Aeroacoustic Investigation of a High-Lift Device by Means of Synchronized PIV and Microphone Measurements

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Abstract In the present paper the causality correlation technique is applied for the experimental detection of noise sources at the leading edge slat in a high-lift device configuration. Velocity measurements in the vicinity of the slat using PIV as well as pressure measurements at the surface of the leading edge of the main-wing are conducted. Synchronously microphone measurements in the far-field of the wing’s suction and pressure side are performed. By calculating the cross-correlation between the obtained near- and far-field quantities, regularities in the near-field related to the radiated sound-field are identified. Results for different angles of attack are compared and analyzed.

1. Introduction

Synchronized measurements in the acoustic near- and far-field enable the calculation of the cross-correlation between the acoustic pressure and the near-field fluctuations. By this flow structures which are subject to the same physical phenomenon as the aeroacoustic sources are identified in a statistical manner. The technique relates the effect to the cause and hence is called a causality correlation (Rackl and Siddon, 1979). It has been applied in the past by means of measuring the near-field fluctuations with various techniques (Lee and Ribner, 1972; Schaffar, 1979; Rackl and Siddon, 1979; Panda and Seasholtz, 2002; Picard and Delville, 2000). To date, the causality correlation technique using PIV in the flow-field has been applied to rather generic flows such as a cylinder wake (Henning et al, 2008), a rod-airfoil configuration (Henning et al, 2010a) and a free jet (Henning et al, 2010b). In the present paper the method is applied to a more industrially relevant flow, i.e. the leading edge slat in a high-lift device configuration. The leading edge slat at high-lift devices has been identified as a major contributor of airframe noise during aircraft approach and landing (Michel et al, 1998; Piet et al, 2002; Oerlemans and Sijtsma, 2004). It was found to be the source of tonal and broadband noise. Various noise generation mechanisms have been proposed. High-frequency tonal noise is caused by vortex shedding at the finite thickness trailing edge slat (trailing edge noise) (Singer et al, 1999; Khorrami and Choudhari, 2003; Khorramp et al, 2003). Low-frequency noise is generated due to an interaction between the slat cove surface and the impinging shear layer (Jenkins et al, 2004; Takeda et al, 2001; Khorramp et al, 2001). It is also proposed that a feedback mechanism between vortices from the slat trailing edge and vortices from the slat cusp acts as a resonator (Storms et al, 1999; Takeda et al, 2002; Olsen et al, 2000). In a previous application of the proposed method to the flow-field inside a leading-edge slat-cove, the signal-to-noise ratio of the resulting correlation-coefficients has been too low to allow an identification of noise-relevant flow structures (Henning et al, 2008). These experiments described in Henning et al (2008) where performed under non-anechoic conditions in a wind tunnel with a closed test section and reverberant side walls. The measurements under free field conditions presented here...
will demonstrate the applicability of the technique for such a flow configuration, if the number
of PIV samples \( N \) is chosen to be high enough (\( N = 16000 \) in the present case). It should
be noted that the present experimental approach differs significantly from sound predictions
based on PIV-data performed by others in the past (Lorenzoni et al, 2009). The experimental
setup and methods are described in the following section. Results are presented in Section 3.

2. Experimental Setup and Methods

Experiments were conducted in the Aeroacoustic Wind Tunnel Braunschweig (AWB) of DLR,
which is an open-jet closed-circuit anechoic test facility with a rectangular 0.8 m by 1.2 m
nozzle exit. Measurements are performed on the DLR F16 model. It is a multi element 2D
high-lift airfoil with a modular design. In the present paper a 3 elements configuration is
investigated. Figure 3 shows a sketch of the high-lift airfoil. The 2D model is installed between
side plates with turntables, designed in prolongation of the nozzle. The model chord length is
\( c = 300 \) mm (clean configuration) and the span measures 800 mm. The deflection-angle \( \delta \), gap
\( g \) and overlap \( ovl \) values for slat and flap are listed in Figure 2 normalized with the model chord.
Measurements have been performed at free stream velocities \( U_\infty = 40 \) m/s (\( Re_c = 800000 \)),
\( U_\infty = 50 \) m/s (\( Re_c = 1000000 \)) and \( U_\infty = 60 \) m/s (\( Re_c = 1200000 \)) and \( \alpha = 11^\circ, 15.5^\circ \) and
19.7\(^\circ\) degrees incidence. In this experiment special slat-tracks on the suction side have been
designed allowing the PIV camera to look inside the slat-cove (see Figure 3). Only results for

