9-12 AUGUST 2015
inter.noise 2015
SAN FRANCISCO, CALIFORNIA USA

Correlation of high channel count beamforming measurement of a car in a wind tunnel using CLEAN-SC.

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Abstract

In aeroacoustics, several beamforming algorithms have become standard tools for sound source localization, CLEAN-SC being the one with the broadest acceptance. Correlation methods allow further determination of individual contributions of wind noise sources related to the interior sound impression. We combine different methods on a series of measurements of a car in a wind tunnel using synchronized measurements from several high channel count beamforming arrays. Applying CLEAN-SC and the shear-layer correction method on the correlated signals, we can show individual contributions of several external sources for every single sound source perceived by the passengers inside the cabin. This paper discusses the quality of achievable results with combined methods in such complex situations.

1 INTRODUCTION

Beamforming methods using microphone arrays have established themselves in many industrial applications during the past years. Often, either simple phase shifting algorithms or methods based on the cross spectral matrix (CSM) are used. A visualization of the sound source distributions and an evaluation according to source strength and frequency content are state of the art [1] [2]. In advanced beamforming algorithms, to distinguish between original source and reflections, an impulse response gate can also be applied [3].

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Very often, a different question is of interest: Which of the various sound sources detected are correlated with a simultaneously measured reference signal, and how strong is that correlation? A typical example is the anlysis of the influence of aeroacoustic sources on a car (e.g. mirror, A-pillar, windshield wipers) onto the sound pressure level at the driver's head position. To answer this question, a reference microphone will be placed inside the car (at the position of the driver's head), whose signal must be sampled synchronously to the channels of the microphone array recording the aeroacoustic sources outside the car. By correlating the signals of the array microphones with the signal of the separate reference sensor, correlated and uncorrelated signals may be separated and the according sound sources can be found [4]. This can be performed using either the simple phase shift method or the cross spectral matrix approach. This paper investigates which of both methods allows for a better separation of correlated and non-correlated sources and how the achieved results can be improved further. An example from a practical application will be demonstrated.

2 THEORY

The theory of beamforming using microphone arrays is well described in many papers. Beamforming methods may be parted into time domain and frequency domain algorithms.

2.1 Time domain beamforming

Time domain beamforming can be written as follows:

$$\hat{f}(\mathbf{x},t) = \frac{1}{M}\sum_{i=1}^{M} w_i\, f_i\big(\mathbf{x},(t-\Delta_i)\big) \tag{1}$$

$\hat{f}(\mathbf{x},t)$:	Calculated time function on location **x** of the map
M:	Number of microphones
w_i:	Weighting factor for microphone signal i
Δ_i:	Time delay for microphone signal i to location **x** on the beamforming map

2.2 Frequency domain beamforming

Within the frequency domain methods, a separation between the simple phase shift method (Eqn. (2)) and methods using the **C**ross-**S**pectral-**M**atrix CSM (Eqn. (3)) is possible:

$$\hat{F}(\mathbf{x},\omega) = \frac{1}{M}\sum_{i=1}^{M} w_i F_i(\omega)\cdot e^{-j\theta_{i\omega}} \tag{2}$$

$\hat{F}(\mathbf{x},\omega)$: Calculated Spectrum on location **x** of the map

$F_i(\omega)$: Spectrum of microphone signal i

$\theta_{i\varpi}$: Phase angle for frequency ω on microphone i to location **x**

$$CSM_{mn}(\omega_k) = \frac{1}{N}\sum_{j=1}^{N} \hat{F}_m^{\,j}(\omega_k)\cdot\left(\hat{F}_n^{\,j}(\omega_k)\right)^* \tag{3}$$

$CSM_{mn}(\omega_k)$: Cross Spectral matrix, microphone numbers m, n and at frequency ω_k

N: Number of blocks for averaging

$\hat{F}_m^{\,j}(\omega_k)$: Complex spectrum of microphone signal m on block j and at frequency ω_k

Each microphone signal is transformed block by block into the frequency domain, the averaged correlation function between the microphone signals is calculated and inserted into the CSM. The CSM contains the averaged cross correlation functions between all microphones as complex coefficients in the frequency domain.
The steering vector for location **x** on the map is:

$$v(\omega_k, x) = \frac{1}{M}\begin{pmatrix} e^{-i\omega_k \Delta t(x,x_1)} \\ \vdots \\ e^{-i\omega_k \Delta t(x,x_M)} \end{pmatrix} \tag{4}$$

A steering vector (Eqn. (4)) contains the phase shifts for frequency ω_k between all microphones to the point **x** on the map.

