Journal of
Ship&Ocean
Technology
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SOTECH Vol. 8, No. 4, pp. 10 ~ 16, 2004

Laminar-Turbulent Transition Research and Control in Near-wall Flow

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Abstract

A response of a swept wing boundary layer to a single free-stream stationary axial vortex of a limited spanwise extent is considered as an example of typical problems that one can find in laminar-turbulent transition research and control. The response is dominated by streamwise velocity perturbations that grow quasi-exponentially downstream. It is shown that the formation of the boundary layer disturbance occurs for the most part close to the leading edge. The disturbance represents itself a wave packet consisted of the waves with characteristics specific for cross-flow instability. However, an admixture of growing disturbances whose origin can be attributed to transient effects and to a distributed receptivity mechanism is also identified.

Keywords: receptivity(hydrodynamic stability), wall-bounded thin shear flows, transition to turbulence

1 Introduction

The origin of turbulence in fluids is a long-standing problem which has been the focus of research for decades due to its great importance in a variety of engineering applications. At the end of the nineteenth century, Reynolds and Rayleigh conjectured that the reason of the transition of laminar flow to the ‘sinuous' state is instability which results in amplification of wavy disturbances and breakdown of the laminar regime. The first calculations of boundary layer stability were fulfilled in pioneer works of Tollmien and Schlichting. Later Taylor hypothesized that the transition to turbulence is initiated by free-stream oscillations inducing local separations near wall. Up to the 1940s, skepticism of the stability theory predominated, in particular due to the experimental results of Dryden. Only the experiments of Schubauer and Skramsted(1948) revealed the determining role of instability waves in the transition. Now it is well established that the transition to turbulence in shear flows at small and moderate levels of environmental disturbances occurs through development of instability waves in the initial laminar flow.

However, boundary layer transition at large external flow perturbations is very different from that under ‘quiet' conditions. It has been first recognized more than 50 years ago that wind tunnel free stream disturbances can significantly affect the process of laminar-turbulent transition in a boundary layer and make the translation of results obtained in wind tunnels to free-flight conditions a nontrivial problem (Schubauer and Skramsted

1948). A limited knowledge concerning the process of the interaction of free stream vorticity with the boundary layer led scientific community to the empirical rule of testing the results in several different experimental facilities. Such an approach is quite time and cost-consuming. This background (as well as obvious turbomachinery applications when free stream turbulence is an imprescriptible participant of the boundary layer development around a blade) stipulates last years inextinguishable interest of the researchers to the interaction of free stream disturbances with boundary layers.

The flow over a swept wing is a typical example of a three-dimensional boundary layer which is subject to several types of instabilities each of which can lead at certain conditions to the transition to turbulence. Usually, the two-dimensional mechanisms as the Tollmien-Schlichting wave instability and possibly further downstream an instability of a separation bubble dominate at low sweep angles (Dovgal et al 1988). Beginning from sweep angles 30-40° and comparatively small flow velocities about 10 m/s a row of streamwise vortices is formed and travelling waves begin to grow. The appearance of the vortices and the waves is caused by inviscid instability of inflectional velocity profiles which are the consequence of spanwise pressure gradient and cross-flow. The cross-flow vortices can arise even at small Reynolds numbers, in which case transition can occur in the region subcritical to the Tollmien-Schlichting wave instability (Kohama 1987, Kohama et al 1991, Dagenhart et al 1990).

An experimental investigation of formation of the stationary disturbances by a localized free-stream vortices which model some basic features of the free stream turbulence related to the formation of the streaks about a swept wing has been not undertaken. To this end the experiments described below were carried out. The development of disturbances excited in swept wing boundary layer by a free stream vortex generator similar to that used by Bertolottin and Kendall(1997) and Boiko(2002) is considered.

2 Experimental setup

The experiments were carried out in a DLR 1MK wind tunnel with contraction ratio 3.8 and an open test section $1\times0.7\,m^2$, see Fig. 1, a. A reference test section r.m.s. disturbance level measured in the frequency range $2<f<2000$ Hz in the empty test section is 0.15%. Almost half of the disturbance content is of acoustic, rather than of vortical nature.

