# RECEPTIVITY OF BOUNDARY LAYERS TO QUASI-STATIONARY FREE STREAM AXIAL VORTICES

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## ABSTRACT

A free stream vortical disturbance generated by a single axial vortex of controlled strength and position was used to investigate vortical receptivity of flat plate and swept wing boundary layers. In both cases, the boundary-layer response was dominated by streamwise velocity perturbations, that grew downstream essentially linearly over the flat plate and quasi-exponentially over the swept-wing model. It was shown that the disturbance characteristics in the flat plate boundary layer are in agreement with data of previous experiments performed under natural and control conditions concerning 'by-pass' transition initiated at high free stream disturbance level. It was proved that the role of the leading edge in the process of streak formation and growth in this case is not dominant. In contrast, the disturbance transformation on the swept wing occurs close to the leading edge followed by formation of a wave packet dominated by waves which are specific for cross-flow instability. Meanwhile, disturbances, which can be attributed to the effect found at the flat plate were also identified.

## INTRODUCTION

The external vortical disturbances in the form of localised quasi-stationary flow modulations or free-stream turbulence (FST) are of those which most frequently contribute to the boundary-layer receptivity. Meanwhile, for an effective excitation of a boundary layer disturbance, the vortical forcing must have both the same frequency and comparable spatial scales. From this point of view two types of phenomena are usually distinguished inside the boundary layer: the generation of traveling modes with characteristics of local linear instability and generation of quasi-stationary longitudinal vortical structures or 'streaks', which characteristics are probably determined by the external forcing (Kendall, 1985; Westin, Boiko, Klingmann, Kozlov, & Alfredsson, 1994; Matsubara, Bakchinov, & Alfredsson, 1999). Both of this phenomena can be responsible for transition to turbulence (Boiko, Westin, Klingmann, Kozlov, & Alfredsson, 1994).

The experiments described below were carried out with intention to consider the formation of the structures excited in Blasius and swept wing boundary layers by a free stream vortex generator Bertolotti and Kendall (1997) and investigate their following development.

## MEASUREMENT PROCEDURE

The flat plate receptivity investigations were done in a low-turbulence wind tunnel of DLR, Göttingen (TUG), see , *www.sm.go.dlr.de/sm-sm_info/TRTinfo*). The flat plate model was the same as in the experiments of Fischer (1993). The model was vertically installed along the test section axis. The $x$ axis directed from the leading edge along the plate chord, $z$ is parallel to the edge, and $y$ is normal to the wall and zero at it. Measurements of the streamwise velocity component were carried out in the central part of the plate. Below, the results obtained at $U_0 = 5.9$ are given.

Another DLR wind tunnel and model was used for swept-wing measurements, see description of both at *www.sm.go.dlr.de/sm-sm_info/TRTinfo* and in (Bippes, 1999). The following two coordinate systems were used. In the first laboratory system $x$ is directed from the leading edge of the wing along the wing chord, $z$ is along the model span and parallel to the swept plate surface, and $y$ is normal to the wall. In the second local system, $x_s$ is tangential, while $z_s$ is normal to the potential streamline at a given point, and, obviously, $y_s = y$. Experiments were done at free-stream velocity of $Q_\infty = 6.5$ m/s.

The vortex in the experiments originated at

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the tip of a micro-wing. A 0.6 mm thick and 5 mm wide NACA FXL V152 K25 profile with 0.3 mm rounded edges and sides was used. It was glued to a long round support sting of 8 mm diameter. To minimise possible end effects and the effect of the wing support, the micro-wing had 80 mm span in the flat-plate case, and 160 mm span in the swept-wing case. The vortex strength was controlled by varying the micro-wing angle of attack and the ambient velocity. It was positioned above of the flat plate model at the distance $x_0 = 215$ mm from the leading edge and in front of the swept-wing model at the nozzle exit at the distance 107 mm. In both cases, if otherwise indicated, the micro-wing tip was located at $y_0$=15 mm from the wall.

Different mean and fluctuating velocity components were obtained by means of standard constant-temperature DISA hot-wire anemometers using standard DISA V- and X-arranged hot wire probe.