Beamforming using CSM and steering vector can be written as follows Eqns. (5):

$$\sum\nolimits_{k=k_1}^{K} v(\omega_k, x)^H \, CSM(\omega_k)\; v(\omega_k, x) \tag{5}$$

2.3 Beamforming using a reference signal

The objective of this procedure is to generate a beamforming map which will only show sources that have a significant correlation with the reference signal while at the same time suppressing all

the others. Similar approaches are known (e.g. from transfer path analyses), but our method also allows it to separate sound sources from their reflections. This can be done using correlation filters or by directly cross correlating the microphone signals and the reference signal. In the following, the paper will compare the phase shift and the CSM method. Cross correlations are utilized to find transfer paths and to give a ranking of the sound sources according to their individual contribution to the reference signal.
First step in both methods is to calculate the cross correlation between the reference signal $F_R(\omega)$ and each microphone signal $F_i(\omega)$, then calculate a beamforming map. Phase shift method Eqn. (6):

$$\hat{F}(\mathbf{x},\omega) = \frac{1}{M}\sum_{i=1}^{M} w_i \left(F_i(\omega)\left(F_R(\omega)\right)^*\right)\cdot e^{-j\theta_{i\omega}} \tag{6}$$

CSM method Eqn. (7):

$$C_{mn}(\omega_k) = \frac{1}{N}\sum_{j=1}^{N}\left(\widehat{F}_m^{\,j}(\omega_k)\cdot\left(\widehat{F}_R^{\,j}(\omega_k)\right)^*\right)\cdot\left(\widehat{F}_n^{\,j}(\omega_k)\cdot\left(\widehat{F}_R^{\,j}(\omega_k)\right)^*\right)^* \tag{7}$$

Each microphone signal and the reference signal are transformed block by block into the frequency domain, the averaged correlation function between the microphone signals and the reference signal is calculated, then the CSM is determined.

3 SIMULATION SETUP

In order to compare both methods, at first a simulation was performed. The setup (Fig. 1) consists of two sound sources emitting non-correlated white noise, their distance is 0,6 m and the distance to the array is 1m. For the measurement simulation, we used a 10 by 10 microphone array that is centered at the origin and parallel with respect to the x-y plane. Its dimension is 1m by 1m. Additionally, we use a reflexive plane at 1.5 m distance to create a correlated reflection of source one. Samplingrate is 48 kHz, simulation time is 1s, and block size for CSM is 4096 samples.

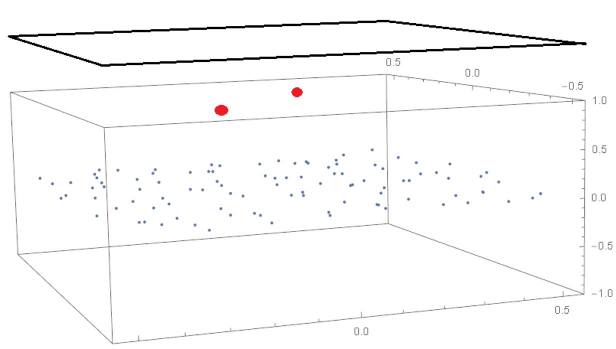

Fig. 1 – Simulation setup, 100 microphones, 2 sources, reflection plate

4 SIMULATION RESULTS

4.1 Beamforming results

At first, a comparison of beamforming using phase shift method (2) and CSM (5), frequency band 2391 Hz – 2625 Hz:

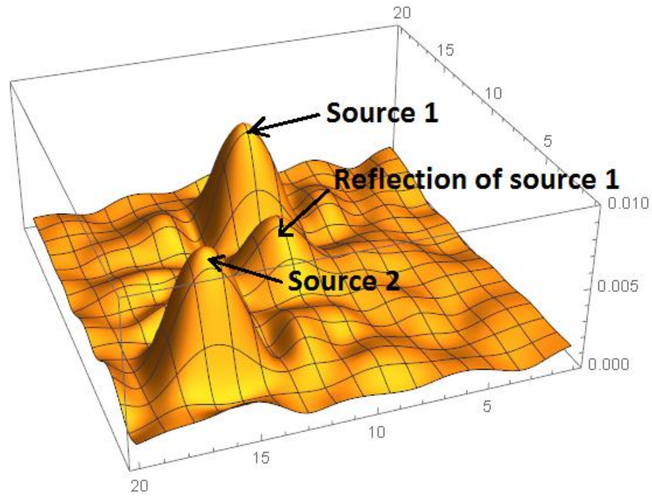

Fig. 2 – Beamforming result phase shift method

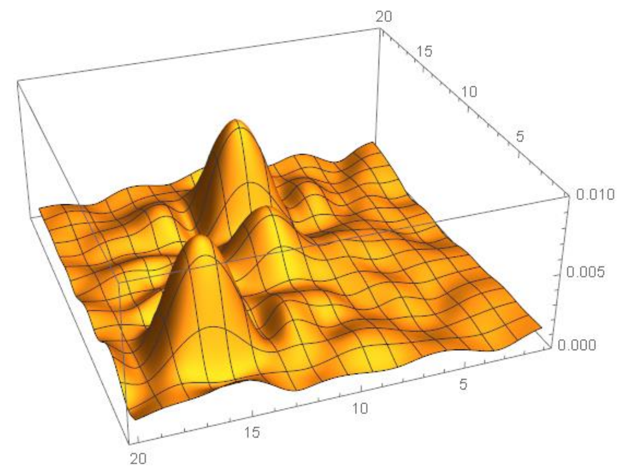

Fig. 3 – Beamforming result CSM method

There are very small differences between both methods. For Standard beamforming, both methods are equivalent.

4.2 Correlation results

Now, we use the signal of source 1 as reference and calculate the beamforming result according to (6) (phase shift method) and to (7) (CSM method):

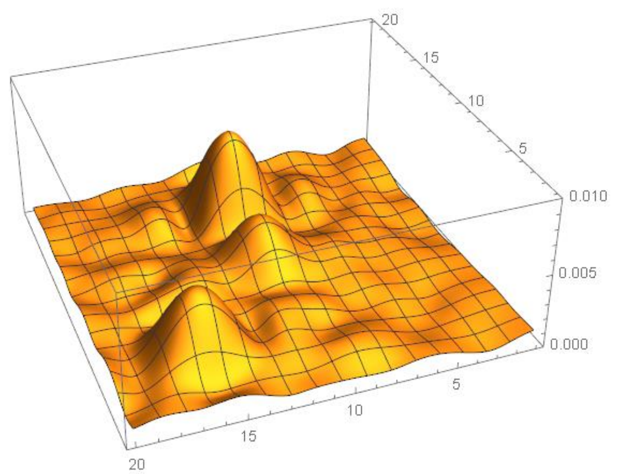

Fig. 4 – Beamforming result phase shift method and cross correlation with reference signal

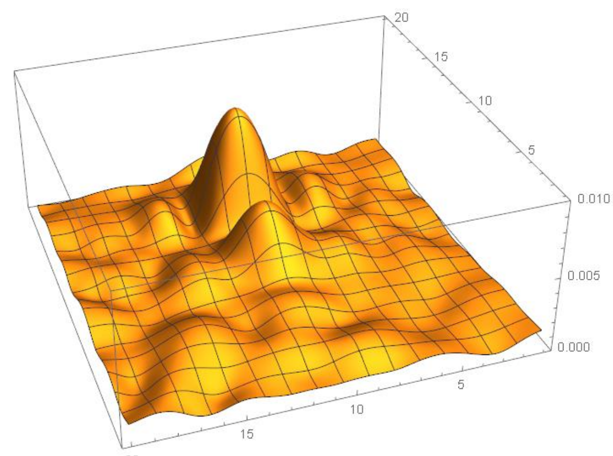

Fig. 5 – Beamforming result CSM method and cross correlation with reference signal

