EFFECTS OF WIND-TUNNEL NOISE ON ARRAY MEASUREMENTS IN CLOSED TEST SECTIONS

K. Ehrenfried[1], L. Koop[1], A. Henning[2] and K. Kaepernick[2]

[1]German Aerospace Center (DLR)
Bunsenstrasse 10, 37073 Goettingen, Germany

[2]Technical University of Berlin

ABSTRACT

Past experiments have shown that aeroacoustic measurements are possible in wind tunnels with closed test sections, although there are several drawbacks compared to measurements in open test sections. Problems can arise from reflections at the hard side walls, the flow about the microphones, and background noise which propagates through the wind tunnel. To investigate the latter effect, array measurements are carried out in the large wind tunnel of the Hermann-Föttinger-Institute at the TU-Berlin. This wind tunnel has a closed test section with a size of 2 m by 1.4 m. A microphone array is mounted at one side wall in the test section. The array has a diameter of about 1m and consists of 144 microphones. Experiments are done at flow velocities of 30 m/s with a wing model installed. The tests show that the background noise which is present in the test section has a characteristic wave-number spectrum. Typically stronger waves are found which propagate in upstream direction. Their signals can cause strange artifacts in the source maps at focus points downstream of the array. A method is proposed to reduce these artifacts by a more sophisticated array evaluation.

1 INTRODUCTION

During the last years microphone arrays became a standard instrument in aeroacoustic experiments. They are used in fly-over measurements [1] and wind tunnel testing as well [2]. For the latter, acoustically optimized wind tunnels exists, which have an anechoic chamber around an open test section and all surfaces of the tunnel are lined with acoustically absorbing materials. In contrast to that, aerodynamic measurements are often performed in wind tunnels with closed test sections and hard side walls. In this tunnels the aerodynamic boundary conditions are well defined and ideal for a comparison with numerical simulations. To increase efficiency and productivity it is desirable to have aeroacoustic and aerodynamic measurements in parallel. Moreover, acoustically optimized wind tunnels are often not available. Hence, there is a certain interest to perform aeroacoustic measurements in wind tunnels with closed test sections.

Previous experiments [3] showed, that it is possible to used microphone arrays in wind tunnels with closed test sections to study aeroacoustic sources. However, closed test sections with hard side walls have two main disadvantages with respect to acoustic measurements. First the microphones are in the flow field. Typically either the microphones are installed in a flat casing which is attached to a side wall or they are directly mounted in the side walls. In both cases the microphones are beneath a turbulent boundary layer, which generates wall pressure fluctuations. The turbulent fluctuations in the boundary layer have a relative small spatial correlation, so that they mainly cause a strong autocorrelation of each microphone signal but no cross-correlation between the signals of different microphones. To overcome the influence of these disturbances the so called diagonal removal (DR) can be applied, where the diagonal of the cross spectral matrix is set to zero. This increases the signal to noise ratio in the calculated source maps significantly. The second disadvantage of a closed test section is the increased background noise level. Acoustic waves are generated at many locations in the wind tunnel and not only at the model in the test section. Because of the hard side walls the sound waves can propagate almost undamped through the tunnel. This kind of noise generates microphone signals which are correlated all over the array. Thus, the effect of the background noise is not eliminated by the DR approach.

In the present paper array measurements in a wind tunnel with closed test section and hard side walls are considered. The background noise in this tunnel is analyzed. It is shown, that strong waves are present, which primarily travel in upstream direction. Furthermore, it is demonstrated by an example, that this waves can have a strong influence on the array results. Artifacts can occur in the source maps. A method is proposed how these artifacts can be reduced using an extra step in the array processing.

2 EXPERIMENTAL SETUP

In the present study array measurements are conducted in the wind tunnel of the former Hermann-Föttinger-Institute of the Technical University of Berlin. This wind tunnel has a closed test section with a total length of 10 m. The cross section is 2 m by 1.4 m. The DLR inflow array is mounted at one side wall in the test section. The experimental setup is shown in figure 1. The array contains 144 microphones, which are placed on nine wound spiral arms. The diameter of the microphone field is about 1m. The array is designed to cover a frequency range from 2 kHz to 50 kHz. In front of the array a swept-wing constant-cord half-model (SCCH model) is installed. The array looks at the pressure side of the wing. For the present test the slat of the wing is deployed and the flap remains retracted. During the tests the flow velocity and the angle of attack is changed, but here only cases with a flow velocity of 30 m/s are considered. In the standard configuration all side walls are reverberant. For comparison, some test are run with a 3 cm thick layer of absorbing foam mounted at the side wall of the test section opposite to the array. The microphone signals are recorded using three VIPER data acquisitions systems from GBM. A sampling rate of 120 kHz is used in all tests.