The model with chord c=500 mm and span 2100 mm (Figure 1, b) had the form of a 25 mm thick swept flat plate manufactured from a polished aluminium with a leading edge designed especially to avoid attachment line instabilities. It consisted of a turned over CLARK-Y profile which was cut down in the thickest section. This model was used previously in numerous experiments related to crossflow instability in DLR. For detail profile characteristics see the review of Bippes(1999) and references therein. The model was adjusted at a small negative angle of attack of about 1° that shifts the stagnation line further towards the upper side of the plate to $x/c\approx0.02$ to eliminate the suction peak possibly causing flow separation. A displacement body was placed above the plate to produce a desirable pressure gradient. The model was designed to simulate closely the infinite swept wing flow conditions which were approximated with the use of contoured end plates, aligned with the streamlines at the edge of the boundary layer. To guarantee identical inflow conditions along the model span, a special nozzle was used Figure 1, c.

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 (x=0 at the leading edge), z is along the model span and parallel to the swept plate surface (the origin is arbitrary), and y is normal to the wall (and zero at it). In the second local system, x_s is tangential, while z_s is normal to the potential streamline at a given point, and, obviously, $y_s=y$. To distinguish values related to this coordinate system they have subscript 's'. Measurements were carried out in the boundary layer up to x=415 mm (83% chord) and spanwise range Δz=120 mm.

