Investigation on trailing-edge noise sources by means of high-speed PIV

A. Schröder, U. Dierksheide*, J. Wolf*, M. Herr° and J. Kompenhans

Deutsches Zentrum für Luft- und Raumfahrt, Institut für Aerodynamik und Strömungstechnik
Bunsenstrasse 10, 37073 Göttingen, Germany
°Lilienthalplatz 7, Braunschweig, Germany
email: Andreas.Schroeder@dlr.de

* LaVision GmbH
Anna-Vandenhoeck-Ring 19, D-37081 Goettingen, Germany

ABSTRACT

The noise generation of turbulent flows over surfaces and around edges of airplanes and automobiles is a general design problem and its importance increases in times of growing traffic in this globalizing world. Turbulent boundary layers near the trailing-edge of a surface are known to generate intense, broadband scattering noise as well as surface pressure fluctuations. The wake of vortices shed depends on the trailing edge thickness and results in the emission of narrow band noise. The noise generating mechanisms depend essentially on the radial components of the velocity fluctuations in respect to the trailing edge. Resulting forces may also cause model vibrations, which are additional low frequency noise sources. In this feasibility study the high-speed PIV (HS-PIV) technique is applied to an investigation of the spatial and temporal development of coherent structures in a turbulent flat-plate boundary layer flow in the vicinity of the trailing-edge (TE). It is expected that with time resolved PIV data obtained in the region immediately up- and downstream of the TE an identification of noise sources and their correlation with the flow structure movement will be possible. On the basis of a large number of time resolved instantaneous velocity vector fields the technique enables also the possibility of determining several statistical quantities of fluid mechanical significance: average velocity profiles, velocity fluctuations (u', v'), rms-fields, probability density functions and space-time-correlations of the velocity fluctuations and the z-component of vorticity.

The far field noise intensity, which is radiated locally at the position of the TE, measured simultaneously with the instantaneous velocity fields by a directional microphone at 50 kHz sample rate. A phenomenological link between noise and flow structure movement by a comparison of the pressure -time -history of the far field with the time-velocity vector fields directly at the noise source is one objective of this investigation. A connection of the velocity fluctuation structures to the far field noise by means of space-time-correlations is a first step towards an identification of the noise generating flow structures.

Fig 1: Instantaneous velocity vector field out of a 4 kHz run at the TE vicinity (top) and corresponding time mirrored directional microphone signal sampled with 50 kHz and focused at the TE.
Introduction

Airframe noise is essentially due to the interaction of unsteady, mostly turbulent flow with the structure, particularly caused by vortical flows around edges or over open cavities. A classical problem in this field is the trailing-edge noise, which involves different noise generating mechanisms. Investigations were made on airfoil- and on flat plate- trailing-edges. Brooks and Hodgson [3] described an experiment with a NACA0012 model with a tripped turbulent boundary layer and different TE thicknesses. They observed a spectral “hump” in the microphone measurements and were able to relate this hump to blunt TE vortex shedding for relatively thick edges, which vanishes with a decrease in TE thickness. For all cases they found a low frequency broadband maximum in the power density spectrum caused by the turbulent boundary layer (TBL) convected past the TE at about 1 kHz. A predictable correlation of pressure tap measurements in the region close to the TE and the far field sound pressure was found. Howe [4] distinguishes TE noise theories of three different types. Those based on Lighthill’s acoustic analogy, like from Ffowcs Williams and Hall [5], those based on a solution of special configurations by linearized hydroacoustic equations and those creating ad hoc models with postulated source distributions. It was pointed out that all theoretical models lead to the same $U^5$ scaling of the velocity dependence of the radiated sound. He also found spectral humps due to blunt vortex shedding which follow more or less the Strouhal law $f_d/U \approx 0.1$. The TBL flow structures causing the pressure fluctuations at the TE were assumed to have characteristic length scales. According to the distribution of the different length scales of the TBL flow structures the distribution of the frequencies of the pressure fluctuation can be recognized in the power density spectrum of the far field noise. An essential result following Ffowcs Williams and Hall is that the far field intensity varies with $\sin(\theta)$, the propagation direction angle, as $\sin(\theta/2)$ postulating a semi-infinite flat plate at $\theta = 180^\circ$ of negligible thickness. In the s.c. Howe’s approach he gave a scheme how to solve the inhomogeneous wave equation from Lighthill’s acoustic analogy for a flat plate. In the absence of any vortex shedding into the wake he showed for a fixed observer at distance $R$ that,

$$\langle p^2 \rangle \approx \rho_0^2 u_0^2 V^2 M_v \left( \frac{L}{R^2} \right) \sin\alpha \sin^2(\theta/2) \cos^2 \beta$$

with $V$ as the convection velocity, $u_0$ the rms velocity, $M_v$ the turbulence convection Mach number, $\rho_0$ the ambient density, $\beta$ the TE swept angle, $L$ the spanwise edge length and $I$ a characteristic length scale of the flow, which has been often identified with the displacement thickness of the TBL. With the three velocity terms in this formula the scaling of the sound pressure goes with $U^5$ consistent with other relevant approaches.

