Investigation of structures of the late non-linear boundary layer transition using Stereo PIV

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ABSTRACT

Stereoscopic (SPIV) and standard PIV measurements on acoustically excited transitional boundary layer flows along a flat plate with zero pressure gradient and additionally along an airfoil will be presented. The experimental results are focused on the structures of the late stages of K- and oblique type transition in case of the flat plate and on comparable structures in the case of an airfoil boundary layer flow excited by a point source.

Instantaneous velocity fields are examined in order to quantify the local and global dynamics of the structures and velocity distributions leading into breakdown. Moreover the experimental results will be compared with spatial DNS and previous investigations.

The comparison shows a good correspondence of our data as well with former experimental results as with the spatial DNS. Location and multi-spike characteristics of the wall normal motion on top of the $\Lambda$-vortices as one of the first sources for shear stress decomposing the transitional structures towards turbulence agree quite well. Also a good correspondence is found for the oblique type of transition, where non-linear generated high- and low-speed streaks cause shear stress due to large velocity gradients at their crossings. On the other hand the SPIV results exclude the presence of frequently predicted streamwise vortices at these crossing positions.

A generic forming process can be assumed for the main part of the non-linear stage where mostly 3D disturbances interact with deformed Tollmein-Schlichting (TS)-waves to $\Lambda$-shaped and streaky structures. This thesis can be confirmed, since some important local processes measured with SPIV are in good correspondence with DNS even for this late stage of transition.

For the point source excited airfoil boundary layer flow we also found a good agreement between the shape, location and quantity of the structures in the PIV results and the spatial DNS, especially for the characteristic M-structure consisting of two $\Lambda$-waves in the experimental data-set.

1. INTRODUCTION

The fluid-mechanical research on transition of boundary layers has become an important field for many different time and space resolving measurement techniques and especially for (spatial) DNS in the last decades. In opposite to all sensor based time recording and averaging methods the non-intrusive Stereo PIV technique is able to determine all three velocity components in a plane of the flow instantaneously with a high spatial resolution. Particularly for the sensitive non-linear stage of the boundary layer transition the non-intrusive PIV technique is a suitable and reliable instrument for the quantitative visualisation of transitional flow structures and their behaviour near the turbulent breakdown.

Even if a principal incomparability between experimental data and DNS for the very late stages of transition and the turbulent breakdown should be supposed (because of the sensitive dependence on initial conditions) the transitional process itself seems to generate similar $\Lambda$-shaped structures for many different boundary conditions with a characteristic behaviour. The SPIV technique is able to give information about instantaneous velocity distributions of these typical transitional flow structures as there are $\Lambda$-vortices, streaks, shear layers, local spikes or the global subdivision in valley- and peak-planes. This is true, although the development of these structures into the
breakdown, which is connected to the turbulence initiating high frequency processes, only can be detected as a result of intrinsic flow processes taking place before.

In the literature three different artificially excited boundary layer transition scenarios were distinguished. The fundamental, harmonic or K-type, the subharmonic, H- or N-type and recently the oblique-type of transition. Each scenario is characterised by a typical arrangement of flow structures as presented in the sketch of Fig. 1.

![Fig. 1: Flow structure arrangement of three different types of transition](image1)

Investigations of the transition of 2- and 3-dimensional acoustically excited boundary layers at a flat plate with zero pressure gradient (Blasius), especially for K- and oblique type, and at an airfoil with a point source excitation using Stereo PIV have been performed. The results of these measurements are suitable for a better understanding of the flow structures in the late non-linear regime of the boundary layer transition, particularly for the dramatic development of the \( \Lambda \)-vortices as generic structures and their induced local and global effects leading into the breakdown, which stands for the transition towards a fully developed turbulent boundary layer. Even if the problem of receptivity (see Fig. 2) as the impossibility to reconstruct the initial cause of transition (such as exactly known boundary conditions), due to the non-linear feedback from the effects to the source, these experimental quantities are of high interest for comparisons with spatial DNS with respect to the assumption that the acoustic waves and wave-packages and their higher harmonics are the main source for the downstream amplification of the TS-waves growing up to \( \Lambda \)-vortices or streaks in the transitional process.

