

Cross-correlation analysis of synchronized PIV and microphone measurements of an oscillating airfoil

Lars Siegel · Klaus Ehrenfried · Claus

Wagner · Karen Mulleners · Arne Henning

Received: date / Accepted: date

Abstract The present study focuses on the correlation between the flow structures evolving during the dynamic stall processes of a two-dimensional NACA64-618 airfoil, which performs a sinusoidal movement about its quarter chord axis, and their aeroacoustic response in the far field. Experiments are conducted in an anechoic wind tunnel at a Reynolds number of 8×10^5 based on the chord length and include

L. Siegel · C. Wagner

German Aerospace Center (DLR), Institute for Aerodynamics and Flow Technology, Göttingen, Germany. Tel.: +49 (0)551 709 2269 E-mail: lars.siegel@dlr.de

Second institute: Technische Universität Ilmenau, Institute of Thermodynamics and Fluid Mechanics, Ilmenau, Germany.

Klaus Ehrenfried · A. Henning

German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology (AS), Göttingen, Germany

K. Mulleners

École Polytechnique Fédérale de Lausanne (EPFL), UNFOLD, Lausanne, Switzerland

simultaneous velocity field measurements in the vicinity of the airfoil and microphone measurements in the acoustic far field. A causality correlation method based on phase locked snapshots of the velocity field allows for the identification of specific structures at different phases of the dynamic stall life cycle that contribute to the sound generation process. The sound emission during the stall development and flow reattachment phases is attributed to coherent structures evolving downstream of the trailing edge. When the flow is fully stalled, the region that contributes to the sound emission increases. The position of the sound emitting coherent structures also fluctuates stronger between oscillation cycles during full stall.

Keywords PIV, aero-acoustics · dynamic stall · cross-correlation · coherent structures

1 Introduction

If the angle of attack of an airfoil exceeds a certain value the flow can detach and the airfoil stalls, which is associated with a significant drop in lift. This critical angle is referred to as the static stall angle of attack. Dynamic pitching oscillations up to angles of attack beyond this static limit can lead to periodic flow detachment and reattachment or dynamic stall. Dynamic stall is associated with the generation and shedding of large-scale leading edge or dynamic stall vortices and a delayed onset of the flow separation with respect to static stall (Carr, 1988; McAlister et al, 1978; McCroskey, 1981). The flow development during dynamic stall has been divided into different stages (Carr et al, 1977; Doligalski et al, 1994; Mulleners and Raffel, 2013). Based on velocity field measurement using particle image velocimetry

(PIV) additional details of the dynamic stall development were identified and lead to the introduction of the concept of the dynamic stall life cycle (Mulleners and Raffel, 2013; Raffel et al, 1995; Zanotti et al, 2014). The cycle starts for moderate angles of attack with the *attached flow* stage. With increasing angle of attack, flow reversal emerges on the suction side of the airfoil. Depending on the airfoil shape, stall development further manifests itself by either a upstream motion of the trailing edge separation region or shear layer roll-up (Degani et al, 1998; Gupta and Ansell, 2017; Reynolds and Carr, 1992). The shedding of the primary dynamic stall vortex marks stall onset and the start of the full stalled stage (Mulleners and Raffel, 2012; Obabko and Cassel, 2002). During the downstroke of the airfoil, the flow remains fully separated until lower angles of attack are reached and the flow reattaches.

The role of the characteristic flow features that are associated with dynamic stall on the dynamic loads and especially on the noise emission is not yet fully understood and remains an import research topic in the field of helicopter and wind turbine aerodynamics. For wind turbines, the pitching of the rotor blades and the associated dynamic stall phenomenon is an important control mechanism for load reduction (Bossanyi, 2003; Petrovic, 2008). Hitherto, most studies have focused on the aerodynamic or aero-elastic effects of this process. The aero-acoustic effect of dynamic stall has not yet been explored with the same efforts. Due to the changing flow characteristics during the pitching motion, different noise mechanisms occur including fluid-structure interactions as well as near- and far-field impacts (Manela, 2013). Trailing edge noise is considered to be the dominant noise source of wind turbines (Brooks and Humphreys Jr., 2003; Oerlemans and Migliore, 2004; Wolf et al, 2014). When the blade trailing edge moves as a result of an active flap or

blade pitch motion, the noise source will move along a complex trajectory and interact with the moving blades trailing edge (Ffowcs Williams and Hawkings, 1969). This complicates not only the localization and characterization of the source of the noise, but also the sound emission characteristics. Various concepts and prediction models have been developed to reduce the noise emission and maintain noise constraints for wind turbines in proximity to urban regions (Doolan et al, 2012; Nagarajan et al, 2006; Wolf et al, 2014).

In this paper, the flow structures associated with the various dynamic stall development stages will be compared to the airfoil self-noise mechanisms (Brooks et al, 1989), which is predominantly the vortex-shedding noise at the trailing edge and the separation-stall noise due to large-scale separation during the deep stall process. Two-dimensional three-component (2D3C) stereoscopic particle image velocimetry is conducted in the near-field of an oscillating airfoil simultaneously with microphone measurements in the far-field, which provide the acoustic pressure fluctuations. This synchronized aero-acoustic measurement technique was successfully applied in the past to fixed bodies like e.g. a rod-airfoil configuration (Henning et al, 2010) or a high-lift device (Henning et al, 2012). These studies revealed that this approach provides the link between coherent flow structures and aero-acoustic noise mechanisms. In continuation of the previous work, the application range of the measurement technique is extended to the oscillating airfoil case to explore its limitations and its applicability and to study the aero-acoustic footprint of dynamic stall.

2 Theoretical background

Based on the measured velocity and pressure fluctuations, the cross-correlation function $S_{\phi,p}$ and coefficients $R_{\phi,p}$ are calculated in order to identify flow structures that are statistically correlated to the aero-acoustic source mechanisms (Henning et al, 2010). The calculation scheme of the cross-correlation operation is presented in figure 1 and the mathematical definition of these quantities is given by:

$$S_{\phi,p}(\mathbf{x}, \tau) = \frac{1}{N} \sum_{i=1}^N (\phi(\mathbf{x}, t_i) - \bar{\phi}(x)) \cdot p'(t_i - \tau). \quad (1)$$

Here, ϕ symbolizes the near-field quantity e.g. a velocity component of the flow field obtained with PIV at the positions \mathbf{x} and the points in time t_i . The spatiotemporal function $\bar{\phi}$ denotes the ensemble averaged value of the near-field quantity and N specifies the overall number of PIV snapshots. The pressure fluctuations recorded with microphones in the far-field are indicated by p' . As the sampling rate of the acoustic recording is much higher than the PIV recording rate (100 kHz vs 14 Hz), the variable τ is introduced representing a time window covering 4097 acoustic samples including 2048 samples before and 2048 samples after the individual PIV snapshots. This corresponds to a time window of ± 0.0205 s. By using this time window, all effects with regard to the sound traveling time between the sound source and the microphone are contained in the calculated cross-correlation values. The time window applies to every single PIV snapshot and defines the temporal resolution of the cross-correlation results as illustrated in figure 1. Normalizing the correlation function with the standard derivations $\sigma_\phi(\mathbf{x})$ and $\sigma_p(\tau)$ of the velocity and the pressure fluctuations, respectively, yields the correlation coefficients:

$$R_{\phi,p}(\mathbf{x}, \tau) = \frac{S_{\phi,p}(\mathbf{x}, \tau)}{\sigma_\phi(\mathbf{x}) \cdot \sigma_p(\tau)}. \quad (2)$$

The calculation of the cross-correlation values can be executed in two different ways. The time between subsequent PIV snapshot (1/14 s) and the oscillation period of the airfoil pitching motion (1/5 s) have a least common multiple of 1 and every 14th snapshot is recorded at the same phase angle of the pitching motion. Hence, phase locked data for 14 different phase angles are recorded during the full oscillation process. This allows to either consider the full data set or an ensemble of phase-locked snapshots at selected phase angles for cross-correlation analysis. Additionally, the standard deviation of the pressure is now a function of τ due to the periodic movement of the profile. This is an important difference to the previously mentioned approaches for flows around stationary objects (Henning et al, 2010, 2012). For flows around stationary objects, a standard deviation of the pressure signal is calculated based on the entire time series of far-field pressure fluctuations yielding a single scalar value. With the aim to study the aero-acoustic footprint of characteristic coherent structures that emerge during different phases of the dynamic stall life cycle, the presented results and discussion are focused on the results of the ensemble of phase-locked snapshots at selected phase angles.