<table>
<thead>
<tr>
<th>( \delta_s )</th>
<th>( g_s )</th>
<th>( ovl_s )</th>
<th>( \delta_f )</th>
<th>( g_f )</th>
<th>( ovl_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.834(^\circ)</td>
<td>2.27%</td>
<td>1.07%</td>
<td>35(^\circ)</td>
<td>2.11%</td>
<td>0.56%</td>
</tr>
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Figure 2: Deflection-angle, gap and overlap values for slat (\( \delta_s, g_s, ovl_s \)) and flap (\( \delta_f, g_f, ovl_f \)) normalized with the model chord.

Figure 3: Cross sectional view of the F16 model. The span of the airfoil is \( l = 800 \) mm. The box indicates the regions of interest (ROI) observed by the PIV camera. Black dots are indicating the positions of the pressure probes at the mid-span.
\( \alpha = 11^\circ, 15.5^\circ \) and \( 19.7^\circ \) at \( U_\infty = 50 \text{ m/s} \) are shown in the present paper.

2.1 PIV-Setup

Velocity data are acquired with a two-dimensional PIV system, capable to capture two components of the velocity vectors in a plane. The system consists of a double-pulse laser system generating the light sheet and a camera (PCO, 1600) recording the light scattered by the tracer particles. The frequency-doubled laser (Q-switched Nd:YAG; Quantel CFR 400) emits laser pulses with a maximum energy of 200 mJ. It is operating at a repetition rate of 10 Hz. The charge-coupled-device cameras have a resolution of \( 1600 \times 1000 \) pixels and a frame rate of 5 Hz, which therefore represents the sampling rate of the whole PIV setup. To avoid shadowing effects, the slat region is illuminated from the top and the bottom of the model simultaneously. The resolution is 19.2 px/mm for the used cameras. The flow is seeded with diethylhexylsebacate (DEHS) tracer particles with a mean particle diameter of approximately 1 \( \mu \text{m} \) (Kähler, 2003). The seeding is injected from a corner of the wind tunnel upstream of the model configuration in a way that the particles have to pass the complete wind tunnel before they reach the PIV field of view. The PIV and the pressure measurements are performed in a synchronized manner. In order to avoid a jitter between the PIV timing and the pressure data acquisition both measurement systems are synchronized by a master clock. The dynamic range was approximately 30 px and the interrogation window size is \( 32 \times 32 \) px with an overlap of 50%.

2.2 Surface Pressure Measurements

Wall pressure fluctuations are measured with a set of pressure probes at the mid-span of the airfoil arranged in the chordwise direction at the leading edge of the wing main-body (see Figure 3). A second set of sensors is distributed in spanwise direction along the leading edge of the wing main-body. These probes are sub-miniature piezo-resistive pressure transducers. The sensors model is XQC-132A-093, manufactured by KULITE. The wiring of the sensor is shielded to reduce electrical noise. The nominal measurement range is 35 kPa. In order to operate the pressure transducers signal-conditioners model 436 manufactured by Endevco were used. The signal conditioners were installed altogether in the rack model 4990A also manufactured by Endevco. In the signal conditioners the voltage signals were pre-amplified. The gain factor was set to 100 during all the tests considered here. Since only unsteady pressure fluctuations were of interest an AC coupling of the signals was used. The analog signals were filtered, digitalized and recorded by the Viper data acquisition system used for the microphone signals with equal parameters. No results from these measurements are shown in the paper presented here.

2.3 Far-Field Microphone Measurements

A 2D-microphone array is located outside the flow-field below the high-lift device (pressure side). It consists of 64 microphones (M51 by LinearX). The distance between the model and the microphone membranes is approximately 5.89 c. A linear microphone array is located above the model (suction-side) at a distance of 3 c. It consists of 8 microphones. The microphone signals were simultaneously sampled with an A/D conversion of 16 bits at a sampling frequency of \( f_s = 100 \text{ kHz} \). All channels had an anti-aliasing filter at \( f_a = 50 \text{ kHz} \). To reduce the influence of low-frequency wind-tunnel noise on the measured signals a high-pass filter with a cutoff frequency \( f_l = 500 \text{ Hz} \) has been applied.
Figure 4: left Microphone-positions in the 2D-microphone array located outside the flow-field below the high-lift device (pressure side). The distance from the model in the y-direction is 5.89c for all microphones. right Microphone-positions in the 1D-microphone array located outside the flow-field above the high-lift device (suction side). All microphones are located at midspan positions. Microphones used in the present paper are labeled and marked by a circle.