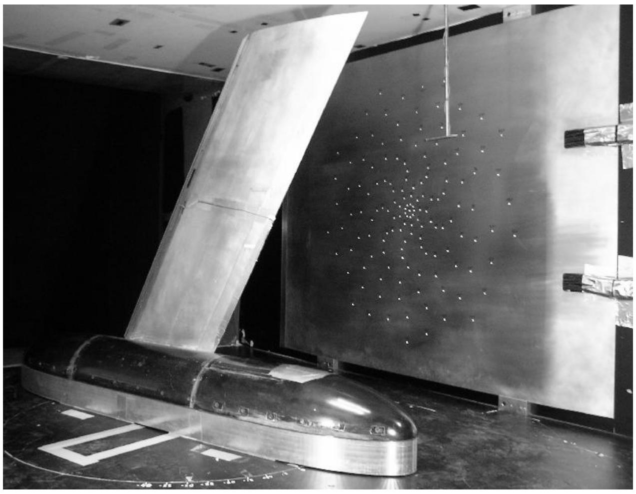

Fig. 1. Photo of experimental setup including SCCH model (foreground) and inflow array with 144 microphones at the side wall of the test section.

3 RESULTS

3.1 Standard beamformer output

The array processing is done in frequency domain. At first cross spectral matrices are calculated for all frequencies of interest. Then a standard delay-and-sum beamforming including diagonal removal (DR) is used to calculate the source maps. As example a case with 7 degree angle of attack is considered. The resulting source map for a single frequency of 2900 Hz is shown in figure 2. The spatial resolution of the map is about 20 mm. x and y are local coordinates in the observation plane, which corresponds to the main plane of the wing and is turned with the model. The local coordinate system is rotated, so that the SCCH model appears upside down and the main flow direction points from left to right. The left map in figure 2 is obtained for an untreated test section, and the right map is the result with foam mounted at the side wall opposite to the array.

The strongest intensity in the source maps is found downstream of the wing. Some sources at the slat of the wing are visible, but they are much weaker than the sources at the right border of the maps. With foam the source strength is reduced in a region at the rear part of the wing and directly downstream of the trailing edge. It appears unrealistic that real sources are present in this area and that they are influenced by the foam. Thus, the high intensity downstream of the wing is more likely an artifact rather than it is caused by real sources in the observation plane. This has to be checked in the following.

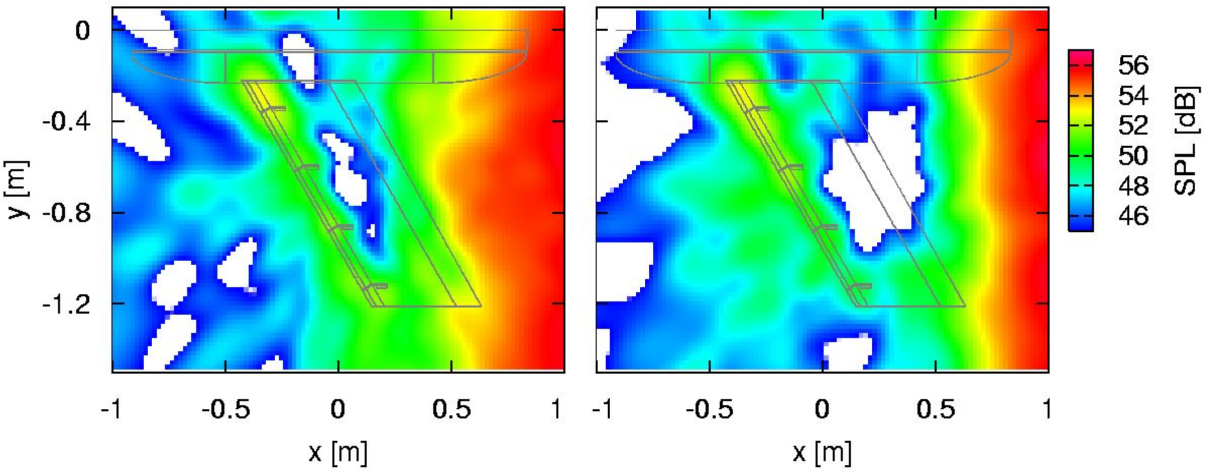

Fig. 2. Source map at a single frequency of 2900Hz calculated using a standard delay-and-sum beamformer. Left: without foam, right: with foam. Flow velocity is 30 m/s and angle of attack is 7 degree. The silhouette of the wing is marked by thin lines.

