Physical phenomena associated with development of streaks in transitional near-wall flows

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Abstract 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. Studying of the onset of turbulence is part of the fundamental physical problem of turbulence description and the philosophical problem of determinism and chaos.

At the end of the nineteenth century, Reynolds and Rayleigh conjectured that the reason of the transition of a laminar flow to a 'sinuous' state is instability which results in amplification of wavy disturbances and breakdown of the laminar regime. Now it is well established that the transition to turbulence in two-dimensional laminar boundary layers at small and moderate levels of environmental disturbances does occur through the development of the instability waves described by the classical linear stability theory.

However, at a high free-stream turbulence level or in a presence of certain spanwise surface inhomogeneity the situation is quite different: the transition to turbulence is usually accompanied with observation of some other structures called 'streaks' or streaky structures. Some peculiarities of their formation and development are reviewed here.

Keywords boundary layers, laminar-turbulent transition, streaky structures

1. General observations

At a high free-stream turbulence (FST) level two types of phenomena are usually distinguished inside the boundary layer, both of which can be responsible for the transition to turbulence [1]: the generation of travelling waves with characteristics of local linear instability and the generation of quasi-stationary longitudinal structures or 'streaks', with characteristics determined substantionally by the external vortical and pressure disturbances. The streaks, which were named due to the flow visualization patterns, are experimentally observed quasi-stationary three-dimensional deformations of the laminar boundary layer which grow downstream in amplitude and length. It is instructive to compare a smoke visualization of a flat plate boundary layer at low (Tu < 0.02%) and high (Tu = 1.5%) FST (Fig. 1). In the first case the boundary layer can be characterized as undisturbed (homogeneous smoke sheet), whereas at Tu = 1.5% the flow is populated by the streaks.

The boundary layer perturbations with the dominating streaky pattern, although random in time and space, are not what is usually called turbulence: the typical energy density spectra of the streamwise velocity disturbances u' obtained in free stream at Tu = 1.5% and in the laminar boundary layer demonstrate an essential difference between the FST and the large-scale boundary layer oscillations: the high-frequency disturbances are much smaller in the last, the spanwise and the wall-normal scales of the low-frequency structures are of the order of the boundary layer thickness, and the amplitudes of wall-normal velocity fluctuations v' inside the boundary layer are several times smaller than u'. However, the distribution of u' in wall-normal direction is quite different from that of two-dimensional Tollmien–Schlichting (TS) waves (e.g. the maximum was found near the middle of the boundary layer, rather than at the wall as for TS-wave).

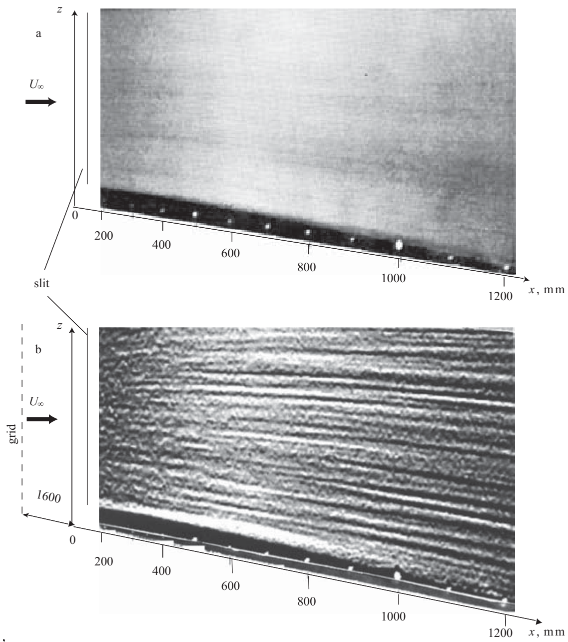

Fig. 1. Smoke visualization of boundary layer at a flat plate surface: Tu<0.02% (a), Tu=1.5% (b); U_∞=6 m/s [2]

2. Theoretical description of the streaks

For engineering purposes, attempts have been made to model the transition in the presence of FST using transport equations. Most such models rely on a transition criterion that is usually derived from empirical correlations for modifying the closure parameters through the transition region. Extensive comparison of corresponding numerical results and experimental data are collected in [3]. The observations indicate strong sensitivity of the transition to imposed free-stream characteristics. It seems that the transport models can barely reproduce the structure of the transitional boundary layer fluctuations needed for closure of the equations. Later in [4] this conclusion was confirmed by analyzing the applicability of different models to describe the boundary layer transition at high FST.

