Identification of aeroacoustic noise sources in automotive industry by microphone array measurements

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Introduction

One possibility to improve the acoustic comfort in a vehicle is to remove flow induced noise sources. In order to find those sources, classical beamforming (CB) with a microphone array can be applied. In this paper, first of all, the mapping of acoustic sources are performed on a 3D vehicle surface with a combination of the Clean-SC [7]. Secondly, the CB is going to be expanded in order to map only sources which are correlated to a reference signal. First results of this so called "correlated beamforming" were already shown in [1] and [4] for the mapping on a 2D plane.

The correlated beamforming on a 3D vehicle surface will be finally shown in this study using interior noise signals.

Beamforming techniques

In the following a brief introduction to the used beamforming techniques is provided.

Classical Beamforming

An array of N microphones recording the signals m_1 to m_N is set up. K focus-points from f_1 to f_K are defined. To calculate the beamforming result B_k at focus-point k the equation for CB is used

$$B_k = \boldsymbol{g}_k^{\mathrm{H}} \boldsymbol{C}_m \boldsymbol{g}_k = \boldsymbol{g}_k^{\mathrm{H}} \left\langle \boldsymbol{m}\boldsymbol{m}^{\mathrm{H}} \right\rangle \boldsymbol{g}_k. \quad (1)$$

In (1) $\boldsymbol{g}_k$ are the N steering-vectors for a focus-point k, $\boldsymbol{C}_m$ is the cross-spectral-matrix of the N measured microphone signals $\boldsymbol{m}$. $\langle \ldots \rangle$ means ensemble average. H denotes the hermitian, i.e. complex conjugate transpose. Different formulations can be applied for the steering vector (cp. [6]). In the present paper the formulation

$$g_{kn} = \frac{1}{N} e^{-j\omega/c r_{kn}} \quad (2)$$

is used, where j is the imaginary unit, ω the angular frequency, c the speed of sound and r_{kn} the distance between focus-point k and microphone n.

Beamforming in an open jet wind tunnel

To locate aeroacoustic noise sources properly in an open-jet wind tunnel, where the microphone array is placed outside the jet, it is necessary to take convection and shear layer effects into account. In this paper a formulation described by OERLEMANS in [5] is used therefor.

OERLEMANS describes a way to compute a time delay Δt_{kn} used in the exponent of the steering vector (2) instead of r_{kn}/c. Δt_{kn} depends on a so called "effective Mach number". This effective Mach number depends on the real Mach number inside the jet and the geometrical relations between focus point positions and microphone positions. For detailed information see [5]. As mentioned in [5] this method has been compared to more sophisticated methods (e.g. [2]), but for Mach numbers smaller than 0.25 and $\pi/4 < \vartheta < 3\pi/4$ the differences are negligible. Whereat ϑ is the angle between focus point and microphone relative to the direction of flow.

2D and 3D beamforming

Using the standard 2D beamforming, focus points f_k are typically defined in a 2D plane with a certain distance to the microphone array plane. The beamforming results from that plane are usually superimposed with a photograph of the measurement setup to be able to map the sound sources on it. For typical Mach numbers in automotive industry sound sources are expected on a surface of the vehicle in the flow. With a 2D focus plane there are always a lot of focus points not being located on the vehicle surface. So it makes sense to map the acoustic sources directly on a 3D vehicle surface instead of mapping them on a 2D plane. The difference from 2D to 3D mapping can be simply realised by changing the focus points correspondingly. Note, that for 3D beamforming, the microphones of the array are still positioned in a 2D plane.

Enhancing the beamforming result

As long as the array system has a finite number of microphones there are always side lobes at the acoustic mapping which can be analysed as a point spread function (PSF). Besides, looking at a microphone array system for the application in an open jet wind tunnel, there must be a difference between the theoretical PSF and the real one due to the shear layer of the wind tunnel and even the wrong source modelling by (2). In order to deal with those effects, there are several deconvolution methods available (see [3]). In this study the so called Clean-SC algorithm is used which was introduced by SIJTSMA in [7]. Clean-SC makes use of the fact that side lobes and other ghost sources are spatially correlated with the main lobe and removes them.

