place under real

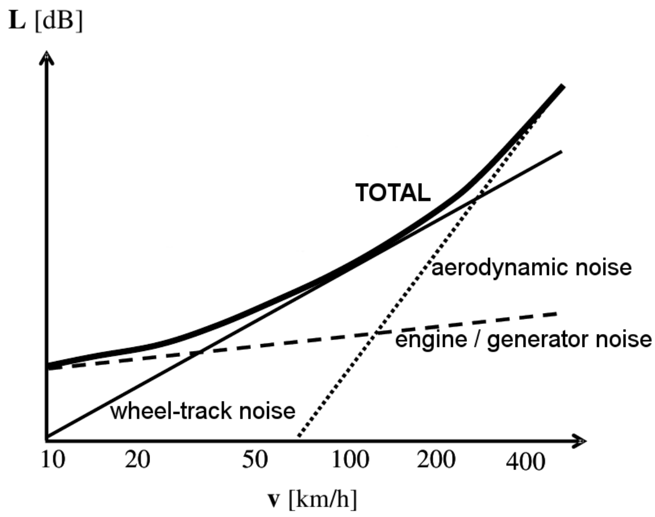


Figure 1: The relation between sound pressure levels of different sources of sound and the velocity of the train, from [13].

conditions and appropriate Reynolds numbers. The disadvantage is that these testings only can be performed when the train is already operational. It is not possible to analyse acoustics during baby joethe design process. Nevertheless, most of the earlier publications report on full-scale testings and have their focus on the so-called wheel-rail noise (see Barsikow et al.: [3, 4]). This kind of noise is generated by the mechanical interaction between the wheels and the rails. It depends on the conditions of rails and wheels like roughness or damping features of the bogies and the driving speed, of course. As already mentioned, at higher velocities aerodynamic noise reveals and in the last years aerodynamic noise became more and more focus of interest. Due to the development of computers and data acquisition systems in the recent years the number of microphones could be increased and beamforming techniques allow the separation of wheel-rail noise from aerodynamic noise, like noise from the pantograph, noise from the gaps between two cars and noise from components like antennas, and so on.(see Martens et al.: [2]).

To predict the aero-acoustic properties of a trains during the design process, wind tunnel testings on down-scaled models are fundamental. Yamazaki et al. [14] used beamforming techniques for the investigation of aerodynamic noise of a simplified train model in the wind tunnel. The focus of interest are the cavities of the bogies an the gaps between the cars. Based on this measurements, modifications for noise reduction were applied. Afterwards the noise reduction arrangements were verified in a wind tunnel as well as by full-scale testings. Other wind tunnel studies just point out investigations of parts of trains. One of the main topics is the acoustic of the pantograph (see: [6, 16]).

Still an open issue is a quantitative aero-acoustic study of the whole train, considering a model in a wind tunnel. Desirable is an identification of all aero-acoustic sources, a validation of the aeroacoustic measurement and a comparability to full-scale testings.

This study presents measurements on a 1 : 25 scaled model of the Inter City Express 3 (ICE3) at the Acoustic Wind tunnel of the DLR in Brunswick (AWB). This train is used for high speed long distance passenger traffic in Germany. The model is constructed for aerodynamic testings. It is less detailed and the surface is smooth. The gap between driving trailer and first car is

idealised by a rectangular gap and the bogie section, depicted in figure 2(a), is reproduced only by some details. Antennas, inlets or outlets for cooling are not realised on the model.
Generally, the open issues can divided into two categories:

1. Pure measurement technique questions:
   - capabilities and limitations of the used beamforming techniques
   - phase- and amplitude calibration
   - acoustically reflexions
   - influence of shear- or boundary layer on microphone array measurements
   - influence of the background noise level of the wind tunnel
2. General differences between full-scale testings and measurements in wind tunnels:
   - different Reynolds numbers
   - missing wheel-rail interaction at wind tunnel testings (in the case of drive-by tests)
   - different levels of itemisation / details of original train and model

These open issues complicate a comparison between wind tunnel testings with full scale drive-by testings.
The objective of this paper is to discuss problems which can occur during array measurements on down-scaled model in wind tunnels. It shows, that beamforming can leave room for misinterpretation. Capabilities and limitations are discussed, a phase calibration is demonstrated and problems concerning acoustically reflexions are shown.

