한국해양공학회 2003년도 춘계학술대회 논문집 PP.257~261

# Development of low-frequency streaks in Blasius boundary layer

A. V. BOIKO†*, H. H. CHUN†

†Dept. of Naval Architecture & Ocean Engineering, Pusan National University
30 Jangjeon-dong, Geumjeong-gu, Busan, Korea

**KEY WORDS:** Drag Reduction, Streaky Structures, Boundary Layer

**ABSTRACT:** *A free stream vortical disturbance generated by a single axial vortex of periodically modulated strength was used to investigate vortical receptivity of a flat plate boundary layer to low-frequency spatially localized free-stream disturbances. It was found that the boundary-layer response was dominated by stream-wise velocity perturbation (streak). However, in contrast to the stationary streaks considered by Boiko (2002), its intensity showed no pronounced growth along the flat plate.*

## 1 Introduction

The need to understand the drag-production processes in laminar sublayer of turbulent boundary layer with the goal to find effective ways of drug reduction stipulated last years inextinguishable interest of researches to phenomenon of streaky structures – one of the main objects responsible for enhanced fluid mixing at the wall (Robinson 1990; Boiko 2002). Related problems are connected with appearance of the streaks in laminar shear flows under effect of free stream turbulence. Experimentally, the streaks can be investigated by generating controlled disturbances, and studying the subsequent development of perturbations excited inside the boundary layer. A rational way to introduce certain controlled 'representative' external disturbances to investigate the streak development was proposed by Bertolotti and Kendall (1997). The idea is to produce a free stream vortex at the tip of a micro-wing. By varying the wing's angle of attack and the free-stream velocity, the vortex strength can be controlled. Successful comparison between the Bertolotti's theory and the Kendall's measurements of the response of the boundary layer to the tip vortex excited in front of the flat plate leading edge indicated that excitation of quasi-stationary disturbances could be modelled in such a way. In the experiment of Boiko (2002), the micro-wing was located above the plate, rather than in front of it as in work of Bertolotti and Kendall (1997), so that the leading edge region was escaped. It was found that the excited stationary boundary layer disturbance has the same phenomenological characteristics as those which appeared in the boundary layer under the effect of high free-stream turbulence levels. A comparison with the study of Bertolotti and Kendall (1997) shows that the local processes at the leading edge can play no dominant role in the streak growth.

The present study is devoted to the disturbances excited by low-frequency modulated micro-wing tip vortex to consider the formation of the boundary layer structures and investigate their following development. It was performed in the same experimental set-up as that of Boiko (2002).

## 2 Experimental procedure

The flat plate model was 1500 mm wide, 1175 mm long, and 40 mm thick. The model consists of a main plexiglas body polished to 0.2 $\mu m$ roughness, a trailing edge flap and a leading edge. The leading edge is elliptical with the axis-ratio 6:1 to eliminate possible leading edge separation (see Davies 1980). The flap was used to adjust the pressure distribution at the leading edge to zero. The model was vertically installed along the test section axis. The large model span prevents disturbances from wall junctions to contribute the measurements along the centerline in the spanwise range of about 2000 mm up to the distance about 1 m from the leading edge.

The coordinate system used was the following:

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 stream-wise velocity component were carried out in the central part of the plate in the range of $\Delta z =$ 100 mm and $x$ = 275, 337, 395, and 450 mm at $U_0$ = 7.45-7.65 m/s above the measurement region.

The vortex in the experiment originated at 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 minimize possible end effects and the effect of the wing support, the micro-wing had 80 mm span. It was positioned above of the flat plate model at $y_0 = 13$ and 20 mm at the distance $x_0$ = 125 mm from the leading edge. Using a specially designed drive, the micro-wing was able to change sinusoidally its angle of attack between certain limit positions. The measurements were performed with frequencies of the motion of $f$ = 4.1 and 5.6 Hz. The synchronous detection (sampling triggered synchronously with the micro-wing motion) was used. It allowed to separate the periodic part of the streak from the stationary component.

Different mean and fluctuating velocity components were obtained by means of standard constant-temperature DISA hot-wire anemometers using standard DISA V–arranged hot wire probe. Such probes neglect the normal-to-the-wall velocity component but allow one measurements close to the wall. The probe axis was aligned with the free-stream direction.