3.2 Wave-number spectrum

To find possible reasons for the strong artifacts in the source maps presented above, all acoustic waves which are propagating through the test section are considered. For this purpose the wave-number spectrum of the wall pressure in the array plane is calculated. This is done using the delay-and-sum beamforming with an infinite focus distance. This means, it is focused on plane waves which reach the array. Each wave can be characterized by a wave-number vector $\boldsymbol{k} = (k_x , k_y , k_z)$, which has the magnitude $k_0 := | \boldsymbol{k} | = 2 \pi f / c$. Hence, the two components k_x and k_y can be used to identify each wave and to display the beamformer output. In this way a map in wave-number space can be obtained. Figure 3 shows two of such maps. In both maps the wave numbers are normalized by k_0, and the intensities are integrated for a 1/3 octave at the mid frequency of 3000 Hz. k_x corresponds to the waves in main flow and k_y to the waves in vertical direction.

The maps in wave-number space are calculated for exactly the same tests as the source maps in figure 2. Again the left map is the result with untreated side walls and for comparison the right map shows the result with absorbing foam at the side wall opposite to the array.

All plane acoustic waves correspond to a wave number (k_x , k_y) inside an ellipse. The maps show, that basically upstream traveling waves with negative k_x are present above the array. The foam reduces the intensity in a certain region of the map. It seems that this region belongs to waves which are reflected at the opposite side wall of the test section before they reach the array. These waves contribute to the artifacts in the source maps. The comparison shows, that at least some waves can be attenuated by the foam. This explains also, why the artifacts in the source maps in figure 2 are slightly different.

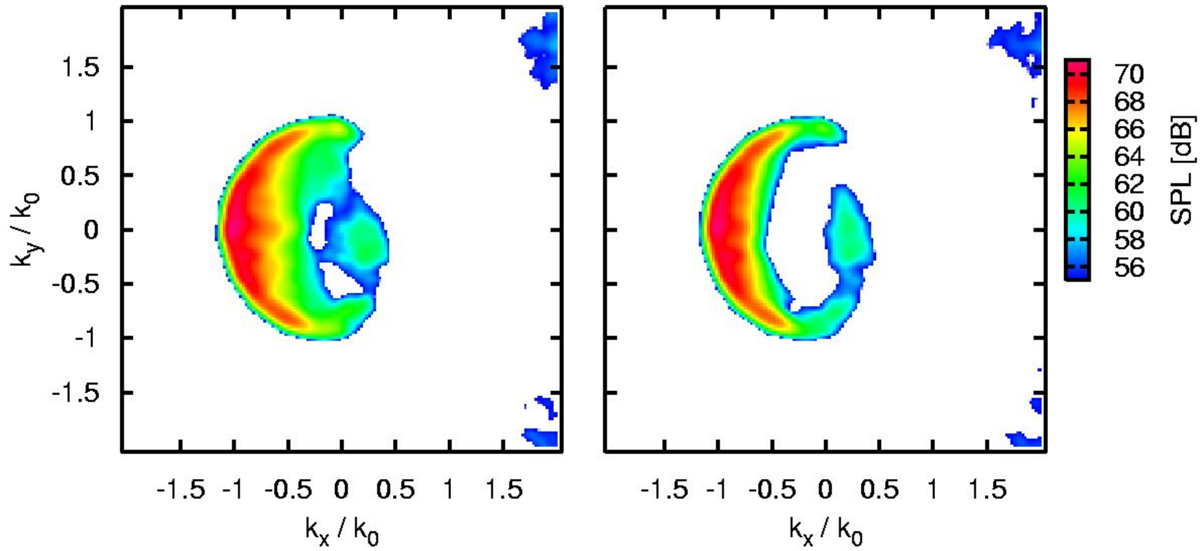

Fig. 3. Map in wave-number space for 1/3-octave at 3 kHz. Left: without foam, right: with foam.