2.4 Calculation of the cross correlation coefficient

The sample correlation coefficient $R_{\psi,p}(x, \tau)$ will be defined as

$$R_{\psi,p}(x, \tau) = \frac{S_{\psi,p}(x, \tau')}{\sigma_\psi(x) \sigma_p} = \frac{\langle \psi'(x, t) p'(t + \tau') \rangle}{\sqrt{\langle \psi'(x, t)^2 \rangle \langle p'(t)^2 \rangle}}$$

where $\psi'(x, t)$ represents the zero-mean part of a near-field quantity $\psi$ measured at position $x$ and time $t$. The variable $\tau'$ is the time shift between the pressure signal and $\psi$. The correlation coefficient is normalized by the root-mean-square (RMS) values of $\psi'$ and $p'$ which are denoted by $\sigma_\psi(x)$ and $\sigma_p$.

3. Results

The axes in the following figures are scaled to the chord $c = 300$ mm. $x$ and $y$ are right-handed Cartesian coordinates with the origin at the leading edge of the clean wing configuration. The local coordinate system of the wing is used in the following illustrations. Due to shadowing effects an area containing no data can be found in the lower slat cavity.

3.1 Flow Field

Averaged velocity vector maps for the selected configurations are depicted in Figure 5. For the purpose of clarity only every second vector is plotted. The velocities are made dimensionless using the free stream velocity $U_\infty$. The development of a shear layer from the separation at the slat-cusp can be observed in the figures as described in the literature (Choudhari et al, 2002; Takeda et al, 2002). Additionally the recirculation region in the slat-cove and the acceleration
of the flow in the slat-gap near the leading edge of the main element are flow patterns typically observed in the vicinity of a slat. The main difference between the selected configurations lies in the path of the shear layer emanating from the slat-cusp. In comparison, the curvature increases with increasing $\alpha$, resulting in a smaller recirculation region and a reattachment point further upstream. It is known from the literature that this shear layer emanating from the slat-cusp with high values of positive sign vorticity, breaks up into discrete vortices. It impinges on the slat-cove wall and vortices either get ejected through the slat-gap or trapped inside the recirculation area in the slat-cove. Previous studies have shown that such coherent flow structures have a strong influence on the correlation coefficients between the near- and far-field data. Their topology and extensions are important for an interpretation of the temporal as well as the spatial coefficient distribution presented in Section 3.3 (Henning et al, 2010a). In order to give an impression of the regularity in the coherent structures, the autocorrelation of the vertical velocity component will be shown in the following. The spatial correlations are calculated using the Pearson product-moment correlation defined as:

$$ R_{\Phi_i,\Phi_j}(x_R, x) = \frac{\langle \Phi_i'(x_R) \Phi_j'(x) \rangle}{\sigma_{\Phi_i}(x_R) \sigma_{\Phi_j}(x)} . $$

The coefficients $R_{v,v}$ for the reference point $x_R = [x/c; y/c] = [0.053; -0.05]$ are depicted in Figure 6. Significant coefficients can be observed in the whole investigated region for all configurations. In case of $\alpha = 11^\circ$ and $\alpha = 15.5^\circ$ the location of local maxima and minima

Figure 5: Averaged velocity vector maps at $U_\infty = 50$ m/s for the different angles of attack. Every second vector has been omitted for clarity.

Figure 6: The autocorrelation of the vertical velocity component $R_{v,v}$ for $\alpha = 11^\circ$, $\alpha = 15.5^\circ$ and $\alpha = 19.7^\circ$ (left to right). The reference point is $[x/c; y/c] = [0.053; -0.05]$. 
in the proximity of the reference points can be explained by the spatial coherence caused by
the vortices emanating from the slat-cusp. The values of these local extrema are observed to
be higher in case of $\alpha = 11^\circ$. Therefore it can be assumed that the large scale vortices are
showing a different behavior in case of the lower angle of attack. This can be either a stronger
periodicity of these structures in the shear layer or a difference in the size and strength of the
vortices. In case of $\alpha = 19.7^\circ$ the spatial distribution of $R_{v,v}$ differs significantly from the two
lower angles of attack. Here regions of high significant values are present at the pressure side
of the slat as well as above and below the slat-gap. Additionally a small region of high values
can be found along the trajectory of the shear layer emanating from the slat-cusp, followed by
an extended region of negative values further downstream. Note that the wavelike structure
of the distribution in this region is not physical but most probably due to Moiré-effects, which
emerge from the limited dynamic range of the PIV evaluation in this region of very low velocity
fluctuations.