Consequently, if the transition is to be modeled without resorting to empirical correlations, it is necessary to correctly reproduce the laminar flow characteristics upstream of its final onset. Last two decades a line of development of the linear stability theory for shear flows was directed to investigation of initial disturbances. This led to formulation of different variations of the so called ‘algebraic instability’ concept. It was conjectured that the development of the observed streaky structures under consideration can be related to this instability (see, e.g., [5]). Moreover, these approaches allow one to describe in a similar way the behaviour of certain streak-like structures induced at the wall behind local surface inhomogeneities as obstacles, humps etc. All of them can lead to modulation of the mean flow in spanwise direction, the modulation being conserved for a long downstream distance behind its source, while its intensity decreases quite slowly [6].

The classical analysis of the linear stability treats the disturbances as separate modes of the linearized Navier-Stokes equations with exponential growth rates. However, the approach does not take into account the fact that these equations are not self-adjoint, i.e. the modes are not orthogonal. Hence, to describe the behaviour of disturbance energy in the near-field of the disturbance source it is not sufficient in such cases to consider their asymptotic stability. The analysis should be supplemented by studying the initial disturbances. It shows that even at subcritical Reynolds numbers a growth of disturbance energy (so-called lift-up effect) can occur in a wave packet, if amplitude functions of the non-orthogonal modes constituting it cancel each other initially, but later, due to, e.g., phase speed dispersion, manifest themselves. Viscosity, however, prevents an unlimited growth of the energy leading to inevitable decay of the disturbance. In practice this corresponds to possibility of strong transient effects for a wide class of initial disturbances.

In the framework of this linear approach directed to describe the peculiarities of the streak formation and developments in shear flows, two following approximations are dominant: complete solution of corresponding initial-boundary-value (IBV) problem and consideration of only most growing (optimal) disturbances.

A review of different formulations and solutions of the IBV problem to describe the development of the streaks in boundary can be found, e.g., in [5]. These and numerous experimental studies [7] indicate that the linear approaches taking into account the non-orthogonality of the modes can explain many features of the streaks even when their streamwise amplitudes reach 15–20% of free-stream velocity.

Despite of the evident limitations in utitlizing the optimal disturbances to describe details of the streaks in laboratory experiments this approximation has some advantages. First of all it is extensively used in modeling different scenarios of laminar-turbulent transition [5]. Another important engineering application the optimal disturbances found in developing schemes for flow robust active control, when it is obligatory for the control system to sustain even most ‘dangerous’ disturbances and affect them predictably [8].

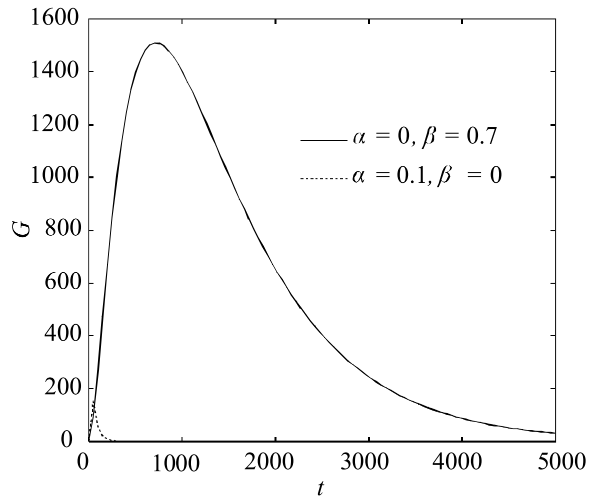

Fig. 2. Maximum amplification of energy $G(t)$ of three- (—) and two-dimensional (---) optimal disturbances in Blasius boundary layer at $\mathrm{Re}_{\delta^*} = 10000$ [7]

A comparison of the growth of two-dimensional and three-dimensional optimal disturbances in the Blasius flow at subcritical Reynolds numbers is given in Fig. 2. This demonstrates that the transient growth of three-dimensional (i.e. localized in the spanwise direction) disturbances are potentially much more dangerous to destroy the initial flow than that of two-dimensional ones.