![Fig. 2: The problem of receptivity: Possible and not exactly determinable factors for initial disturbances of a boundary layer flow leading into the laminar-turbulent transition.](image2)
In the following we will present SPIV measurements of structures in an acoustically excited transitional boundary layer flow along a flat plate with zero pressure gradient and secondly in a point source excited airfoil boundary layer flow.

2. EXPERIMENTAL SET-UP

2.1 SPIV Measuring Technique

For both experiments the illumination of the \( \approx 1 \mu m \) olive-oil tracer particles, two frequency doubled Nd:YAG-lasers delivering up to 130 mJ during a pulse duration of 6 ns were employed. Utilizing a lens system the laser beam was formed into a light sheet of about 0.8 mm thickness. For the imaging of the illuminated particles, two PCO Sensicam full frame cameras with cooled 1280 by 1024 pixel resolution CCD sensors were used in an angular imaging configuration fulfilling the Scheimpflug condition by tilting the camera housing mounted in special tilt-adapters. For this configuration a de-warping procedure has to be applied, because the magnification is not constant over the field of view. The theory and application of the image de-warping and adjusting to match the images exactly to the same physical flow field positions for both camera views is explained in Willett 1997 and Raffel et al 1998. The exact matching of the calibration grid and the laser light sheet plane should be proofed with a particle image correlation of two frames captured at the same light pulse from both cameras. Also a particle image distortion by sub-pixel re-sampling during the de-warping process has to be taken into account (Kähler 2000).

The observation areas for different flow field magnifications varied between \( 35 \times 42 \) mm and \( 64 \times 80 \) mm. They were imaged by means of two Zeiss 60 or 100 mm lenses. The two short laser light pulses scattered from the tracer particles were captured on two CCD frames. Camera PCs with fiber linked frame grabbers stored the images on disk in a 12bit mode. With our PIV evaluation software an online check of the data quality enabled an interactive control and optimization of the experimental parameters. A high displacement dynamic of more than 7 pixels for the correlating particle images was adjusted to reduce the “peak-locking” effect. An exact phase locked triggering of the flow structure is done by means of a programmable sequencer which synchronizes the acoustical disturbance frequency (plus a given phase shift) with the laser Pockels cells and the frame opening of the two CCD cameras.

The stored data-sets were de-warped as described and evaluated with a FFT based cross-correlation method with a \( 32 \times 32 \) window size and a Levenberg-Marquardt peak fitting algorithm, which determines a vector field with over 12000 vectors in sub-pixel accuracy and minimizes the “peak-locking” effect (Ronneberger 1999). In order to determine all three velocity components in a plane of the flow, a reconstruction of the back-projection of the particle image displacement into the light sheet plane has to be done after de-warping and evaluation of the single PIV images of each camera. Physically unreasonable vectors (less than 1% for each data set) were deleted and re-interpolated by a fit to their next neighbors. As the last evaluation step the conversion into physical units was calculated.

2.2 Wind Tunnels and investigation tools

a) Flat plate experiment

The experiments on the flat plate were performed in the low-turbulence wind tunnel (TUG) at the Institute of Fluid Mechanics at DLR Göttingen. It is an open wind tunnel with the fan at the inlet. Through a honeycomb and a plane 16:1 contraction the turbulence level is reduced to 0.065% for the wind speed of \( U = 12 \) m/s that was used for all our experiments.