4 ADVANCED ARRAY PROCESSING

In the following a method is proposed, how the artifacts in the source maps can be reduced by a more sophisticated array processing. The idea is, to split up the cross-spectral matrix $\boldsymbol{R}$ into a first part $\boldsymbol{R}_1$, which represents the real sources in the observation plane, and a second part $\boldsymbol{R}_2$, which describes the disturbing waves. At the beginning the diagonal of the cross spectral matrix $\boldsymbol{R}$ is set to zero. Then an iterative procedure is started, where $\boldsymbol{R}$ is successively reduced. In the first step of each cycle, both, a source map and a map in wave-number space, are calculated using the current matrix $\boldsymbol{R}$. Then the absolute maximum over both maps is searched. This maximum is either at a location in the observation plane or at a certain position in wave-number space. A synthetic cross-spectral matrix $\boldsymbol{R}_S$, which belongs to the maximum, is calculated as the outer product of the corresponding steering vector $\boldsymbol{s}$ with removed diagonal:

$$\boldsymbol{R}_S = DR(\boldsymbol{s} \,.\, \boldsymbol{s}^H).$$

Then this synthetic matrix is normalized by:

$$\boldsymbol{R}_{SN} = \boldsymbol{R}_S \left(\boldsymbol{s}^H \boldsymbol{R}\, \boldsymbol{s} \,/\, \boldsymbol{s}^H \boldsymbol{R}_S\, \boldsymbol{s}\right)$$

In the next step the normalized matrix $\boldsymbol{R}_{SN}$ is subtracted from the matrix $\boldsymbol{R}$ and added to either $\boldsymbol{R}_1$ or $\boldsymbol{R}_2$, depending on wether the maximum was in the source map or in the map in wave-number space. The whole cycle is repeated until the absolute maximum is below a certain threshold. In the present case simply 200 iterations are performed. Then the maximum has less than one percent of its initial value. In a last step the remaining matrix $\boldsymbol{R}$ is added to the accumulated matrix $\boldsymbol{R}_1$. Thus, the sum of the final matrices $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$ corresponds to the initial cross-spectral matrix. To calculate an improved source map, the matrix $\boldsymbol{R}_1$ is taken instead of the initial cross-spectral matrix $\boldsymbol{R}$.

To verify the proposed method, the same example as in the previous section is considered. The improved source map for the case without foam is shown in figure 4. Now, the sources at the slat are dominating the whole map. The strong sources downstream of the wing have disappeared. A closer look at the result shows, that compared to the source map in figure 2 (left, without foam) the source strength at the slat is slightly reduced as well.

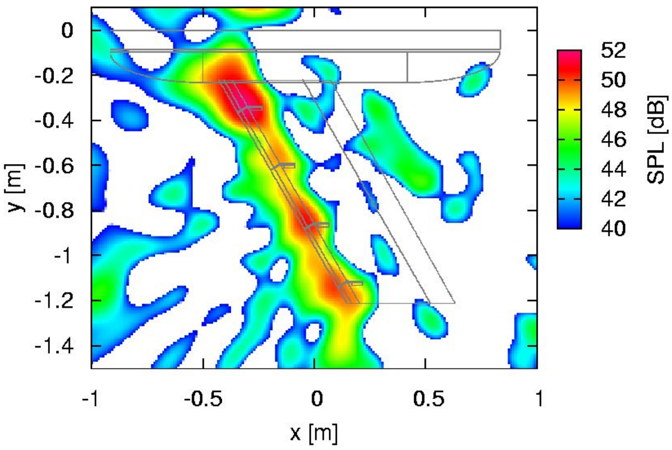

Fig. 4. Improved source map at a single frequency of 2900 Hz without foam in the test section. Flow velocity is 30 m/s and angle of attack is 7 degree.

5 CONCLUSIONS

The experiments show that strong background noise is present in the wind tunnel with closed test section. This noise consists mainly of upstream propagating waves. They can disturb array measurements and cause artifacts in source maps. The proposed iterative method is able to reduce these artifacts or remove them almost completely. Further experiments are needed to check, if the results are characteristic for all wind tunnels with closed test sections, or if they depend on specific properties of the present wind tunnel.

REFERENCES

[1] U. Michel, B. Barsikow, J. Helbig, M. Hellmig, and M. Schuettpelz, "*Flyover noise measurements on a landing aircraft with a microphone array*", AIAA paper 98-2336, 1998

[2] W.M. Humphreys, T.F. Brooks, W.W. Hunter and K.R. Meadows, "*Design and use of microphone directional arrays for aeroacoustic measurements*", AIAA paper 98-0471, 1998

[3] L. Koop, K. Ehrenfried, A. Dillmann, and U. Michel, "*Reduction of flap side edge noise by active flow control*", AIAA paper 2002-2469, 2002.