Coherent Structures in Critical Wing Flows

by

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ABSTRACT

The study is concerned with the analysis of the turbulent flow detached from an unswept wing at large angles of attack. The transition regime between subcritical and supercritical separation, which is well known to delimit the low Reynolds number regime at \( \text{Re} \sim 10^{5} \), is in the focus of the investigation. The coherent structures that develop with trailing edge separation are extracted from Particle Image Velocimetry (PIV) data by means of Proper Orthogonal Decomposition (POD). Thus, the three-dimensionality of the flow in terms of spanwise morphology is studied, and a reduced representation by (geometrical) symmetry plane investigation turns out to be justified. Additionally, fluctuations of the flow velocity and the wall pressure exhibit an interval of characteristic, preferred length scales of the vortical structures. The decomposition of both the separation scenarios, inspecting the suction side of the wing and the near wake flow, yields to a qualitative identification of the large-scale structure. Moreover, POD dissects the vortical motion according to the energy contained in the various modes, and thus with respect to the respective impact on flow dynamics. These insights into coherent structures, and the characterization of their dynamics is beneficial particularly to the basic validation of Large Eddy Simulations (LES) of such complex flows.

Fig. 1: Experimental setup as it is placed in the open test section of the 1m-wind tunnel at DLR in Goettingen. On the right hand side the coordinate system is given, and simplified sub- and supercritical separation topology is sketched (recording devices aside the test section excluded).
1. INTRODUCTION

The flow around smooth airfoils at large angles of attack is basically determined by the occurrence of laminar to turbulent transition and, eventually, by the location and other geometrical parameters of the transition. Indeed, considering so-called low Reynolds number flows, a narrow Reynolds number interval is found, wherein the glide ratio \((\frac{c_L}{c_D})_{\text{max}}\) dramatically varies due to the significant change in flow field topology (see for example Gad-el-Hak 1990).

Until today, this so-called critical Reynolds number regime still remains challenging to investigations (Abegg 2001, Jovicic 2004) due to the complexity of the flow. The reliability of numerical simulations of such complex flows (e.g. flows with separation) sensitively depends on the implemented turbulence model. So from an intimate interconnection between experimental and numerical studies of wing flows basic insights into the involved dynamics are expected and, simultaneously, modeling capabilities are improved. Particularly, LES, which comprises the Direct Numerical Simulation (DNS) of the large scale structures and turbulence modeling of smaller scales strongly relies on physical scaling information.

Hence, a NACA-4415 airfoil is chosen where three-dimensional separation occurs combining simple geometry and moderate Reynolds numbers that are accessible also to numerics. In the following the Reynolds number \(Re=\frac{u_0\cdot c}{\nu}\) is based on chord length \(c\). An angle of attack of \(\alpha=18^\circ\) and the Reynolds number of \(Re=2\cdot 10^5\) allows the preparation of both the states of transition due to hysteresis. These are sketched in Fig. 2. When the Reynolds number is increased, the \textit{simple} flow field due to leading edge separation assumes a more complex topology including reattachment, formation of a laminar separation bubble, and turbulent trailing edge separation. Following the nomenclature introduced by Schewe (2001), the former condition is called subcritical and it may be regarded to be well investigated. The latter state is classified as supercritical. It will be considered here in detail while the subcritical flow is taken as a reference state.

![Fig. 2: Simplified topological representation of a) the subcritical and b) the supercritical flow regime (characteristic points of separation magnified); according to Schewe (2001).](image)

For the case of subcritical separation it is well known that the separated shear layer is subject of an instability of Kelvin-Helmholtz type which leads to transition and thereby forms typical vortical structures detaching from the suction side of the airfoil. These coherent structures occur at a characteristic frequency which provides exhaustive phase information for experimental access. The simplicity of the flow, i.e. its two-dimensionality might be understood in terms of very weak coupling between primary and higher order instabilities in laminar shear layers (Lasheras and Choi 1988).