Interestingly enough, theoretical and numerical results [5] indicates the weakness of the mechanism of selection of

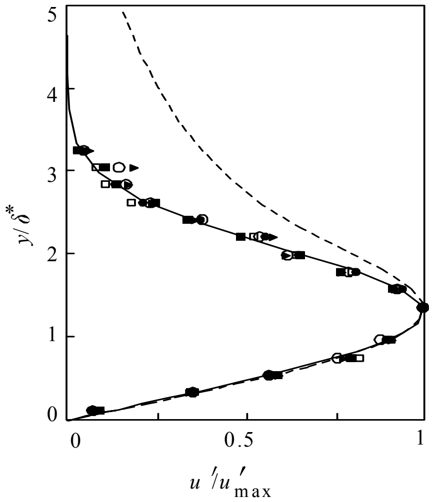

Fig. 3. Amplitude functions of the streaks with $F = 26.9 \times 10^{-6}$, $\alpha = 0.022$ and $\beta = 0.419$ (■), 0.582 (□), 0.791 (●), 0.977 (○), 1.163 (▶) [9]; TS-wave profile for $\alpha = 0.022$ and $\beta = 0.419$ (---); stationary boundary layer mode (—) [10]

characteristic spanwise scales of the streaks that is supported by large scattering of corresponding data obtained in different experiments [7]. This leads to a possibility to extend some relations obtained for the optimal disturbances to disturbances of laboratory experiments. For example, an important feature of the 'optimal' stationary disturbances derived theoretically [10] and observed in experiments is the self-similarity of the disturbances in the streamwise direction. This is demonstrated in Fig. 3: as seen, the experimental profiles follow the theoretical self-similar curve for the optimal disturbances almost perfectly.

3. Experimental studies of the streaky structures in boundary layer

Due to limitations and difficulties in application of the theoretical approaches, up to now the main instruments in studying the streaks and their influence to the laminar-turbulent transition are laboratory and numerical experiments.

It had been understood quite early that the streak-like structures can be excited not only from the free stream, but also from the wall. It seem that for the first time the streaks were intentionally excited in a flat plate boundary layer in [11]. It was done by a localized periodic sucking and blowing of fluid at different intensities and frequencies.

This and later studies led to recognition of necessity of performing the 'streaky' experiments in control conditions in low-turbulent wind tunnels. While the external background disturbances are very important for excitation of 'natural' boundary layer disturbances and following transition to turbulence, in detail studying of their development it is desirable to minimize the background noise to minimum and consider situations with artificial (simulated) excitation of the streaks. This allows one to separate the effect of different factors influencing the flow and simplify the investigation.

3.1. Localized generation of the streaks

To this end, different isolated obstacles, roughness elements, periodic suction-blowing at a wall and leading edge etc. had been applied for localized (in the streamwise direction) excitation of the streaks [5]. Generally, it appeared that the response of the boundary layer to such control excitations localized in time and space leads to the streak-like disturbances irrespective virtually of the design of disturbance sources over a wide range of excitation amplitudes.