3 Experimental set-up and data processing

3.1 Flow configuration

The experiments were conducted in the aero-acoustic wind tunnel Brunswick (AWB) of the German Aerospace Center (DLR). The AWB is an open-jet closed-circuit anechoic test facility with a rectangular 0.8 m \times 1.2 m nozzle exit. The two-dimensional airfoil model with a NACA64-618 profile of chord length $c = 0.3$ m and span $s = 1.1$ m was integrated in a modular setup enabling a configuration

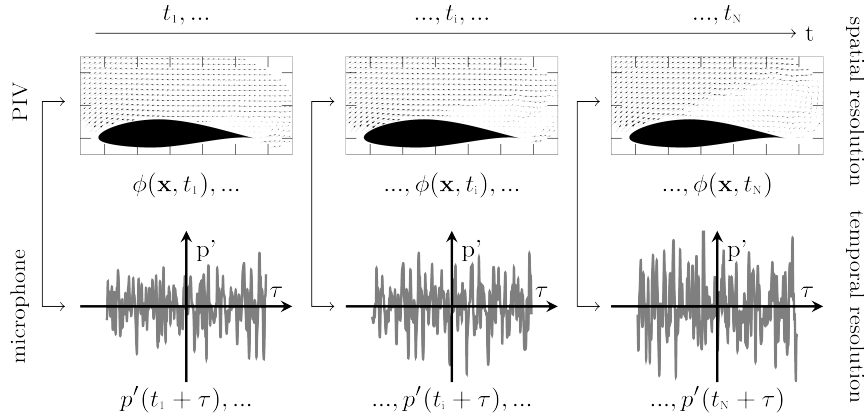


Fig. 1 Calculation scheme of the cross-correlation of the fluctuating velocity fields measured via PIV (top) and the pressure signal recorded with a microphone (bottom).

with side-plates to reduce shear and boundary layer effects of the wind tunnel flow. The airfoil was placed in a uniform flow at a free-stream velocity of $U_\infty = 40$ m/s ($Re = U_\infty c / \nu = 8 \cdot 10^5$ with ν the kinematic viscosity). An electric servo motor ensured a sinusoidal movement of the airfoil about its quarter chord axis with an mean angle of attack $\alpha_0 = 20^\circ$, amplitude $a_1 = 8^\circ$ and oscillation frequency $f = 5$ Hz. This corresponds to a reduced frequency $k = \pi f c / U_\infty = 0.12$ which lies within the typical range of reduced frequencies for dynamic stall of $0.01 \leq k \leq 0.2$ (Mcalister et al, 1982). The instantaneous angle of attack was measured based on laser triangulation to assign the correct angle of attack to the captured PIV recordings. The experimental setup is schematically represented in figure 2.

3.2 Velocity field measurements

The velocity field data were acquired using a stereo PIV system which measured three velocity components in a vertical plane at mid-span (figure 2). Two CMOS

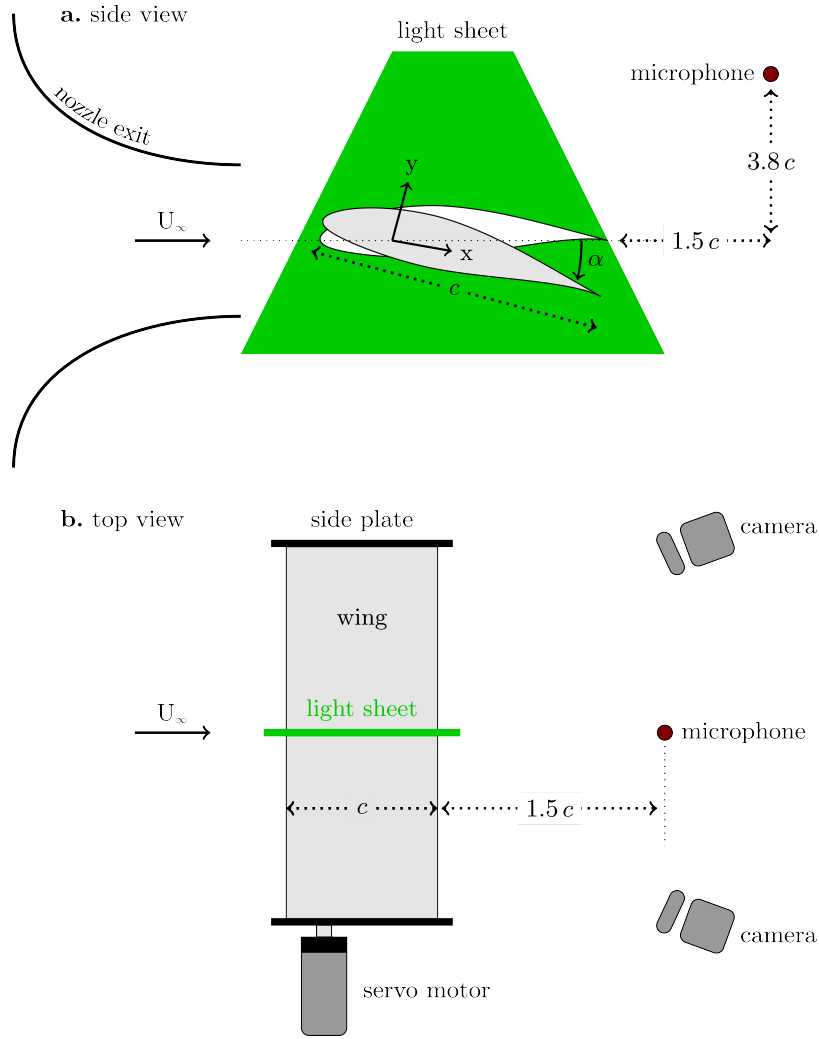


Fig. 2 Schematic sketch of the (a.) side and (b.) top view of the experimental setup (not to scale), including the 2D airfoil with side plates, servo motor, and the positions of the microphone, PIV cameras, and light sheet.

cameras (Type: PCO edge 5.5) with a resolution of $2560 \text{ px} \times 2160 \text{ px}$ were placed in a 90° angle to each other left and right downstream of the field of view to record the illuminated particles on the suction side of the airfoil. Scheimpflug adapters were used in order to align the focal- and image-planes therewith compensating

for the inclination between the optical axes and the field of view. The recording frequency of the PIV system was 14 Hz and a total number of 15000 images were recorded in direct-to-disc storage mode for each configuration. The flow was seeded with diethylhexylsebacate (DEHS) tracer particles with a mean particle diameter of approximately $1\text{ }\mu\text{m}$ (Raffel et al, 2007). The seeding particles were injected from a corner of the wind tunnel upstream of the model configuration in a way that the particles had to pass the complete wind tunnel before they reached the field of view. The DEHS particles were illuminated using a double-pulse laser (Q-switched Nd:YAG; Type: Innolas Spitlight 600) with a maximum energy of 350 mJ per pulse and a repetition rate of 14 Hz. The PIV data were recorded simultaneously with the microphone data. The trigger signals for the camera exposure and the laser-light emission were recorded too in order to be able to subsequently assign the corresponding acoustic data to the respective PIV frames. In order to minimize reflections and unwanted scattered light, light absorbing tubes were installed along the beam guidance and the model was equipped with a thin mat black foil.