2 METHODS

The measurement of aero-acoustic noise is a challenging objective due to the relatively low noise level of train models. Accordingly, a high effort concerning the measurement technique is necessary to localise the weak sound sources of a train. Beside a wind tunnel with a very low noise level a microphone array with a high number of microphones is necessary in order to obtain a reasonable signal-to-noise ratio (SNR) and to assure a good spatial filtering.
To gain more quantitative results, beside the test section a single $1/4$ inch microphone (Gras, type 40BF) was installed, as depicted in figure 2(b). This microphone is calibrated with a pistonphone.

2.1 The microphone array

The microphone array is constructed for out-of-flow measurements in open jet-wind tunnels. It consists of 143 microphones which are mounted on an aluminium lattice. The microphones of the type LinearX M51[1] are arranged in a three-dimensional array layout. The used layout results from a optimisation for a frequency range between 10 kHz and 35 kHz. The optimisation was performed in order to obtain a good spatial resolution and a good mainlobe-to-sidelobe ratio. Therefore, the response of a monopol source, positioned in front of the array, is considered. By shifting every single microphone consecutively the point spread function of the array can

[1] LinearX Microphones - Tualatin Sherwood, http://www.linearx.com

be optimised, so that it closely matches a pre-given objective function, in this case a three dimensional Gaussian distribution.

2.2 The phase calibration

Among other data, the beamforming algorithm requires the accurate position of all microphones. In-accurate microphone positions lead to phase uncertainties which decrease the quality of the beamfoming results. The patented[2] phase calibration procedure works similar to the well known global positioning system (GPS): several monopole-like acoustical point sources with known positions and a reference microphone which is installed close to the sound sources are used to compute the position of the microphones of the array in the three-dimensional space. The procedure allows an estimation of the microphone positions with an accuracy better then 1.0 mm. This accuracy is necessary especially for higher frequencies. The procedure is discussed in Lauterbach et al.[1].

2.3 Algorithms

Beamforming

Standard beamforming in the frequency domain was performed.

$$A = \frac{\mathbf{e}^{\dagger}\mathbf{W}\mathbf{R}\mathbf{W}^{\dagger}\mathbf{e}}{M^2} \tag{1}$$

Thereby, $\mathbf{R}$ denotes the cross-spectral matrix, $\mathbf{W}$ a weighting matrix, M the number of microphones and $\mathbf{e}$ the steering vector. $(.)^{\dagger}$ indicates the complex conjugate and transposed vector or matrix. Especially in noisy surroundings one can achieve a higher signal-to-noise ratio by subtracting the diagonal elements[9], the auto spectra, of the cross-spectral matrix. Equation 1 is modified as follows:

$$A = \frac{\mathbf{e}^{\dagger}\mathbf{W}\mathbf{R}_{\mathrm{diag}\,=\,0}\mathbf{W}^{\dagger}\mathbf{e}}{M^2 - M}. \tag{2}$$

Shear layer correction

Furthermore, in the presented case the array is positioned outside the flow and the sound which is emitted by the model has to propagate through the wind tunnel shear layer. Phase shifts and variations in amplitude, induced by refraction on the shear layer, are corrected according Amiet[10, 11]. This correction is applied by a modification of the steering vector.

Focused spectra

Besides noise maps, which map the distribution of sound sources, an integration technique described by Brooks et al. [8] is applied in order to compute sound pressure level spectra for specified scan areas. For the integration technique the diagonal elements have not been subtracted because this procedure does not work reliable here. It can be assumed that this is

[2] Patent DE 10 2008 017 001.1-09

due to the fact, that the cross-spectral matrix is not positive definite anymore.

