MICROPHONE ARRAY MEASUREMENTS ON AEROACOUSTIC SOURCES

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ABSTRACT

The flow around obstacles is often very complex, leading to distributed aeroacoustic sources. In experimental investigations, microphone arrays can help to separate, analyze and quantify these partial sources. In order to do so, a microphone array with a high spatial resolution and a high dynamic range is essential. In this publication, the setup and application of a microphone array for aeroacoustic measurements in a model scale wind tunnel will be discussed.

Initially, the development and optimization of the microphone array will be described. Preliminary considerations and the derivation of major quality criteria will be explained. Methods for the enhancement of the measurement results as well as for the source characterization will be presented. These methods include the variation of the measurement conditions as well as advanced signal processing.

Results of measurements on various test structures will be presented. These structures do all possess aeroacoustic sources with dipole sound radiation but do also exhibit different frequency behaviour of narrowband (cylinder) and broadband (generic wing profile) radiation.

1 INTRODUCTION

During recent research projects aeroacoustic examinations of small model structures in a wind tunnel were carried out in order to validate numerical simulations. As a contribution to these wind tunnel examinations it was necessary to obtain information about the position and the strength of the aeroacoustic sources at the test structures. For this purpose a microphone array was set up and a series of measurements was carried out.

Firstly, the development and optimization of the microphone distribution and the signal processing will be described, followed by the demonstration of advanced experimental investigation methods for practical source detection. Finally, selected results of measurements on aeroacoustic structures with of dipole source type will be presented.

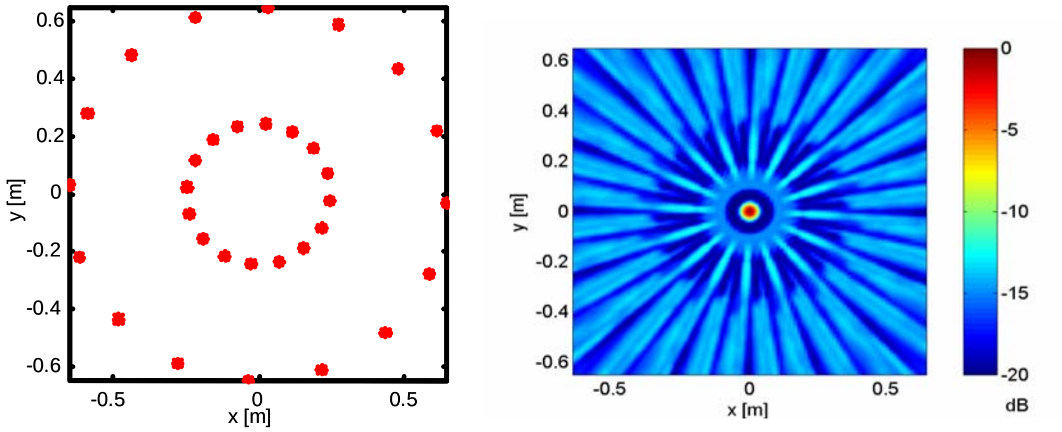

Figure 1: Double ring array: Microphone distribution (left hand side, 32 microphones) and array pattern (right hand side, normalized SPL in dB, $f_{m,oct}$=8000Hz, array–source-distance=1m)

2 DESIGN AND OPTIMIZATION OF ARRAY GEOMETRY

The performance of a microphone array during measurements is strongly dependent on the geometrical properties of the array. These geometrical properties can be described using the array pattern, which is the directional characteristic of the array in an analysis plane with a certain distance to the array plane. For the comparison of array patterns, mostly two quality criteria are of interest: the main lobe width (-3dB-width of the array’s main lobe, MLW) and the side lobe suppression (signal-to-noise ratio, SNR). For aeroacoustic measurements on small structures a high SNR is wanted for a good suppression of unphysical “ghost images” in the measurement results as well as a small MLW for the precise localization of the source regions.

An optimum microphone geometry had to be found in order to obtain a high SNR and a small MLW at the same time. A lot of geometrical properties, like array dimensions and number of microphones, are defined by the application (in-situ-measurement conditions) and the hardware in use (number of data acquisition channels). The microphone distribution is often the only free parameter, which can be influenced. Thus different parametric microphone distributions were derived from literature studies and own considerations. The quality criteria of their corresponding array patterns were combined into cost functions and optimized.