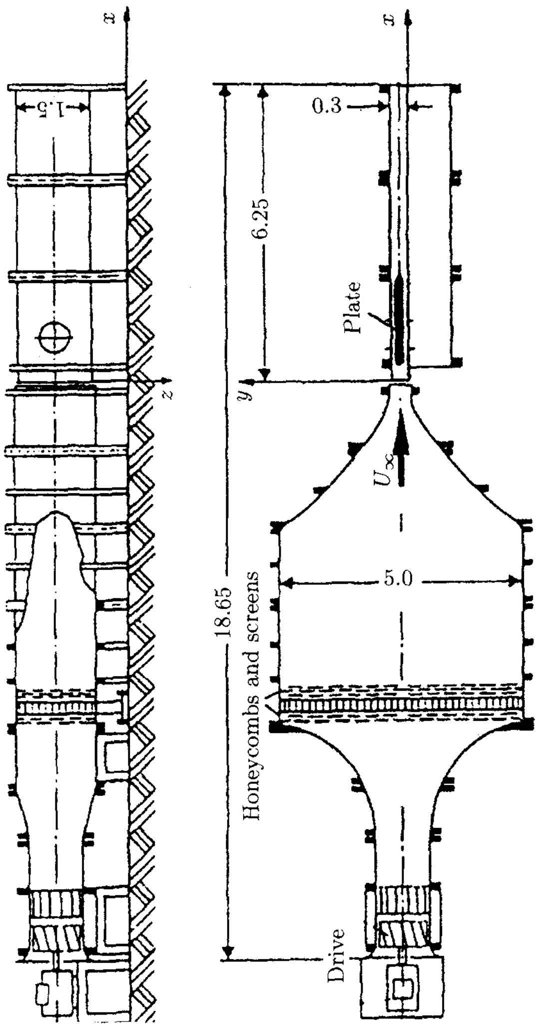


Figure 1: Scheme of low-turbulent wind tunnel TUG of DLR, Göttingen. Sizes in meters.

# 3 Results

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

For reference purposes, measurements were carried out for stationary vortices in positions denoted below as 'n' and 'p' that correspond to approximately opposite angles of attack of the micro-wing in respect to the $(xy)$-plane (loosely speaking negative and positive angles). The micro-wing limit angles of attack were adjusted and fixed such as to produce a laminar tip vortex in the measurement region. To provide initial conditions for the interaction between the vortex and the boundary layer, the tip vortex mean axial and a span-wise velocity components were measured in several $(yz)$-planes downstream of the micro-wing.

The characteristic feature of the motion is the appearance of a stream-wise velocity defect, $\Delta U = U - U_0$, and a circumferential velocity, $\Omega$. To obtain them, the stream-wise $U$ and a transverse velocity $V$ were measured by a V-wire probe in $(yz)$-plane. Then $\Omega$ was reconstructed using the formula $\Omega(y - y_0, z - z_0) = V(y - y_0, z - z_0)/\cos\psi$, where $\psi = \arctan[(z - z_0)/(y - y_0)]$, the coordinate system being centered about the vortex axis at $(y_0, z_0)$. To exclude error caused by small values of $V$ at large angles $\psi$, the reconstruction was done in the range $\psi \in [-45; 45]$ degrees. Then the data of $\Delta U$ and $\Omega$ were 'unwrapped' in polar coordinate system. Neighboring points were used to estimate the value of data 'scattering' that roughly correspond to a random error of the data measurements. The obtained mean velocities and error bars based on the data standard deviations in $\pm 0.15$ mm ranges are

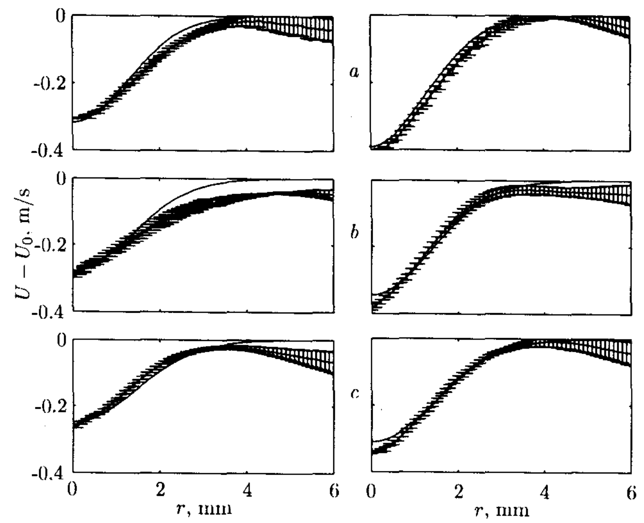


Figure 2: Free stream stream-wise velocity component distortions called by the tip vortex in positions '*n*' (left) and '*p* (right): **a**, $x = 275$; **b**, $x = 337$; **c**, $x = 395$ mm.

presented against the radial coordinate $r$ in Fig. 2 for $\Delta x = 275$, 337, and 395 mm downstream of the micro-wing. The data show a slow downstream decay of the vortex in both cases in accordance with previous observations (Boiko 2002).

