



APPLICATION OF BEAMFORMING AND DECONVOLUTION TECHNIQUES TO AEROACOUSTIC SOURCES AT HIGHSPEED TRAINS

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ABSTRACT

The experimental analysis of aeroacoustic sources requires the presence of flow. Acoustic measurements with microphones in the flow or in the presence of unwanted flow-induced sources have a number of practical limitations. The nature of these limitations is briefly reviewed. It is then explained how microphone arrays, beamforming and deconvolution techniques can be used to overcome these limitations. A number of measurements at different scale models of highspeed trains (scale between 1:87 and 1:1) is used as an illustration. Using these examples, in-flow measurement techniques, the separation of sources and unwanted noise, the scaling and the extraction of quantitative spectra are discussed.

1 INTRODUCTION

Noise sources at trains can be thought of falling into one of three categories [1]. First, the noise connected with the engine and powertrain is generally important at slow speeds. Second, the wheel and track rolling noise dominates at a wide range of speeds for conventional trains such as freight trains and regional trains. Finally, aerodynamic noise sources at trains become important at higher speeds and dominate the noise produced by highspeed trains.

The pantograph of such trains is of special importance. The flow around its supporting structure and the contact strips causes the generation of sound making it one major aeroacoustic source. Another major source region are the bogies, especially the leading one. Apart from these major sources there are a number of other aeroacoustic sound sources such as parts protruding from the roof (antennas etc.) or the sides (steps, door handles etc.) of the train.

Noise control at all these sources requires to predict and to characterise the influence of design parameters on the generation of sound. While it may be possible to find some answers using mathematical models and simulation tools, the experimental characterisation of the sources remains necessary for a successful design. One possibility is to conduct measurements during the high speed pass-by of trains. The contribution of the different noise sources can then be separated using directional microphone arrangements such as mirrors or microphone arrays. However, such measurements require an operational highspeed train and it is not practicable to compare a number

of different designs. In addition, during the pass-by non-aeroacoustic sources such as rolling noise are present complicating the characterisation of aeroacoustic sources.

One possible solution is to do measurements in a wind tunnel at a train at rest. Then, only aeroacoustic sources are present and design changes can be researched more easily. However, acoustic measurements are preferably done in special wind tunnels with relatively quiet flow and a test with a full-scale train would require a huge and very costly facility. Thus, only aeroacoustic tests of scale models or sub-assemblies of the train are practicable. In what follows, the ratio-nale for the use of microphone array beamforming and deconvolution techniques in such tests is discussed and illustrated using some examples.

2 MATERIALS AND METHODS

2.1 Acoustic measurements in wind tunnels

The experimental analysis of aeroacoustic sources in a wind tunnel requires the presence of flow. In general, acoustic measurements will be performed using microphones, that are nothing else than sensitive dynamic pressure sensors. Thus, if the microphone is placed in the flow, it will sense not only sound pressure but also any (non-acoustic) turbulent pressure fluctuations. While a number of devices such as wind screens and nose cones can be used to reduce the sensitivity to the turbulent pressure fluctuations, it is not possible to eliminate this problem completely. Consequently, it is very difficult to get reliable results from measurements with individual microphones, especially with weak acoustic sources in high speed flows. One solution is to use wind tunnels with an open test section that make it possible to place the microphones out of the flow.

Another problem is that the necessary presence of flow produces also additional flowinduced sources in the wind tunnel itself. While in specially equipped aeroacoustic wind tunnels the sound from these sources can be of minor importance, in many practical situations these sources produce a background noise that influences the results of the measurements. Moreover, in almost every case there is more than one source or source region of interest. While the contributions from these sources should be measured separately, it is physically not possible to operate them independently. This makes it very difficult to get results for each individual noise source mechanism from measurements with single microphones.

The application of multiple microphones (microphone arrays) with simultaneous processing of their output signals offers a solution to these problems. By using this technology it is possible to characterise multiple sources separately and remove background noise. Moreover, turbulent pressure fluctuations can also be removed from the results quite effectively. To this end, the microphone signals are digitally filtered in a process called beamforming.

2.2 Microphone array beamforming

In beamforming, the output signals from an array of microphones are used as the input for a spatial filter [2] that is designed to let pass only those components that originate from a certain location or direction. In other words, only certain wavenumber vector components are filtered out while all others are suppressed. These are those associated with other origins or with pressure fluctuations that propagate with a speed different to and lower than that of sound.