The 1500 mm wide and 1175 mm long Plexiglas plate was mounted vertically, had an elliptic leading edge and a flap at the trailing edge to adjust the pressure gradient close to zero along the plate. To take the actual pressure gradient at the elliptic leading edge into account a theoretical fit to a virtual leading edge was made: It was located 20 mm downstream the real leading edge. The device to generate controlled acoustic 2- (and 3)-D disturbances was situated at 194 (and 206) mm downstream of the leading edge. The 2D disturbance device is a 420 mm long spanwise slot with 0.3 mm width connected to a pressure chamber and two loudspeakers through a plastic tube. The 3D disturbance device consists of 40 slots, 10 mm wide and also 0.3 mm broad in streamwise direction, placed with 0.5 mm spacing in spanwise direction. Each slot led to a pressure chamber inside the plate and was connected to a loudspeaker through a plastic tube. Through each slot a sinusoidal acoustic wave has been introduced into the flow.
which generates small periodic velocity fluctuations: spanwise TS-waves for the 2D slot and oblique waves due to a definite constant phase shift between each single slot for the 3D disturbance device. In detail this set-up is described by Wiegel (1997) (see also Fig. 3).

Fig. 3: Experimental setup for Stereo PIV measurements at an acoustically excited flat plate boundary layer flow with zero pressure gradient at TUG (DLR Göttingen)

The K-type transition of the boundary layer flow was achieved through 150Hz sinusoidal acoustic waves which were introduced through the 2D slot and two oblique waves of the same frequency with 3% of the 2D-wave amplitude and 60° phase shifting through the 3D device. The amplitude of the 2D disturbances which leads into TS-waves has been varied during the experiment. Also a phase locked measurement has been done with 20°-phase steps.

The oblique type transition was performed through two 90 Hz and 60° constant phase shifted oblique waves (without 2D disturbance) generating (1, ±1)-modes in the (ω, β)-wave numbering. Three different phase locked measurements with 60°-phase steps were managed with 10% steps in amplification of the initial disturbances.

The laser light sheet was introduced into the test section parallel to the plate in 1 mm wall distance. The measurement volume was situated between 570 and 630 mm downstream the virtual leading edge. The opening angle between the stereoscopic cameras has been adjusted to 61° in a symmetrical setup outside the test section.

b) Airfoil experiment

The SPIV experiments on an airfoil boundary layer flow were performed at the laminar wind tunnel at the University of Stuttgart. This wind tunnel has the fan at the outlet and a contraction ratio of 80:1 in vertical and 60:1 in horizontal direction to minimize free stream turbulence. The 2D airfoil-glove otherwise used for free flight experiments has an extension of 800 mm spanwise and 1350 mm streamwise. It was mounted vertically in the test section.

At a free stream velocity of 37 m/s corresponding to a Reynolds number of $2.96 \cdot 10^5$ and an angle of attack of 1.25° for the airfoil profile the parameters were comparable to these of the free flight experiments and the DNS (Stemmer 1998). The acoustical disturbance device was formed as a small ring of point-holes to avoid bypass transition and to realize a smooth disturbance injection. The point source was positioned at $x/c = 0.27$. Each point was connected to one pressure chamber loudspeaker through a plastic tube. The loudspeaker transformed sinusoidal 800 Hz waves produced by a signal generator into acoustical waves. Their amplitude was varied by means of an amplifier.

Standard SPIV measurements from outside the test section were performed at a streamwise position between $x/c = 0.46$ and $x/c = 0.52$ and two different light sheet wall distances: at 3 mm (upper border of the laminar boundary layer) and at 1.8 mm. Because of a missing optical access at this time the SPIV set-up was situated inside the test section with an opening angle between the camera views of 51.4°. This causes a slight change of the pressure gradient along the airfoil. In order to re-positioning the affected transition into the same $x/c$-area the amplification of the acoustical
disturbance was increased. The measurement plane was positioned at ~1 mm distance from the wall regarding a slightly curved wall surface.

In the next chapter we will present instantaneous velocity vector fields of transitional structures of the described experiments comprising all three flow velocity components (u,v,w) in a plane, where x is in flow-, y is in spanwise- and z is in wall-normal-direction.