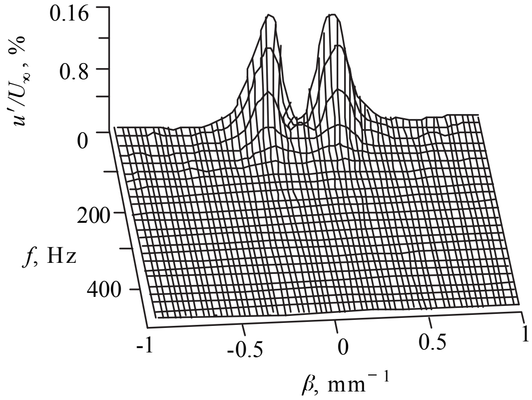

Fig. 4. Typical spectral content of localized disturbance. Measurements at a subcritical Reynolds number close to the disturbance amplitude maximum [12]

The main phenomenological features of these structures are the following. They appeared to be deterministic, localized three-dimensional formations with velocities of propagation of the leading and trailing fronts equal to about 0.5 and 0.9 of the free-stream velocity U_0, respectively (as opposed to the group velocity of the TS-wave packet of about 0.3–0.4 of U_0). They quickly elongate downstream experiencing practically no expansion in the spanwise direction, the magnitude of the maximum velocity defect continuously decaying downstream.

The results of the spectral analysis showed that as the boundary layer streaks propagate downstream, the majority of harmonics – except those at low frequencies – decay, so that the oblique waves dominate in the wave number spectra (Fig. 4). It is remarkable that they are observed in the region where straight TS-wave (i.e. those with the spanwise wave number $\beta = 0$) are highly damped. The maximum amplitude of the disturbances is centred at zero frequency, which is interpreted as quasi-stationary flow distortion.

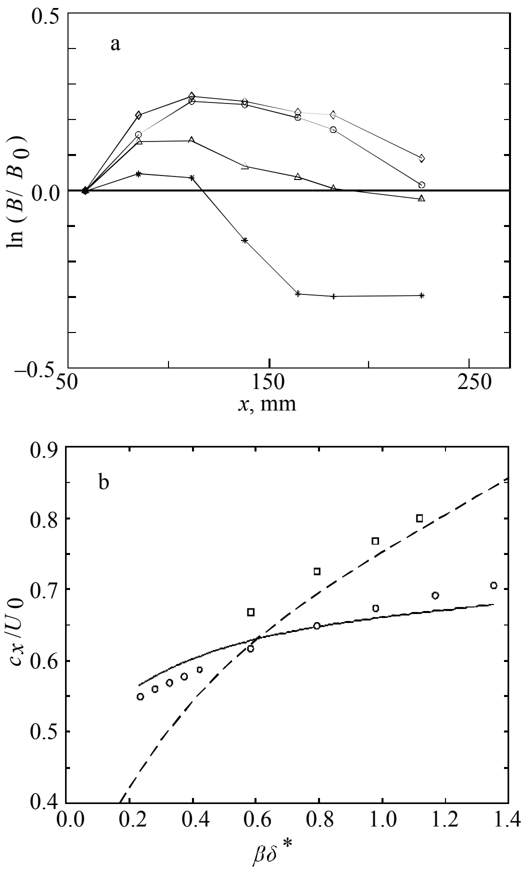

Fig. 5. Normalized amplitudes of spectral components vs. x (a): $F = 26.9\times10^{-6}$, $\beta = 0.442$ (*), 0.614 (Δ), 0.834 (○), 1.031 (◊) rad/mm. Phase velocity vs. spanwise wave number β at Re = 420 (x = 150 mm) (b). Experiment: $F = 26.9\times10^{-6}$ (○) 80.6×10^{-6} (□). Calculations: $F = 26.9\times10^{-6}$ (—), Luchini, private communication; linear stability theory: $F = 26.9\times10^{-6}$ (-.-), $F = 80.6\times10^{-6}$ (---) [9]

As the appearance of the streaks is determined by transient effects near the disturbance source, it has a close relation to receptivity problem. The first careful experiments on leading edge receptivity of the laminar boundary layer to vortical disturbances of the free stream that are localized in time and space were carried out in [13]; further details were given in [9, 12].

