Investigation of a turbulent spot using multi-plane stereo PIV

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ABSTRACT

The multi-plane stereo PIV (MSPIV) technique has been applied to an investigation of the spatial and temporal development of turbulent spots in a laminar flat-plate boundary layer flow with a slight adverse pressure gradient. The spot was induced by a locally blown injection at $Re = 318$ with $Re = Re_{x}^{1/2}$, with $x$ as the distance from the leading-edge, and the measurement volume was located at different downstream positions, at Reynolds numbers between $448 \leq Re \leq 550$. For the calculation of the velocity vectors, $32 \times 32$ pixel interrogation windows were used, corresponding to a resolution down to $1.6$ mm in each direction of physical space. On the basis of a large number of evaluated instantaneous 3- and 2-component velocity vector fields, measured synchronously and separated in space, or with different time separations in one or two planes, the technique enabled the possibility of determining several statistical quantities of fluid mechanical significance: ensemble averages and velocity fluctuations ($u'$, $v'$, $w'$), $rms$-fields, Galilean accelerations, probability density functions (PDF) and space-time-correlations of the velocity fluctuations, the instantaneous Reynolds stresses ($u'v'$) of all four quadrants and the $y$-component of vorticity.

The shape and role of coherent substructures for the growth and turbulent mixing of the spot were the focus of this investigation. The average substructures have been identified as hairpin-like vortices arising at the rear of the spot and as wall near stream-wise streaks with strong shear layers (compare with average $\omega_y$-vorticity field in Figure 1), similar to those in fully turbulent boundary layer flows, but in this case more orderly. The interpretation of the results of the statistical analysis and of the instantaneous velocity vector fields leads to the development of a model which can describe, as the main source for turbulent mixing, the interaction of the dominant substructures and the fluid exchange normal to the wall. The described model allows an explanation for the growth of the spot in both stream-wise and span-wise directions, the self-similar arrowhead shape and the role of Q2- and Q4-events in the most dynamic region directly downstream of the trailing edge and the center of the spot.

![Fig. 1. Ensemble average of the y-component of vorticity at $T = 78$ ms after initiation, $y = 4$ mm](image-url)
1. INTRODUCTION

Paths from laminar to turbulent boundary-layer flow were mostly investigated with a focal point on slightly growing disturbances initially introduced under controlled conditions. Beyond a critical Reynolds number disturbances of specific wavelength are amplified and form TS-waves, others are damped. Due to non-linear secondary and later instability mechanisms the TS-waves become three-dimensional structures and produce strong shear stress, which initiates a rapid breakdown to turbulent flow. However, in "natural" transition scenarios small patches of turbulent flow appear inside the laminar boundary layer in a stochastical manner. Turbulent spots are growing downstream in stream- and span-wise direction and, after a span-wise merging, they develop to a fully turbulent boundary-layer, Emmons (1951). Former research on artificially generated turbulent spots in laminar boundary-layer flows utilized essentially hot-wire anemometry and visualization techniques. Results of hot-wire measurements are mainly based on ensemble averages and enable to determine only certain quantities: The convection velocity, spreading angle, shape and altitude of the whole spot and some linear instability events in the near vicinity of the spot, Cantwell et al. (1977) Wylanski et al. (1982). But the hot-wire technique was not able to achieve sufficient spatial information about the substructures of the spot as the main carriers of the turbulent mixing process. On the other hand visualizations show hairpin-like vortices, Matsui (1980), and wavy streaks, Gad-el-Hak et al. (1981), as the main structures inside the spot. The first investigation focusing on the topology of the substructures was made by conditionally sampled cold-wire anemometry and answered questions about the convection velocity and inclination angle (about 45°) of the substructures, Sankaran et al. (1987). Recent numerical simulations of turbulent spots and of cascades of evolving hairpin vortices reach a certain level of accuracy and spatial resolution and confirm experimental datasets and visualization descriptions substantially, Singer (1996), Tufo et al. (1999). Some status quo characteristics: The spot has the average shape of a curved arrowhead with the tip pointing downstream and a thickness of about three times the height of the laminar boundary layer. Hairpin-like vortices evolve at the trailing-edge (TE) and increase the region of the turbulent spot in stream- and span-wise direction. These vortices with an inclination angle of about 45° to the wall form the spot and convect downstream with approximately 75% \( U_{\infty} \), depending on the distance from the wall. The average TE convection velocity is ca. 62% \( U_{\infty} \), and the leading-edge (LE) velocity ca. 87% \( U_{\infty} \). Typically stream-wise streaks appear in the near-wall region and persist behind the TE of the spot, which has up to now only be found in visualization experiments. An overhang region characterizes the LE of the spot consisting of the convecting, dissipating and stretched vortex heads above a laminar layer.