The beamformer filter is realised by calculating the weighted sum of the microphone sound pressures (components of the vector \mathbf{p}) using complex-valued weight factors. The vector $\mathbf{h}(\mathbf{x}_t)$ of these factors is called steering vector and depends on the assumed origin \mathbf{x}_t of the sound waves. The filter output is then:

$$p_F(\mathbf{x}_t) = \mathbf{h}(\mathbf{x}_t)^{\mathrm{H}} \mathbf{p},\tag{1}$$

where the superscript H denotes the hermitian transpose. The use of the real-valued auto power

spectrum B of the filter output instead of p_F enables the use of the cross spectral matrix of microphone signals G as basis of the calculations in the frequency domain:

$$B(\mathbf{x}_t) = E\{p_F(\mathbf{x}_t)p_F^*(\mathbf{x}_t)\} = \mathbf{h}^{\mathrm{H}}(\mathbf{x}_t)E\{\mathbf{p}\mathbf{p}^{\mathrm{H}}\}\mathbf{h}(\mathbf{x}_t) = \mathbf{h}^{\mathrm{H}}(\mathbf{x}_t)\mathbf{G}\mathbf{h}(\mathbf{x}_t)$$
(2)

where $E\{\}$ denotes the expectation operator.

The parallel application of many of such beamformer filters, each designed for a different origin of sound waves, is used to construct maps of sound pressure contributions from different sources ('acoustic photographs'). Unfortunately, the spatial filters have non-ideal characteristics. This leads to spatial passbands that can be much wider (spatially) than desired and stopbands with less attenuation and with ripple. The consequences for the maps of sound pressure contributions are that closely spaced sources can not be clearly separated and the image of a single source is accompanied by weaker ghost images of that source. To mitigate these problems, a number of deconvolution techniques are available that computationally remove the known or otherwise estimated influence of the real filter characteristics from the result. Here, the CLEAN-SC deconvolution method [3] was applied.

The deconvolved maps can be seen as ideal images of the source contribution. Thus, it is straightforward to yield a quantitative estimation of source spectra, which was done by simple integration of the map over the regions where the sources of interest (in case of a train model e.g. the pantograph) are situated.

2.3 Model measurements

The results of measurements on scale models are different from those on real size objects. However, it is still possible to draw conclusions with relevance to the real size object case. The key is to take the proper relation between the quantities for the scale model and those for real size object in account. To this end, it is common practice to use dimensionless quantities for the analysis of the results.

Most aeroacoustic scale model measurements can be characterised using the sound pressure p, a characteristic flow speed U, a characteristic dimension d, the frequency f, and the properties of the fluid such as the speed of sound c, the density ρ and the viscosity μ . From these, the dimensionless quantities Mach number Ma = U/c, Helmholtz number He = fd/c, Strouhal number Sr = He / Ma = fd/U, and the Reynolds number Re = $\rho dU/\mu$ can be derived. All these quantities can be calculated for both the model scale and the real size case. If they would be all the same for both cases (which is not realistic), then the dimensionless sound pressure P = $p/\rho c^2$ would also be the same.

In the present research, the fluid was always air at approximately room temperature. Thus, c, ρ and μ were not different compared to the real size case. Consequently, in order to get the same Mach number, the flow speed needed to be the same as in the real size case. To get the same Helmholtz and Strouhal numbers for smaller characteristic lengths (model scale), higher frequencies than in the real size had to be considered. It was not possible to maintain the Reynolds number. This would have required to alter the fluid properties considerably [4] and such an option was not available in the facilities used for the tests.

2.4 Example cases

Here, the application of beamforming and deconvolution techniques shall be discussed using three different cases. The first one is a setup with an 1:20 scale model of a high speed train that was analysed in the large wind tunnel at TU Berlin (Fig. 1). The acoustic measurements were done using a microphone array with an aperture of 38 cm and 64 electret microphones with 6 mm diameter that are arranged in 7 logarithmic spiral arms. The wind tunnel that was operated at wind speeds up to 35 m/s (126 km/h) has a closed measurement section that requires the microphone

array to be placed in the flow. Two provisions minimized the turbulent pressure fluctuations at the array microphones. First, the plate holding the array microphones was not mounted in the wall, but was equipped with a leading edge and mounted separately in the flow. Thus, the distance available for the turbulent boundary layer growth was much shorter and consequently it was much thinner. Second, the array microphones were covered with an additional flat windscreen made of very permeable cloth. Because of the small aperture of the array it was not possible to analyse both regions of interest - the pantograph and the train head - at once. Instead, the array was successively used at two different positions (Fig. 1(a)). The wind tunnel used is not fully equipped as an aeroacoustic wind tunnel, thus the background noise was considerably high.

The second case to be considered is a setup with a scale of 1:87 that was realized in the aeroacoustic wind tunnel at the Brandenburg University of Technology Cottbus. A model of the Intercity Express 3 (ICE3) that is readily available as a 'H0' gauge model railway train was used for the measurements and placed on a ground plate directly behind the exit of the wind tunnel nozzle (Fig. 2). The wind tunnel was operated at speeds up to 72 m/s (260 km/h). The acoustic measurements were done using the same microphone array, but placed out of the flow in a distance of 36 cm. The microphone signals were sampled at a rate of 102.4 kHz, thus allowing to produce results up to approx. 50 kHz (corresponding to the 500 Hz third octave band in the real size case).