## RESULTS

### Undisturbed mean velocity profiles

It was verified that the velocity distribution inside the most part of the flat plate plate boundary layer is quite close to the Blasius one, the theoretical and experimental values of $\delta^*$ differ by less then approximately 3%. The realized swept-wing flow led to mean velocity profiles that can be approximated, except close to the leading edge region, by a Falkner-Skan-Cooke profile with Hartree parameter $\beta_H = 0.5003$.

### Development of the free stream tip vortex above the flat plate

To provide initial conditions for the interaction between the vortex and the boundary layer, the tip vortex mean axial and circumferential velocity components were measured in several $(yz)$-planes downstream of the micro-wing above the flat plate.

Batchelor (1964) model describing a similarity solution of the flow in the tip vortex far downstream of the wing was applied to fit all sets of the experimental data obtained by means of multi-variable least-square technique, see Fig. 1. As can be seen, it quite accurately predict the vortex development, and although this was not used later in the present study, it may be helpful for future theoretical flow modeling.

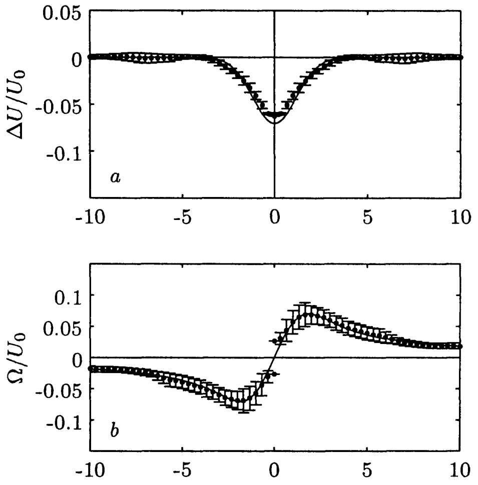

Figure 1: Tip vortex in free stream at $\Delta x = 130$ mm at $U_0 = 5.9$ m/s. *a* — streamwise velocity defect; *b* — circumferential velocity. Points — measured mean values; bars — error estimations; solid lines — data approximation by means of the model of Batchelor (1964).

### Development of free stream tip vortex above the swept plate

The openness of the 1MK wind tunnel test section and the blockage of about 25% of the model lead to a significant modification of the tip-vortex formation and development. The fluid flux into the surrounding space through slits above and below the test section results in elongation of the velocity defect produced by the micro-wing tip in vertical direction. Meanwhile, the spanwise scale of the vortex is similar to that for the flat plate case.

### Flat plate boundary-layer response

Isolines of the velocity defect measured at several $x$ locations downstream the micro-wing are given in Fig. 2. As can be seen, the defects experiènce continuous growth, while the disturbance spanwise structure remains the same, exhibiting one velocity maximum and one minimum with spacing between them, in fact, independent of the downstream coordinate and equal to 20 ± 2 mm. It was found that the presence of the vortices does not significantly affect the mean velocity distribution, although $\overline{U}(y)$ reaches about 15% of $U_0$ at the end of the measurement region. Except at the points closest to the micro-wing, the disturbance maximum is located at virtually the same coordinate scaled with the boundary layer displacement thickness $y/\delta^* \approx 1.3$. The shapes of velocity standard deviations after integration of the defects over $z$ are in fact, close to self-similar. The same conclusion was done

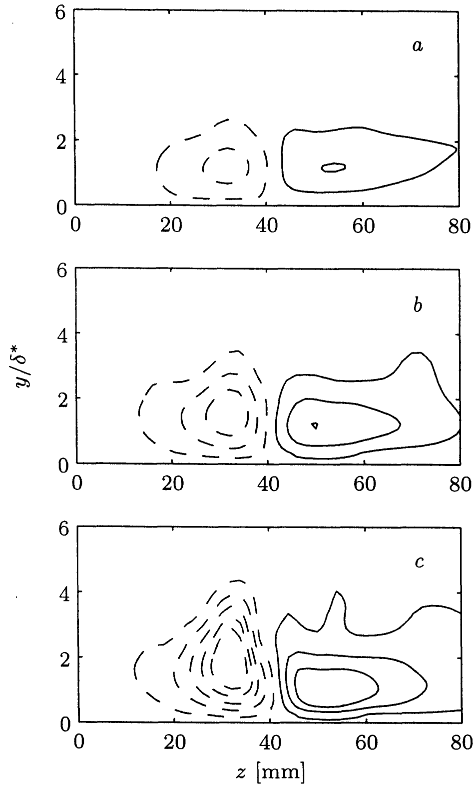

Figure 2: Velocity defects induced at $U_0$=5.9 in flat plate boundary layer by free stream tip vortex at $\Delta x$=40, 130, 265 mm, *a*, *b*, *c*, respectively. Solid lines — exceeds, dash lines — defects. Equidistant isolines from -0.290 to 0.140.

previously by Kosorygin and Polyakov (1990) concerning the shape of the naturally occurring Klebanoff mode at a high FST level.