3.3 Far-field microphone measurements

The pressure measurements were conducted with overall 16 microphones (Type: 1/4" 40BF; G.R.A.S.) in the far field outside the flow. Eight microphones were installed above and the other eight below the airfoil arranged in a horizontal plane. In this paper, we concentrate on the data of a single microphone located at $1.5\text{ }c$ downstream of and $3.8c$ above the trailing edge of the airfoil. A multi-analyzer (Type: Viper; GBM) simultaneously recorded the microphone signal, the camera trigger, the q-switch of the laser and the laser triangulation signals with a sampling

frequency of $f_s = 100\text{ kHz}$ and a dynamic range of 24 bit. All channels had an anti-aliasing filter at $f_u = 50\text{ kHz}$. To reduce the influence of low-frequency wind-tunnel noise on the measured signals, a high-pass filter with a cutoff frequency $f_l = 500\text{ Hz}$ was used. Additionally, the microphone was protected by wind shields against potential flow in the plenum.

3.4 PIV data processing

Prior to the evaluation of the velocity fields, several preprocessing steps have to be performed, including data management, filtering, and masking. The velocity vector fields are calculated with a multi-pass stereo cross-correlation algorithm with a final interrogation window size of $32\text{ px} \times 32\text{ px}$ and an overlap of 50% yielding a physical resolution of 3.16 mm . All vector calculations are performed using a high-accuracy mode for the final pass by means of the bi-spline-6 reconstruction. With these settings, more than 6000 valid velocity vectors were obtained with an average displacement of 10 px . Due to the mentioned phase-locked characteristic of the PIV recording frequency (14 Hz) and the oscillation frequency of the airfoil (5 Hz), phase locked data was recorded for 7 phase angles during pitch-up and 7 phase angles during pitch-down.

The signal of the microphone downstream above the airfoil is used for the cross-correlation calculation. The following analysis focuses on the values in y -direction (the v -components of the velocity vectors) which is the direction in which the acoustic perturbations propagate to the microphone. The coordinate system shown in figure 2 is used for the representation of the flow field and cross correlation diagrams. The depicted axes are scaled with the chord length of the airfoil while

the zero point is set to the pitching axis of the airfoil. All the fields of view are rotated into the airfoil coordinate system. In the flow field and cross correlation diagrams presented below, the contour of the profile is drawn in black.

4 Results and discussion

4.1 Spectrum and spectrogram of the acoustic signal

Before discussing the flow fields and the cross-correlation results, the acoustic information is presented here. First, the acoustic spectrum of the periodically pitching airfoil has been calculated which represents the averaged sound pressure level in function of frequency. The acoustic spectrum of the selected configuration (black solid line) is compared to those obtained for two reference configurations in figure 3. The maroon line reflects the noise level measured for a non-oscillating airfoil which produces no lift. The orange line displays the acoustic response when the airfoil is completely removed from the setup. All spectra are calculated using 200 individual time series with a total of $2 \cdot 10^5$ samples and an overlap of 50% covering multiple oscillation cycles for the test configuration. The time series are weighted with a Hanning window and Fourier-transformed. The squared values of the resulting short-term spectra are then averaged to represent the sound pressure levels. The threshold of human hearing ($p_0 = 2 \cdot 10^{-5}$ Pa) is used as the reference sound pressure in air. The resulting frequency resolution is 0.38 Hz. The high number of samples are selected to achieve a high frequency resolution and a spectrum that adequately reflects the acoustic response in high and very low frequencies.

Second, a spectrogram is generated from the pressure field of the flow which is presented in figure 4. The spectrogram presents time and frequency dependent

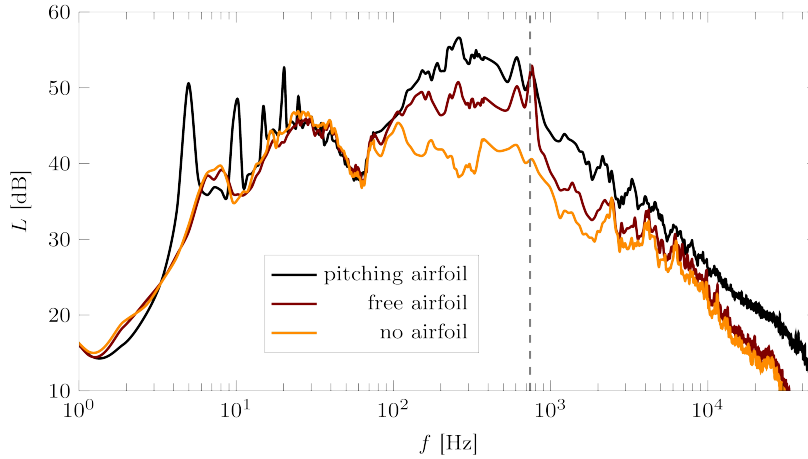


Fig. 3 Spectra of the oscillating airfoil configuration and two reference configurations, a freely hinged airfoil that is not oscillating and not generating lift, and a configuration without the airfoil present.

sound pressure levels and allows for the comparison of sound pressure levels during different stages of the dynamic stall life cycle. The calculation is now based on a series of $2 \cdot 10^4$ consecutive pressure samples, covering a full cycle of the airfoil oscillation according to the sampling frequency of 100 kHz and the oscillation period of 0.2 s. Figure 4a displays the result, which is linked to the respective phase angle of the airfoil (figure 4c), in order to obtain an overview of the prevailing acoustic response in the corresponding oscillation stage.

The selected input parameters, including the window function, the overlap, and the sampling points result in a temporal resolution of $7 \cdot 10^{-4}$ s and a frequency resolution of 12.2 Hz for the data presented in figure 4a. Due to the frequency-time uncertainty, an increased frequency resolution can only be obtained at the expense of a lower temporal resolution which is not desirable here and a compromise must be found between frequency and temporal resolution.