3. RESULTS

3.1 SPIV results and the problems of the late stage of transition

In general all described SPIV results, which are quantitative visualizations of structures of the late non-linear stage of different types of transition, confirm the problem of receptivity even in this case of controlled acoustical excitation and fixed experimental boundary conditions: The periodicity and especially the stadium of amplification of the late transitional structures are, within given limits, affected sensitively and stochastically by unknown initial boundary conditions. The pre-history, slightly changing free stream conditions or pressure gradients and model vibrations have a tremendous effect on this stage of transition. Therefore reliable statistical statements even for the phase locked SPIV measurements need a higher number of images as could be captured in the present work. Also the quasi-time resolving phase stepping method for later POD evaluation is undermined mostly by the described fluctuations in this regime.

Nevertheless the results are instantaneous velocity vector fields with a high spatial resolution and an error of at most 1.5% for the displacement detection. They comprise information about different stages of coherent structure development, effects of asymmetry and all three velocity components in a plane. But although the possibility of quantitative comparison to point measurements of time recording methods or the necessarily symmetrical data of DNS is given, we always have to keep in mind the special boundary conditions and the problems of the high-non linearity in this late stage of transition.

For all following considerations about the presented PIV results the interpretation of the described flow structures suppose a comparability with DNS and former experiments on the basic assumption that general processes even in the development of the late non-linear regime of transition take place, which is not trivial and required careful conclusions.

3.2. K-type of transition

Since fundamental works on the flat plate boundary layer transition in the mid of the last century the K-type of transition (Klebanoff 1959) is known as an artificially induced breakdown scenario with streamwise arranged Λ-vortices. The simple wave structure model of the disturbances and their downstream effects gave researchers the possibility to analyze the characteristics of growing rates, non-linear secondary instabilities (Herbert 1988) and the resonant nature (Kachanov 1987) of the transitional structures by abstracting from irrelevant and not known boundary conditions in the transitional regime.

Every transitional flow structure has a singular history of development (in a given frame) while it is transported downstream, but the difference in growing rates normally doesn’t affect the principal scheme of Λ-structure forming, which is triggered essentially by the acoustical excitation. In order to obtain information about the principal metamorphosis of these generic flow structures, the instantaneous flow fields need to be analyzed in detail.

The presented SPIV results immediately continue the experimental work of Wiegel 1997 under the same conditions but for the later non-linear stages of K- (and oblique-) type of transition generated through higher disturbance amplitudes and now employing Stereo PIV. Vector fields with subtracted u-components (noted as U ref) in order to visualize the structures are presented in the figures.

A beginning two-spike development on top of the downstream growing Λ-vortices is shown in the vector fields of Fig 4 and 5. In such a spike low speed fluid from near-wall regions is transported in wall normal direction producing strong shear layers (velocity gradients of 5 m/s within 0.5 mm interval in this wall parallel plane). These spikes are the first step of an energy transportation from the mean flow to the wall and coincide with turbulence initiating high-frequency processes.
a) **Fig. 4:** K-type transition at a two-spike stadium and 150Hz 2D, 60° phase 3% Amplitude 3D oblique waves

b) **Fig. 5:** Zoom into the two-spike top of the Λ-vortex shown in Fig. 4 with a wall-normal velocity component up to 35% of $U_\infty$

A wall normal flow velocity of up to 35% of the free stream velocity is found in this stage of spike development in good agreement with newest spatial DNS investigations (Preliminary work presented in Meyer 1998). The shape of the Λ-structure and the spike development is also in good correspondence with former DNS of the K-type of transition on a flat plate without pressure gradient (Rist 1990).

A case with a, in respect to Fig 4 & 5, 30% higher amplification rate for the 2D disturbance device generates the more complex flow structures and velocity distributions shown in Fig. 6 & 7. The spikes on top the Λ-vortices were already transported upwards through this plane and an asymmetric arrangement due to different amplification stadiums of neighboring structures arises.

a) **Fig. 6:** Near breakdown for K-type of transition with a spanwise asymmetric arrangement of Λ-vortices and a large variation of velocity between valley- and peak- plane (magnitude of velocity color coded, $U_\infty=12$ m/s)

b) **Fig. 7:** Zoom inside Fig 6 in the region with large velocity gradients at the border to the valley region where high frequency processes generate turbulent flow with strong wall normal components (here w-component color coded)
This scenario is near to the turbulent breakdown of the K-regime and consists a large velocity range in this plane: From nearly free stream velocity of 11.5 m/s in the peak plane area down to 3.7 m/s in the “legs” of the $\Lambda$-vortices. This shows, that hot-wire measured relative $u_{rms}$ values of up 12 % in this stage of breakdown corresponds to ~60 % velocity fluctuations of the spatially spanwise distributed local maximums.