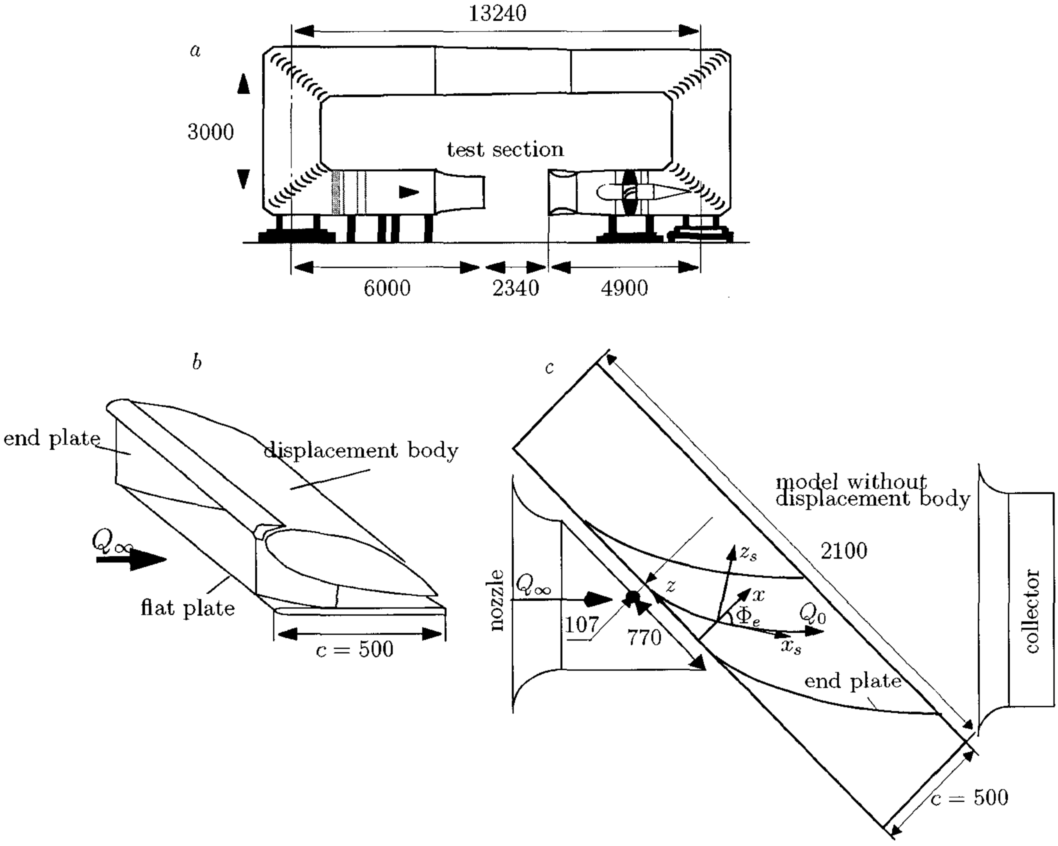

Figure 1: 1MK wind tunnel of DLR used for the swept-wing measurements. Sizes in millimeters. • — micro-wing location

The vortex in the experiments originated at the tip of a micro-wing. A 0.6 mm thick and 5 mm wide Worthman 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 160 mm span. The vortex strength was controlled by varying the micro-wing angle of attack and the ambient velocity. In present paper results of the measurements with two different angles of attack about ±5° denoted as cases I and II are presented. The micro-wing was positioned in front of the swept-wing model at the nozzle exit at the distance 107 mm in front of the model, see Figure 1, c, at y_0=15 mm from the wall. Shapes of the Wortmann FXL V152 and CLARC-Y profiles are given in Figure 2.

Steamwise and spanwise mean and fluctuating velocity components were obtained by means of DISA 55M01 constant-temperature 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.

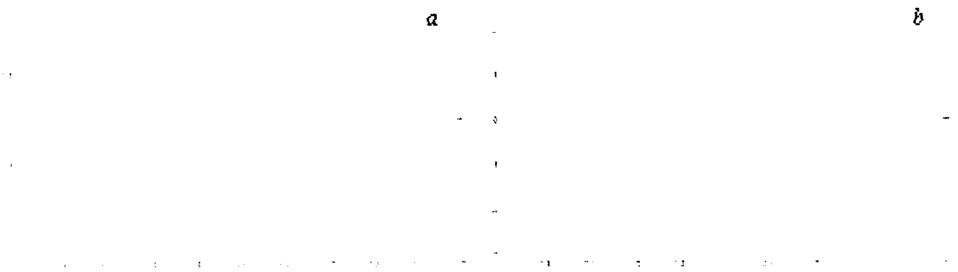

Figure 2: Microwing Wortmann FXL V152 profile (a) and displacement body CLARC-Y profile (b)

3 Results

Tests showed that in the absence of the micro-wing, the boundary layer was laminar to the end of the model, without a formation of any detectable stationary vortex structure. On the contrary, the presence of the micro-wing tip vortex in free stream led to a formation of pronounced stationary disturbances inside the underlying boundary layer. Distributions of streamwise (in the local coordinate system) velocity defects are presented in Figure 3. The data are presented in the range of 90 mm along z-coordinate, such as to show the main features of the boundary layer response. It is seen that the presence of the cross-flow leads to a multiplication of the excited velocity defects downstream. Another characteristic feature of the velocity distributions is an initial decay of the disturbance intensity followed by the disturbance growth with a smaller spacing between disturbance velocity deficits and exceeds.

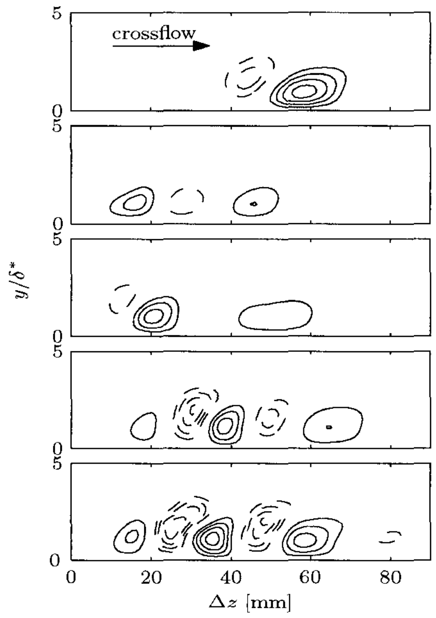

Figure 3: Development of the streamwise stationary velocity disturbances at x=191, 238, 300, 353, and 415 mm (from top to bottom). Equidistant contour lines from -0.130 to 0.116. Dashed lines – negative contour lines; solid lines – positive contour lines