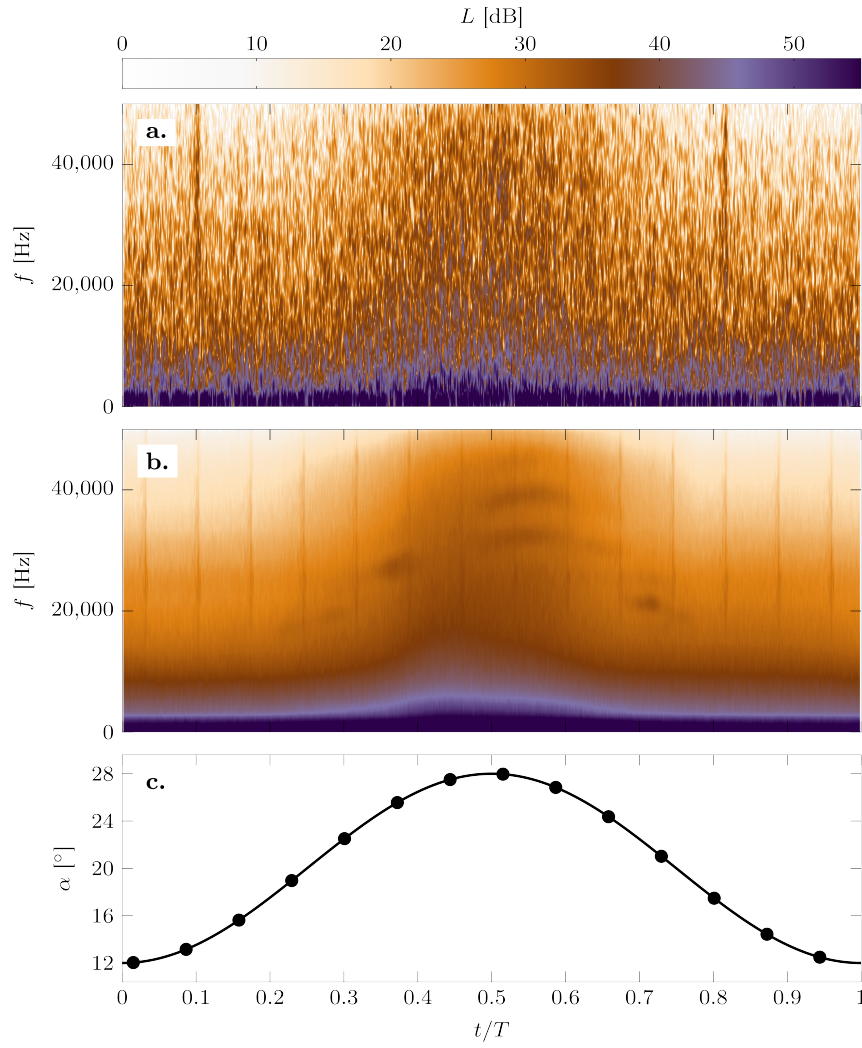


Fig. 4 (a.) Spectrogram of the pitching airfoil configuration for a single oscillation period and (b.) its phase average over 500 cycles. (c.) The pitching oscillation and the measured phase angles of the selected flow configuration are also depicted in relation to the airfoil oscillation period.

The spectrum and the spectrogram are different representations of the acoustic information contained in the microphone signal. The spectrum provides overall sound pressure levels in function of frequency and requires high frequency resolu-

tion. The spectrogram gives more insight into the temporal variation of the sound pressure levels within a pitching cycle and requires a higher temporal resolution and a lower frequency resolution. As a result of the difference in frequency resolution, the amount of acoustic energy per frequency bin and the sound pressure level magnitudes are lower for the spectrum than for the spectrogram, as the overall acoustic energy is spread over substantially more frequency bins.

The spectrogram averaged over 500 cycles is shown in figure 4b. Here a short-time broadband signature can be observed at the time of the PIV recordings, resulting in thin vertical lines in the spectrogram. This signature is caused by the typical clicking sounds accompanying the emission of the laser pulses caused by the discharge of the capacitors providing the energy for the laser flash lamps. It should be noted that they are uncorrelated with the velocity field and do not affect the correlation results presented in section 4.3.

The oscillation frequency of 5 Hz and its harmonics corresponding to the airfoil motion can be readily identified in the spectrum in figure 3. This is also reflected in an extended spectrogram calculated based on a larger signal section (not shown here), in which a dominant event takes place every 0.2 seconds. Based on the acoustic response for the oscillation cycle (figure 4a,b), we conclude that the overall sound pressure level increases with increasing angles of attack ($\alpha > 20^\circ$), especially for higher frequencies. In general, most of the sound energy is contained in the frequencies below 1000 Hz which can be observed both in the spectrum and the spectrograms. Furthermore, the comparison of the spectra reveals that the main contributions of the airfoil to the sound radiation are in the range between 100 and 900 Hz. All in all, the aero-acoustics of the airfoil have a rather broad-band character with a more pronounced frequency component between 200 and 300 Hz.

Noteworthy is the peak around 740 Hz (marked with a dashed line in figure 3) in the case of the stationary airfoil, which can be attributed to periodic vortex shedding from the trailing edge. This assumption is supported by the fact that 740 Hz corresponds to a Strouhal number of 0.32 using the airfoil thickness at 80% chord as the characteristic length scale. The airfoil thickness at this location is a measure for the wake width and a suitable characteristic length scale when trailing edge vortex shedding is observed. Time-resolved PIV investigations are planned in the future to confirm periodic vortex shedding at 740 Hz.

4.2 Measured velocity fields

In figure 5, six out of the 14 available phase angles are selected for the discussion of the dynamic stall life cycle and its associated flow characteristics. Phase averages and standard deviations are calculated for each phase angle using approximately 1000 PIV snapshots or approximately 1000 oscillation cycles. They are used to determine the cross-correlation values and the underlying velocity fluctuations. Figure 5 shows the phase averaged velocity fields for selected phase angles as a vector plot. Only every third velocity vector is plotted in each direction for the sake of visibility. The normalized vorticity is color-coded. For each phase angle, the angle of attack of the airfoil is indicated which is followed by an arrow which indicates whether it concerns a phase during the pitch-up (\nearrow) or during the pitch-down movement (\searrow). The corresponding phase-locked standard deviations are presented in figure 6. They are a measure for the cycle-to-cycle velocity fluctuations. In addition, representative instantaneous velocity vector fields are shown in figure 7 for the six selected phase angles with the normalized vorticity color-

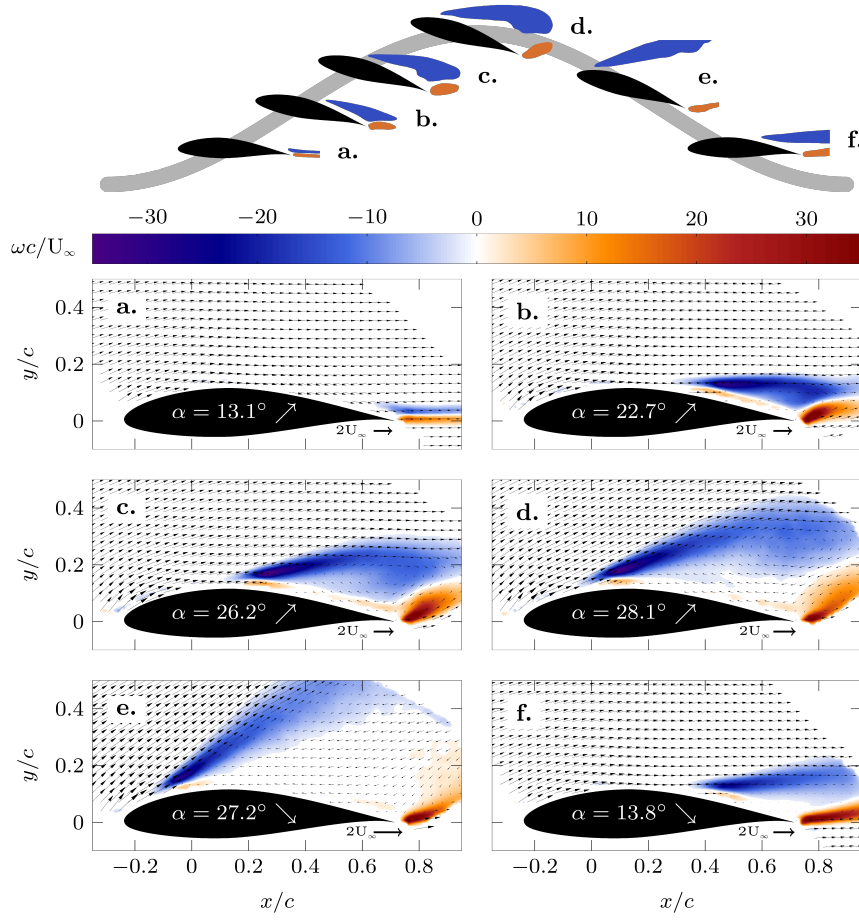


Fig. 5 Mean velocity vector fields for six selected phase angles representing the dynamic stall life cycle. The vorticity is color-coded. For each phase angle, the angle of attack is given followed by an arrow which indicates whether it concerns a phase angle during the pitch-up (\nearrow) or during the pitch-down movement (\searrow). The different stages of flow development are schematically represented at top where the gray line represents the angle of attack variation during the pitching cycle.

coded. These serve to give a deeper insight into the prevailing flow behavior of the individual phase angles.