It came out that the most important “principal edge noise dipole” is the component normal to the plate in $x$- and $y$-direction of the acoustic dipole $\omega \times V$, where $\omega$ is the vorticity vector and $V$ is the convection velocity. The measurement of the time resolved instantaneous velocity vector fields in the plane normal to the plate by means of HS-PIV in this feasibility study is a novel approach to obtain the required data for Howe’s approach and also for the calculation of an exact solution of the main terms to the solution of the inhomogeneous wave equation applying a suitable Green’s function for the flat plate.
Set-up

A flat plate with an elliptic leading edge was mounted vertically in the AWB, the aero acoustic wind tunnel of DLR, Braunschweig (see Fig 2). At a free stream velocity of $U_\infty = 40 \text{ m/s}$ and $50 \text{ m/s}$, and a stream-wise length of the flat plate of $x = 2 \text{ m}$ a turbulent boundary layer flow develops with a thickness of approx. $\delta \sim 0.03 \text{ m}$ on each side at the TE. Convection of vortical flow structures past the TE occurs. The Reynolds number this configuration corresponds to $Re = 5.3 \times 10^6$ and $6.6 \times 10^6$ respectively based on the chord length. Towards the trailing edge the plate is slightly and symmetrically convergent, but no flow separation occurs. A full description of the experimental set-up without HS-PIV system can be found in [2]. The PIV measurement volume was located at the trailing-edge in a x-y-plane inside the turbulent boundary layer in order to track the flow structures with a spatial resolution of 256 pixels in y- and 1024 pixels (x ~135 mm) in x-direction.

The high speed PIV system used consists of a New Wave Pegasus PIV, dual cavity Nd:YLF DPSS laser with an output beam wavelength of 527 nm, a pulse length of 135 ns and 2x10 mJ at 1 kHz and approximately 2x 7 mJ at 4 kHz for each resonator, optics to produce a light sheet and a HighSpeedStar4 (HSS4) CMOS camera with a spatial resolution of max. 1024x1024 Pixel at 2 kHz frame rate. The pixel size of the CMOS chip is 17.5 x 17.5 µm², and the full area chip size is 17.92 x 17.92 mm². In this application we achieved 4 kHz double frames, thus 8 kHz images at a spatial resolution of 1024x256 pixel with a 10bit greyscale dynamics (for details see [1]). With 2.6 GB camera memory inside the camera housing we were able to capture 4096 double-images per run. The camera lens used was a Nikon 105 mm with an aperture of $f_\varphi = 1.8$. The evaluation of the particle images has been performed with a cross correlation scheme using standard FFT with 4 x multi-pass with image deformation, interrogation window shift and a final window size of 32x32 pixel, with 75% overlap, corresponding to a resolution down to 3 mm in each direction of physical space. The Whittaker reconstruction was used for the deformation scheme and peak detection was achieved by a three point Gaussian fit. For post-processing a median filter was used to remove vector outliers.

A directional microphone measuring the scattered far field noise intensity radiated at an angle of 90° and running simultaneously with the HS-PIV at 50 kHz sample rate focused locally at the position of the TE. An average run time difference from the TE noise sources to the microphone of approx. $T_\varphi = 6.05 \text{ ms}$ has to be taken into account for comparison of PIV vector fields and the sound pressure-time history of the microphone output signal. Because of the local focusing of the microphone a frequency cut off at about 1 kHz for the long wavelengths side has to be considered. A second measurement under the same conditions has been performed applying a noise reduction device. A stream-wise oriented brush with 0.03 m length was mounted at the TE in order to reduce the scattered noise, especially the spectral “hump” of the blunt vortex shedding.