The disturbances were introduced by isolated pulses of sucking or blowing through a narrow tube located in front of the leading edge. It was found that in a range of spansise wave numbers and subcritical Reynolds numbers, the streamwise amplitude of quasistationary boundary layer disturbances experience a growth, see Fig. 5a. Phase velocities c_x calculated both for TS-waves corresponding to the experimental conditions and for optimal disturbances are shown in Fig. 5b. As seen, the last theory quite accurately predicts phase velocities of the low-frequency (viscous frequency parameter $F = 26.9 \times 10^{-6}$) disturbances: the deviation is less than 4.5%. Moreover, the dominant spanwise wavenumbers as well as amplitude and phase profiles also appeared to be close to optimal ones. In contrast, at the high frequency ($F = 80.6 \times 10^{-6}$) the classical linear stability theory gives a quite accurate prediction for c_x.

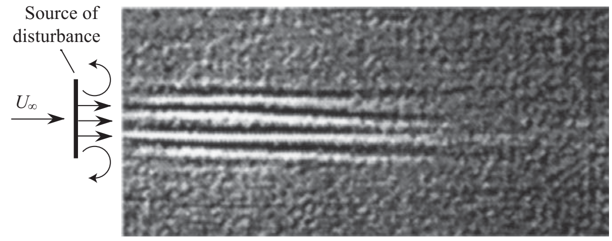

Fig. 6. Smoke visualization of the streamwise localized structures generated in a boundary layer of a flat plate by blowing air through a spanwise slot; Tu = 0.02% [14]

The receptivity of flat plate boundary layer to three-dimensional localized disturbances excited at the wall is similar to that at the leading edge. The flow reacts by generating the streaks independent of the disturbance source characteristics in a wide range of excitation intensities and flow velocities [7]. A typical narrow streamwise disturbance structures generated at the slot edges are seen in the smoke visualization in Fig. 6.

3.2. Distributed generation of the streaks

The identity of the observed boundary layer response to three-dimensional free-stream vortical disturbances over a broad range of their amplitudes, experimental models, and facilities indicates a generality of the mechanism of the boundary layer distortion. However, the continuous decay of the amplitude of the locally introduced disturbance in all these cases is in contrast to the continuous downstream growth of the streamwise disturbance velocity observed in the presence of FST that supports the idea of distributed receptivity of the boundary layer in respect to free-stream vortices at high level of turbulence. Similar conclusions regarding the inability of the localized receptivity mechanisms to explain the observed streak growth in the Blasius boundary layer were given in [15] based on a consideration of experimental and theoretical data.

It is noteworthy that the free-stream three-dimensional inviscid disturbances are assumed to have scales comparable with the streaks and that they penetrate deep into the boundary layer, i.e. the mechanism of the wave-scale reduction is not necessary or is of less significance than for TS-wave excitation [16]. It means that a quite effective distributive forcing of the streaks along the whole region of boundary layer development is not unlikely. As a consequence, the leading-edge effect might be dropped when considering the distributed receptivity, while the streak generation can be linked to the FST by incorporating non-parallel effects.

An experimental way to introduce certain controlled ‘representative’ perturbations in free stream to investigate the distributed receptivity of a flow to the streaks was suggested in [15]. 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. Such an approach provides a possibility of investigating in detail the distributed receptivity of the flow.

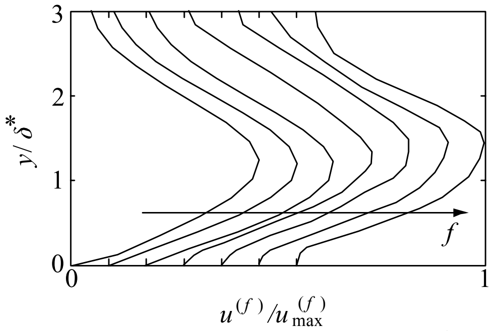

Fig. 7. Streamwise velocity profiles for $F\times10^6$ = 0, 6.9, 9.3, 13.6, 18.5, 20.3, 27.8 (from left to right) [18]

In [17], the micro-wing was located above the plate so that the leading edge influence was eliminated. 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 FST levels. Comparison with the study of [15], in which the microwing was located in front of the flat plate, confirms that the local processes at the leading edge can play no dominant role in the streak growth. Amplitude profiles of the streamwise disturbance velocity are self-similar in the downstream direction and correspond to the characteristic streak shape (see Fig. 3) generated by other means.