In Fig. 4, cross correlation and phase shift method, source 2 (not correlated to reference signal) is suppressed, but the result is disappointing. In Fig. 5 using CSM method the suppression of source 2 is much better. To understand this effect, one has to have a look at the correlation function used in the phase shift method. Inverse Fourier transform of the complex cross correlation gives the correlation function in time domain (8).

$$f_{C_i}(t) = FFT^{-1}\left(F_i(\omega)\left(F_R(\omega)\right)^*\right) \tag{8}$$

As an example of this function, the correlation function between microphone 1 and the reference signal is shown in Fig. 6 and Fig. 7.

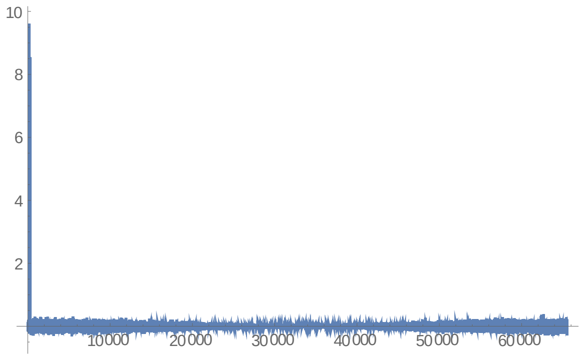

Fig. 6 – correlation function between microphone 1 and reference signal, no block averaging

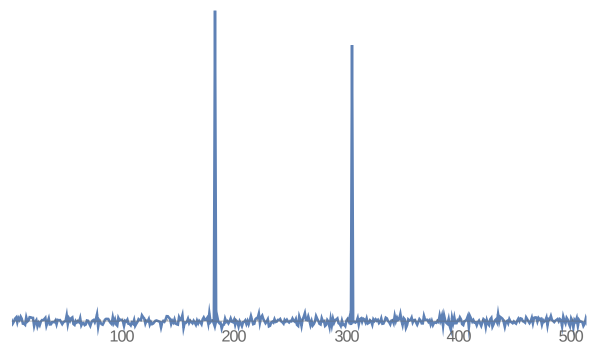

Fig. 7 – zoom of correlation function from Fig. 6 – first 500 samples

As shown in Fig. 6, for the most part the correlation function consists of noise. Only the first 500 samples (Fig.7) contain the correlation between the reference signal and source 1 (first peak) and the reflection of source 1 (second peak). Source 2 is not correlated with the reference signal, therefore it will not be visible as a peak in the correlation function. However, a lot of the signal content of source 2 is hidden within the noise floor of the correlation function. Therefore, if we use the complete correlation function for beamforming, we have a poor suppression of source 2 (Fig. 4). Using the CSM method, the block by block processing and the following averaging in this method give a better suppression of the non-correlated parts (Fig.5).

4.3 Correlation results using a rectangular window (Gate)

To further improve the results in Fig. 4 and Fig. 5, a rectangular window can be applied to the correlation function (Fig. 8). The width and position of this window is defined by the earliest and latest correlated source in the measurement scene we want to see in the beamforming map. It operates as if it were an additional spatial filter.

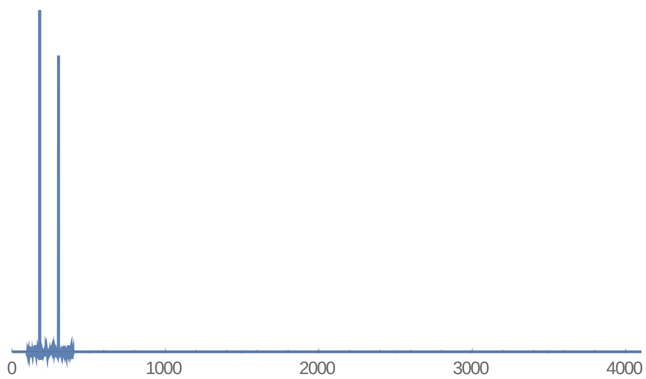

Fig. 8 – rectangular window applied correlation function

Results of applying a rectangular window on the correlation function are shown in Fig. 9 and Fig. 10. The improvements of the suppression of the non-correlated source 2 are shown in Fig. 11 and 12.