While the very small scale allows for the simultaneous measurement of two complete railcars, the Reynolds number is 87 times smaller than in the original case and thus very different. One can expect that this prevents the correct quantitative analysis of such sound generating processes that are mainly caused by the boundary layer flow phenomena. Moreover, the train is not moving relative to the ground, making the flow under the train unlike that for the real size moving train. This circumstance makes a conclusive analysis of sound sources in the region of the bogies somewhat harder.

The third case concerns a 1:1 model of a train roof section with pantograph [5]. This setup was analysed at wind speeds up to 78 m/s in a large aeroacoustic wind tunnel facility (Fig. 3). At a full-size train travelling, a turbulent boundary layer of a certain thickness will build up in flow above the roof. This boundary layer will influence the sound generation at the pantograph both in its upper and lower operating position. The wind tunnel section is much to short to allow for the development of a realistic roof boundary layer. Nevertheless, to mimic the boundary layer velocity profile a fence of spires was used at the leading edge of the model. While the fence successfully controls the boundary layer flow, it acts also an aeracoustic source that produces noise. In order to be able to separate these sources from each other, acoustic measurements were carried out with an array of 84 microphones with an aperture of 4 m.

3 EXAMPLE RESULTS AND DISCUSSION

One of the regions of interest for the 1:20 model train was the pantograph. The aim of the analysis was to compare different versions for the pantograph and the train roof regarding the noise emitted in order to help making design decisions. This required to have spectra available for this aeroacoustic source that are not deteriorated by background noise and other sources.

Fig. 4(a)-(f) show example sound maps from measurements with the microphone array at position A for the 5 kHz, 6.3 kHz and the 10 kHz third-octave band. Because of the 1:20 scale of the model, this corresponds to frequencies between 250 Hz and 500 Hz, for the real size case. The maps resulting from the application of beamforming clearly show the influence of the imperfect filter properties. While the approximate position of any sources appears, the dynamic range of the map is small and beside the major sources some additional minor sources seem to be present. Moreover, a source area is present downstream that represents the background noise from the wind tunnel exit vanes.

Both the minor sources and the background noise vanish in the maps when a deconvolution technique (CLEAN-SC) is applied. Then, the maps clearly show the position and strength of the

sources. Using the sector shown in Fig. 4(g), the maps can be integrated to yield a spectrum for the contribution of the pantograph region to the measured sound pressure level. The resulting spectra for different designs of the pantograph and the roof section are shown in Fig. 4(h). The different modifications made to the baseline design show a reduced sound level, especially for the tonal components. While the lower frequency bands contain more sound energy, the higher frequency range with the tonal components is still important because it makes an noticeable contribution to the A-weighted overall level.

Fig. 5 shows example sound maps for the H0 gauge model train. Unlike in the case of the 1:20 model, where common two-dimensional sound maps were used, in this case the sound maps were calculated using a three-dimensional grid. While the computational effort is many times higher, this allows to isolate unwanted background noise from sources that have another distance to the array as the sources of interest. The maps show the bogic region, the pantograph and the inter car gap between the first and second car as sound sources. Again, the quantitative contribution of these sources were calculated by integration of the map. This time, block-shaped volumes (Fig. 5(c)) were used.

From the analysis of multiple measurements that were taken at a number of different speeds between 30 and 72 m/s it is possible to draw conclusions about source characteristics. The dependence of the sound pressure from a certain source on the wind speed can often be approximated by the simple model $p_{\rm rms} \propto U^n$ [6]. If this model applies, the scaled sound pressure level

$$L_{p,\text{scaled}} = L_p - 10n \lg(U/U_0) \, \text{dB} \tag{3}$$

will be the same for all measurements regardless of the wind speed. However, if frequencydependent sound levels such as third-octave band levels are considered, the shape of the spectrum must be taken into account.

A distinction between two different cases can be made. In the first case, the spectral shape does depend on the ratio of sound wavelength and a characteristic length, but not on the wind speed (or this dependence is weak and can be neglected). Then, the spectrum can be characterised in terms of the Helmholtz number, that can be seen as a dimensionless frequency. The scaled levels in this spectrum will be the same regardless of speed. In the second case, the spectral shape does depend on both characteristic length and speed. To get scaled spectral levels that are the same for all wind speeds in this case, the Strouhal number must be used as a dimensionless frequency.