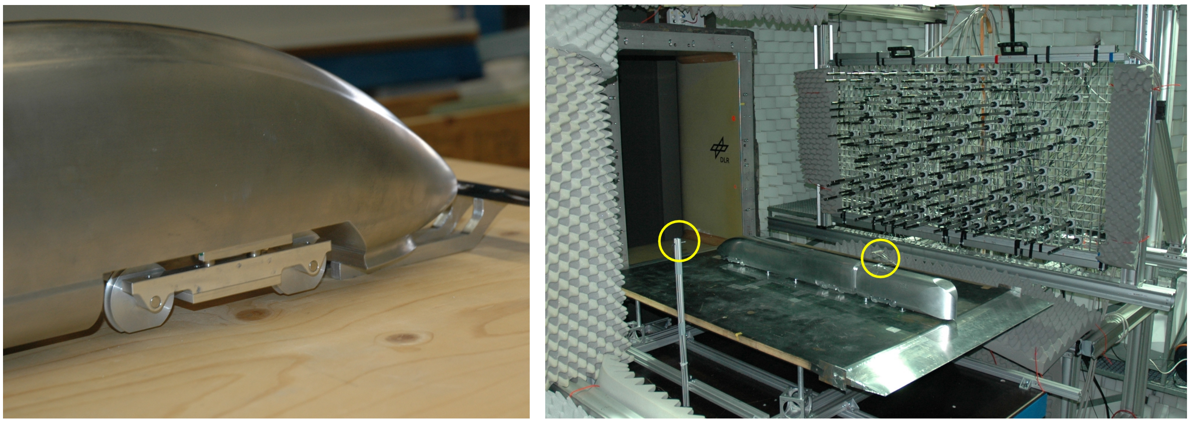
Identification of mirror sources

One major problem during wind tunnel testings are acoustical reflexions. Inside the test section of the wind tunnel normally there are acoustically hard surfaces which reflect impinging sound waves. Due to aerodynamic issues one can not avoid all of these surfaces, e.g. it is technically complex to construct a sound absorbing wind tunnel nozzle or a splitter plate where the model is installed on. One can make use of the physical property of the main source and the mirror source: they are coherent. Horne et al.[5] proposed a modification of the beamforming algorithm which evaluates the coherency between two scan points as follows:

$$B = \frac{|\mathbf{e}^{\dagger}\mathbf{R}\,\mathbf{d}|^2}{(\mathbf{e}^{\dagger}\mathbf{R}\,\mathbf{e})(\mathbf{d}^{\dagger}\mathbf{R}\,\mathbf{d})} \tag{3}$$

Here, **e** and **d** are the two steering vectors, corresponding to the two scan points. Later in this paper, coherence maps are presented. Therefore, one steering vector is kept constant and steers on a reference focus point. The other one varies and corresponds to the scan points in the map.

3 SETUP



(a) The bogie section of the ICE3 model

(b) Setup in the AWB: Inside the test section on a splitter plate the model of the ICE3 is installed. In the background outside the flow the microphone array is mounted. In the foreground the one can see the single microphone, marked by a circle. The Pantograph on top the train is also marked.

Figure 2: Detailed view of the model and overview of the setup.

The experiments were carried out in the Aeroacoustic Wind Tunnel facility (AWB) of the German Aerospace Center (DLR) in Brunswick[12]. This open-jet Göttingen-type wind tunnel is optimised for aero-acoustic testings and has a low background noise level. The test section is surrounded by an anechoic chamber and the whole air duct of the tunnel is covered with noise-absorbing foam. The nozzle has the dimensions 80 by 120 cm. The maximum flow velocity is 65 m/s. The train model was installed on a splitter plate, which has an elliptical leading edge and a sharpened trailing edge. This plate is positioned 10 cm above the lower edge of the nozzle to peel off the wind tunnel shear layer. At the leading edge of the splitter plate a new boundary layer is formed which is thinner than the wind tunnel boundary layer. The aim is to keep the boundary layer as thin as possible. In the full-scale world the train penetrates the fluid, which is at rest. Neglecting influences like wind one will not expect a boundary layer on the ground.

The ICE3 model is less detailed and the surface is smooth. The gap between driving trailer and first car is idealised by a rectangular gap and the bogie section, depicted in figure 2(a), is reproduced only by some details. Antennas, inlets or outlets for cooling are not realised on the model. As already mentioned, the main aero-acoustic sound source is the pantograph, and some of the experiments were performed with an pantograph on top the train.