The selected flow fields in figure 5 represent the various flow stages of the dynamic stall development which are also schematically indicated at the top of the figure. The dynamic stall cycle starts at a moderate angle of attack ($\alpha = 13.1^\circ$ ↗) with the attached flow stage. Here, the flow remains attached to the airfoils surface during the first part of the pitch-up motion of the airfoil (figure 7a). Near the leading edge, the velocity increases to approximately $1.5U_\infty$. During the attached flow stage, a narrow wake is observed behind the trailing edge as a result of the velocity deficits in the suction and pressure side boundary layers. The wake edges are recognized by increased vorticity concentration in the shear layers at the interface between the wake velocity deficit and the outer free stream flow (figure 5a and 7a). This wake is quasi-steady and only very small velocity fluctuations are measured in the narrow wake behind the trailing edge yielding low standard deviations. The values of the standard deviation during attached flow are so small that they are only visible in figure 6a directly behind the trailing edge with the selected color scale. The attached flow stage prevails for the first part of the upward motion.

With increasing angle of attack ($\alpha = 22.7^\circ$ ↗) beyond the static stall angle of attack of approximately 18° (Timmer, 2009), a negative vorticity region develops above the trailing edge indicating flow reversal (figure 5b). This is accompanied by significantly stronger flow fluctuations in a confined area behind the trailing edge (figure 6b). From this area, a shear layer is formed upstream (figure 7a) indicated by small-scale clockwise rotating vortices, which characterize the early stages of the dynamic stall. In addition, the velocity at the leading edge increases further to approximately twice the inflow velocity, which is associated with a higher lift

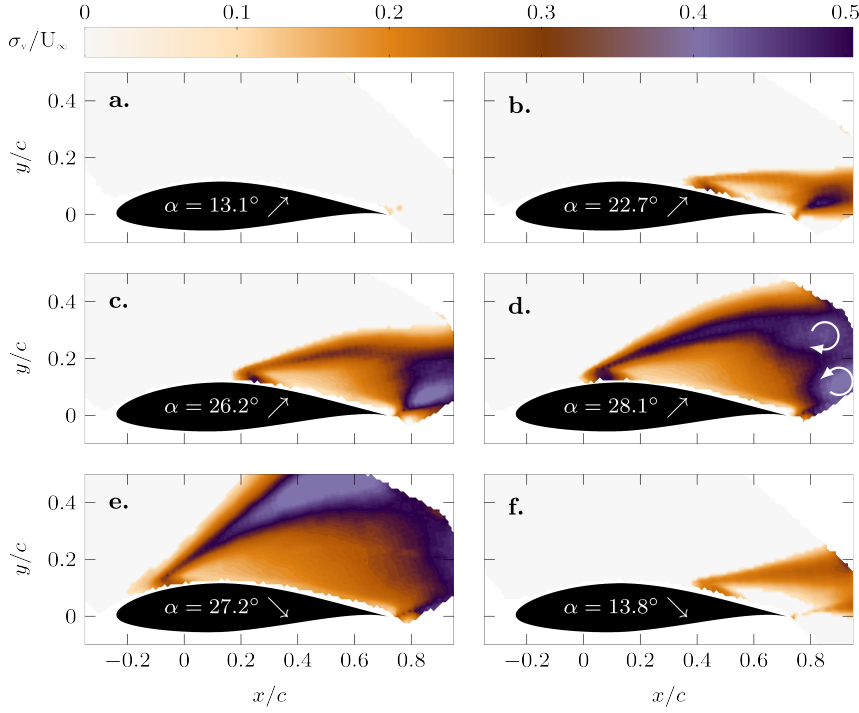


Fig. 6 Standard deviation of the velocity field for six selected phase angles representing the dynamic stall life cycle.

coefficient.

The next stage ($\alpha = 26.2^\circ$ ↗) is characterized by the expansion of the recirculation region and the movement of the separation point towards the leading edge (figure 5c). This advanced stall development is accompanied by the strongest fluctuation velocities in the recirculation area (figure 6c) and the highest velocity values at the leading edge in comparison with other stages. The most salient feature here is the clockwise rotating coherent structure within the reverse flow area (figure 7c). Thereafter, the pitch-up motion ends and the separation point reaches its most upstream location marking the transition into a fully stalled stage

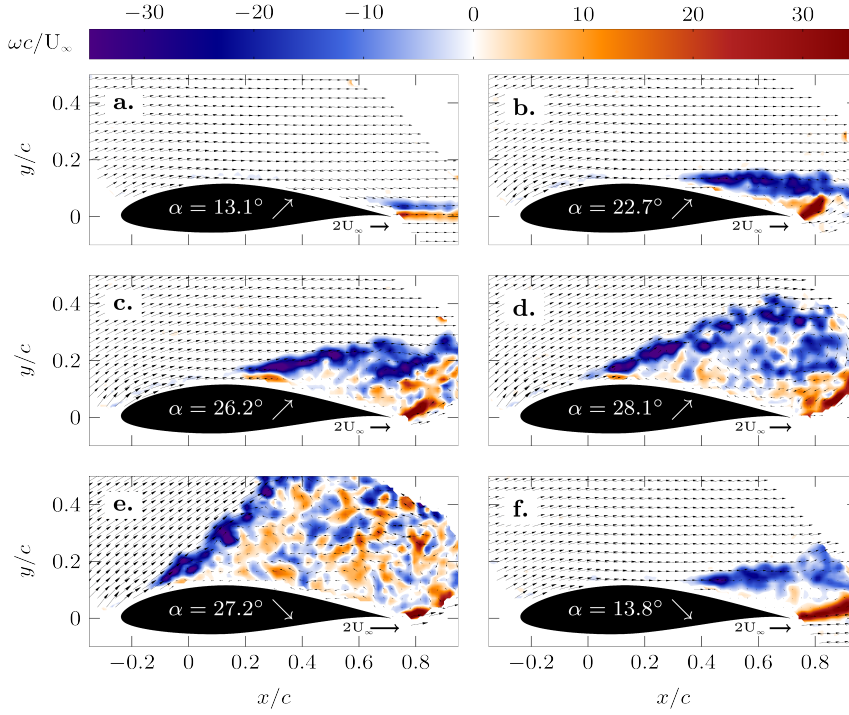


Fig. 7 Instantaneous velocity vector fields of six selected phase angles representing the dynamic stall life cycle. The vorticity is color-coded.

(figure 5/7d-e). The shear layer is now significantly enlarged and the recirculation region moves upwards and upstream with respect to the airfoil as it expands. Noteworthy is the formation of two counter-rotating vortical structures near $x/c = 0.8$ in figure 6/7d: a clockwise rotating structure underneath the shear layer and an opposed vortex in the detached flow near the trailing edge, which can be also observed in the instantaneous velocity field (figure 7d).

At the beginning of the downward motion of the airfoil ($\alpha = 27.2^\circ \searrow$) there is a noticeable drop in the maximum flow velocity at the leading edge of the airfoil, as well as a reduction in the maximum standard deviation due to the wide-stretched separation area (figure 6e). The recirculation region has evolved into

a fully developed turbulent wake flow (figure 7e), whereas the mean direction is still pointing against the inflow (figure 5e). The separation point is very close to the leading edge and the shear layer separates the inflow and the wake region in an almost straight line. The counter rotating vortices seem to prevail further downstream of the wake since the mean values show diverging directions of the velocity vectors in the upper and lower part of the wake.

Lastly, the wake region settles again with further decreasing angle of attack ($\alpha = 13.8^\circ \nearrow$) indicating the flow reattachment. During this stage, the maximum flow velocity is the lowest in comparison to the flow situation during upstroke. It is noteworthy that the flow still shows increased fluctuations in the area close behind and above the trailing edge, especially in comparison to the equivalent angle of attack during the upstroke (figure 6f vs a). This is the so called hysteresis effect which is typical for the dynamic stall process.