Some questions still exist and some new arise: What is the reason for the lateral extension, especially the curved form between the wing-tips and LE of the spot? How is the turbulent mixing due to the (instantaneous) negative Reynolds stress \( \rho u'\nu' \), the so called Q-2- and Q-4-events, connected to the spot substructures quantitatively? Why does the turbulent mixing proceed automatically while the characteristic flow structures are always self-organizing? How to explain the axisymmetry and self-similarity of the whole spot (as it is shown in ensemble averages and \( rms \)-fields)? Some of these problems are directly connected to the research on fully turbulent boundary-layers. The turbulent spot itself combines the characteristics of transition, breakdown and "young" turbulent flow in a local domain. Although the turbulent spot has not developed a logarithmic region of the ensemble averaged velocity profile and the skin-friction-velocity is a function of the stream- and span-wise position, the substructures of the spot governing the turbulent mixing process are obviously very similar to those in fully turbulent boundary layer flows. In the last decades considerable experimental and numerical work providing new perspectives in understanding turbulence phenomena in wall bounded flows has been carried out. Besides viewpoints based on point-measurement systems and statistical methods a certain amount of qualitative spatial-temporal models of the characteristic flow structures in turbulent and late transitional boundary layer flows have been developed (for example Robinson (1991), Meinhart (1994), Schoppa & Hussain (1997)). Especially the fast development of field measurement techniques in the last years enables spatially and temporally resolved quantitative data in completion to visualization techniques and enables comparisons to direct numerical simulations. This initiates an increasing interest in the importance of coherent structures for the interpretation of turbulent flows. Although the exact form and function of different structure-models are still in discussion two main models dominate the interpretation of measured fluid motions inside such flow types: Streaks and hairpin vortices.

To investigate the role of coherent structures in wall bounded flows the evolving substructures governing the turbulent mixing process and composing the spot are in focus of the present investigation. The results obtained by means of multiplane stereo PIV comprise all three components of the velocity vector in two spatially and/or temporally separated planes. It will be shown that this data-set gives valuable hints to answer some of the above
mentioned questions. Beside instantaneous velocity vector fields especially two dimensional space-time-correlations of the vorticity and the velocity fluctuations and their phase relation can give information about the shape and extension of the dominant substructures and their flow motions.

2. EXPERIMENTAL SET-UP

An artificially excited turbulent spot in a laminar flat-plate boundary layer flow is a special bypass transition scenario. The scenario shows an increasing area of turbulent flow in a self-similar arrowhead shape downstream a local disturbance source (see Figure 2).