When the supercritical regime is entered by the initiation of turbulent reattachment, three-dimensional effects gain major importance. Primarily, various macro-structures such as a laminar separation bubble and a highly three-dimensional trailing edge separation region are formed. These are bordered laterally by horse-shoe-vortices (HSV) evoked within the airfoil-end plate junction (Winkelmann and Barlow 1980). These HSV arise from the interaction between the boundary layers of the wing and the end plates. Though the HSV are laterally separated from the trailing edge separation region by a narrow stripe of fully attached flow, the HSV also have to be considered as a generator of instationary spanwise motion (which may affect the entire flow field).

In particular the trailing edge separation, which is associated with a folded turbulent shear layer forming a pair of counter rotating streamwise vortices with an embedded central back flow region, has to be considered as the fundamental source of coherent motion that is emitted into the wake. Those structural cells are also known to occur sequentially and to be strung together in spanwise direction on wings and cylinders. The interaction between these different macro-structures is not yet understood.

The structure generation in the trailing edge separation thereby absorbs organized structures released into the flow by the separation bubble upstream. The separation bubble couples to the trailing edge separation by its
inherent movement and structure shedding into the turbulent boundary layer that detaches subsequently. The POD analysis of two-dimensional numerical simulations reinforce this point of view (Herberg 1995).

The trailing edge separation itself contains two major aspects. On the one hand there is structure formation in the turbulent shear layer and on the other hand significant vortex formation has to be expected to appear at the sharp trailing edge of the airfoil.

The work presented is composed of the following issues. We present local frequency measurements aiming at the identification coherent structures typical time scales regarding supercritical separation and their variation in the critical regime transition. The three-dimensional morphology is studied, which leads to a two-dimensional representation accessible for PIV. The main aim is to study the supercritical airfoil flow using structure identification by means POD, in order to reduce the investigation of transitory wing flows to treating critical airfoil flows.

2. EXPERIMENTAL SETUP AND DATA ANALYSIS

2.1 Setup and Instrumentation

The measurements have been conducted in the low speed wind tunnel at the DLR Institute for Aerodynamics and Flow Technology in Goettingen. This wind tunnel features an open rectangular test section (0.7m by 1.0m). The turbulence level is approximately 0.15% at operational velocities between 7.5 m/s and 25 m/s.

The experimental setup, sketched in Figure 1, consists of a NACA 4415 airfoil with chord length \( c = 0.2 \text{m} \) and aspect ratio of \( A = 4 \), which is equipped with circular end plates with diameter \( R_e = 1.75c \). In order to reduce the three-dimensionality of the flow field in the core of the test section and thus to ease the numerical simulation, base and top plates have been introduced to confine the flow also in the normal direction without restricting the accessibility of the measurement area. The origin of the Cartesian coordinate system used here is located at the trailing edge in the geometrical symmetry plane of the wing (for the definition of the symmetry plane and the trailing edge plane see also Fig. 1).

Within these planes velocity measurement are carried out by means of PIV. A flash lamp-pumped double pulse Nd:YAG laser (70mJ per pulse) provides illumination of an area of interest (AOI) of about \( 100 \text{mm} \times 130 \text{mm} \) (applying a light sheet thickness of approximately 1mm). Bis(2-ethylhexyl)Sebacat, a synthetic oil, is used to generate particles (droplets) of 1\( \mu \text{m} \) in diameter to seed the flow. The image recording system basically consists of a PCO-SensiCam CCD sensor with 1370px \( \times \) 1040px resolution and 12bit quantization. Series of \( N=160 \) image pairs have been collected taking image pairs, i.e. snapshots of the flow field every 125ms (this interval is much longer than the time constants that govern the flow).

Furthermore, a hot-wire anemometer (55M01, DISA) with a dual-sensor-probe is used to simultaneously measure the fluctuation of two velocity components. Time series of \( N_s = 30000 \) samples are recorded at a sampling frequency \( f_s = 5000 \text{Hz} \).