4.3 Coherent structures represented by cross-correlation functions and coefficients

Different results of the cross correlation analysis are presented in order to demonstrate the applicability and adequacy of the experimental approach for studying the acoustic footprint of dynamic stall. Spatial distributions of the maxima of the absolute cross-correlation function $S_{p,v}$ and coefficients $R_{p,v}$ with respect to τ for the six selected phase angles based on the ensembles of phase-locked snapshots are shown in figure 8 and 9, respectively. This presentation provides an overview of where spatially coherent structures occur that are related to the sound emission in the statistical sense. The values of the v -velocity component are depicted, since they point in the direction in which the acoustic perturbations propagate to the

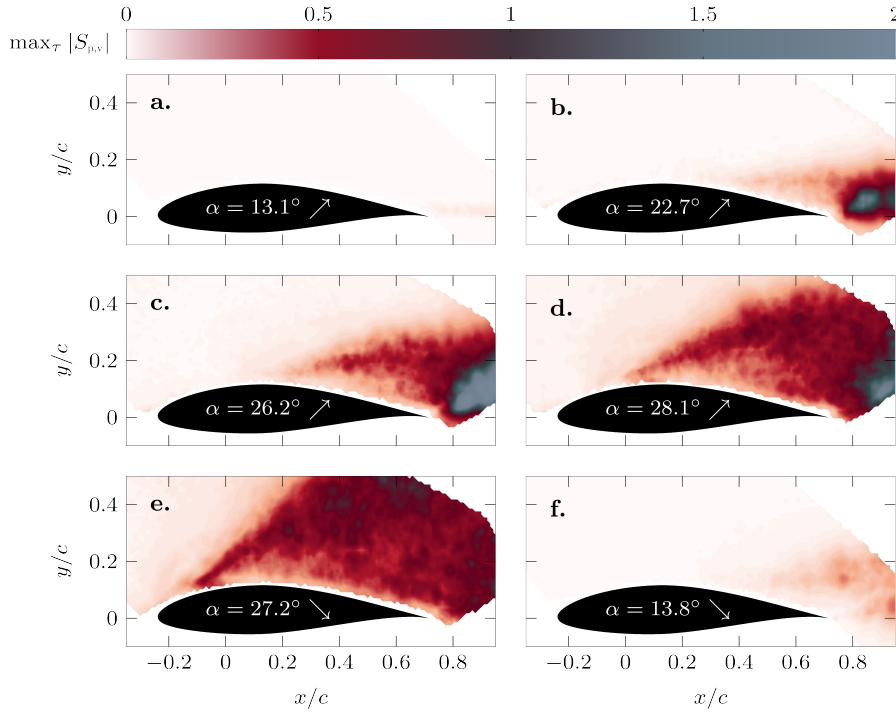


Fig. 8 Spatial distributions of the maxima with respect to τ of the absolute cross-correlation functions of the six selected phase angles representing the dynamic stall life cycle (v -component) based on ensembles of phases locked velocity snapshots.

microphones. In the case of the cross-correlation function, the values are scaled with the inflow velocity U_∞ and the reference sound pressure p_0 in order to achieve a dimensionless representation.

Comparing the distributions of the cross-correlation function and the standard deviation values of the selected phase angles reveals that both analysis approaches lead to significant values in the same regions. Despite the fact that the distributions of the correlation functions appear somewhat blurred and stained, the main structures are still preserved. Therefore, the main features of the dynamic stall development are also represented on the basis of the correlation function. Since

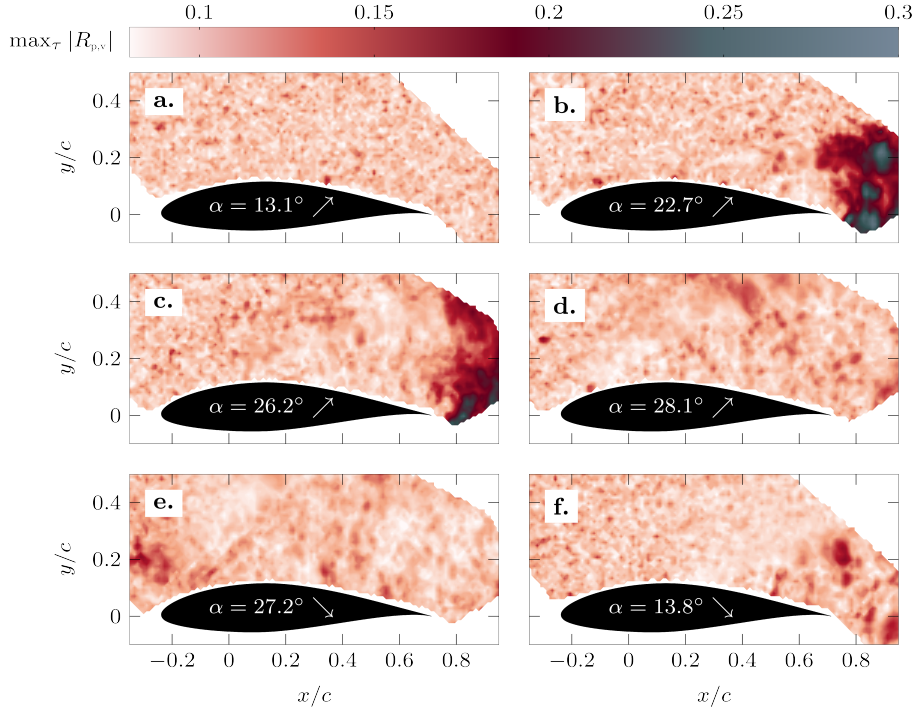


Fig. 9 Spatial distributions of the maxima with respect to τ of the absolute cross-correlation coefficients of the six selected phase angles representing the dynamic stall life cycle (v -component) based on ensembles of phases locked velocity snapshots.

the cross-correlation operation provides a link between the acoustic and the velocity fluctuations, it is valid to conclude that regions with significant values are to a certain extent related to the noise source mechanisms. However, it is only with the help of the cross-correlation coefficients that a reliable statement about the quality of the correlation can be made because they specify the correlation with a percentage information. Hence, the coefficients are considered in combination with the airfoil self-noise mechanisms (Brooks et al, 1989) such as the vortex-shedding and the separation-stall noise to identify those flow structures associated with the noise emission at the respective phase angles.