The investigation was performed at the low turbulence wind tunnel at DLR Göttingen (turbulence level $Tu = 0.065\%$ at 12 m/s) on a vertically mounted flat-plate with an elliptical leading-edge and a flap at the trailing-edge. A slight adverse pressure gradient was adjusted to accelerate the growing of the spot until it reached the measurement domain. The spot was induced by a locally blown injection of air of 1 ms duration through a $x$-$z$-slit with $0.2 \times 2$ mm extension at $Re = 318$, at a free stream velocity of $U = 7$ m/s (see Figure 3). The measurement volume was located at different downstream positions, at Reynolds numbers between $448 \leq Re \leq 550$. The multi-plane stereo PIV system used consisted of a four pulse Nd:YAG laser-system ($Quantel$) with an output energy of 300 mJ per pulse at $\lambda = 532$ nm, optics to produce one or two light sheets from two orthogonally-polarized laser beams and four PCO Sensicam cameras with Zeiss 100 mm and 135 mm objectives (for details see Kähler & Kompenhans (1999), Kähler (2000)). The separation of the light scattered by the particles due to the two illuminations was achieved with polarizing beam-splitter cubes and simple polarizing filters (see also Figure 3). An event-locking and shifting of the downstream convecting flow structure for the data acquisition was applied with special triggering electronics. This enabled the synchronization of the four laser light-sheet pulses and the frame opening of the CCD-Cameras, with the moment the spot arrived at the measurement volume. The time separation between initiation and measurement was abbreviated with $T$. Two different principal set-ups were constructed: a two-component (2-C)-multi-plane PIV set-up, with two measurement volumes attached to each other in stream-wise direction and light-sheets parallel to the wall, in order to obtain velocity data from the whole structure downstream of the disturbance source in two different planes simultaneously and after certain time steps. Additionally, a stereo (3-C-) multi-plane PIV set-up was employed with a smaller field of view to resolve the substructures of the spot in detail. For both applications different time separations between the two orthogonally polarized light sheet pulses were utilized. This time separation $t$ varied between 0.5 and 15 ms and in different set-ups the measurement planes were located at $y = 4$, 4.5, 6, 8.5 and 10.5 mm. Two principal combinations of the orthogonally polarized light sheet planes were used in this investigation. Figure 4 shows the spatial and temporal alignment of the intensity fields of the laser light-sheet pulses in the $y$ (wall-normal) direction and in time. $\Delta t_1$ and $\Delta t_2$ are the time distances between the two illuminations of the tracer particles in order to produce one velocity vector field each and $t$ is the time separation between these two PIV images. Employing this technique always two velocity vector fields are related in time and/or space and can be used for further evaluations.
Fig. 3. Experimental setup for multi-plane stereo PIV measurements on artificially excited turbulent spots in a flat plate boundary layer flow at TUG (DLR Göttingen)

Fig. 4. Used spatial and temporal combinations of polarized laser light sheets in multi-plane PIV set-up. I Intensity profile, $y$ wall-normal direction, $t$ time

For the calculation of the velocity vectors the PIV recordings were interrogated in overlapping windows of $32 \times 32$ pixel, corresponding to a resolution down to 1.6 mm in each direction of physical space. Beside a particle image displacement dynamics of almost more than 8 pixels, an iterative Levenberg-Marquardt two-dimensional Gaussian peak-fit has been applied to reduce the peak-locking effect. Less than 1% spurious vectors for all velocity fields and a correlation coefficient between 0.55 and 0.8 are an indication for high quality PIV recordings. Furthermore, the velocity vector fields were ensemble averaged on the basis of up to 1050 single realizations. $Rms$-fields, fields of the velocity fluctuations, the instantaneous Reynolds stresses of all four quadrants (Q-1 = $u' + v'$; Q-2 = $-u' + v'$; Q-3 = $-u' - v'$; Q-4 = $u' - v'$) and the $y$-component of vorticity were calculated. This data-set was used to achieve statistical information by means of probability density functions (PDF) and two-dimensional space-time-correlations of all instantaneous quantities and their phase relation. Characteristic length and time scales can be derived from the correlation functions such as the dissipation length and the integral length-scale which play an important role in the transport equations, Rotta (1972). By separating the signs of the velocity fluctuation fields, the space-time-correlation functions of the “phase relations” (e.g. $-u'$ with $w'$) enable an interpretation of the mean flow directions of the identified, dominant substructure also. This statistical approach defines a generic substructure. A recombination of all characteristics of the different correlation functions of the velocity fluctuations in comparison with instantaneous velocity vector fields can lead to an idealized, spatial-temporal model of the dominant flow structure.
3. RESULTS

3.1 Instantaneous velocity vector fields and global statistics

First of all the results of the 2-C-multiplane PIV measurements will be presented to give an overview of the whole spot structure. The x-axis is directed stream-wise, the y-axis wall-normal and the z-axis span-wise, the corresponding velocity components are \( u, v \) and \( w \). Two instantaneous velocity vector fields of the same spot at a wall distance of \( y = 4.5 \) mm and with a time-separation of \( t = 5 \) ms are shown in Figure 5. The upper velocity vector field was captured at \( T = 78 \) ms after the disturbance. A wavy to streaky structure inside the spot is noticeable and a convection of the (sub-)structures can be registered, while the spot is growing in stream- and span-wise-direction.