2.2 PIV Data Acquisition and Processing

The PIV raw data is evaluated using PivView (by PivTec). A cross-correlation algorithm including an iterative multi-grid interrogation is applied in order to enhance spatial resolution in regions with strongly sheared flow. Interrogation windows down to 20px \( \times \) 20px were used corresponding to 3mm \( \times \) 3mm in physical space. In the following we refer to the suction side and the near wake flow as position I and II.

Subsequently, a POD analysis on the based on the collected snapshots of the flow field has been performed using the INVEST software developed at DLR by H. Gebing (1994). For a comprehensive review of POD in flow field diagnostics we refer to Stirovich (1987).

The POD of the set of the 160 snapshots of the studied flow field returns a significantly smaller set of typically 10 orthonormal modes which can be used as a basis for the best possible approximation (in the sense of least square error) of the original 160 versions of the flow field by linear combinations of these modes. This is achieved by the eigenvector decomposition of a correlation matrix which comprises all possible correlations between the spatially distributed flow velocities in the considered field. The greatest eigenvectors are the mentioned POD modes while the eigenvalues represent the energy of the respective modes, i.e. the amount of ‘turbulent energy’ associated with the respective component of the dynamics of the flow field. So the eigenvalues can be taken as a measure of the relative importance of the respective modes in comparison to the other modes. However, we have to keep in mind that POD is non physical. Hence, the interpretation of these mathematical structures requires additional considerations.

In the present study the POD was applied only to the fluctuating part of the flow since otherwise the mean motion being the mode with the greatest eigenvalue would dominate the remainder of the modes due to the inherent requirement that the modes have to be orthonormal.
3. RESULTS

The transition regime is restricted to the Reynolds number interval \( Re=[1\cdot 10^5,2.5\cdot 10^5] \), approximately. In this flow regime the state of the flow turned out to be rather unstable. Transitions between the different states due to small outer disturbances are observed. For this reason, we decided to perform the hot wire measurements at a Reynolds number \( Re=2.6\cdot 10^5 \) slightly above the transition regime because the insertion of the probe unavoidably disturbs the flow. Nonetheless, the PIV measurements have been carried out at \( Re=2\cdot 10^5 \) and \( \alpha=18^\circ \). Both, sub- and supercritical separation can be realized at this Reynolds number due to the hysteresis of the flow.

3.1 Characteristic Frequencies

In the course of preliminary work on complex wing flows (in addition to Abegg 2001) measurements of wall pressure and velocity fluctuations close to the surface on the suction side of the airfoil have been performed at \( Re=2.6\cdot 10^5 \). As expected, the subcritical flow exhibits oscillations at Strouhal numbers \( (Sr=f s/u_0) \) of \( Sr=0.2 \) based on streamwise projection \( s\cdot c\cdot \sin(\alpha) \) of the chord length \( c \). Approaching the regime of supercritical separation, Strouhal numbers escalate and hysteresis is observed. At the same time the Strouhal number peak in the power spectral density function almost vanishes and a broad plateau centered at \( Sr=0.4 \) is formed. This transition may be interpreted to start with a nearly single-scale characteristic coherent structure that decays with the onset of supercritical conditions. The hot wire measurements indicate that the broad maximum in power spectral density function is independent of the location in the entire trailing-edge separation structure that extends between the bounding streamwise vortices (measured in the trailing edge plane). Here, the flow field is dominated by a whole range of preferred length scales of vortical structures. Indeed, these results well correspond to the idea of redistribution of energy between different scales due to coupling of primary and secondary (spatial) instabilities associated with the formation of macro-structures. Generally, we expect a shrinking of the length scales of the coherent structures, possibly scaling with the maximum distance between the turbulent shear layer and the trailing edge.

Hence, regarding the supercritical scenario, neither a single time scale could be established, nor could phase locked PIV measurements be performed. Because of the lacking of this phase information, the PIV measurements are triggered at a rate which differs as far as possible from any multiple of the center of the separation frequency interval, and the POD evaluation of the snapshots of the velocity field in the lateral symmetry plane had to be performed without adhering to the time evolution of the flow field.