Fig 2: Set-up and trigger scheme of the high speed PIV system at the flat plate trailing-edge (left), view against flow direction and the directional microphone with concave mirror (right) at AWB, DLR-Braunschweig
Results

As a selection of the different HS-PIV runs the results of a $U_\infty = 40$ m/s and $U_\infty = 50$ m/s case with a clean TE are shown in the following. In Fig 3 two average velocity fields of the vicinity of the TE for both free stream velocities are shown in the streamwise plane between $-0.06 \text{m} < x < 0.08 \text{m}$ with $x = 0$ located at the TE and normal to the flat plate between $-0.018 < y < 0.018 \text{m}$ with a color coding of the magnitude of velocity. The velocity profiles of the lower half of two developed TBL’s can be extracted out of this field, which show symmetry on both sides of the plate. In the edge wake near region velocities of nearly 0.5 times the free stream velocity can be found. Further downstream the wake gets weaker mainly due to the turbulence mixing process occurring at the shear layers on both sides of the wake.

![Average velocity field of 4096 velocity vector fields at $U_\infty = 40$ m/s (top) and $U_\infty = 50$ m/s (bottom)](image)

Fig 3: Average velocity field of 4096 velocity vector fields at $U_\infty = 40$ m/s (top) and $U_\infty = 50$ m/s (bottom)

The calculation of the probability density functions of the two measured velocity fluctuation components $u'$ and $v'$ over the whole flow field is shown in Fig 4. As expected the velocity distributions are very similar to those known for turbulent boundary layers. The slightly asymmetric distribution of $u'$ with more often appearing lower positive $u'$ on one side and higher values for negative $u'$ on the other side is consistent with the known spatial distribution of low and high speed streaks in the TBL. The $v'$ distribution is nearly symmetric and has lower values as $u'$. All distributions became broader with increasing free stream velocity shown in the bottom row. The spike at zero velocities is due to the fact that in the region of the plate all velocity values have been set to zero. The velocity range between +/- 10 m/s for $u'$ and +/- 5 m/s for $v'$ is also consistent with other measurements of TBL’s and shows in which range the noise generating fluctuation velocities are located and how often the different values appear.
Fig 4: Probability density functions of fluctuation velocities $u'$ (left) and $v'$ (right) at $U_\infty = 40$ m/s (top) and $U_\infty = 50$ m/s (spike at 0 is due to model area). Broader $u'$ than $v'$ distributions which is typical for TBL.

In Fig. 5 the corresponding rms-field is shown for the $U_\infty = 50$ m/s case. The color coding makes visible that the highest values can be found directly behind the TE and in the shear layer between the wake and the ‘free’ TBLs, which is more or less the extrapolated position of the highest rms values in the TBLs before they convect past the TE at about 15% of the boundary layer thickness. In addition these values increase at this y-position after having passed the edge. The shear layers on both sides of the wake show consequently also the highest contribution to the average z-vorticity (see Fig. 6), which is mostly represented by shear vorticity in this case. The spatial extension of the average z-vorticity here is narrow as the transition between wake and TBL is of small scale, but with mixing further downstream the shear softens out.

Fig 5: Rms field at $U_\infty = 50$ m/s with high values at the shear layers of the wake region (corresponding to the average field in Fig. 3 bottom).
Fig 6: Average z-vorticity at \( U_\infty = 50 \) m/s with strong shear vorticity at the transition of 'free' TBL to the wake

In Fig. 7 it is shown, that the contribution of the turbulent vortex shedding into the wake region leads to high corresponding rms values of the z-vorticity, which decrease in flow direction as the turbulent interaction with the boundary layer flows on both sides forces the vortex street to a faster decay. Particularly high values can be found in the near wake, where the alternating vortex shedding process occurs only in the direction of the measured component of vorticity, while further downstream the structure became three dimensional, which can only be revealed by stereoscopic PIV arrangement.

Fig 7: Rms field of z-vorticity with high values in the wake region (vortex shedding) (corresponding to Fig. 6)

In the following figures of the two-dimensional space and space-time correlation functions of one-point-space correlations of \( u', v' \) and the z-vorticity fluctuation component fields are shown at interesting positions inside the flow field. The axes in this correlation plane are denoted with \( \Delta x \) and \( \Delta y \), but the initial coordinates stay fixed in the experimental coordinate system for the auto-correlation functions shown. The size of the region of peak correlation is directly related to the averaged size of the coherent flow structure in x- and y- direction. In Fig. 8 two auto-correlation functions of the z-vorticity and \( u' \) velocity component at a point \((x = 0, y = -0.01)\) m in the TBL directly at the TE location are shown. The correlation of the z-vorticity fluctuations shows an elliptic shape elongated in the streamwise direction and negative correlation areas below and on top of the averaged vorticity structure due to shear effects in directions of the highest velocity gradient. A slight upward tilted area of higher correlation values indicates, in consistency with TBL theory, the presence of cascades of hairpin like vortices moving away from the wall at a characteristic angle.
Fig 8: Space auto-correlation of the z-vorticity (top) and the $u'$ (bottom) component fields directly at the TE at point $x = 0$ and $y = -0.01 \text{m}$ inside the TBL.