To a reference signal correlated beamforming

In order to evaluate the acoustic mapping from a perspective of a reference signal y, $\boldsymbol{C}_m$ from (1) is supposed to be modified. Let's assume that the microphone signal m_n can be split into the part u_n, which is linear related to the signal y, and n_n, which is not

$$m_n(\omega) = \underbrace{y(\omega)h_n(\omega)}_{u_n(\omega)} + n_n(\omega).\tag{3}$$

In (3) h_n is a linear time invariant transfer function between y and m_n. The target is to replace $\boldsymbol{C}_m$ by a cross spectral matrix $\boldsymbol{C}_u$ consisting of u_n. Assuming all n_n to be uncorrelated to u_n, the auto-spectrum $S_{u_n u_n}$ is the product of the auto-spectrum $S_{m_n m_n}$ and the coherence γ_n^2 between m_n and y

$$S_{u_n u_n} = S_{m_n m_n}\gamma_n^2.\tag{4}$$

The cross spectral matrix of all u_n is

$$\boldsymbol{C}_u = \langle \boldsymbol{u}\boldsymbol{u}^{\mathrm{H}}\rangle = \frac{\langle \boldsymbol{m}y^*\rangle\langle y\boldsymbol{m}^{\mathrm{H}}\rangle}{\langle yy^*\rangle}.\tag{5}$$

For correlated beamforming $\boldsymbol{C}_m$ from (1) is replaced by $\boldsymbol{C}_u$

$$B_k^{(\mathrm{corr})} = \boldsymbol{g}_k^{\mathrm{H}}\boldsymbol{C}_u\boldsymbol{g}_k.\tag{6}$$

The relationship between B_k and $B_k^{(\mathrm{corr})}$ is

$$B_k^{(\mathrm{corr})} = B_k\gamma_k^2,\tag{7}$$

where γ_k^2 is the coherence between B_k and y. For this study, the reference signal y is an interior noise of a vehicle.

Array properties

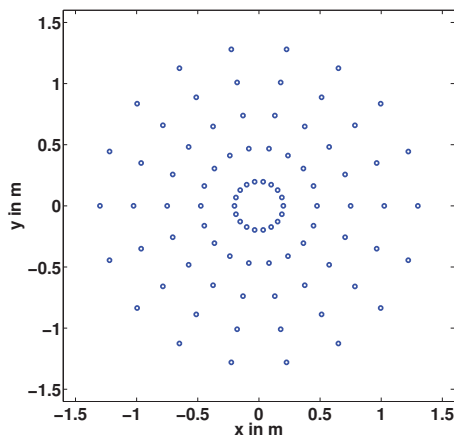The layout of the microphone array is shown in figure 1.

Figure 1: Layout with 90 microphones of the array.

A 3D PSF of the array on the surface of a Mercedes-Benz C-Class at 1 kHz is shown in figure 2.
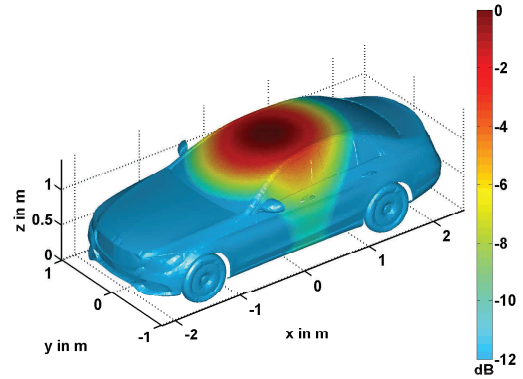

Figure 2: 3D point spread function of the microphone array at 1 kHz. Distance between array plane and wind tunnel floor 5.99 m. Car model: Mercedes-Benz C-Class, 2014.

Measurement setup

In the present paper one measurement with a Mercedes-Benz C-Class is shown. It was conducted in an open jet wind tunnel at a wind speed of 140 km/h. 90 microphone signals from the array and reference signals from vehicle interior were recorded simultaneously. The array was placed above the car, outside the jet. Distance between array plane and wind tunnel floor was 5.99 m. Inside the vehicle microphone A was placed (see figure 3) and an artificial head at driver's seat was used to record two more reference signals.

Figure 3: Position of the reference microphone A inside the vehicle.

Different beamforming applications for the same measured results

All presented beamforming results are evaluated for 1/24 octave at a centre frequency of 3 kHz.