Finally a series of different optimized microphone distributions was obtained [1]. For the recent investigations, a microphone geometry with 32 microphones, aligned in 2 concentric rings was chosen. The microphone distribution and the corresponding array pattern for an examination plane in distance of 1m to the array (d_{array} = 1,3m, $f_{m,oct}$ = 8kHz) are shown in figure 1. During the experimental investigations, the microphones were mounted in a reflecting surface to provide defined acoustic boundary conditions.

3 SIGNAL PROCESSING

Since the examinations were carried out for sources with a small distance to the array, the near field beamforming algorithm [2] was applied to evaluate the microphone signals. The algorithm is based on the evaluation of the cross spectral density matrix S_{xy} and the steering vector $\vec{e}$ for a given steering location *x*. S_{xy} and $\vec{e}$ are calculated from the *M* microphone input signals and the distances between the source and each microphone, respectively. The power spectral density output of the array for a focused steering location can then be expressed in the form

$$S(\vec{x}) = \frac{\vec{e}^H S_{xy} \vec{e}}{M^2} \tag{1}$$

where $\vec{e}^H$ indicates the Hermitian-transposed of the steering vector $\vec{e}$. This result represents the equivalent SPL in the array center, stemming from the targeted source location.

To suppress sidelobe fragments the frequency band averaging technique [3] was applied. Since the sidelobe structures of the array pattern are a function of frequency, it is possible to decrease them by summing the magnitude values of the spectral lines of the array's output signal in a certain frequency band. This leads to less ghost images in the later array measurement results.

Another signal processing technique to increase the SNR is the modified correlation method [4]. For a targeted steering location the disturbance noise information on the individual microphones is mostly uncorrelated. Hence this information is only present in the auto correlation terms of the microphone signals. The noise can therefore be suppressed by eliminating the main diagonal of the cross spectral matrix, obtaining the modified cross spectral matrix S_{xy}^0. Compensating the limited number of matrix elements, the beamforming algorithm can then be expressed as

$$S(\vec{x}) = \frac{\vec{e}^H S_{xy}^0 \vec{e}}{M^2 - M} \tag{2}$$

Further advanced signal processing techniques like a separation of orthogonal source mechanisms [5] or a compensation of the elliptic beam shapes in large lateral distances to the array center will not be discussed in this publication. Instead, practical suggestions for advanced experimental investigation methods are given in the next section.

4 ADVANCED MEASUREMENT AND ANALYSIS TECHNIQUES

In practical array measurements, analogous to single microphone measurements a common way to obtain more information about the sound sources and about the measurement setup is to vary the measurement conditions.

One additional experiment was the measurement with the array in situ but without flow and with an electroacoustic point source at the spatial position of the expected aeroacoustic source. This examination delivered information about the ghost images in practical array measurements due to sidelobe structures of the array pattern. The result of this measurement can be found in figure 2. The concentric rings of ghost images around the only physical sound source are caused by spatial aliasing effects are clearly visible. These ghost image structures can be found in some of the later measurement results with test structures.

The second experiment was carried out at the empty open jet test section without test structure and the array in situ. This measurement was intended to determine the location and shape of the wind tunnel nozzle as a disturbance noise source. The measurement result for a mean flow of v_0=38m/s is also presented in figure 2. The characteristic shapes of the aeroacoustic sources at the nozzle edges can also be found in the later measurement results with test structures.

