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ROLE OF LOCALIZED STREAMWISE STRUCTURES IN THE PROCESS OF TRANSITION TO TURBULENCE IN BOUNDARY LAYERS AND JETS (REVIEW)

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Results of the analysis of specific features of the laminar–turbulent transition in various subsonic shear flows, which are caused by localized stationary and nonstationary streamwise structures, are presented. One mechanism of flow turbulization is considered, which involves the origination and development of secondary high-frequency disturbances in regions of flow instability generated by its modulation by streamwise structures. It is shown that this process is identical in different types of shear flows (boundary layers and jets) and in flows of the type of localized streamwise structures (stationary or nonstationary).

INTRODUCTION

Attention of many researchers is currently riveted to stationary and nonstationary localized streamwise disturbances, which is caused by their important role in the process of the laminar–turbulent transition in various shear flows. The classical transition to turbulence in the boundary layer at low free-stream turbulence is known to be related to the development of instability waves — the so-called Tollmien–Schlichting waves. This type of transition has been studied in detail both theoretically and experimentally [1], at least at the linear stage. These studies involve the linear theory of hydrodynamic stability, which describes rather accurately the linear and weakly nonlinear stages of transition, which is confirmed by numerous experiments.

The last, nonlinear stages of transition are more complicated for theoretical description. It should be noted, however, that much progress is observed in studying these stages of transition, especially in the field of experimental studies. The beginning was the classical experiments of Klebanoff [2] who considered transformation of a two-dimensional Tollmien–Schlichting wave at the nonlinear stage of its development into three-dimensional vortex structures (so-called Λ vortices) and their evolution downstream. This type of transition is called the Klebanoff transition or the K-regime. Another type of transition called the N-regime (subharmonic regime) was obtained experimentally [3] and described theoretically [4]. In both regimes, Λ vortices appeared, but they followed one another in the K-regime, which was confirmed by smoke visualization of the process, and were arranged in a staggered order in the N-regime. Later, a number of methods of implementation of both regimes were proposed, which were confirmed by experimental and theoretical investigations.

Without considering in detail all possible mechanisms of transformation of Λ vortices to turbulent spots, we mention one of them, which is associated with the development of secondary high-frequency disturbances on these vortices. It is known that distortion of mean velocity profiles in the shear flow, i.e., the presence of inflection points, makes such a flow unstable to secondary high-frequency disturbances. In this case, secondary disturbances may increase and transform the flow to a turbulent state. The concept of secondary high-frequency instability was confirmed by numerous experimental studies, in particular, for near-wall shear flows, where the flow is modulated in

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the transverse direction by streamwise stationary Görtler-like vortices [5, 6] and crossflow vortices on swept wings [7, 8]. Modulation of the mean flow by such vortices generates local velocity gradients both normal to the surface ($\partial U/\partial y$) and in the transverse direction ($\partial U/\partial z$). It is in regions with inflection points on the velocity profile that the secondary disturbances start to grow.

Streamwise disturbances localized in the transverse direction may be stationary or nonstationary. An explicit example of such disturbances is the so-called streaky structures observed in the boundary layer at high free-stream turbulence or in the viscous sublayer of a turbulent boundary layer. The streaky structures were first modelled experimentally [9]. The measurements showed that secondary disturbances whose downstream development leads to the formation of turbulent spots may appear on these structures (for different reasons, including interaction with high-frequency waves). As in the case of stationary streamwise structures, nonstationary streaky structures move downstream and locally distort the mean flow. Local instability regions, where secondary disturbances can grow, appear due to velocity gradients in the normal and transverse directions.

The “legs” of the Λ structures mentioned above are nonstationary localized streamwise vortices. Localized distortions of the mean velocity profiles in the region of the “legs” of these structures may also be the reason for the development of secondary disturbances on them [10].

Instability of jet flows is usually associated with instability of vortex rings — the so-called Kelvin–Helmholtz vortices. The dynamics of development and turbulization of ring vortices has been studied by many researchers. Among the latest works, special attention should be given to the review [11], where the results of studying the eigen oscillations of the vortex ring, origination of turbulence in it, and generation of sound in an ideal incompressible fluid were analyzed.