4 RESULTS

4.1 Train aero-acoustics

First of all, spectra of the wind tunnel background noise (empty test section), the clean train and the train with pantograph are considered, all at $U_\infty = 40$ m/s. The data were acquired with the calibrated microphone beside the test section. The results are shown in figure 3. All data have been recorded with a sampling frequency of 150 kHz. The spectra are computed using hanning weighted windows with 8192 samples and 50% overlap. This results in a frequency resolution of 18.31 Hz.

The comparison of the spectrum of the background noise (blue line) with the clean train configuration without pantograph (red line) shows that the train produces a broadband noise starting at 100 Hz. The sound pressure level of the train exceeds the background noise by 5 to 10dB. The overall shape of the spectrum is quite smooth what means that there are no strong tonal noise components, except of the region between 2000 Hz and 3000 Hz. Here, the spectrum starts getting more “wavy”. The comparison of the sound emitted by the train with and without the pantograph shows that, the pantograph also emits broadband noise at higher frequencies, starting at 4000 Hz. Furthermore, the spectrum of the pantograph is not as smooth as the spectrum of the clean train configuration.

In the next step a beamforming approach is presented to give a overview over the sound source distribution. Both measurements in figure 4 were conducted at a flow velocity of $U_\infty = 40$ m/s. Figure 4(a) shows the clean train configuration and figure 4(b) the configuration with pantograph on top of the train. As on can see, there are three main sources of sound: The bogie sections, the gap between driving trailer and first car and, last but not least, the pantograph.

The bogie sections represent cavities and one can assume that the aero-acoustic mechanisms are similar to the classical cavity noise. Rossiter et al.[7] proposed a semi-empirical model to describe the acoustic modes which can be excited in cavities. Note, that a comparison is difficult because the shape of the bogie cavities differs to classical rectangular cavities described in literature. The first bogie is the strongest sound source. This may be caused by different aspects: The ICE3 has a front spoiler which accelerates the flow, and leads it directly into the cavity.

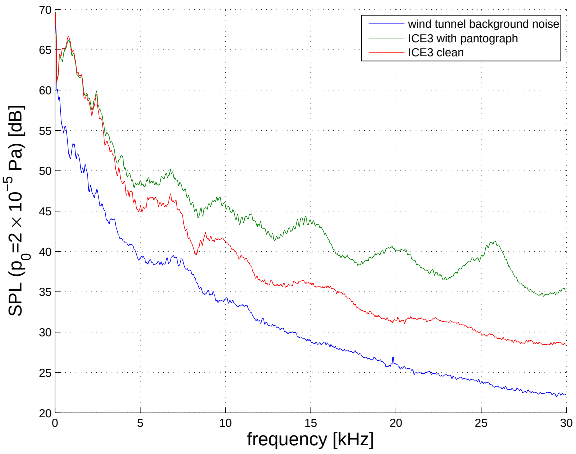
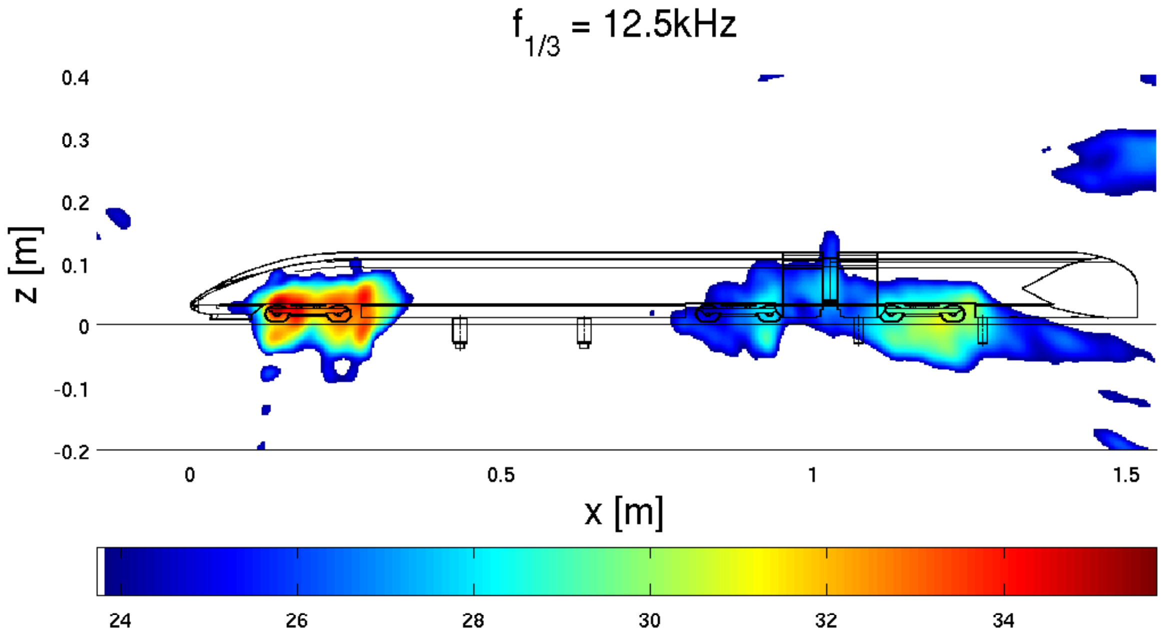