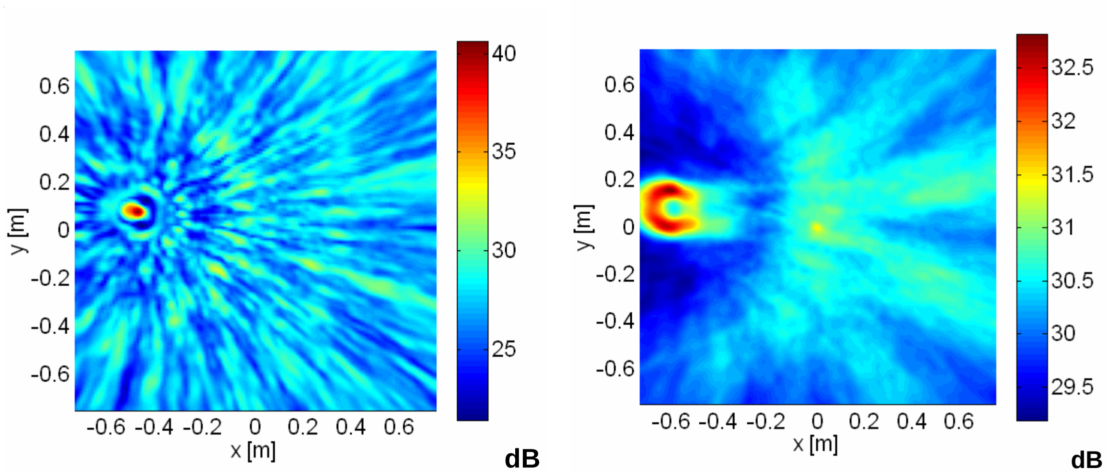

Figure 2: Advanced experimental investigations:
Left hand side: artificial point source at the location $P_{x,y}$(-0.49m,0.08m) of later aeroacoustic sources
Right hand side: Wind tunnel nozzle noise source, wind speed v_0=38m/s
(Both measurements: $f_{m,oct}$=8000Hz, array–source-distance=0.8m)

Additionally to the considerations mentioned above, special precautions are necessary for aeroacoustic investigations: the influence of the air stream has to be taken into account. For the investigations presented herein, the microphones were located outside the air stream. Hence the refraction of the sound waves on the shear layer of the free stream during the propagation from the aeroacoustic source region to the microphones had to be considered. An approximate estimation of the influence of this refraction on the localizations results was done using a model of a plane, infinitely thin shear layer. The calculated errors for source position and for the source level were below 0.01m and 0.1dB respectively.

5 MEASUREMENT RESULTS

Two different aeroacoustic test structures were subject to investigations as described in this publication: a cylinder and a generic aerodynamic profile NACA0012.

The first test structure was a cylinder with a diameter of d_{cyl} = 4.5mm. For this structure the noise of a von-Kármán vortex street with tonal components at the resonant frequency ($f_{r,cyl}$ = 1700Hz for v_0 = 38m/s) and its harmonics and slight broadband noise content was expected. In figure 3 two results of this measurement are presented: the source localization in the octave band of $f_{m,oct}$ = 2000Hz and the equivalent SPL spectrum in the center of the array for the source location. With the source plot, a good estimation of the source position can be given, but the spatial resolution is limited due to the high MLW of the array patter in this frequency band. For a better spatial localization of the source, an evaluation of the microphone signals at higher frequencies is necessary. The SPL spectrum reveals the tonal character of the von-Kármán vortex street. Note that the higher harmonics of this oscillation are not visible in the results of single microphone measurements at the array position.