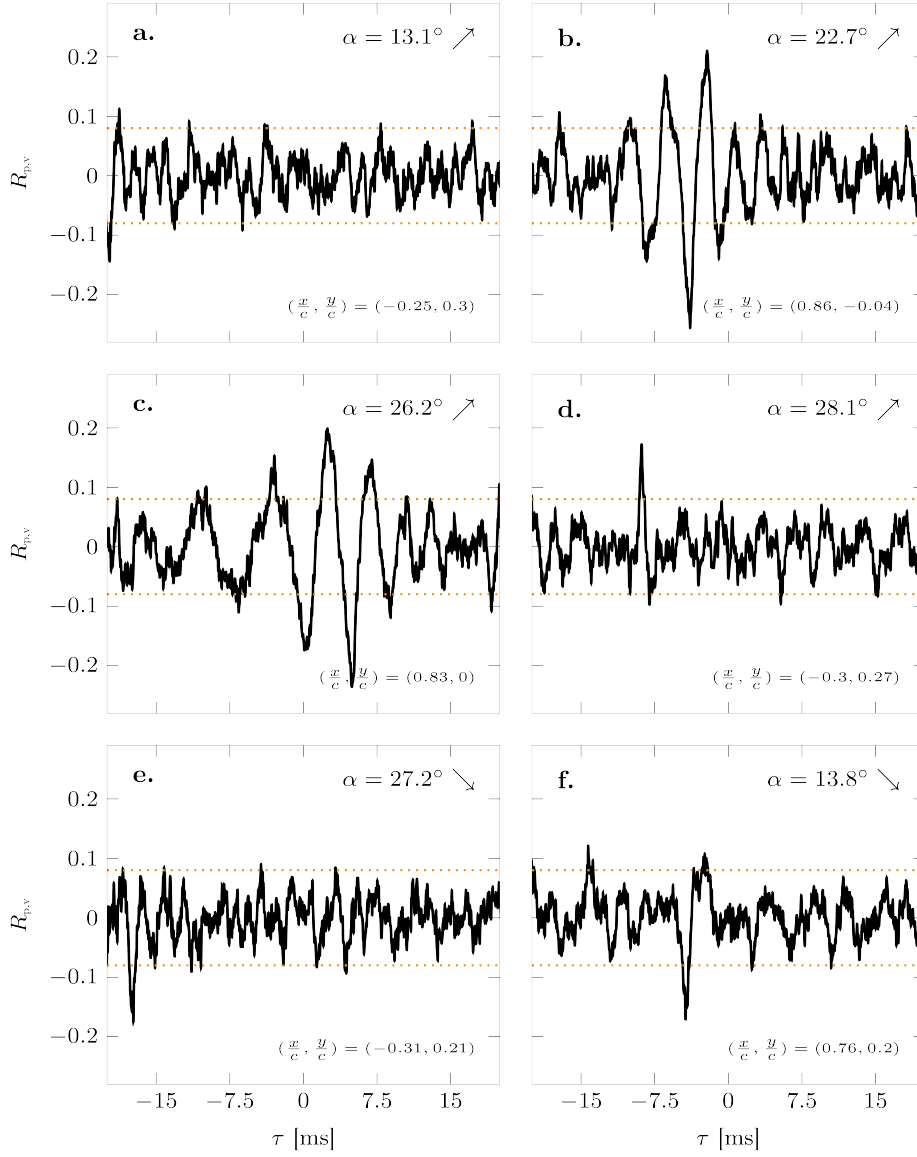


Fig. 10 Temporal evolution of the cross-correlation coefficients at the points where the global maximum of the absolute values occurs for the six selected phase angles representing the dynamic stall life cycle (v -component) based on ensembles of phases locked velocity snapshots.

At first glance it becomes clear that the presence of coherent structures that contribute to the sound emission is highly dependent on the phase angle of the airfoil's motion. Prominent acoustically relevant structures occur mainly during the stall development stages where flow reversal spreads over the airfoil chord. It can be assumed that at these phase angles periodic vortex shedding is present. This observation is supported by the temporal evolution of the coefficients at the points where the global maximum of the absolute value occur (figure 10). This figure also shows the error margins of the cross-correlation coefficients based on a t-test against zero with 99% probability, which are approximately ± 0.08 for the ≈ 1000 PIV snapshots used here per phase angle. Consequently, it can be stated that the detected periodic vortex shedding is most likely not a coincidence, as the values clearly exceed these error limits in the strongly periodic range with a frequency of ≈ 245 Hz and ≈ 220 Hz in case (b) and (c), respectively. In contrast, the correlation coefficient results during the attached flow do not reveal acoustically relevant flow structure (figure 9) and the values of the temporal evolution of $R_{p,v}$ remain within the error bands. This is not surprising as the flow follows the airfoils contour nicely and only a very thin wake region is observed in which noise-generating vortical structure can develop. Based on the low values of the cross correlation function and the standard deviation, it can be concluded that there are no noise-generating flow effects in this phase angle range. In addition, that the overall sound pressure level for the lower angle of attack ranges is low.

Even during full stall (d-e) there are no clear coherent structures that can be identified in the spatial distribution of the maximum of the correlation coefficient with respect to τ , even though the corresponding distribution of the cross-

correlation function and standard deviation are much higher here than during attached flow. In the temporal evolution, the signal remains within the error bands.

When the separation region is large in (d) and (e) there are also no distinct coherent structures observable in the spatial distributions of the maxima in relation to τ of the absolute cross-correlation coefficients even though the corresponding cross-correlation function and standard deviation values are much higher than in stage (a). While the flow development during the growth of the separation region is dominated by smaller scale structures that can be identified within the field of view, the flow during full stall is dominated by larger scale structures that cause lower frequency responses in the fluctuations. The latter are much harder to identify in the cross-correlation results. In the temporal evolution, only a short, conspicuous event occurs with a significant portion above the error margin.

During reattachment, the flow structures are again smaller and identifiable in confined areas within the region of flow separation. However, the coherent motion is still superimposed with random turbulent fluctuations resulting in a less pronounced periodic shedding in comparison with the separation region growth stages (figure 10f vs b-c). The inherent hysteresis associated with dynamic stall is once again evident from the direct comparison of the results at an angle of attack of 13 during pitch-up and during pitch-down, respectively.

In order to gain a further insight into the characteristic structures during dynamic stall development at the individual phase angles, the instantaneous vector fields of the cross-correlation coefficients at the point in time where the values are maximal are studied (figure 11). In figure 11, all available vectors are plotted to obtain a better overview of the various structures. As expected, during attached flow no structures are identified (figure 11a) but the periodic vortex shedding

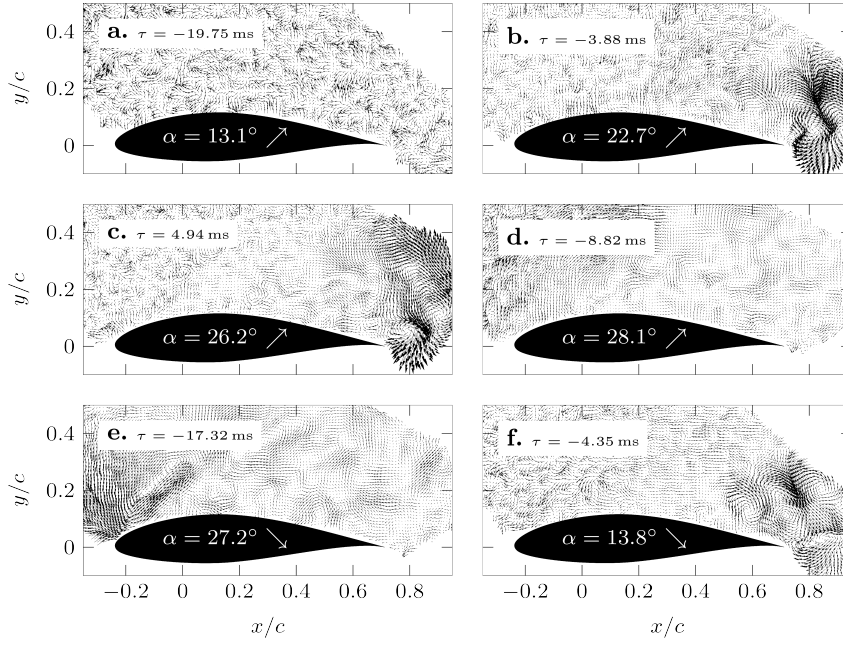


Fig. 11 Instantaneous vector fields of the cross-correlations coefficients based on ensembles of phases locked velocity snapshots at the points in time when the absolute values are maximal for six selected phase angles.

during the growth of the separation region is nicely visualized (figure 11b-c). In figure 11b, two counter-rotating vortical structures are identified in the wake behind the airfoils trailing edge. As indicated by the corresponding time evolution in figure 10b, these structures are convected downstream in a periodic manner with a frequency of ≈ 245 Hz corresponding to a Strouhal number of 0.245 based on the height of the separation region at the trailing edge. The case (c) shows a subsequent stage of the vortex shedding where the trajectory of the vortex shedding is shifted upwards in the airfoils frame of reference. This is due to the increased angle of attack. Additionally, the distance between the counter-rotating structures is slightly increased but the periodicity is preserved with a frequency of ≈ 220 Hz corresponding to a Strouhal number of 0.411 based on the increased height of the

separation region at the trailing edge. Furthermore, small-scaled turbulent structures can now be detected within the entire separation region. When approaching full stall, the number of small scale structures within the separation region increases reflecting the turbulent character of the flow behavior. The large turbulent separated flow region stretches diagonally above the wing downstream. At maximum angle of attack a relative clear separation between the accelerated inflow and the turbulent region can be noticed while a more fluent transition is observed in the beginning of the downstroke motion. In the latter case, the correlation field near the leading edge is enhanced and this effect spreads along the shear layer edge. All in all, both cases exhibit a characteristic behavior that can be attributed to the separation-stall noise (Brooks et al, 1989), which is characterized by the noise radiation from the chord as a whole.