![Fig. 5. Two instantaneous 2C-velocity vector fields of the same turbulent spot with a time separation of \( t = 5 \) ms at \( y = 4.5 \) mm. Wavy streaks with lower velocity pass through the whole spot.](image)

An ensemble average of 1050 single realizations was calculated. The single realizations were all captured at \( T = 78 \) ms after the disturbance pulse. In this wall-distance at \( y = 4.5 \) mm, which is approximately the laminar boundary layer height on the upstream boundary of the velocity plot, the spot structure is slower than the surrounding laminar flow and the slowest average velocity is in the center of the spot with down to 65\% \( U_\infty \).

Also streaks of lower and higher \( u \)-velocity pass through the spot in stream-wise direction. A region of higher velocity, the s.c. “calmed region”, is following the spot. In Figure 6 the corresponding \( rms \)-field is shown. The \( rms \)-value is a measure for the average kinetic energy in the flow field. The regions of high \( rms \)-values are located downstream of the TE, in the center and the wing-tips of the spot. Also the low-speed streaks show higher \( rms \)-values than in their direct vicinity. The highest values correspond to a turbulence-level of nearly 10 \% with respect to the free stream velocity in this wall distance at \( y = 4.5 \) mm.
The averaged field of the $y$-component of vorticity in $y = 4$ mm wall distance ($y^+ \approx 87$, Schröder (2001) (closest wall distance in this investigation)) (see Figure 1) emphasizes the streaky characteristic inside the spot. The low- and high-speed streaks are located between span-wise alternating vorticity streaks and are clearly visible in the region at the LE. The phase of the streak wiggles is not correlated between single realizations at the leading edge, but seems to be correlated in the center and at the TE of the spot. These data are based on 840 single realizations. These vorticity-streaks inside the turbulent spot are a possible reason for the center-line symmetric and self-similar shape of the spot and are shown here for the first time. The average span-wise equidistance of streaks is up to now only known for fully turbulent boundary layer flows. We will see in the following results, that this $y$-vorticity located at the boundaries of the low- and high-speed streaks has its foundation in both, the hairpin-like vortices and the shear flow.

A look at the probability density functions (PDF’s) in Figure 7 shows the distribution of the $u'$, $v'$, $w'$ and $u'v'$ values of the whole spot in different planes parallel to the wall. These curves were calculated on the basis of more than 1500 single realizations for each distance $y = 4$ mm, $y = 6$ mm and $y = 10.5$ mm from the wall. The $u'$ curves show characteristic shoulders in the positive and the negative area, these being more pronounced in the plane at $y = 4$ mm. Analysis shows that these shoulders represent coherent structures in the instantaneous velocity fluctuation fields: quite narrow, wiggly low-speed streaks for the negative shoulder with single events of highly negative $u'$ along them and broader high-speed streaks for the positive shoulder. The asymmetry of the shoulders with respect to $u' = 0$ cm/s exists due to the characteristics of the streak formation: the narrower low-speed streaks are less frequent spatially, but with higher amplitudes than the high speed streaks. The asymmetry of the PDF’s of $v'$ is somehow connected to the $u'$ streak formation. Positive $v'$ correlates to negative $u'$ and vice versa. The structures responsible for this correlation form negative instantaneous Reynolds stresses $Q-2$ and $Q-4$, which are the main events for the production of turbulence. The $w'$ curve shows exact symmetry, which represents a physical necessity for turbulent shear flows. The PDF’s of $u'v'$ are asymmetric to the negative side, which indicates a plus in turbulence production for the whole spot. This asymmetry increases towards the wall and higher negative values can be found at $y = 4$ mm, which correspond to measurements in fully turbulent boundary layers, where the highest values for negative Reynolds stress have been found above the laminar sub-layer.