The remarkable feature of the quasi-stationary disturbances excited in flat plate boundary layer under the effect of homogeneous FST to preserve $H$ close to the laminar value up to their amplitudes of 10% of $U_0$ had been already documented by Klingmann, Boiko, Westin, Kozlov, and Alfredsson (1993). The mean and individual values of the shape factor in the region of vortex localisation in present experiment were also close to the laminar value $H = 2.59$.

The simplest way to estimate the growth of the disturbances is to consider their magnitude as the difference between the maximum disturbance exceed and defect. It was done, e.g., by Bertolotti and Kendall (1997) in a similar experiment, when the boundary-layer streak was excited by a tip vortex from a micro-wing located *in front of* the flat plate. It was found there both experimentally and theoretically, that the magnitude grows virtually linearly with $x$ *for the case of stationary disturbances*, the slope of the growth being smaller with the micro-wing tip distance to the wall. Results of current measurements, when the micro-wing was located *above* the flat plate are shown in Fig. 3 for two free stream velocities. As can be seen in both test cases, the disturbance growth is linear with $x$ and the curve slope is smaller for the case of the tip vortex with lower peripheral velocity interacting with the boundary layer. Combined with the data of Bertolotti and Kendall (1997) these results prove, that *the leading edge plays no dominant role in the mechanism of the stationary streak amplification for the Blasius boundary layer.*

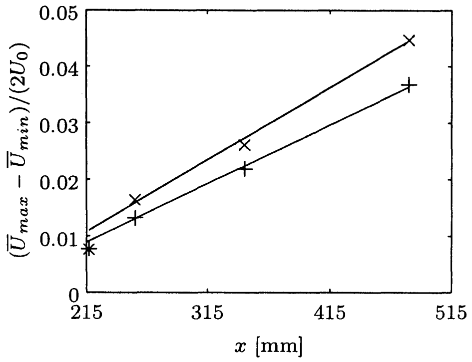

Figure 3: Effect of the vortex strength on the boundary-layer response, $U_0$: + — 5.9; × — 7.8 m/s.

A result of spatial Fourier transformation in spanwise stationary wave components is shown in Fig. 4. Downstream the micro-wing, disturbances are localized inside the boundary layer and concentrated at fixed $\beta = 0.082$ and $y/\delta^* \approx 1.3$. This is in accordance with above discussed independence of the distance between the disturbance exceed and defect in Fig. 2 and definitely indicates that in the frame of the current experimental conditions, the scale of the excited structure is independent in the region of the streak generation and propagation ($\delta^* = 1.09$–$1.99$). The last is also in accordance with measurements of Matsubara et al. (1999) at Tu $\approx$ 1.5% and model experiment of Westin, Bakchinov, Kozlov, and Alfredsson (1998), where stationary velocity modulations maintained their spanwise scale during the downstream propagation.

The remarkable similarity of the disturbance shapes found in different experiments as well as of the shapes obtained with the help of different theoretical models (see Fig. 5) has been discussed repeatedly in literature (Westin et al., 1994; Bertolotti & Kendall, 1997; Berlin & Henningson, 1999; Luchini, 2000). It was observed that the streamwise velocity component of 'natural' streaks at a high FST are

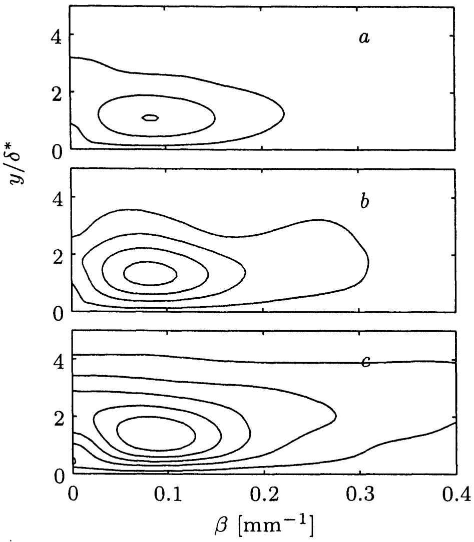

Figure 4: Spectral distribution of $\Delta U$ at $U_0$=5.9. $\Delta x$ = 40, 130, 265 mm (from top to down). Equidistant isolines from 0.1 to 1.1.