Development of a streak excited at a flat plate by periodically modulated tip vortex was considered in [18]. Due to the modulation an isolated streak, whose intensity changes in time, developed in the boundary layer. The streamwise velocity profiles of the stationary and periodic components are compared in Fig. 7. It is seen that the velocity maximum experiences a monotonic shift out of the wall as the frequency increases. The same behavior is also known for ‘natural’ streaks excited by a high level of FST [19]. This phenomenon has been observed also in numerical calculations [20] at F>18 and the spanwise scale close to that of the described experiment.

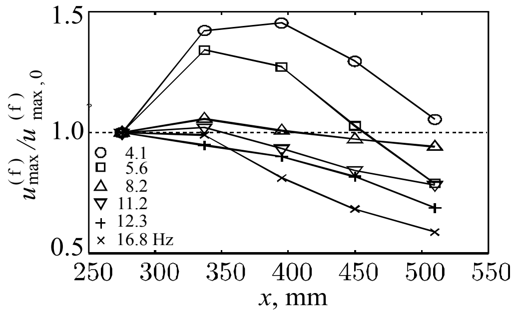

Fig. 8. Downstream behavior of maximum rms values of disturbance streamwise velocity for different frequencies [18]

Downstream behaviour of maximum rms values $u'_{max}(f)$ for different frequencies of the modulation is shown in. Fig. 8. As the frequency becomes higher, the range of the amplitude growth shrinks and at f > 12.3 Hz only decay occurs. The results appeared to be in a good quantitative accordance with numerical data given in [21].

3.3. Generation of streaks in 3D flows

Experiments [21-23] showed that disturbances excited at the leading edge of a flat plate through a tube oriented at an angle to the free stream, i.e. with a predominant spanwise disturbance velocity, represent asymmetric streaks in the boundary layer. In this case, the streak can contain only a single region of streamwise velocity defect or excess, with its axis well as the direction of propagation inclined to the free-stream velocity vector.

To study generation and development of the streak in a swept-wing flow, experiments [24] were peformed. After Fourier transformation along the spanwise coordinate, integration of the disturbance amplitudes across the boundary layer and normalization to the front-most measured amplitudes, the data for disturbance streamwise velocity are presented in Fig. 9. Additionally, the corresponding results of the linear stability analysis in a parallel flow approximation of the Falkner—Skan—Cooke profiles are shown by solid lines. It can be seen that in this case the theory correctly predicts the wavelength of the most-amplified stationary mode. However, a strong deviation from the theory is found in the present experiments at low wave numbers. Moreover, the normal-mode approach cannot explain the appearance and development of amplitude peak at ≈ 0.1—0.2, below the spanwise number of neutral disturbances. Its origin can be attributed to the distributed receptivity due to the presence of the tip vortex along the whole model chord.

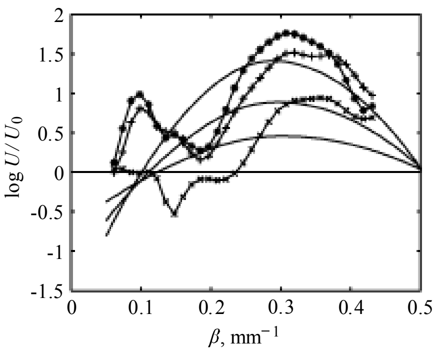

Fig. 9. Averaged spectral disturbance growth normalised by different initial amplitudes, x = 300 (×); 353 (+); 415 mm (□) [24]

3.4. Generation of streaks in local separated regions

It follows from the linearized Navier—Stokes equations that the transient effects can take place in separated flows. Experimental study of quasi-stationary streaks of different intensity has been undertaken in [25]. It was concluded that the transition to turbulence was dominated by classical TS-wave instability. Taking into account that the TS-instability in separated flows occurs even at rather small Reynolds numbers, this is not surprising. Hence, it was conjectured that for the 'streaky' laminar turbulent transition the predominance of stationary disturbances might be important in this case.