Remarkable is the development of secondary “legs” of the $\Lambda$-structure propagating in spanwise direction and colliding with the ones generated by the neighboring structure in the valley plane. Also the acceleration of the flow in the surrounding area of the transported spikes in the peak-plane by forming a streaky structure seems to be a generic process for this scenario. Flow visualizations made by Wiegel 1997 showed the same structures qualitatively.

In Fig. 7 a zoom into the region at the border between the high speed region formed around the peak-plane and the upper valley-plane is presented. This is the region where firstly a strong, chaotic three dimensionality of the flow appears, which can be interpreted as local turbulent breakdown with first regional notable $u'w'$-values. In correspondence to the oblique-type breakdown the first extension of turbulent regions seem not to be generated in the peak-plane for K-type, respectively in the high speed regions for oblique-type, but at their borders to low speed regions where strong velocity gradients in spanwise direction supply the decay of these structures propagating into the valley-plane, resp. low-speed region, and simultaneously starting the production of turbulence. In former experimental investigations these spatial effects lead to larger $u_{rms}$ values and the successive filling of the higher frequency area independent of the higher harmonics of the initial disturbance frequency.

### 3.3 Oblique-type of transition

This type of transition firstly was investigated experimentally by Wiegel 1997 and numerically by Berlin 1999 for the same flat plate boundary layer flow. The oblique type of transition has the special feature that only 3D disturbances, in the streamwise-spanwise wave numbering (1, $\pm$1), cause the non-linear development of growing high and low-speed streaks (0, 2) as shown in Fig. 8. The structures of the S-shaped alternating streaks changes from a wavy to a streaky appearance by an increase of the amplitude of disturbance.

$\Lambda$-shaped structures inside the low-speed regions can be detected in a global arrangement, which is comparable to the H-type of transition. This spanwise displaced arrangement of $\Lambda$-shaped structures is divided by high-speed streaks, but streamwise vortices at the crossings of the streaks as assumed in Berlin 1999 cannot be found (no wall-normal velocity).

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**Fig. 8:** Oblique type transition at a late stage wherein streaky structures starting to decay and high-frequency processes begin to dominate, which leads into breakdown (magnitude of velocity color coded, $U_{ref} = 12$ m/s).

**Fig. 9:** Local start of turbulent breakdown with a chaotic 3D-flow at the shear layers at the borders of the high speed streaks evolving inside the low speed region at its smallest extension (Zoom of Fig 8, w-comp. color coded)
Furthermore large wall-normal components do not appear until the beginning of breakdown (Fig. 9) in contrast to the role of well structured (multi-)spikes for the initial phase of the late non-linear stage of K-type transition. There first $u'v'$-events are connected to the spike development, whereas in the presented oblique-type SPIV results these events can only be found in decaying structures near large velocity gradients. But the strong $u-v$-plane velocity gradients are not a sufficient condition for turbulence production, just the decay of these shear layers coincide with the appearance of turbulent regions. This conclusion can be made as an interpretation of Fig. 9. The decay of the transitional streak-structures is connected to the appearance of high-frequency processes detected in hotwire measurements.

3.4. Point source excited airfoil boundary layer

In Fig. 10 an instantaneous velocity vector field of a measurement in the upper border of the airfoil boundary layer flow is shown. In the spanwise centerline at $y = 0$ the point source is positioned upstream at $x/c = 0.27$, the lower left of this plot starts at $x/c = 0.46$. Clearly the amplified TS-waves enter in a half-circle formation from the left.