3.2 Acoustic Results

Acoustic frequency spectra are calculated with a number of 600 averages using a Hanning
window and a total averaging period of 30 s. The frequency resolution is 10 Hz. Sound pressure
levels (SPL) are given in dB with a reference pressure of $p_{ref} = 2 \cdot 10^{-5}$ Pa. A set of spectra
for the selected configurations with $U_\infty = 50$ m/s is depicted in Figure 7 (left), measured at a
single microphone $pb36$ (see Figure 4) of the 2D-Array located at $90^\circ$ to the flow direction at
$x/c \approx 0.5$ (pressure side). The main difference between the configurations is the presence of

Figure 7: Comparison of sound pressure levels for the different configurations with $U_\infty = 50$ m/s. left: Measured at a single microphone $pb36$ (see Figure 4) of the 2D-Array located at $90^\circ$ to the flow direction at $x/c \approx 0.5$ (pressure side). right: Measured at a single microphone $pt5$ (see Figure 4) of the 1D-Array located at $90^\circ$ to the flow direction at $x/c \approx 0.7$ (suction side)

stronger tonal components in case of the lowest angle of attack. Here, high peaks in the far-field
spectrum can be observed at approximately 1900, 2300 and 3100 Hz. In case of $\alpha = 15.5^\circ$ this
peaks are reduced significantly and for $\alpha = 19.7^\circ$ no strong maxima are observable. The spectra
of the pressure fluctuations at the suction side are depicted in Figure 7 (right), measured at a
single microphone $pt5$ of the 1D-Array (see Figure 4). In case of $\alpha = 11^\circ$ peaks at the same
frequencies observed for the pressure side can be identified. This is not the case for \( \alpha = 15.5^\circ \) and \( \alpha = 19.7^\circ \) where only peaks at approximately 3100 Hz are present in the spectra.

### 3.3 Cross-Correlation Results

16 000 PIV snapshots are considered for the comparison of the cross-correlation results; this number corresponds to the maximum number available for all investigated configurations. The final error margin for \( R_{\psi,p} \) with 16 000 samples is approximately \( \pm 0.02 \) based on a \( t \) test against zero (99% probability). Note that \( \tau = \tau' - r/c_0 \) is the retarded time shift. \( r \) is the distance from the measurement point in the flow field to the microphone and \( c_0 = 341 \text{ m/s} \) is the defined ambient sound speed. In the results shown in the following \( p \) are the pressure fluctuations measured at a single microphone. In the bottom part of the following figures \( p \) is taken from the microphone \( pb36 \) at the pressure side of the wing, 90° to the flow direction at \( x/c \approx 0 \). The top part of the figures are showing the results with \( p \) being the pressure fluctuations from the microphone \( pt5 \) at the suction side (see Figure 4).

Figure 8 shows the maximum values of the cross correlation coefficient \( \max_\tau(|R_{v,p}|) \) with respect to \( \tau \) observed at the selected configurations for \( U_\infty = 50 \text{ m/s} \). In case of \( \alpha = 11^\circ \) the regions of significant values are distributed around a curved path from the slat-cusp to the slat-gap and further downstream along the suction side of the airfoil. The path corresponds to the region where a free shear layer emanates from the slat-cusp as described in Section 3.1. In case of \( \alpha = 15.5^\circ \) the region of significant values is smaller and limited to an area at the beginning of the slat-gap. For both lower values of \( \alpha \) the coefficients are higher in case the velocity fluctuations are correlated with \( p \) measured at the pressure side (bottom row), compared to the results with \( p \) from the suction side (top row). In case of \( \alpha = 19.7^\circ \) the distribution of