In Figure 8 two instantaneous 3C- velocity vector fields of the trailing-edge of the same turbulent spot with a time separation of $t = 0.5$ ms are shown. The measurement plane is located at a wall distance of $y = 6$ mm and the $v$ component is color coded. Hairpin-like vortices appear inside the flow, which reaches the spot from upstream direction. Analysis shows that these hairpin-like structures are often asymmetrical and oscillate in their span-wise component one after the other. This wiggling corresponds to the shown streaky structures (see Figure 1 and 5), which supports the assumption that these two identified flow structures are connected directly. The question is; how?
The counter-rotating structures with a Q2-event in between (marked with arrows in Fig. 8) grow explosively in the direction normal to the wall while they are convecting towards the turbulent region of the spot. How and why do these vortices evolve here? Flow visualizations show persistent near-wall streaks upstream of such spots. The question is posed whether or not the shear flows along these structures are unstable and initiate the explosive growth of such hairpin structures?

Fig. 7. PDF’s of $u'$, $v'$, $w'$ and $u'v'$ of the spot in different planes parallel to the wall

Fig. 8. View inside two temporal subsequent ($t = 0.5$ ms) instantaneous velocity vector fields at the trailing-edge of the same spot. Arrows mark evolving hairpin-like structures. $y = 6$ mm, $v$ color coded
These vortices appear mostly upstream of a convected one and have a mutual induction so that they are alternating in the \( w \)-component of the velocity, while Q-II-events were produced in between their vortex-heads. In that way all three velocity fluctuations are growing simultaneously and the streak characteristics and the vortex-forming process seem to be linked in the same way as in fully turbulent boundary layer models, Meinhart (1994). Hairpin vortices play also a significant role in late transitional boundary layer flows (e. g. at the top of lambda-vortices). Here Q-II-events are often precursors of stochastic flow motions which appear after these vortices produced strong shear stress.

The spot itself acts like an obstacle for the surrounding faster laminar flow. This can be shown regarding the \( v \)- and \( w \)-components of the ensemble-averaged velocity vector fields (see Figure 9 for the \( w \)-component). The flow reaching the rear of the spot is deflected in wall-normal and each span-wise direction. Even the average deflected flow velocity in span-wise direction reached up to 6% \( U_\infty \).

![Fig. 9. Ensemble average velocity vector field at T = 78 ms, span-wise velocity component \( w' \) color coded](image)

After the flow has passed the center of the spot there appears also a small noticeable component from both sides directed to the center-line (middle of the vector plot). This deflected flow seems to be the carrier for the span-wise transport of turbulent flow and allows an explanation for both the high dynamics in the wing-tips and the curved form between the downstream tip and the wing-tips of the spot: The disturbances of the hypothetic hairpin-like vortices appearing at the TE are transported in span-wise direction due to this deflected flow. Additionally, the oncoming faster fluid in regions of the “calmed flow” below the level of the laminar boundary layer thickness “hits” the laminar boundary layer itself on the position of the wing tips. Furthermore the adverse pressure gradient, Coles & Savas (1980), for the flow approaching the spot from upstream can be explained with this obstacle effect. This pressure regime amplifies certain disturbances similar to well known transitional scenarios and it may explain the rapid growth of the wiggling hairpin-like vortices on the basis of sinusoidal and shear instabilities at persistent near-wall streaks, Schoppa & Hussain (1997).

But what is the driving force for the (ongoing) mixing process in the turbulent regime of the spot? And: How is this fluid motion organized spatially on the basis of the assumed hairpin-like structures? In considerations about the energy cascade only Q-IV-events, the transport of highly ordered flow to the wall, can be the motor of the mixing process. Also probability density functions (PDF’s) show that Q-4-events mainly appear with high values and density only downstream of the TE and the center of the spot, Schröder (2001). In order to investigate the substructures in detail, vorticity and velocity fluctuations have been analyzed with two-dimensional space- and space-time-correlations in the center of the spot.