Such experiments were performed in [26]. In Fig. 10 the streamwise behaviour of the amplitudes of the streaks in some typical situations is shown. Under the conditions of the experiment the wave-number components amplified in the separation bubble are those of □ ≈ 2π/□ = 0.63 mm^{-1}. When the span-wise spacing between the stationary sourves was larger, then the amplitude growth became smaller and disappeared.

3.5. Effect of the streaks on the laminar-turbulent transition

The transient effects should occur close to their source, but the (quasi)stationarity of the streaks leads, as a rule, to a very long downstream region of their propagation. They even can penetrate into the zone of linear TS-wave instability. 'Natural' TS-waves were detected at moderate levels of FST, by many investigators [7]. These studies showed that the transition in a boundary layer on a flat plate at Tu ≈ 0.7% can occur through the development of TS-wave packets, which were observed together with the streaks discussed earlier. However, the instability waves packets were not found for a long time in experiments at Tu > 1% even at large Reynolds numbers.

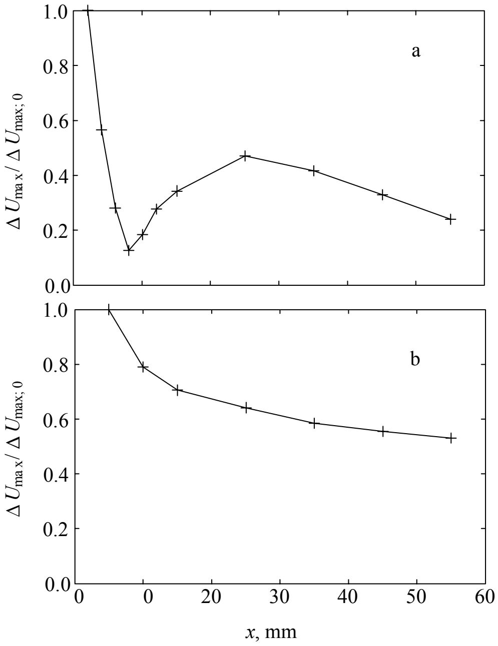

Fig. 10. Maximum amplitudes of the streaks with different spacing λ between the roughness elements vs. stream-wise distance: (a) λ = 5 mm; (b) λ = 20 mm [26]

The possibility of generating and studying the TS-waves under controlled conditions in boundary layers at FST level up to Tu ≈ 4% of U_0 was shown for the first time in [27]. These results were advanced in the experiments [1]. In that study, development of a small-amplitude two-dimensional TS-wave excited by a vibrating ribbon in the presence of high FST was investigated. The amplitude and phase distributions of the waves were extracted using a phase filtering technique. At Tu = 1.5% the overall value of u'/U_0 in the middle of the boundary layer was 5% at the most downstream position. In spite of this, the extracted wave exhibits the same characteristic features as the TS-wave in an undisturbed boundary layer. It was found that in these and similar measurements, the dependence of the phase on the streamwise coordinate could be approximated by straight lines, and the wave phase velocity was the same as at small Tu.

Amplification curves for the wave at low and high FST are shown in Fig. 11. The study indicated that the decrease of the amplification rate is associated with a delicate mechanism caused by the presence of the streaks. Moreover, the amplification rates of the TS-wave appeared to be independent of the experimental conditions of the excitation amplitude. These and later observations demonstrated that different kinds of interactions, which could transfer energy between the TS-waves or between large-scale flow structures and the TS-waves, may be present.