The result for 2D CB is shown in figure 4. From this evaluation the main sources seem to be located on the engine bonnet.

3D CB is shown in figure 5. Based on this evaluation the noise sources seem to be located not only on the engine bonnet but also on the front bumper. Looking at the left a-pillar, this source also seems to be kind of "smeared out" in z-direction. So, it is not easy to interpret from this 3D CB where exactly the noise sources are located.

The result for 3D Clean-SC beamforming is shown in figure 6. The Clean-SC algorithm obviously removes a lot of side lobes and/or ghost sources. Sources from the
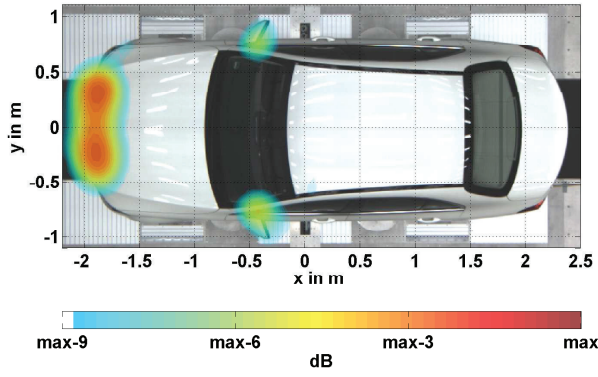
Figure 4: 2D CB results for a measurement at a wind speed of 140km/h. 1/24 octave, centre frequency 3 kHz.
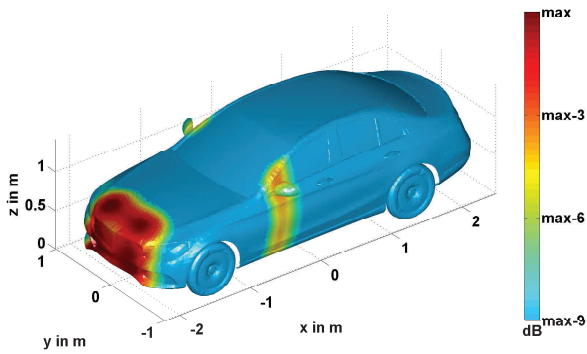

Figure 5: 3D CB results for a measurement at a wind speed of 140km/h. 1/24 octave, centre frequency 3 kHz.

engine bonnet completely disappeared as they were spatially correlated to the ones located on the front bumper. Looking at the left a-pillar, this source is much more compact now. The lobe in z-direction disappeared.
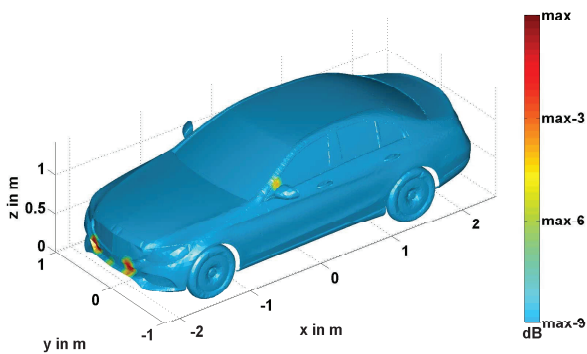

Figure 6: 3D Clean-SC beamforming results for a measurement at a wind speed of 140km/h. 1/24 octave, centre frequency 3 kHz.

The results of the correlated beamforming are shown in figures 7 and 8 with two reference signals. The first one is the microphone A signal and the other one is the microphone signal from the right ear of the artificial head. For both reference signals the exterior noise source located at the intersection between the mirror arm and the side window is the most important one. The noise sources