Fig. 6(a) shows the scaled sound pressure level from the first bogie using a scaling exponent of six. This exponent was found to produce a minimal deviation from the model (3) in the least square sense. It can also be derived from theory for aeroacoustic dipole sound [6]. To allow conclusions for the real size case, the spectrum is given depending on a Helmholtz number that utilises the gauge width as characteristic dimension. For the second bogie (Fig. 6(b)) the scaled level is considerably lower than for the first. While the model from (3) fits the spectra from the first bogies nicely, it is less good for the second bogie at lower wind speeds because the scatter of the data points is larger. This could result from a dependence on the Reynolds number that is not part of the model.

The noise from the pantograph is governed by a tonal component due to periodic vortex shedding at the contact strips that is speed dependent, but has also broadband components. In the lower operating position the broadband noise is the major source and again has an U^6 dependency, as can be seen in Fig. 6(c). In the upper operating position this dependency holds only for those frequency ranges without influence from the tonal components (see Fig. 6(d) for He < 0.5). The tonal component can be better characterised using a Strouhal number based on the contact strip diameter as characteristic dimension. Even though the pantograph has two contact strips, the vortex shedding frequency that governs the tonal peak (see Fig. 6(e)) in the spectrum agrees with the value of Sr = 0.2 that was found for the flow around a single circular cylinder in the past (see [7] for an in-depth discussion). For the peak level however, a scaling exponent of four fits best and was applied in Fig. 6(e). The speed dependency of spectral shape of the noise from the inter-car gap is less distinct (Fig. 6(f)). Using the model from (3) again an exponent of six gives the best results, but the scatter is quite large (>10 dB). Interestingly, some temporary modifications at the gap (it was partially closed using modelling clay) had no distinct influence on the results, but altered the sound pressure level by less than 2 dB.

Finally, Fig. 7 shows example results from the measurements at the real size pantograph. The same principles as for the scale model are applied for the analysis. The three-dimensional example sound map in Fig. 7(a) clearly shows the collector head with the contact strips and the knee of the pantograph as the major noise sources for this position of the pantograph. Moreover, the fence of spires shows itself as a background noise source. Some other background noise is produced by cables and instrumentation (not shown) at the wind tunnel floor.

The peak frequency of the tonal component of the noise from the pantograph is relatively low (approx. 500 Hz at 280 km/h). Thus, the A-weighted spectrum of the sound pressure level is not governed by the tonal component, but is mainly broadband. The application of the model (3) yields again an exponent of six that best fits the results best. This is in agreement with the findings for the broadband noise at the model scale pantograph and allows to extrapolate to higher speeds that cannot be realized in the wind tunnel (Fig. 7(c)).

4 SUMMARY

The application of beamforming and deconvolution techniques to aeroacoustic sources at highspeed trains is especially helpful for the analysis of train models in wind tunnels. It is shown that such analysis benefits from the ability to separately quantify sources and to mitigate the influence from background noise and from turbulent pressure fluctuations. Results from different model scale measurements demonstrate the available analysis options. First, different design variants or versions can be compared with minimized effort in a model scale. Second, dependencies on speed and frequency can be found. For most sources it was found that the speed dependency fits an U^6 model. Finally, the results from the measurements can be used to extrapolate or predict the sound pressure level under conditions that cannot be realized in the wind tunnel.

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(a) schematic of the setup

(b) detail view with array at position A

Figure 1. Setup with 1:20 model train



Figure 2. Setup with H0 gauge model train in aeroacoustic wind tunnel



Figure 3: Real size pantograph and roof section in aeroacoustic wind tunnel view with microphone array in the background



(b) 5 kHz (250 Hz) CLEAN-SC deconvolution



(a) 5 kHz (250 Hz) beamforming



(d) 6.3 kHz (315 Hz) CLEAN-SC deconvolution



(c) 6.3 kHz (315 Hz) beamforming



(f) 10 kHz (500 Hz) CLEAN-SC deconvolution



(h) spectra from pantograph region at 35 m/s,—baseline, upper position, —lower pos., —removed, ———— different modifications of pantograph and roof



(e) 10 kHz (500 Hz) beamforming



(g) pantograph sector for integration

Figure 4: Third-octave sound maps and spectra for the train head of the 1:20 scale model train at 35 m/s



(a) 3D map for 13.92 kHz third octave band (equivalent to 160 Hz)





(c) bogie 1, bogie 2, gap and pantograph sectors used for integration

Figure 5. Sound maps from the H0 gauge 1:87 scale model train at 72 m/s



Figure 6: Scaled spectra for the H0 gauge 1:87 scale model, colors give the wind speed in m/s, $L_{p,\text{scaled}} = L_p - 60 \lg(U/(1 \text{ m/s}))$ except for (e), where instead $L_{p,\text{scaled}} = L_p - 40 \lg(U/(1 \text{ m/s}))$



(a) 4 kHz octave band sound map, dynamic range 30 dB, wind speed 280 km/h $\,$



(b) A-weighted third-octave band spectra for differ- (c) Extrapolation of overall SPL for higher speeds ent speeds

Figure 7. Results for the real size pantograph