Figure 3: Spectra of the wind tunnel background noise, the configuration ICE3 with pantograph and the clean ICE3. All at $U_\infty = 40$ m/s.

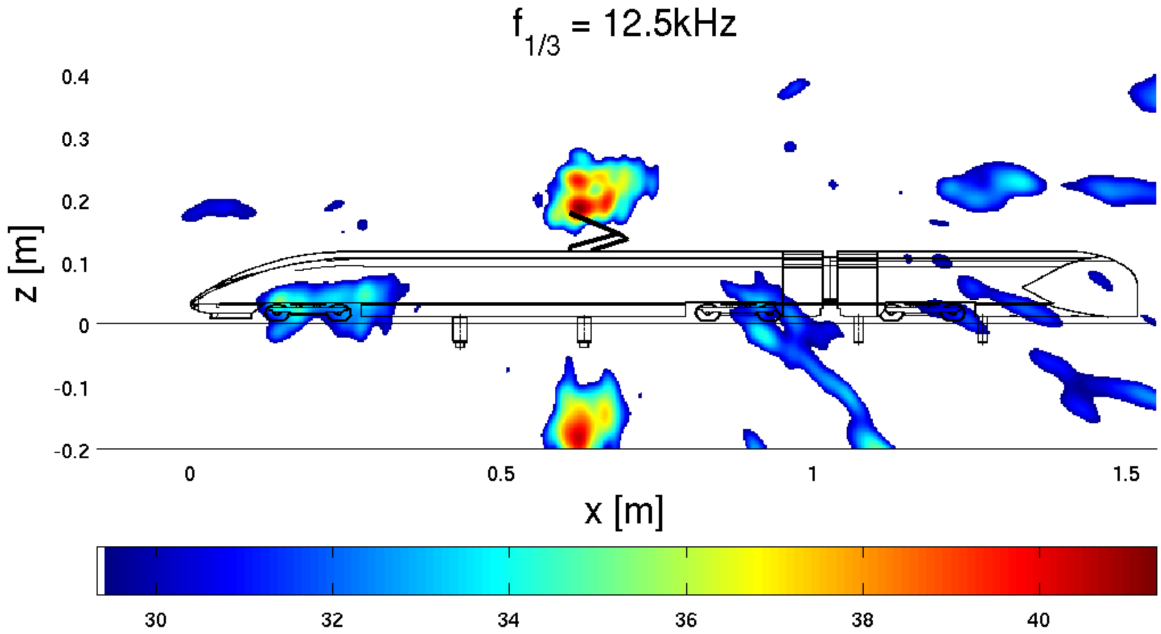
Aside from that, the boundary layer is thin and one can assume that it is laminar. Laminar flows over cavities always produce a higher noise level with tonal components. To quantify the cavity noise from the train, the integration method is applied in order to compute focused spectra. At first we consider a measurement at $U_\infty = 40$ m/s, depicted in figure 5(a). For comparison, a spectrum from a single microphone is also plotted. As one can see, up to 3 kHz the spectra have a similar shape, but differ in the overall level. The single microphone is calibrated, but for the array microphones a unitary sensitivity for all microphones was assumed. Other reasons are the coherence loss due to the sound propagation through the wind tunnel shear layer, the source coherence and the directivity of the cavity. Determination of absolute levels from array measurements is a complex task with many free variables (see Oerlemans et al.[15]). The advantage of the integration method is a better resolution of weak contributions. In the presented case the integration method allows to detect a peak at $f = 3442$ Hz, which is not present in the single microphone spectrum. The results for measurements at different flow velocities between 20 m/s and 60 m/s are demonstrated in figure 5(b). At first sight it seems to be surprising, that three peaks at $f = 769$ Hz, $f = 2455$ Hz and $f = 3442$ Hz are not flow velocity depended. As already mentioned cavity noise is concerned. Obviously, a certain cavity mode is activated and within the treated velocity range no other mode can be excited. The quintessence is, that it is problematic to extrapolate these results to the full-scale conditions. Initially, further studies have to disclose the mechanisms of this special cavity.