Table 1: Batchelor's model parameters.

| case | $S$ mm$^2$ | $\gamma_0$ m$^2$/s | $x_{\rm v}$, mm |
|---|---|---|---|
| m | 0.280 | $5.82 \cdot 10^{-4}$ | 130 |
| p | 0.213 | $5.50 \cdot 10^{-4}$ | 130 |

Bertolotti (private communication) suggested to use Batchelor (1964) model describing a similarity solution of the flow in the tip vortex far downstream of the wing. In terms of similarity coordinate $\eta = U_0(r/2)^2/(\nu x)$, the stream-wise velocity defect produced by the vortex is expressed as

$$\Delta U = \frac{\gamma_0^2 P(\eta) - U_0^2 S e^{-\eta}}{8\nu x},$$

where $\gamma_0 = \Gamma_0/2\pi$, $\Gamma_0$ denotes circulation at the vortex origin. Value $S$ is a constant with the dimension of area and the second term accounts for any initial velocity defect which may be independent from circulation. The term $P$ is given by the formula

$$\begin{aligned} P(\eta) &= e^{-\eta}\left[\log(\eta/\mathrm{Re}_x) + \mathrm{Ei}(\eta) - 0.807\right] \\ &\quad +2\mathrm{Ei}(\eta) - 2\mathrm{Ei}(2\eta), \end{aligned}$$

where $\mathrm{Ei}(\eta) = \int_\eta^0 e^{-\xi}/\xi d\xi$ is the exponential integral function. An asymptotic solution for the circumferential velocity component $\Omega$ far away downstream from the wing tip is found as

$$\Omega = \gamma_0(1 - e^{-\eta})/r.$$

The formulae were applied to fit all sets of the experimental data obtained by means of multi-variable least-square technique, see Fig. 2. To improve the fit, a 'virtual' vortex origin was used, so that $x \mapsto x + x_{\rm v}$. It can be seen, the lines corresponding to the theoretical fit quite accurately predict the vortex development, and although this was not used later in the present study, it may be helpful for a theoretical flow modelling. The data used for the vortex approximation are given in Table 1.

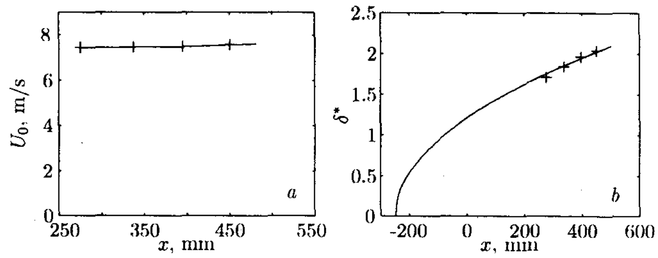


Figure 3: Flow characteristics: **a**, free stream mean velocity in the region of measurements; **b**, displacement thickness + calculated based on the experimental data; *solid line*, approximation based on theoretical formula.

## 3.2 Integral boundary layer characteristics

It was found that in the region of measurements, local free stream velocity $U_0$ is almost constant (it grows monotonically from 7.45 to 7.65 m/s), Fig. 3, **a**. Comparison of measured and Falkner–Skan theoretical mean velocity profiles showed that they fit each other when parameter Hartree $\beta_{\rm H} = 0 \pm 0.02$, i.e. the flow is essentially the Blasius one in the region of measurements.

Moreover, calculations of displacement thickness

$$\delta^* = \int_0^\infty (1 - U/U_0) dy,$$

showed that it can be quite well approximated using theoretical formula

$$\delta^* = 1.72\sqrt{x\nu/U_0},$$

provided $x$-coordinate is counted from a 'virtual' origin $x_{\rm v} = 249$ mm upstream the flat plate leading edge, Fig. 3, **b**.