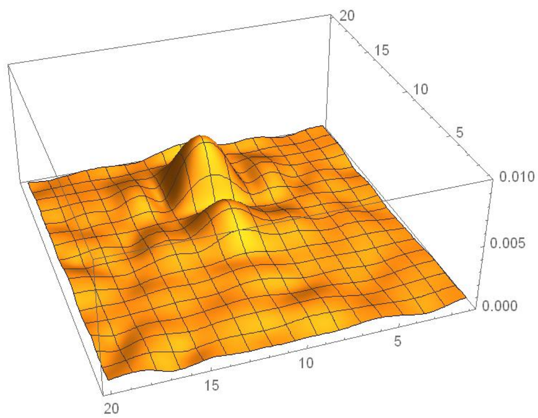

Fig. 9 – beamforming result using gated phase shift method

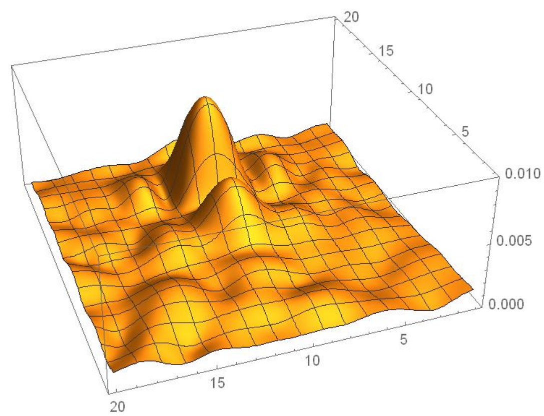

Fig. 10 – beamforming result using gated CSM method

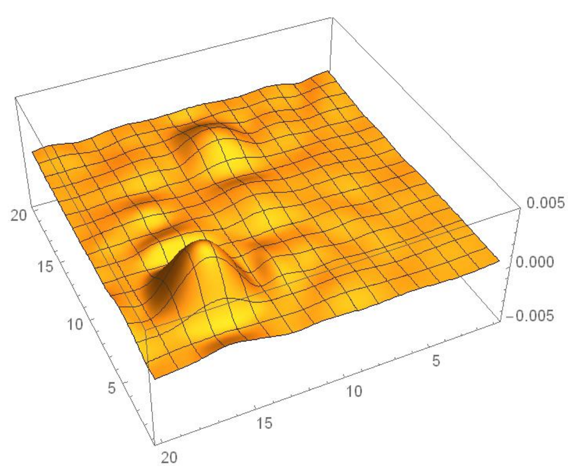

*Fig. 11 – Improvement of the suppression of source 2 using rectangular window and **phase shift method** (difference between Fig. 9 and Fig.4)*

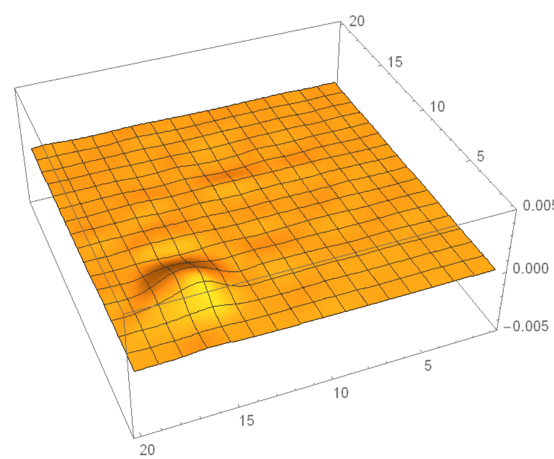

*Fig. 12 – Improvement of the suppression of source 2 using rectangular window and **CSM method** (difference between Fig. 11 and Fig.5)*