3.2 Three-dimensional Effects

As mentioned earlier, the present part of the study is restricted to the supercritical regime. With regard to the spatial distribution of characteristic Strouhal numbers as discussed in the previous section, cross-flow PIV measurements in the trailing edge plane ranging from \( y/c=-1.75 \) to \( y/c=1.75 \) have been performed. Vertical cuts through the trailing edge separation structure at various spanwise locations show that this structure extends from \( y/c=-1 \) to \( y/c=1 \), approximately, and that it is well centered at the geometrical symmetry plane of the wing. A counter rotating vortex pair encloses a region of moderate vertical flow exhibiting minimal velocities perpendicular to the mean flow. This is topologically in good agreement with Winkelmann and Barlow (1980). Scrutinizing the cross-flow fluctuation field, we observe large root mean square \( (rms) \) values within the turbulent shear layer itself \( (rms(v/u_0)^{-0.2}) \), but minimal values are found in the center of the trailing edge separation zone. Probably, the strong fluctuations might be understood as streak formation typically emerging in turbulent shear layers. There are no hints to an organized lateral motion which otherwise would be found also in the vorticity distribution. Therefore, the lateral symmetry plane is elected for the representation of the flow field because the flow in this plane is minimally affected by streamwise rotation and thus by spanwise motion.

3.3 PIV of the Symmetry Plane

Figure 3 gives an overview over the time averaged flow fields with supercritical (top) and the subcritical separation (bottom). Regarding the supercritical scenario, the separation bubble and turbulent detachment further downstream can be identified. The separation bubble is a focal point of streamwise fluctuation including a backward facing part with \( rms(v/u_0)^{-0.3} \) compared to the average of \( rms(u/u_0)^{-0.15} \). Time averaging the flow field of the trailing edge separation reveals a single rotation with backflow close to the wall. Fluctuations in both velocity components are negligibly small. Streamwise fluctuations are concentrated in the shear layer. Interestingly, the vertical fluctuations turn out to be dominant in the shear layer developing from the trailing edge about half a chord length downstream the trailing edge \( (rms(v/u_0)^{-0.3} \) compared to \( rms(u/u_0)^{-0.2} \). Since the largest velocity gradients are localized at the trailing edge, vortex formation and subsequent effects like vortex coupling might produce such instationary movement comparable to vortex shedding in subcritical flow. The subcritical flow field is characterized by the early separation of the boundary layer forming a large rotation, on average. The inner region of the separated flow on the suction side seems to consist of uniform backflow at
small velocities and fluctuations. Within the separated shear layer streamwise fluctuations indicate shivering of the detachment point, and a main area of transition extending from $x/c \sim -0.5$ to $x/c \sim -0.25$. In the wake flow, we observe very dominant vertical fluctuations extending far into the trailing edge shear layer. The characteristic structures are formed and assume their typical length scales at $x/c \sim 0.5$. The decomposition of the subcritical near wake flow should therefore lead to very few but highly energetic modes.

Figs. 3: Flow field of supercritical (top) and subcritical flow (bottom) in the symmetry plane of the wing. Contours denote velocity magnitude calculated with the in plane components $u$ and $w$ only; $a=18^\circ$, $Re=2 \cdot 10^5$.

3.4 POD Analysis

The problem of triggering mentioned above results in PIV sequences that cannot be sorted according to the phase in an anticipated time history that represents the typical development of the coherent structures. Surveying characteristic large scale motions contained in the first few POD modes, the reconstruction of a typical time evolution had to be discarded. So the POD analysis becomes much more qualitative.

Let us first discuss the supercritical flow field the POD results of which are shown in Fig. 4 and Fig. 5. The decomposition of the flow on the suction side shown here (Fig. 4) focuses on turbulent detachment. We note that the separation bubble dynamics needs more than five modes (not shown here) for an adequate representation of the whole suction-side flow field. Hereby, a very complex dynamics of the bubble itself including coupling to the trailing edge detachment is indicated.