The transformation of the TS-waves into two M-arranged $\Lambda$-vortices generates a spike development on their tops, which take place underneath this plane (see also Fig. 12). These spikes break through the measurement plane and eject low speed fluid from lower boundary layer areas into this plane (blue vectors) by a simultaneous increase of the boundary layer thickness and an introduction of breakdown.

A good qualitative agreement to the DNS in the shape of the structures is noticed. All flow parameters were the same, only the disturbance frequency was 900 Hz. ($\omega_z$-contours at the wall color coded). Source: [http://www.iag.uni-stuttgart.de/telefon_fram.html –Stemmer]

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A good qualitative agreement to the DNS in the shape of the structures is noticed. All flow parameters were the same, only the disturbance frequency was 900 Hz in the case of DNS. The presented DNS data in Fig. 11 is part of the work of Stemmer 1998 and shows the near-wall $\omega_z$-contours qualitatively. The results led to the conclusion that the boundary layer flow structures also appear at the wall. This is also found in comparisons with Piezo (PVDF-) measurements at the same object.
In Fig. 12 the velocity distribution of a plane below that of Fig. 10 at 1.8 mm wall distance is shown. The low speed fluid inside the spikes at the top of the Λ-vortices is up to 25 m/s slower than the surrounding velocity. The spikes have an extension of not more than 0.1 cm², which explains the dramatic character of the start of turbulent breakdown due to this large shear stress. Remarkable is the appearance of a co-peak structure in the centerline downstream at the upper right side of the vector plot. A centerline co-peak also appears earlier in Fig. 13 at different boundary conditions during the SPIV measurements (see chapter 2.2. b)). This co-peak instability could only be detected in the present PIV results. Possible reasons for the difference to the DNS results are existing 2D waves in the initial disturbances of the experimental realization or the asymmetry of the non-linear development of the M-shaped double Λ arrangement in the real flow.

Fig. 12: Symmetrical situated, but asymmetrical developed Λ-vortices in a M-shaped structure in a plane below that of Fig 10 (1.8 mm wall distance) with strong spikes and large velocity gradients

In Fig 13 a SPIV result at a wall distance of 1 mm is presented. In this plane the turbulent boundary layer flow in the right part of the figure has a higher velocity than the laminar one in the left part. The M-structure can be detected, but also an upstream Λ-vortex in the centerline appears, which is different to the standard PIV measurements from outside the test section, but the global symmetry of the arrangement of the structures in the breakdown process is not broken. We assume that the slight change of the pressure gradient caused by the SPIV setup inside the test section and the higher disturbance amplitude leads to this modified transitional scenario. Although in this case comparisons are inappropriate, it is remarkable that also a Λ-structure is formed in the centerline in addition to the double Λ- M-structure. This affirms the supposition of Λ’s as generic transitional structures and the experimental confirmation of the insight that a simple superposition of different boundary conditions and initial disturbances doesn’t lead to a superposition of the effects for any given non-linear regime of transition.
4. CONCLUSIONS

SPIV measurements on acoustically excited boundary layer flows for different transitional scenarios have been done. The K- and oblique-type transition was generated at a flat plate with zero pressure gradient and a singular scenario was measured at a point source excited airfoil boundary layer flow. The SPIV data-set contains information about the instantaneous velocity distributions of all three velocity components in a plane of the transitional flow, complementing time recording methods and spatial DNS. All results are in a good correspondence with DNS and former experimental results. The problem of comparability for the late non-linear stage of transition is presented and the assumption of a generic structure forming process for many transitional boundary conditions could be confirmed. Although the breakdown processes start with the non-linear amplification of different waves or wave-packages a non-vanishing similarity has been found in the structure forming process: A different weighted appearance of streaks and Λ-vortices can always be detected, whereby the oblique-type is dominated by streaky structures and the K-type by Λ-structures. The understanding and interpretation of the still unknown non-linear processes of structure development leading into breakdown will find strong support by the presented and future SPIV or Multiplane SPIV measurements.

Fig. 13: SPIV result of transitional structures of an acoustically point source excited airfoil boundary layer flow
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