located at the front bumper completely disappear within the displayed dynamic range. The maximum values of the mappings in figures 7 and 8 are equal. A zoomed view is given in figure 9. Under the following two assumptions the different $B_k^{(corr)}$ values due to the two reference signals could be validated with the spectra of those (see figure 10). One assumption is that the exterior noise source placed at the intersection between the mirror arm and the side window has a contribution to each of the reference signals. The other one is that all other uncorrelated interior noise sources have the same contribution to both reference signals. Under these assumptions the interior noise difference of those two different microphone signals at 3 kHz should be in the range of the difference between the two $B_k^{(corr)}$ (about 4 dB).
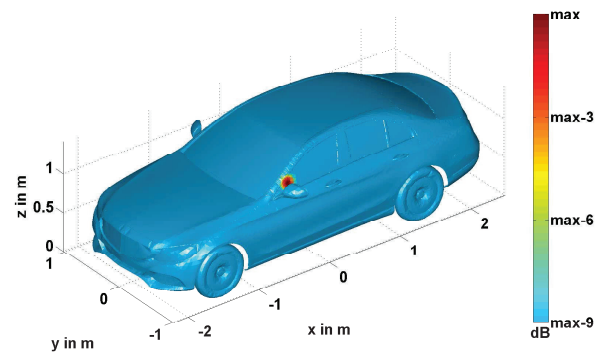

Figure 7: 3D correlated beamforming results for a measurement at a wind speed of 140km/h. Reference signal recorded near a-pillar. 1/24 octave, centre frequency 3 kHz.
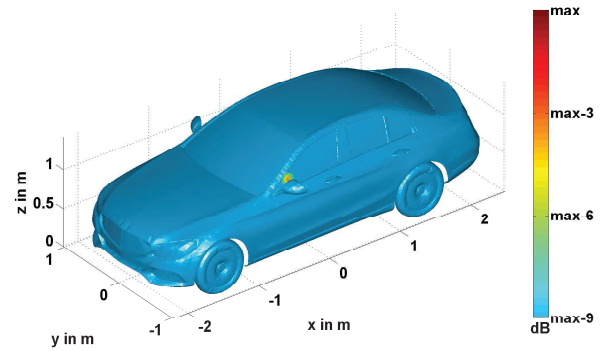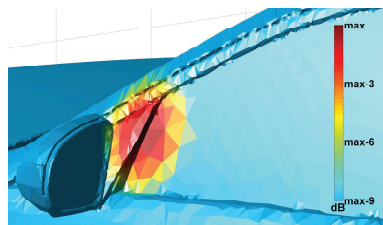

Figure 8: 3D correlated beamforming results for a measurement at a wind speed of 140km/h. Reference signal recorded at driver's right ear. 1/24 octave, centre frequency 3 kHz.

Conclusion

Without any further post processing like the deconvolution the 3D mapping of the CB does not help much for finding locations of the noise source excitation in comparison to the 2D mapping.

With a combination of the deconvolution, however, a very precise idea which vehicle construction elements are responsible for those noise sources can be given by the 3D mapping.

In order to reduce the interior noise at a certain position

(a) Reference signal: Microphone near a-pillar.
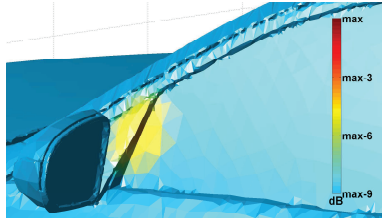
(b) Reference signal: Artificial head, driver's right ear.

Figure 9: 3D correlated beamforming results for a measurement at a wind speed of 140km/h. 1/24 octave, centre frequency 3 kHz.
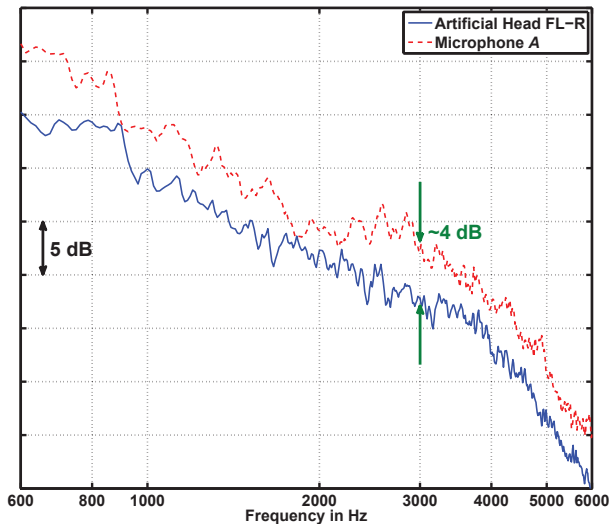

Figure 10: 1/24 octave spectra of two reference signals inside the vehicle.

efficiently, the application of the correlated beamforming must be very useful since those results in this study could show clearly which exterior noise sources are relevant to the reference signals.

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