From the eigenvalue distribution we conclude the first fifteen eigenvalues to be non-statistical. The first mode (Fig. 5) embodies 29.8% of fluctuation energy revealing uniform streamwise movement in the separation region leading to accumulation at about $x/c=0.2$. We will refer to this again in the discussion of the wake flow. The two following modes, containing 11.8% and 10.1% of energy might be coupled. Eigenvalue coupling is usually interpreted as a coherent structure consisting of a time-dependent superposition of two characteristic states. However, by virtue of the complex field structure a distinct source of this movement cannot be allocated. Including the forth and fifth mode (6.5%, 4.8% of fluctuation energy), this becomes even more obvious. All these four modes represent structures of the trailing edge separation and in the turbulent boundary layer downstream of the bubble. Probably, these structures are somehow governed by the vortex formation in the
wake. In addition it cannot be excluded that the passage of the structure elements through the boundary of the analysis window affects the decomposition of the flow field.

Turning to the near wake field decomposition of the supercritical regime (Fig. 5) interpretation of the POD modes becomes more intuitive. Obviously, the first to third mode (40.3%, 8.3% and 5.8% of turbulent energy) are mainly concerned with dominant vortex shedding in the wake of the separation region fed by the trailing edge shear layer. The first and third mode seem to be interrelated. Both consist of alternating vortical structures horizontally aligned. The mean distance between core structures is 0.25c. We note that the shape of structures is non physical, but it is due to the fields being free of divergence. However, these modes should be associated with vortices with length scales typical of vortex shedding from the airfoil. POD herein supports the idea of quasi periodic structures since there are at least three coupled pairs of eigenvalues to be found (3, 4; 8, 9 and 10, 11). Especially, mode three and four give an idea of time evolution of vortices formed in the trailing edge shear layer. They are shed into the wake and experience stretching or even bifurcation of their cores. Furthermore, non intuitive small structures from the inner zone of trailing edge separation region are participating in the dynamics of the flow. We also state that structure formation from the upper shear layer is diffuse. Generally, the wake flow dynamics turns out to be much less complex compared to the flow over the suction side of the airfoil. Exponential regression of the eigenvalue distributions shows that the number of modes necessary for a certain accuracy of the reconstruction of the field (Karlhunen-Loève dimension) differs significantly between field I and II. The wake flow can be reconstructed by approximately one fifth of the number of modes needed for the suction side flow.

Figure 6 and 7 display the decomposition of the subcritical flow field. In contrast to the supercritical suction side flow, structure formation in the shear layer is of major importance in Fig. 6. The first four modes (26.4%, 11.6%, 9.3% and 7.7% of energy) have to be associated with vortical motion in the laminar to turbulent transition area of the separated shear layer. The intense large scale structures of the first mode probably represent movement of the whole stall region that is non periodic. Subsequently, modes two to four contain the dynamics of the shear layer itself characterized by vortex formation. These modes are influenced also by the wake (which is consistent with the supercritical state). Referring to the eigenvalue distribution one could argue that there are two mode ensembles (2, 3, 4 and 6, 7, 8, 9) dominating the dynamics and also including coupled pairs. Unfortunately, all the modes embody rather complicated field structures as a consequence of a large field of view. It would be of great benefit to repeat these decompositions on the area of the shear layer excluding effects from the wake. According to the region of backflow, there is very few energy located in the near wall region of the modes. The decomposition of position I of the subcritical flow reveals much higher organized motion than the supercritical state, and structure formation in the shear layer is more regular, respectively periodic. Effects at the border of the flow field have to be understood as a result of the cut off of further velocity information. Therefore, structures located at x/c > -0.15 are excluded from interpretation.