![Figure 8: Spatial distribution of the maximum coefficient values max_\tau(|R_{v,p}|) observed at the 3 selected configurations with \( \alpha = 11^\circ, \alpha = 15.5^\circ, \alpha = 19.7^\circ \) at \( U_\infty = 50 \text{ m/s} \) (top to bottom). Pressure data are taken from microphones \( pb36 \) on the pressure side (bottom) and \( pt5 \) on the suction side (top).](image-url)
maximal coefficients changes significantly. If \( p \) is taken from the microphone at the suction side, the distribution shows a strong similarity to the autocorrelation \( R_{v,v} \), depicted in Figure 6 (right). Regions of high significant values (\( R_{v,p} > 0.2 \)) are present at the pressure side of the slat as well as above and below the slat-gap. A region of high values can be found along the trajectory of the shear layer emanating from the slat-cusp, followed by an extended region of high values further downstream. Note again that the wavelike structure of the distribution in this region is not physical but most probably due to Moiré-effects (see Section 3.1). In the results for the pressure side at \( \alpha = 19.7^\circ \), comparable small correlation-values can be observed, not being higher than \( R_{v,p} = 0.06 \).

The temporal evolutions of the cross-correlation coefficient \( R_{v,p} \) are depicted in Figure 9 at positions where the overall maxima of the correlation-coefficients are observed in Figure 8. In

\[
\begin{align*}
\alpha = 11^\circ & \quad [x/c; y/c] = [0.053; 0.055] \\
\alpha = 15.5^\circ & \quad [x/c; y/c] = [0.067; 0.057] \\
\alpha = 19.7^\circ & \quad [x/c; y/c] = [-0.013; 0.015] \\
\end{align*}
\]

Figure 9: Temporal evolution of the cross-correlation coefficients \( R_{v,p} \) for the selected configurations at positions \([x/c; y/c]\) where the overall maxima of the correlation-coefficients are observed in Figure 8. *bottom part* \( p \) from mic. \( pb36 \) at pressure side. Pressure data are taken from microphones \( pb36 \) on the pressure side (*bottom*) and \( pt5 \) on the suction side (*top*).

case of \( \alpha = 11^\circ \) the temporal evolution of \( R_{v,p} \) shows a strong periodicity with a maximum value at \( \tau = 0 \). This is different in case of \( \alpha = 15.5^\circ \) and \( \alpha = 19.7^\circ \) where the correlation function shows only a relatively short event which consists mainly of a single positive and negative deflection. Previous studies have shown, that in case of periodic structures in the flow field and tonal components in the far-field pressure fluctuations, the correlation between the velocity fluctuations and the acoustic pressure shows the same oscillations as the input signals. Figure 10 shows the instantaneous distribution of the cross correlation coefficients \( R_{v,p} \) for the selected configurations at \( \tau = 0 \). In case of \( \alpha = 11^\circ \) regular patterns of significant positive and negative values can be identified along the described trajectory of the shear layer. The temporal evolution depicted in Figure 9 together with the spatial distribution of the coefficient corresponds to a regular pattern of discrete vortices emanating from the slat-cusp and being accelerated and ejected through the slat-gap. Thus these coherent structures can be identified as part of the sound generation process in case of \( \alpha = 11^\circ \). For the higher deflection-angle \( \alpha = 15.5^\circ \) very similar flow structures are present in the slat-cove region. But here only a comparatively small
α = 11°

α = 15.5°

α = 19.7°

Figure 10: Instantaneous distribution of the cross correlation coefficients $R_{v,p}$ for the selected configurations at $\tau = 0$. Levels lower than the error margin are set to white (99% probability). Pressure data are taken from microphones $pb36$ on the pressure side (bottom) and $pt5$ on the suction side (top).

A region of significant correlation values can be identified. This corresponding single positive and negative deflection in the temporal evolution of the correlation function is typical for a source process with a broadband characteristic. This is especially true for the result with $\alpha = 19.7^\circ$ and $p$ being the pressure at the suction side. Here a single peak at $\tau = 0$ dominates the temporal evolution of the correlation coefficient $R_{v,p}$ and no periodicity in the spatial distribution can be identified in Figure 10 as found for the lower angles of attack.

4. Conclusion

The noise sources at the leading edge slat in a high-lift device configuration are investigated by means of the causality correlation method. The cross-correlation between the acoustic far-field pressure and near-field fluctuations obtained via particle image velocimetry (PIV) is calculated. A parametric study is performed varying the deflection-angle, the slat-gap and -overlap as well as the flow speed $U_\infty$. The results for different deflection-angles are shown in the study presented here. The results show that a parameter change can be directly assigned to a change of flow structures which are part of the sound generation process by means of the proposed causality correlation method. This includes also the directivity, meaning that the results are showing a strong dependency on whether the correlation is calculated for pressure signals from the pressure or suction side of the airfoil.
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