During flow reattachment, counter-rotating vortical structures emerge again (figure 11f) but the temporal evolution of the coefficient does not allow for the identification of a distinct shedding frequency.

5 Conclusion

The aeroacoustic relationship between flow structures that are generated by an oscillating airfoil and the acoustic radiation in the far field is investigated by means of simultaneous PIV and microphone measurements. In the acoustic spectrum a maximum amplitude around 740 Hz is attributed to the periodic vortex separation at the trailing edge of the airfoil. Further maxima at lower frequencies in the range of 250 Hz correspond to the large scale vortex shedding occurring during the onset of the stall.

Selected flow fields at six angles of attack during the up- and downstroke of the airfoil pitching cycle that represent different stages of the dynamic stall flow development were analyzed by means of a causality correlation method. For the selected phase angles, the phase locked PIV velocity fluctuations on the suction side of the airfoil were cross-correlated with the pressure fluctuations recorded with microphones in the acoustic far-field. By means of the causality correlation, acoustic signals can be associated with the coherent flow patterns that cause them. The presence of coherent structures that contribute to the sound emission is highly dependent on the phase angle of the airfoil's motion.

In the beginning of the upstroke, when the flow is attached, no noise sources are identified in the flow field. With increasing angle of attack, vortex shedding in the wake of the airfoil is initiated giving rise to significant correlation coefficients and noise. The Strouhal numbers of the vortex shedding at different phase angles we determined between 0.25 and 0.41 based on the temporal evolution of the cross-correlation coefficients. When the flow is fully stalled, the region with significant cross-correlation coefficients increases while the maximum values within the field of view decrease. This is due to the fact that the locations of the coherent structures that contribute to the sound emission during full stall fluctuate stronger between oscillation cycles than during stall development and even reattachment. The sound pressure levels however reach the highest values during full stall.

The cycle-to-cycle variations of vortex generation and shedding during full stall thus smear the causality correlation coefficients based on phase-locked data across the entire chord length and do not allow for individual noisy generating structures to be identified. During stall development and flow reattachment, the phase-locked data is well suited to identify the wake structures causing noise.

Furthermore, hysteresis is clearly observed on the flow topology at similar angles of attack during up and downstroke and in the acoustic signature.

References

- Bossanyi EA (2003) Individual blade pitch control for load reduction. *Wind Energy* 6:119–128
- Brooks TF, Humphreys Jr WM (2003) Flap-edge aeroacoustic measurements and predictions. *Journal of Sound and Vibration* 261:31–74
- Brooks TF, Pope DS, Marcolini MA (1989) Airfoil self-noise and prediction. NASA Reference Publication 1218 p 142
- Carr LW (1988) Progress in analysis and prediction of dynamic stall. *AIAA Journal* 25(1):6–17
- Carr LW, McAlister KW, McCroskey WJ (1977) Analysis of the development of dynamic stall based on oscillating airfoil experiments. Technical Report, NASA
- Degani AT, Walker JDA, T SF (1998) Unsteady separation past moving surfaces. *Journal of Fluid Mechanics* 375:1–38
- Doligalski TL, Smith CR, Walker JDA (1994) Vortex interactions with walls. *Annu Rev Fluid Mech* 26:573–616
- Doolan CJ, Moreau DJ, Brooks LA (2012) Wind turbine noise mechanisms and some concepts for its control. *Acoustics Australia* 40(1):7–13
- Ffowcs Williams JE, Hawkings DL (1969) Sound Generation by Turbulence and Surfaces in Arbitrary Motion. *Philosophical Transactions of the Royal Society of London Serie A, Mathematical and Physical Sciences* 264(1151):321–342

- Gupta R, Ansell PJ (2017) Unsteady flow physics of airfoil dynamic stall. In: 55th AIAA Aerospace Sciences Meeting, Reston, Virginia
- Henning A, Koop L, Ehrenfried K (2010) Simultaneous Particle Image Velocimetry and Microphone Array Measurements on a Rod-Airfoil Configuration. AIAA Journal 48(10):2263–2273
- Henning A, Wrede B, Geisler R (2012) Aeroacoustic Investigation of a High-Lift Device by Means of Synchronized PIV and Microphone Measurements. In: 16th Int Symp on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal
- Manela A (2013) On the acoustic radiation of a pitching airfoil. Physics of Fluids 25:16
- McAlister KW, Carr LW, McCroskey WJ (1978) Dynamic stall experiments on the NACA 0012 airfoil. Technical Report, NASA
- Mcalister KW, Pucci SL, McCroskey WJ, Carr LW (1982) An Experimental Study of Dynamic Stall on Advanced Airfoil Sections Volume 2. Pressure and Force Data. Tech. rep.
- McCroskey WJ (1981) The Penomenon of Dynamic Stall. Technical Report, NASA
- Mulleners K, Raffel M (2012) The onset of dynamic stall revisited. Experiments in Fluids 52:779–793
- Mulleners K, Raffel M (2013) Dynamic stall development. Experiments in Fluids 54:1469–1477
- Nagarajan S, Hahn S, Lele SK (2006) Prediction of Sound Generated by a Pitching Airfoil: A Comparison of RANS and LES. In: 12th AIAA/CEAS Aeroacoustics Conference, Cambridge, Massachusetts

- Obabko AV, Cassel KW (2002) Detachment of the Dynamic-Stall Vortex Above a Moving Surface. *AIAA Journal* 40(9):1811–1822
- Oerlemans S, Migliore P (2004) Aeroacoustic wind tunnel tests of wind turbine airfoils. 10th AIAA/CEAS Aeroacoustics Conference; Manchester, United Kingdom
- Petrovic V (2008) Reduction of wind turbine structural loads based on individual pitch control. Annual Conference of IEEE Industrial Electronics
- Raffel M, Kompenhans J, Wernert P (1995) Investigation of the unsteady flow velocity field above an airfoil pitching under deep dynamic stall conditions. *Experiments in Fluids* 19:103–111
- Raffel M, Willert CE, Wereley ST, Kompenhans J (2007) Particle Image Velocimetry. Springer Berlin Heidelberg
- Reynolds WC, Carr LW (1992) Review of unsteady, driven separated flows. Technical Report, AIAA
- Timmer WA (2009) An overview of NACA 6-digit airfoil series characteristics with reference to airfoils for large wind turbine blades. In: 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, AIAA 2009-268
- Wolf A, Lutz T, Würz W, Krämer E, Stalnov O, Seifert A (2014) Trailing edge noise reduction of wind turbine blades by active flow control. *Wind Energy* 17:657–669
- Zanotti A, Ermacora M, Campanardi G, Gibertini G (2014) Stereo particle image velocimetry measurements of perpendicular blade-vortex interaction over an oscillating airfoil. *Experiments in Fluids* 55:1811