The multiplication of stationary vortices is a known feature specific for the development of a localized wave packet of stationary cross flow modes generated, e.g., with the help of a small-scale boundary inhomogeneity. In particular, 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 such cases basically a linear phenomenon (Streett 1998). As can be seen, the disturbances with shorter spanwise wavelengths appear on the lee-ward side of the wave packet, whereas those of longer wavelengths propagate on the wind-ward side that is consistent with observations made by Streett(1998), for the packet excited from the wall. This implies that some components of the developing packet are the structures appeared due to the cross-flow instability and excited close to the leading edge. In contrast to the mechanisms of disturbance excitation in a swept-wing boundary layer considered by previous investigators, no boundary condition modification was necessary here to excite the vortices, i.e. an independent mechanism, related most probably to the presence of streamwise pressure gradient, was observed in present study.

Corresponding mean U_s velocities measured at Δz=0 (out of the core of the induced vortices) together with theoretical Falkner-Skan-Cooke profiles corresponding to the case under consideration are shown in Figure 4 a. Figure 4 b presents the measured standard deviations of the profiles from the laminar case ΔU_s in the range Δz=0–120 mm. Such streamwise disturbance profiles with one maximum are characteristic for both the stationary cross-flow vortices (Bippes 1999) and the streaks (Corbett and Bottaro 2001).

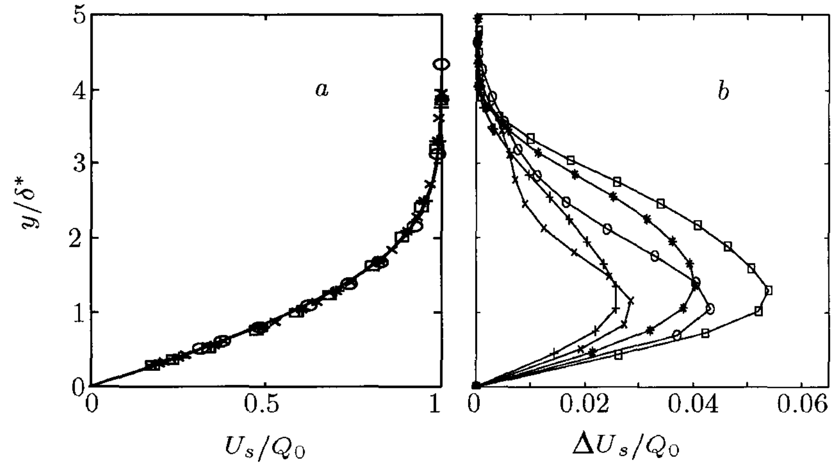

Figure 4: Streamwise mean velocity (a) and disturbance (b) profiles normalized to free stream velocity Q0 at x: o — 191; × — 238; + — 300; * — 353; □ — 415 mm

To understand better the nature of the disturbances, the velocity defect at a fixed coordinate x can be considered spectrally (after Fourier transformation) as a localized wave packet consisting of independent stationary waves with different spanwise wave numbers $\beta = 2\pi/\lambda$ (λ is a spanwise wavelength) and zero frequency.

To describe the disturbance growth one has to choose an appropriate physical criterion of it. The criteria widely accepted for the boundary-layer disturbances are based on the value of characteristic disturbance maximum and on tracing the square root of the disturbance energy, integrated across the boundary layer, U_β; the last is also useful to minimize random errors of measurements due to a well-known integration property to cancel out them.