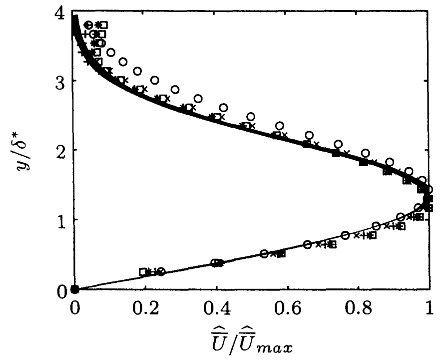

Figure 5: Disturbance velocity profiles at $U_0$ = 5.9 m/s, $\Delta x$=130 mm for individual $\beta$: o — 0.050; × — 0.075; + — 0.100; $*$ — 0.125; □ — 0.150 mm$^{-1}$. Bold solid line — a disturbance produced by quasi-stationary variations of boundary-layer thickness. Line with marker — results of Berlin and Henningson (1999); dash dotted line — results of Anderson et al. (1999); ◇ — Westin et al. (1994).

similar to quasi-stationary modulations of the Blasius mean velocity profile, when the local boundary-layer thickness experiences small changes (Kendall, 1985) ('breathing'). The breathing may be caused by, e.g., small amplitude oscillations in time of the stagnation line at the leading edge or of the free-stream velocity. The shape of this small amplitude 2D breathing has an analytical expression to be $y\partial U/\partial y$ (Libly & Fox, 1964). Normalized by its maximum, it is shown in Fig. 5 by the bold solid line. As can be seen, it almost perfectly follows the amplitude shapes of individual 3D stationary modes found in the present as well as in the other former studies.

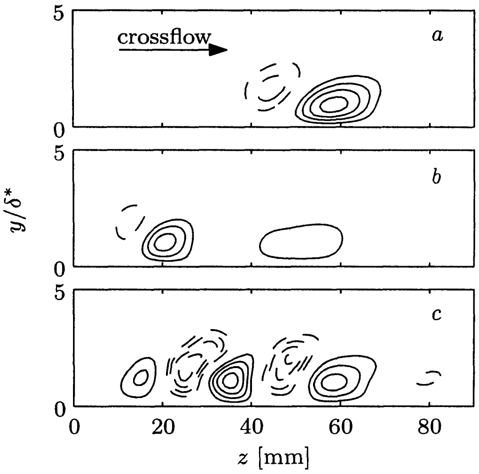

Figure 6: Development of the streamwise stationary velocity disturbances at $x$=191, 300, and 415 mm (from top to down). Equidistant isolines from -0.130 to 0.116.

### Boundary-layer measurements above the swept-wing model

In contrast to previous DLR experiments with the same model (Bippes, 1999), where the cross flow stationary vortices were observed under 'natural' conditions, their absence in the present study was stipulated by smaller free-stream velocity, (relatively small Reynolds numbers). On the contrary, the presence of the forcing led to a formation of pronounced stationary disturbances in the boundary layer. Distributions of streamwise (in the local coordinate system) velocity defects are presented in Fig. 6. It is seen that the presence of the cross-flow leads to a multiplication of the excited velocity defects downstream. Another observed characteristic feature is an initial decay of the disturbance intensity followed by the disturbance growth with a smaller spacing between disturbance defects and exceeds.