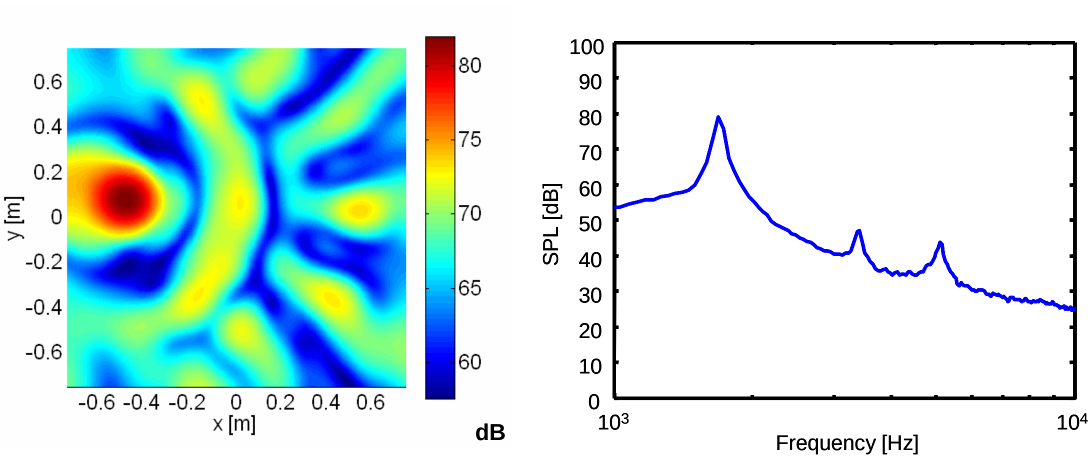

Figure 3: Array measurements on a cylinder in an air stream
Left hand side: source plot / $f_{m,oct}$=2000Hz, right hand side: SPL spectrum (source position),
[v_0=38m/s, array-source-distance=0.8m, Position of cylinder: P_x(-0.49m), D_y(-0.045 … 0.245)]

The second test structure to be presented herein is a generic aerodynamic profile NACA0012. The aeroacoustic sound radiation of structure exhibited broadband frequency behavior. Only the octave frequency band of 8 kHz will be examined herein, since in this frequency range a small MLW and a reasonable SNR can be obtained. Selected results of the investigations on this structure are shown in figure 4. The position of the wing profile during the measurements is indicated by an underlying photograph. The side view of the NACA0012 is shown on the left hand side. The spatially sharp limited cylindrical source area at the trailing edge of the profile is clearly visible. By turning the setup about an angle of 90° the “cross sectional view” of the profile could be obtained (right hand side of figure 4). In this view the source areas at both sides of the profile are visible, forming an aeroacoustic dipole. In this direction the aeroacoustic source has a very low sound radiation. So in this graph also the nozzle as a disturbance source can be recognized (compare figure 2).

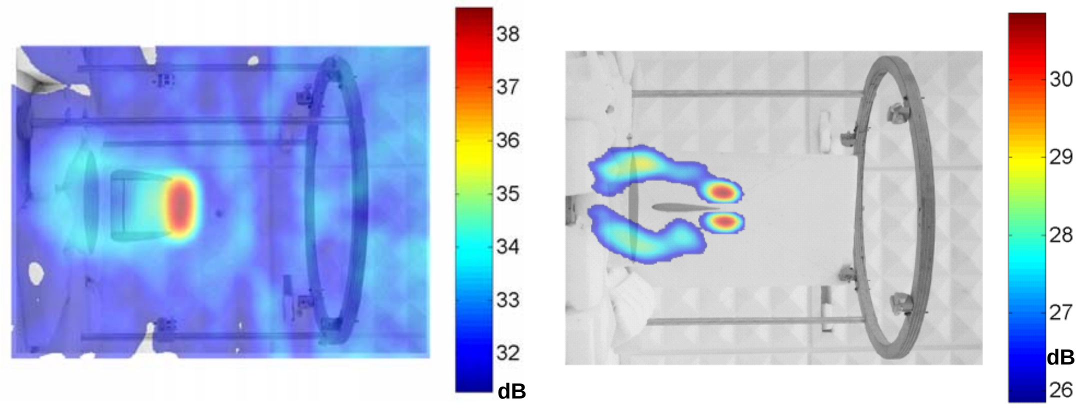

Figure 4: Array measurement on a NACA0012 profile, left hand side: side view, right hand side "Cross sectional view" (v_0=38m/s, $f_{m,oct}$=8000Hz, array–source-distance=0.8m)

6 CONCLUSIONS

A microphone array was developed and optimized for measurements on aeroacoustic model structures. The frequency domain near field beamforming algorithm was applied in combination with frequency band averaging and a modified correlation method. The sidelobe structures of the array in situ and the nozzle as an aeroacoustic disturbance source could be determined by preliminary measurements. An estimation of the influence of the refraction of the sound waves on the shear layer of the free stream delivered maximum errors of source position below 0.01m and maximum errors of source level below 0.1dB

Two different aeroacoustic test structures (cylinder and NACA 0012 profile) were examined. The structures showed individual frequency behavior from tonal to broadband noise sources. The dominating sound sources were mostly located on the trailing edges of the structures.

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