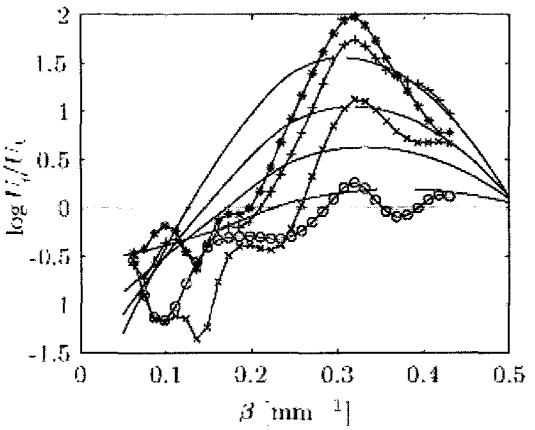

Figure 5: Averaged spectral disturbance growth normalized by different initial amplitudes at x: o — 238; ×— 300; + — 353; * — 415 mm

After normalization of U_β by the initial amplitudes, the data becomes the growth rates independent of the initial conditions. The disturbance intensity at x=191 mm was used for the normalization (see Figure 5). Additionally, the corresponding theoretical growth based on the local parallel spatial linear stability of the Falkner-Skan-Cooke profiles was calculated (shown by solid lines).

As can be seen, the parallel linear stability theory applied for the Falkner-Skan-Cooke profiles does not seem to be ideal for describing the development of small amplitude cross-flow vortices in real swept-wing boundary layers (Bippes 1999). It is known that the largest difference between local and non-local stability approaches occurs in the region of neutral stability (Haynes and Reed 1997). Such a strong discrepancy with the theory is also evident in the present experiment, especially for the case of low wave numbers. While the theory predicts neutral disturbances at $\beta \approx 0.1mm^{-1}$, the experimentally observed neutral point is close to 0.2 mm-1. However, the local parallel linear stability theory correctly predicts the wavelength of the most amplified stationary mode that is also in accordance with previous findings (Haynes and Reed 1997).

The parallel linear stability theory cannot also explain the development of the amplitude maximums at $\beta \approx 0.1-0.2mm^{-1}$. Disturbances centered about these wave numbers experience initially a decay followed by a quite fast growth. However, the development of a streak excited in a flat plate boundary layer by a free-stream tip vortex by Boiko (2002) led to appearance of dominant spanwise wave numbers of about $\beta \approx 0.1mm^{-1}$. Present experiment was performed in quite similar conditions using the same micro-wing, close free stream velocities and the distances of the micro-wing tip to the wall as by Boiko (2002). It has been shown also by Boiko(2002) that the formation and growth of the streak was stipulated by a mechanism of disturbance excitation related probably to the model proposed by Bertolottin and Kendall(1997).

4 Conclusions

The response of a swept wing boundary-layer to free stream axial vortex was considered in the present study. It was found that the free stream disturbance transformation occurred close to the leading edge leads to the 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 spanwise wave numbers specific for the cross-flow instability.

However, the growth rates of the disturbances, similar to what has been observed in previous studies at larger Reynolds number with the same swept wing model (Bippes 1999), do not follow to the predictions of the parallel linear stability theory. Comparison of the obtained data with previous numerical and experimental results supports the conjecture expressed by Corbett and Bottaro(2001) that such a discrepancy is stipulated mainly by a presence of transient disturbances 'shadowing' and affecting the development of the crossflow vortices.

Additionally, the presence of disturbances with larger spanwise scale (with lower spanwise wave numbers) was observed. Their origin can be attributed to a continuous forcing of the boundary layer by the tip vortex along the whole model chord. This is similar to the effect found by Boiko(2002). However, the precise nature, the role and the effect of the disturbances on the laminar-turbulent transition must be still clarified.

Acknowledgements

The work was financially supported by German Aerospace Center (DLR), Institute for Aerodynamics and Flow Techniques, Göttingen, Germany and by Advanced Ship Engineering Research Center of Pusan National University through Korea Science & Engineering Foundation. Experimental facilities were provided by DLR, Göttingen, Germany. The final stage of the data processing was made available by Pusan National University, Pusan, Korea.

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