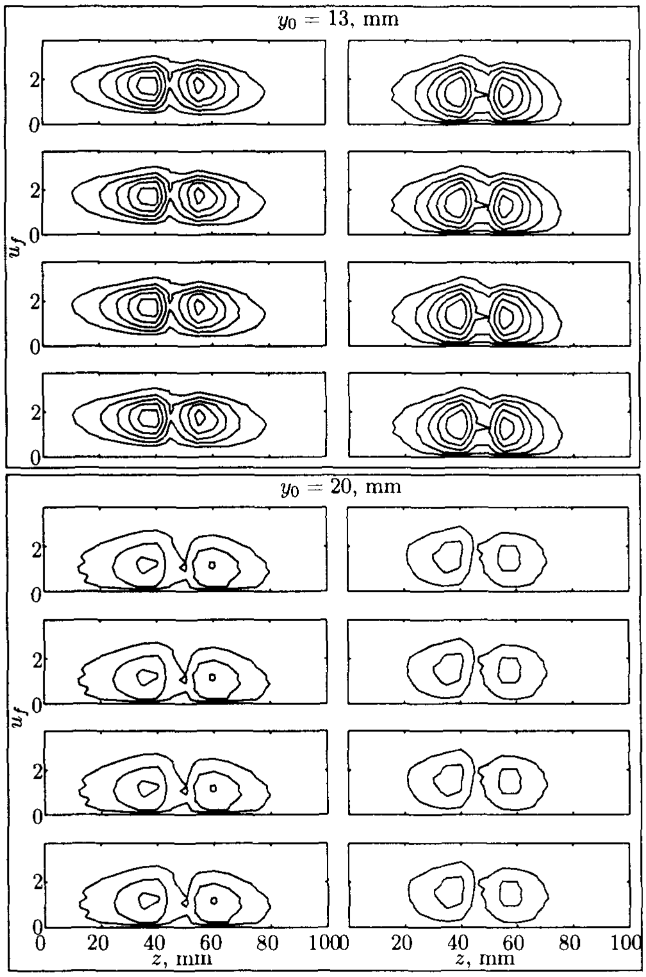

Figure 4: Amplitude distribution of periodic streak component at $f$ = 4.1 Hz (*left*) and 5.6 Hz (*right*) excited by tip vortex at the micro-wing tip; $x$ from top to down.

### 3.3 Behavior of low-frequency modulated streak

The amplitude distributions of the selected periodic component are presented in Fig. 4. It is seen that all distributions consist of two lobes which are symmetric in respect to $y$. The overall intensity of the disturbances at the higher frequency is smaller than at the same flow conditions, but the lower frequency. This is in accordance with the filtering property of the boundary layer, in which only low frequency survive in the case of free stream turbulence level (Westin, Boiko, Klingmann, Kozlov and Alfredsson 1994; Boiko, Westin, Klingmann, Kozlov and Alfredsson 1994). Also, disturbance at $y_0$ = 13 mm had larger amplitude than that at $y_0$ = 20 mm. The corresponding phase distributions are antisymmetric with 180° shift at the edge of the amplitude lobes. However, the disturbance

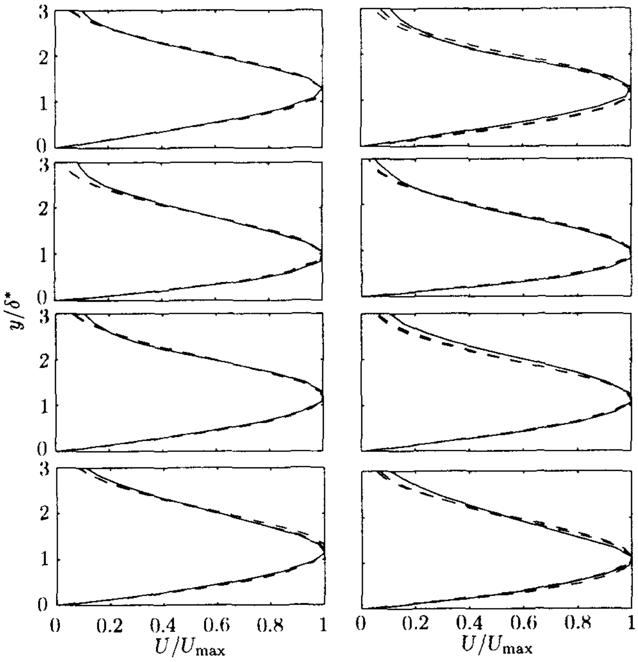

Figure 5: Disturbance profiles: *solid line*, stationary disturbances, *dashed line*, periodic disturbances; $y_0$ = 13 mm (*left*); $y_0$ = 20 mm (*right*).

intensity is virtually unchanged downstream, i.e. the periodic component of the streak shows neither definite growth nor decay that is in contrast with pronounced growth (Boiko 2002) or decay (Grek, Kozlov and Ramazanov 1985) of stationary streak.