The multiplication of stationary vortices is a known feature specific for the development of a localized wave packet of stationary cross flow modes generated from a small-scale boundary inhomogenity, as it was shown by numerical simulations (Joslin, 1995; Streett, 1998). In particular, it was shown, that a small variation of the wave angle and the growth direction across the range of the cross flow instability is the main reason for the visible vortex multiplication, being in that cases basically a linear phenomenon. In present case, in accordance with this finding, the disturbances with shorter spanwise wavelengths appear at one side of the wave packet, whereas those of longer wavelengths propagate on the other side, Fig. 6. This suggests that one of the component of the developing packet are the structures appeared due to the cross-flow instability and excited by means of a localized receptivity to the free stream vortical disturbance close to the leading edge. It is significant to remind, that in contrast to receptivity mechanisms on a swept-wing considered by previous investigators, no boundary condition modification was necessary here to excite the vortices, i.e. an independent localized receptivity mechanism was observed here.

As in the flat plate case the Fourier analysis was undertaken. The sequences of the spectral distributions integrated over the boundary-layer thickness up to $y/\delta^* = 5$ and normalization to initial amplitudes at different $x$ are given in Fig. 7. Additionally, the corresponding theoretical growth based on the local parallel spatial linear stability of the Falkner-Skan-Cooke profiles was calculated.

As seen, the local parallel linear stability theory correctly predicts the wavelength of the most amplified stationary mode, the tendency of better correspondence between the theoretical and experimental behaviour of the overall packet growth occurring further downstream. Meanwhile, the parallel linear stability theory does not seem to be ideal for describing the development of small amplitude cross-flow vortices for this model flow (Bippes, 1999). In particular, Haynes and Reed (1997) found the largest difference between local and non-local stability approaches in the range of neutral stability. Such a strong difference with parallel stability theory is also found in present experiments, especially for the case of low wave numbers. While the theory predicts neutral disturbances at $\beta \approx 0.1$, the experimentally observed neutral point is close to 0.2.

The theory cannot explain the appearance and the development of amplitude maxima at $\beta \approx 0.1$–$0.2$ below the neutral spanwise number. Disturbances centered around these wave numbers experience an initial decay followed by quick growth. Such a behaviour is in contrast to continuous linear growth due to the distributed receptivity over the flat plate. A possible explanation of this effect is that the flat plate boundary layer is almost neutrally stable for stationary disturbances, while for low Reynolds numbers the damping rates of stationary disturbances at this $\beta$ is high. Downstream, the neutral $\beta$ is stabilized and the forced disturbances closed to it can survive. Appearance of two peaks in this region is not well understood.

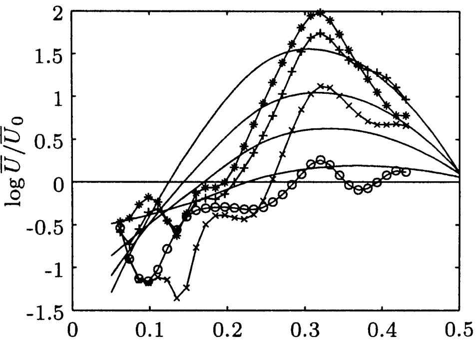

Figure 7: Averaged spectral disturbance growth normalized to an "initial amplitude", $x$: ○ — 238; × — 300; + — 353; $*$ — 415 mm.

## CONCLUSIONS

The responses of a flat-plate and swept wing boundary-layers to free stream axial vortices were considered in the present study. It was found that in the flat plate boundary layer, the generation of a single streak occurs. This streak has the same phenomenological characteristics as those which appeared in the boundary layer under the effect of a high FST levels. In particular, it has the single amplitude maximum which location in normal-to-the-wall direction scales with the boundary-layer thickness at $y/\delta^*{=}1.3$; the dimensional scale of the streak in spanwise direction is preserved; its amplitude growth is linear with $x$; whereas its magnitude reaches several percent of free-stream velocity, the streak causes only a moderate effect on integral boundary-layer characteristics.

A comparison with study of Bertolotti and Kendall (1997) shows that the leading edge plays no dominant role in the receptivity process.

As for the swept wing boundary layer, the free stream disturbance transformation occurred close to the leading edge leads to the he formation of the initial single vortex structure followed by multiplication of the vortices. In spectral space, this process is characterized by an amplification of disturbances with wave numbers, specific for the cross-flow instability.

Additionally, the presence of disturbances with larger spanwise scale (with lower spanwise wave numbers) was observed. Their origin is attributed to the presence of the tip vortex along the whole model chord, but their precise nature, the role and the effect on the laminar-turbulent transition is still unclear.

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