The pantograph is the next sound source which is discussed in more detail. The single microphone spectrum in figure 3 shows that the pantograph emits a broadband noise.

As one can see in figure 4 the sound pressure level of the 12.5 kHz 1/3 octave band of the pantograph surpasses the cavity noise of the first bogie by about 6 dB. The spectrum in figure 6(a) shows a linear velocity dependency of the tonal components. The model of the pantograph consists of several cylindrical elements with different diameters and different orientations to the mean flow. Therefore one can suggest that various Kármán's vortex streets form what results in tonal noise of different frequencies. The vortex shedding frequency f behind a cylinder in the cross flow depends linear on the mean flow velocity U_∞ and can be described by the



(a) Clean train configuration.

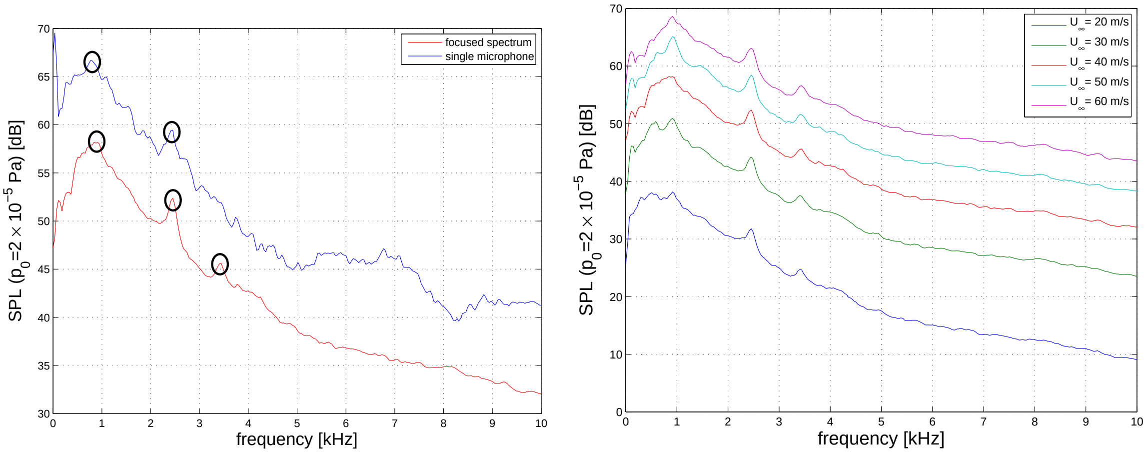


(b) Train with pantograph

Figure 4: $1/3$ *octave noise maps for two different configurations, both @* $U_\infty = 40$ *m/s, plotted with a dynamic of 12 dB, colour-coded is the sound pressure level in dB.*

dimensionless Strouhal number:

$$\mathrm{Sr} = \frac{fL}{U_\infty} \tag{4}$$

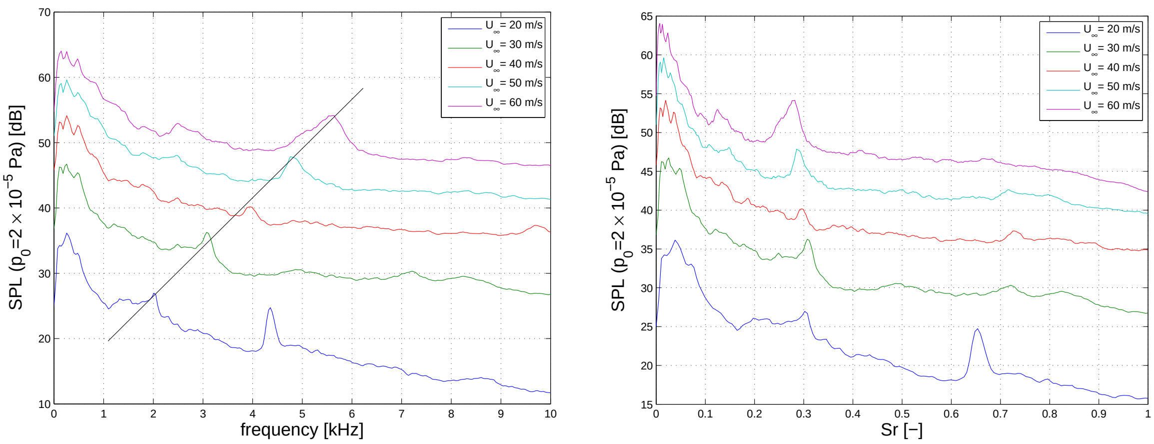


(a) Spectrum from the single microphone and a integrated spectrum

(b) Integrated spectra for different flow velocities. Scan area is the first bogie section

Figure 5: Spectra of the configuration train with pantograph.

L denotes a characteristic length (typically the diameter of the cylinder). Several investigations have shown, that the Strouhal number is almost constant over a wide range of the Reynolds number between $\mathrm{Re} = 0.5 \times 10^3$ to 1×10^5 with $\mathrm{Sr} = 0.2$. Figure 6(b) shows the same data as presented before, but here plotted over the Strouhal number to highlight the linear frequency dependence. $L = 0.003$ m has been adopted as characteristic length. This dimension corresponds to the typical diameters of the elements of the pantograph. The Strouhal number is quite constant and decrease only slightly from $Sr = 0.31$ to $Sr = 0.28$ with increasing flow velocity.



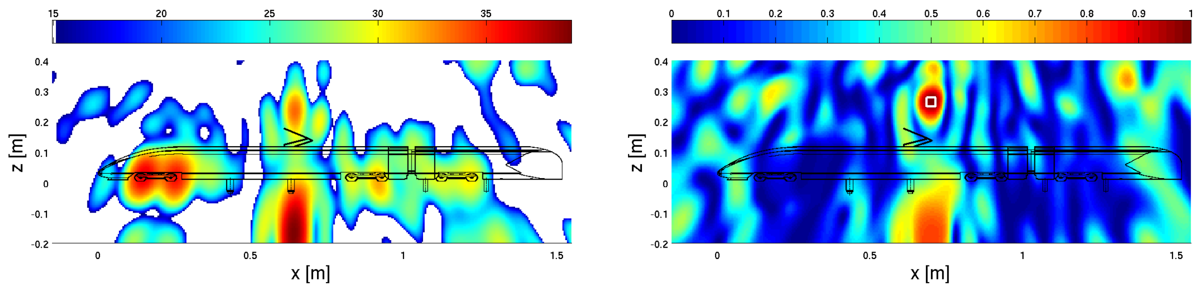
(a) Scan area is the pantograph.

(b) Spectra as in 6(a), but plotted over the Strouhal number.

Figure 6: Integrated spectra for different flow velocities.