Also the $u'$ correlation function is in good agreement with other TBL measurements showing an average elongation of about 0.03 m in the streamwise direction at $U_\infty = 50 \text{ m/s}$ and are slightly tilted upwards in downstream direction. The elongation can be explained with the presence of high- and low- speed streaks in this area. Taking the local convection velocity into account which has been determined by space-time-correlation to $V = 35 \text{ m/s}$ at this point the main part of the radiated frequency at about 1 kHz seems to be linked to the convection of such structures past the TE. In theory the exact solution requires a calculation of the cross-product of the velocity with the z- vorticity, but the main variation of the $u'$ component should then only be overlaid with other fluctuation structures of higher frequencies.

The space-time correlation of the z-vorticity in the wake of the flat plate shown in Fig. 9 gives us information about the connected average convection velocity, the average size of the vortices and the coherence of the wake itself. The negative correlations on both sides are due to local shear vorticity with an inverse sign. The convection velocity in this wake region can be determined to 24 m/s at $U_\infty = 40 \text{ m/s}$ free stream velocity. Together with the average size of the vortex structures at about 0.006 m one ends with the characteristic hump at 4 kHz in the radiated noise spectrum of the wake appearing at the microphone position (see Fig. 10). The wake vorticity itself correlates with values up to 0.4 for a range of $\Delta x = \pm 0.03 \text{ m}$. Although a turbulent and three dimensional wake vortex shedding is present the vortex street has this relatively long coherence length.

The microphone spectrum measured at 90° scattering angle towards negative y-direction was calculated for all three velocities at $U_\infty = 40 \text{ m/s}, 50 \text{ m/s}$ and 60 m/s. It confirms the velocity dependency of the noise intensity and shows the spectral humps moving to higher frequencies with increasing free stream velocity. This effect can simply be explained with the larger convection velocity in the wake and the Strouhal dependence.

In Fig. 10 at the right side the effect of the damping of the noise scattering from the wake and also from the TBL at the TE is demonstrated applying just a simple brush device mounted at the TE in streamwise direction with 0.03 m length.
Fig. 9: Two space-time-correlations of the z-vorticity fluctuation component field in the wake at the starting point \( x = 0.005 \) and \( y = 0 \) and a time delay of \( \Delta t = 250 \) µsec (top) and \( \Delta t = 1000 \) µsec (bottom).

Fig 10: Frequency spectra of noise emission measured by a directional microphone at the TE region simultaneously with HS-PIV runs at \( U_\infty = 40, 50 \) and \( 60 \) m/s with characteristic “hump” due to TE vortex shedding (left) Spectra of TE noise at \( U_\infty = 40 \) with clean TE (black) and with mounted brush (red).
Conclusions and Outlook

The work presented in this paper was one of the first applications of time-resolved PIV to a “classical” aero-acoustic problem in a wind tunnel (AWB) at industrially relevant free stream velocities, Reynolds numbers, a sufficiently large field of view and enough spatial resolution to resolve all main features of the sound generating flow. Time-space-correlations of the velocity- and vorticity-fluctuation components provide information of the coherent structure sizes inside the TBLs and in the wake region and enable to determine their specific convection velocities.

As this data-set of time resolved instantaneous velocity vector fields is relatively “fresh” all straight forward applications of aero-acoustic equations and calculations will be performed in the near future. A direct correlation of the single fluctuation components around the TE location with the time-history of the microphone signal will follow in order to distinguish the different flow structures contributing to the spectrum. If this application of the “optical” detection of aero-acoustic source terms is reasonable a huge amount of at least low speed problems at velocities up to 60 m/s can be investigated non-intrusively. The big benefit is that all relevant flow structures are visualized quantitatively and the interaction of the vortices with the structure can be investigated in detail in order to suggest modifications in further design.

Acknowledgement

The author would like to thank Prof. J. Delfs of the Institute of Aerodynamics and Flow Technology, Department of Technical Acoustic, DLR, Braunschweig, for the initial idea of implementing such a HS-PIV system to this principal acoustic experiment in the AWB. As the mostly desired output of this collaboration a direct calculation of the noise source terms will be performed in his department.

References

1) http://www.lavision.de