The root-mean-square profiles of stationary and periodic disturbances (averaged also over its period) are compared in Fig. 5. It is seen that they coincide. This result is in accordance with previous findings of Grek et al. (1985) and other investigators who found no differences between the profiles of artificially excited low-frequency and stationary streaks.

For an effective excitation of the instability wave of a given frequency, forcing is usually needed which has not only the same frequency, but also comparable spatial scales. If the disturbances are introduced from inside the near-wall shear flow (e.g. by a vibrating ribbon, periodic heating of the surface or sucking and blowing), these scales are usually matched (Gaster and Gupta 1993; Hill 1995; Tumin 1996). The vortical free-stream disturbances are controlled by inviscid dynamics and, consequently, the wavelengths of the disturbances are, as a rule, quite different in a viscous boundary layer. Hence, for the effective transformation of some classes of external disturbances to boundary layer structures, there should be a mechanism of wavelength reduction.

It seems, that in contrast to the stationary case, when interaction of the tip vortex with the boundary layer can be effective over quite a long downstream distance, the mismatch between the tip vortex propagation velocity and propagation velocity of the boundary layer streak in the periodic case, limits the power of the interaction. Therefore, the mechanism of disturbance excitation is in this case is less effective, but still probably takes place, since no streak decay, as in experiments with locally generated streaks was found. Such a velocity mismatch can explain the 'filtering property' of the laminar boundary layer (Westin et al. 1994), which leads to a quick decay of time-periodic disturbances, the effect growing with frequency increase.

## 4 Conclusions

The response of a flat-plate boundary-layer to free stream axial vortex with intensity modulated in time was considered in the present study. It was found that 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 span-wise direction is preserved. The results indicate that the amplitude of the excited streak is quite conservative inside the boundary layer: it was preserved almost constant in the region of measurements for the both considered frequencies and distances of the tip vortex to the wall. The last effect can be caused by a mismatch between the propagation velocity of the tip vortex in free stream and the streak velocity in the bulk of the boundary layer that inhibits the streak growth.

## 5 Acknowledgements

The work was financially supported by DLR–Institut für Aerodynamik und Strömungstechnik, Göttingen, Germany and by Advanced Ship Engineering Research Center of Pusan National University through Korea Science & Engineering Foundation.

## References

Batchelor, G. K. (1964). Axial flow in trailing line vortices. J. Fluid Mech., 20, 645–658.

Bertolotti, F. P. and Kendall, J. M. (1997). Response of the boundary layer to controlled free-stream vortices of axial form (AIAA Paper 97–2018).

Boiko, A. V. (2002). Receptivity of a flat plate boundary layer to free stream axial vortex. European J. Mech. B Fluids, 21, 325–340.

Boiko, A. V., Westin, K. J. A., Klingmann, B. G. B., Kozlov, V. V. and Alfredsson, P. H. (1994). Experiments in a boundary layer subjected to free stream turbulence. Part 2. The role of TS-waves in the transition process. J. Fluid Mech., 281, 219–245.

Davies, M. R. (1980). Design of flat plate leading edges to avoid flow separation. AIAA J., 18(5), 598–600.

Gaster, M. and Gupta, T. K. S. (1993). The generation of disturbances in a boundary layer by wall perturbations: The vibrating ribbon revisited once more. In D. E. Ashpis, T. B. Gatski and R. Hirsh (Eds.), Instabilities and Turbulence in Engineering Flows (pp. 31–50). Dordrecht: Kluwer.

Grek, G. R., Kozlov, V. V. and Ramazanov, M. P. (1985). Three types of disturbances from the point source in the boundary layer. In V. V. Kozlov (Ed.), Laminar-Turbulent Transition (pp. 267–272). Berlin Heidelberg New York: Springer.

Hill, D. C. (1995). Adjoint systems and their role in the receptivity problem for boundary layer. J. Fluid Mech., 292, 183–204.

Robinson, S. K. (1990). A review of vortex structures and associated coherent motions in turbulent boundary layers. In A. Gyr (Ed.), Structure of Turbulence and Drag Reduction (pp. 23–50). Berlin Heidelberg New York: Springer.

Tumin, A. (1996). Receptivity of pipe Poiseuille flow. J. Fluid Mech., 315, 119–137.

Westin, K. J. A., Boiko, A. V., Klingmann, B. G. B., Kozlov, V. V. and Alfredsson, P. H. (1994). Experiments in a boundary layer subjected to free stream turbulence. Part 1. Boundary layer structure and receptivity. J. Fluid Mech., 281, 193–218.