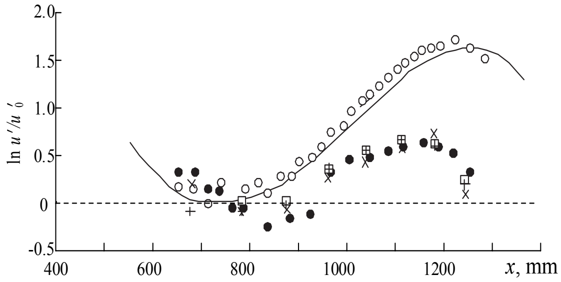

Fig. 11. Amplitude evolution of TS-waves normalized to wave amplitude at branch I of the neutral curve: measurement without a grid (○); measurements with the grid at different amplitudes of excitation (+, ×, □ ●); calculation by PSE (—); $F = 100\times10^{-6}$ [1]

In the presence of the streaks, the boundary layer may be considered locally as a spanwise-modulated flow. In such cases the mode shapes, phase velocities and amplification rates depend not only on the frequency and Reynolds number but also on the intensity and spanwise scale of the modulation. This means that in a boundary layer subjected to high FST, the TS-wave amplification rates may be expected to depend on the amplitude and typical spanwise scale of the disturbance in a boundary layer, which in turn depend on the free-stream characteristics.

As a result of the interaction, a non-linear wave packet occurs, which transforms downstream into the turbulent spot. The interactions between the streaks and the TS-wave were also studied in [13] and later in [4, 28]. The observed interactions also produced non-linear wave packets (either on a streak or behind it) which gradually developed into turbulent spots.

3.6. Secondary instability and nonlinear effects in the streaks

Provided that the initial amplitude of a streak is large enough, it is also capable of transforming into a turbulent spot in subcritical region. In the smoke visualization (Fig. 12) the streaks begin to oscillate in the spanwise direction before the final flow becomes turbulent. The oscillations can be attributed to a secondary instability of the streaks to certain travelling disturbances. One can conjecture that the streak breakdown mechanism caused by the disturbances could be similar to the secondary instability of Görtler or crossflow vortices.

The physical background of the secondary instability concept consists in considering the flow modulated by the streaks as a new fundamental flow, whose stability is the subject of investigation. An example of spatial distribution of amplitudes of growing disturbances in a similar case are shown in Fig. 13. The maximum of disturbances is located near the critical layer in the regions of maximum velocity gradients.

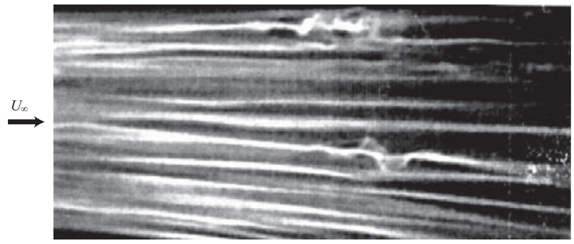

Fig. 12. Smoke visualization of generation of the high-frequency wave packets during natural transition on a flat plate at Tu = 1.5% [29]

The final process of the transition to turbulence depends significantly on specific flow characteristics, different nonlinear interactions between the streaks, TS-waves etc. and still requires efforts to be understood in detail.

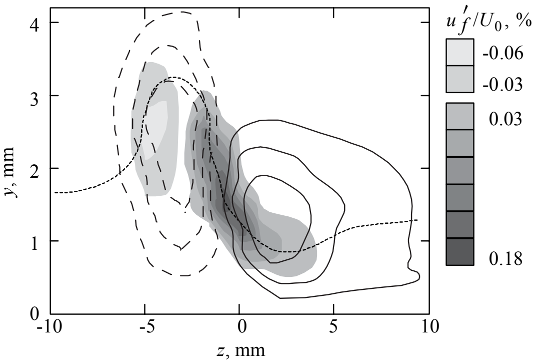

Fig. 13. Isolines (*grey*) of u'_f/U_0, %, of secondary disturbances inside a stationary streak-like structure in a swept-wing boundary layer, indicated by contours of $\Delta U/U_0$; location of the 'critical layer' $U/U_0 = 0.6$ (···)

4. Acknowledgements

The preparation of the paper was financially supported by Russian Foundation for Basic Research Grant No. 10-08-00276-a.

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