### 3.2. Space-time-correlations and a coherent structure model

Space-time-correlations of the velocity fluctuations give information about the average extension of the dominating substructures. If the measurement-planes were located at different geometrical positions or phase relations between different fluctuation components have been calculated, they can also give a statistical view of
the fluid motion. The space-correlation function of two fields of velocity fluctuation components in the x-z-plane is defined as:

$$R_{ij}(\Delta x, \Delta z) = \frac{\sum_x \sum_z u'_i(x,y,z) \cdot u'_j(x+\Delta x, y, z+\Delta z)}{\sqrt{\sum_x \sum_z u'_i^2(x,y,z) \sum_x \sum_z u'_j^2(x+\Delta x, y, z+\Delta z)}}.$$

For space-time-correlations, the function has to be extended with t and t + \Delta t. In the case using multi-plane PIV, \Delta t is constant for each of two velocity fluctuation component fields which are cross-correlated. In Figure 10, the y-component of the vorticity of two different planes parallel to the wall has been correlated. The lower plane was located at y = 4 mm and the upper at y = 8.5 mm. The correlation function indicates that approximately 20% of the vorticity structure possesses enough elevation normal to the wall to penetrate both planes. For a separation time of t = 0 ms, the inclination angle of the average vorticity substructure can be estimated (using the location of the maximum) to ca. 48° to the wall. The streak-structure of the vorticity (see Figure 1) can be recognized: the correlation function has a domain of negative coefficients in both span-wise directions which are elongated in stream-wise direction. The upstream effect of the vortical structures can be seen in the asymmetry of the stream-wise elongation of the correlation function. Furthermore the functions show that the vortices move in wall-normal direction because a higher correlation coefficient was calculated after t = 5 ms than in the simultaneous case (t = 0 ms). The convection velocity of the vorticity substructure can be determined from the location of the maximum after t = 5 ms to 75% \(U_{\infty}\), which exactly confirms former investigations, Sankaran et al (1987).

**Fig. 10.** Crossed space-time-correlation of the y-component of vorticity in two wall parallel planes at \(y_1 = 4\) mm and \(y_2 = 8.5\) mm wall distance at t = 0 ms and t = 5 ms time separation

**Fig. 11.** Space-correlation of the “phase relation” of the positive (p) and negative (n) signs of the \(v'\)- and the \(w'\)-components in the center of the spot at \(y = 4\) mm wall distance

For the construction of a model which can link the assumed hairpin-like vortex substructures with the Q-2 and Q4 events it is necessary to show that these vortices are the average dominant substructures and to explain how...
Q-2- and Q-4-events fit in this vortex-model spatially and temporally. For this purpose a space-correlation of the phase relation of the positive (p) and negative (n) signs of the $v'$- and the $w'$-fluctuation components have been calculated (see Figure 11). These correlation functions are each mirror-inverted to the $\Delta z = 0$ axis for a sign change of $w'$ (not shown here!).

For an interpretation of these correlations it is also useful to know that positive $v'$ exhibit stronger correlations with negative $u'$ and vice versa, Schröder (2001). The more elongated and span-wise narrower structure of the positive $v'w'$-correlation function is linked to the narrow low-speed streaks. The positive $v'$ is produced here, as assumed, due to evolving hairpin-like vortices and is stream-wise elongated because of the shear flow. If we superimpose an idealized hairpin vortex structure with two symmetrical vortex legs (necessarily for space-correlations) with a stream-wise inclination to the wall in our imagination at position $(\Delta x, \Delta z) = (0, 0)$ in Figure 11 (left), the average flow motion hidden in the topology of the shown positive $v'w'$-correlation function and the mirror-inverted negative $w'$ counterpart in mind can be explained easily. The $u'w'$ correlation functions look very similar. Also in $y = 6$ mm wall distance the topology of the correlation function is mainly the same, Schröder (2001), so that the assumed hairpin-like vortex with a wall normal elevation can be accepted as a dominant substructure. On the right hand side of Figure 11 the correlation function of negative $v'$ and $w'$ is shown. It is nearly the same basic structure, but broader in span-wise directions and with an opposite flow motion. The ideal vortex structure to explain these correlations has to be counter-rotating with respect to the first well known hairpin vortex. This can be explained by a spatial span-wise line-up of the average hairpin-vortices which is visualized as a model in Figure 13. This so called “mixer-model” is based on several space-time-correlations, PDF’s and the analysis of instantaneous velocity vector fields of the turbulent spot in different wall distances. The span-wise line-up of the inclined hairpins combines the various Reynolds stress events.