4.2 Identification of mirror sources

In the next step a narrow-band noise map is presented, which will lead to the problems of reflexions. Figure 7(a) points out again the $U_\infty = 40$ m/s case with the pantograph on top the train. The noise map is computed for the frequency $f = 3955$ Hz. This frequency is identified in figure 6(a) as a tonal contribution to the noise of the pantograph. As we can see in figure 7(a) strong reflexions on the splitter plate occur. The reflexions are stronger than the source itself. As described in section 2.3 source coherence in beamforming maps can point to mirror sources. The coherent map in figure 7(b) reveals, that the spot on the plate is coherent with the noise of the pantograph. Consequently, one can assume that the spot on the plate is a mirror source. On one hand, one might conclude that for aero-acoustic testings a noise absorbing splitter plate is necessary. On the other hand, the question arrises why the mirror source is stronger than the pantograph itself. One can make a guess that the acoustical directivity of the pantograph is responsible for this. Assumed, the horizontal parts of the pantograph emit a strong dipole sound field in vertical direction, then the open question can be explained by a simple geometric acoustic approach.
Lack of knowledge of the source directivity together with the given circumstances by the setup can lead to misinterpretation of microphone array measurements.



(a) Noise map for the frequency $f = 3955$ Hz, @ $U_\infty = 40$ m/s, plotted with 24 dB dynamic range

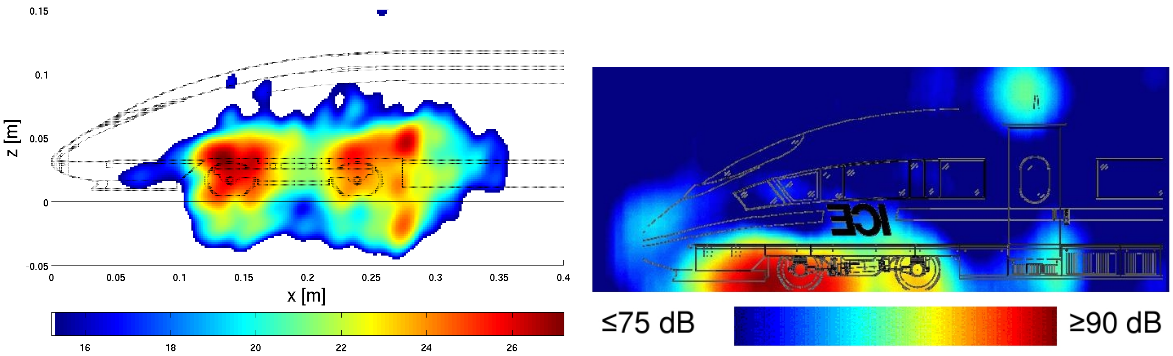
(b) Source coherence between a reference scan point and the whole scan area. The reference point is marked by a white box.

Figure 7: Detecting reflexions by regarding source coherence.

5 CONCLUSIONS AND OUTLOOK

Beamforming technique is a suitable approach for the investigation of sound sources on down-scaled models in wind tunnels. Due to the fact that the sound sources of a train model are relatively weak, a high experimental effort is necessary. The used microphone array with 143 microphones enables the resolution of different sound sources of the train model. A wind tunnel with a low background noise level is essential. It turns out that noise from the bogie section within the regarded velocity range is not velocity depended. As long as the mechanism of the cavity noise is not clear, it is not possible to extrapolate the results from the wind tunnel testings to the full-scale case.
Noise from the pantograph contains tonal components. These frequencies are linear velocity

dependent. In the presented setup strong acoustical reflexions of the noise from the pantograph occur, clearly identified by a coherence map. The strong mirror source on the splitter plate indicates that the pantograph behaves probably like a dipole with vertical direction.
If the open issues are solved, a more quantitative comparability of wind tunnel testings with full scale testings will be possible. Figure 8 gives an impression of the current status. Note, that in the case of the wind tunnel measurement no wheel-rail interaction takes place. Nevertheless, the results match qualitatively, what leads to the conclusion that it makes sense to conduct aero-acoustic testings of trains in wind tunnels.



(a) 20 kHz 1/3 octave band of the wind tunnel measurement at $U_\infty = 40$ m/s.

(b) 0.8 kHz 1/3 octave band of the drive-by measurement at $U_\infty = 92$ m/s. From [[2]

Figure 8: Comparison between wind tunnel test and full-scale drive-by test.

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