The decomposition of the near wake flow shown in Fig. 7 is, in a sense, related to the supercritical regime. The spatial arrangement of focal structures is nearly similar. The first mode (33.5% of fluctuation energy) represents the global motion, including, for example, wake buffeting. Unlike the supercritical separation, a strong periodicity is underlying represented by the conjugated modes two and three (8.4%, 7.4% of turbulent energy). Typical Strouhal numbers of about Sr~0.2 should be associated with these two modes. Considering the mode structures, one may also come to the conclusion that the main structure is given by modes one and two with a substructure added by the third mode. Furthermore, all the following modes carry diffuse vortical behavior of inherent shear layer interaction and inner wake structures. Complexity of this flow field is slightly increased in relation to the supercritical wake flow.

In comparison, both wake field decompositions, supercritical and subcritical, exhibit strong vortical structure formation, and the idea of maximal vortex circumference scaling with separation region width holds. Periodicity of the subcritical state could be deduced from POD modes, but it is not outstanding, which is consistent with broadened maxima in power spectral density within the critical regime. Although differences in structure formation are reproduced properly, the AOI should be adjusted in terms of focusing on transition area for example.

Regarding the lacking information on the time evolution of the POD modes, some efforts are spent to flow field approximation by variation calculations with a view to structure recovery. Much to our regret, the algorithm for this is yet highly unstable. Interpretation of POD modes could only be disambiguated using flow field approximation. Hence, the hitherto qualitative interpretation still needs validation by flow field reconstruction.
Fig. 4: Eigenvalue distribution and first to fifth weighted eigenmode of the supercritical separation in area I in the lateral symmetry plane of the airfoil; $\alpha=18^\circ$, $Re=2\cdot10^5$. 
Fig. 5 Eigenvalue distribution and first to fifth weighted eigenmode of the supercritical separation in area II in the lateral symmetry plane of the airfoil; $\alpha=18^\circ$, $Re=2 \cdot 10^5$. 
Fig. 6 Eigenvalue distribution and first to fifth weighted eigenmode of the subcritical separation in area I in the lateral symmetry plane of the airfoil; \( \alpha = 18^\circ \), \( Re = 2 \times 10^5 \).
Fig. 7 Eigenvalue distribution and first to fifth weighted eigenmode of the subcritical separation in area II in the lateral symmetry plane of the airfoil; $\alpha=18^\circ$, $Re=2\cdot10^5$. 
4. CONCLUSIONS

Critical wing flows have been investigated by means of PIV measurements in the lateral symmetry plane of the wing, providing a reduced flow field representation. Concerning supercritical flow conditions a characteristic and experimentally assessable frequency which delivers phase information of structure formation is lacking. The collected time series have been analyzed by POD disregarding the time evolution. Regarding the supercritical regime, certain structures in the turbulent detachment are hardly detected. The occurrence of vortices is found to be inherent leading only to local backflow. The separation bubble could clearly be identified as a coherent structure undergoing very complex dynamics. Its motion is spread into many POD modes and it seems to be coupled to wake movement. The appearance of trailing edge vortices and their dynamics can be seen in the decomposition. Compared to the subcritical flow, the turbulent energy is distributed into more eigenmodes, and no eigenvalue coupling was found. With subcritical separation the development of the shear layer instability and, as a result, the formation of large coherent vortices at the trailing edge is observed. In agreement with the results of fluctuation measurements, most of the turbulent energy is contained in a very few POD modes, which leads to simple frequency spectra. Furthermore the coherence of main structure life-cycles is indicated by eigenvalue coupling.

Finally, we conclude that in supercritical flow the vortices cover a certain range of length scales. However the trajectory of the vortex cores does not seem to differ substantially from the subcritical state. As a conclusion, it emanates from our analysis, that the vortex dynamics in supercritical flow cannot be understood if not the whole trailing edge separation cell structure and its the dynamical behavior are taken in account. Furthermore, a coupling to the leading separation bubble exists including further stimuli from the lateral boundary conditions. Future work should therefore approach the coupling by applying an outer excitation in order to simplify the flow field dynamics gaining access to the interaction between the separation bubble and the trailing edge separation. Eventually, the boundary conditions should be varied to study their impact on the separation cell, and flow field measurements concentrating on trailing edge separation should be conducted with artificially fixed laminar-to-turbulent transition.

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