In Figure 12 the two “phase-relations” of the velocity fluctuations of the negative sign of $u'$ and the positive sign of $v'$ and vice versa, which can be combined to the turbulence producing Q-2 (II) and Q-4 events (IV), are correlated in the $x$-$z$-plane. In this plane at $y = 4$ mm, negative $u'$ correlates very well with positive $v'$ in a very narrow and local domain (left). This can be reduced to the local Q-2-producing hairpin-like vortices indicated by the minima in both span-wise directions. However, the correlation-function is also stretched in both stream-wise directions corresponding to the low-speed streaks in which positive $v'$ occurs more often than negative $v'$ in the high-speed streaks. In the opposite case, the correlation is broader, with a lower peak amplitude (right) and a significant upstream correlation can be recognized. This asymmetry in the upstream direction can be explained thus: every positive $u'$-event correlates preferably with an upstream negative $v'$-event. That means that high-speed fluid, which is transported towards the wall is somehow deflected from it, producing a maximum positive $u'$ at the deflection point, similar to what correlations of Q-4 with Q-1 events show also (see Schröder (2001)).

![Fig. 12. Space-correlation of negative $u'$ with positive $v'$ (left) and vice versa (right) at $y = 4$ mm $\rightarrow y^+ \approx 87$](image)

This asymmetry also indicates the “starting-point” of the turbulent mixing process, because high-speed fluid towards the wall has to be the first step in this self-organizing energy cascade inside the turbulent boundary layer, in which coherent structures minimize (after the “price of transition” has been paid) the production of entropy in certain levels. Destabilization of shear flow forms mostly hairpin-like vortices and these reorganize the streaky structures. All these and other forms of flow structure interaction are very complex spatial and temporal developments, which can not be reconstructed in a simple model. However, the relative order of the
identified dominant substructures as idealized hairpin-vortices and streaks allows a simplification, if essential aspects of the turbulent flow found in previous investigations can be reflected.

If we assume, that Q-4-events govern the turbulent mixing process, a certain level can only be explained in this model, if a span-wise line-up of the hairpins due to the streak characteristic inside the turbulent spot is organized. The Q-4-events have smaller amplitudes than the Q-2-events but they are spatially broader. In the wall-near region this fluid produces strong shear stress at the wall and at low-speed-streaks and new hairpin-like vortices are formed. In that way the self-sustaining process of turbulent mixing is well structured. Although this model is based on a huge number of instantaneous velocity vector fields and is just a complementary idea to existing models it is preliminary and has to be discussed in future.

Fig. 13. “Mixer”. Model: A span-wise line-up of hairpin-vortices combine the Reynolds stress events in space

4. CONCLUSIONS

An extensive experiment on artificially excited turbulent spots in a flat plate boundary layer flow using multi-plane stereo PIV has been carried out. Based on a high number of instantaneous 2C- and 3C-velocity vector fields, which were acquired in two planes parallel to the wall simultaneously and with different subsequent time steps, the spot structure and its substructures have been analyzed in detail. Statistical approaches have been utilized in order to achieve data with fluid-mechanical significance: ensemble averages, fields of the velocity fluctuations, the Reynolds stresses of all four quadrants, the \( \gamma \)-component of vorticity, \( \text{rms} \)-fields, the corresponding probability density functions (PDF) and space- and space-time-correlations have been calculated. The interpretation and analysis of this data-set led to the development of a model which allows the description of the interaction of the dominant substructures and the fluid exchange normal to the wall. The average substructures have been identified as hairpin-like vortices and streaks with strong shear layers, similar to those in fully turbulent boundary layer flows, but they are more orderly. This model provides an explanation for the growth of the spot in both stream-wise and span-wise directions, the self-similar arrowhead shape and the role of Q-2- and Q-4-events in the most dynamic region directly downstream of the trailing-edge and the center of the spot. A comparison with coherent structures in fully turbulent boundary layer flows shows essential similarities. Future measurements closer to the wall should give new information about the forming process of hairpin-like vortices at the low-speed streaks inside the spot and especially up-stream of the trailing-edge of the spot, where the oncoming fluid seems to be destabilized due to the persistent low-speed-streaks near the wall in an adverse pressure regime.
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