5 EXAMPLE OF WINDTUNNEL MEASUREMENT USING REFERENCE SIGNAL AND CLEAN SC

CLEAN SC (CLEAN Based on Spatial Source Coherence) [5] is an iterative deconvolution method that is especially well-suited for stationary sound source analyses, where it leads to improved map dynamics and to an improved resolution of microphone array results. The following example visualizes that both methods can be used together successfully. In Figure 13 to 16 we show a car in a wind tunnel at a 140kmh wind speed with a modified upper trail edge of the passenger side mirror. As a reference channel a microphone was places at the driver's ear position. This reference channel will be used to identify the relevant sources to the driver experience and excluding the sources not participating to the interior sound field affecting the driver.

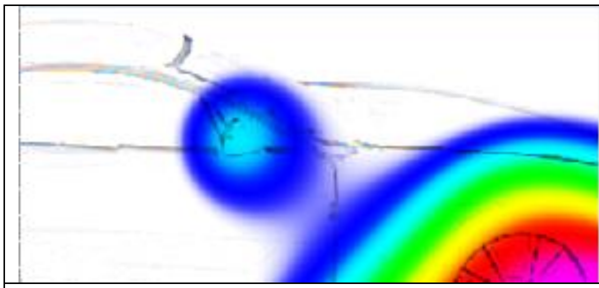

Fig. 13 – measurement result using Eqns.(5)

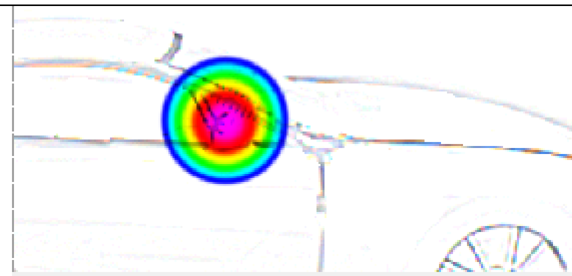

Fig. 14 – measurement result using Eqns.(7)

Fig. 15 – measurement result using Eqns.(5) and rectangular window

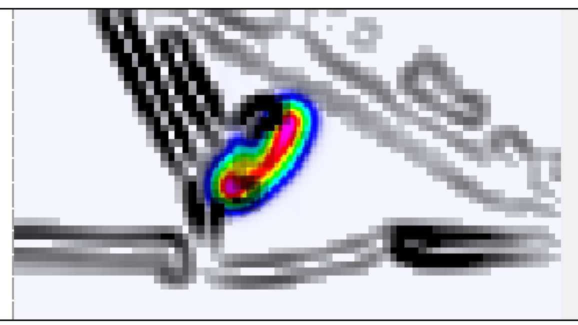

Fig. 16 – zoom of Fig. 15

Figure 13 displays a standard Beamforming result of the car exterior. The side mirror can be identified as the second loudest source and front wheelhouse as main source. When applying the beamforming method calculated with the reference channel (Fig. 14) we can see that the front wheel house has no great impact to the driver's ear position. The Acoustic Photo shows no significant influence of the wheelhouse but the entire mirror. For the actual modification of the mirror this may not be enough information to justify a production adaptation. Applying the CLEAN SC method in combination with the reference channel and rectangular windowing of the correlation function we increase the resolution of the acoustic Photo. We see the rear edge of the mirror and gain information on the acoustic source location influencing the sound field of the driver.

4 DISCUSSION AND CONCLUSIONS

In many cases, beamforming with an additional reference channel allows for the analysis of relevant transfer paths as well as a ranking of sound sources according to their contribution to the sound immission at a reference location. This can either be performed utilizing a simple phase shift method (without block by block averaging) or by using beamforming with the averaged CSM. The latter approach can yield useful results already without a separate gating function, while this gating is mandatory for the non-averaged phase shift algorithm. But, to correctly apply the CSM-method, the run time difference between the reference channel and the microphone array channels must at least be located within the chosen block size. Both methods profit significantly from the application of gating by a rectangular windowing of the correlation function, which achieves an additional suppression of non-correlated signal components.

5 ACKNOWLEDGEMENTS

This research work has been funded by the German Federal Ministry for Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie, BMWi) under project registration number MF120190.

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