Numerous theoretical and experimental studies of streamwise vortex structures in the process of turbulization of free shear flows, for instance, jets, have been conducted. Crow and Champagne [12] were the first to show that the shear layer of an axisymmetric jet contains orderly vortical structures. The measurements of Yule [13] showed that the vortical structures interact and merge. Later, the “vortex street” model was proposed, which describes evolution of azimuthal vortex rings [14]. Measuring a round jet in the vicinity of the nozzle, Liepmann and Gharib showed [15] that the primary Kelvin–Helmholtz instability appears first, which leads to consecutive rollup of shear layers into vortex structures consisting of a series of vortex rings. Secondary instabilities form streamwise vortex structures interacting with primary vortex rings. The streamwise structures are formed between the neighbouring vortex rings and have a significant effect on mixing processes and flow dynamics.

The study of turbulent jets [16] revealed the existence of coherent structures. Hussain [16] performed detailed measurements of coherent rings and found the mechanism of azimuthal vortex interaction. The experimental and numerical studies [17] showed that there are streamwise structures between vortex rings, which play an important role in the transition to three-dimensional turbulence. It was also shown [17] that the most important process in the development of coherent structures in a turbulent jet is a volcanic-type “burst” caused by the azimuthal coherent structure or ring passing near the potential core of the jet. Ring vortices inject a high-velocity fluid. Penetration of this fluid between the neighbouring rings generates high shear stresses, which play an important role in evolution of streamwise vortex pairs (ribs) rotating in the opposite directions.

In contrast to the round jet, the plane jet is studied much better. A theory that describes the life cycle of coherent structures in the shear layer has been developed. In this case, the mixing process in the shear layer is mainly determined by the Kelvin–Helmholtz vortices. The streamwise vortices arise and develop between the latter, as in the round jet. In contrast to the round jet, however, their role in the process of evolution of the plane jet is insignificant [18]. Nevertheless, the formation of streamwise vortices indicates the transition to turbulence [19].

Thus, the streamwise structures often play the determining role in the process of transition to turbulence both in near-wall and free shear flows. The goal of the present review is to analyze the results of experimental studies of the mechanisms of origination, development, and transition to a turbulent state of various shear flows with streamwise structures, which were performed in the last decade of the 20th century.

1. BOUNDARY LAYER

Stationary Streamwise Vortices. It is known that instability of flows in the boundary layer on concave surfaces, swept wings, and in some other cases leads to the generation of stationary streamwise structures. The reason for their appearance is centrifugal forces in the first case and a transverse flow caused by the flow around a wing whose leading edge is located at an angle to the main stream in the second case. The origination of such vortices is called the primary instability of the flow. The transition to turbulence in the cases considered is related to the development of secondary high-frequency disturbances in regions with unstable velocity profiles both in the transverse and normal-to-wall directions. This instability of velocity profiles is created by modulation of the flow by stationary streamwise vortices.

In situations frequently encountered in practice, the initial flow is disturbed in three directions, for example, if the surface has three-dimensional roughness, rivets, forward-and backward-facing steps, and also in the case of suction or injection through orifices. A stationary three-dimensional distortion in the boundary layer may also appear due to its instability to stationary disturbances. For instance, Taylor–Görtler vortices may appear in the boundary layer on a thick airfoil because of the concavity of streamlines near the frontal point [20], and powerful crossflow vortices may arise on a swept wing due to crossflow instability [8, 21].

Transverse modulation of boundary-layer flows (first of all, a three-dimensional one) is observed in various problems of fluid mechanics. The study of stability of three-dimensional boundary layers has been paid much attention to lately both in theoretical and experimental works [5, 22–24]. This is primarily caused by the necessity of investigating the nature of the laminar–turbulent transition in complex flows and solving the following application problems: control of transition processes, drag reduction on swept wings, blades of turbines and compressors, etc.

One of the reasons for the transition of a laminar flow to a turbulent one is the travelling Tollmien–Schlichting waves in boundary layers on flat walls and convex bodies and Taylor–Görtler vortices on concave bodies [25]. Instability of a three-dimensional boundary layer (for example, boundary layer on a disk, sphere, or cone rotating in a quiescent fluid) and instability on a swept wing are also related to the formation of three-dimensional disturbances: stationary Taylor–Görtler vortices or crossflow vortices [26, 27]. The appearance of these vortices is caused by several factors. Centrifugal forces are most important in the flow around disks, spheres, or cones. The flow around a swept wing has a transverse component of the mean velocity, which is responsible for generation of stationary streamwise vortices on the leading edge of the wing in the region of accelerated motion of the fluid. As a result, the so-called primary crossflow instability arises. In this case, stability of boundary layers is significantly different from the stability of a two-dimensional boundary layer, which is mainly determined by the presence of transverse modulation of the flow by stationary streamwise structures. The study of the “natural” transition showed that high-frequency (secondary) disturbances of the travelling-wave type are observed on stationary vortices, and the transition to turbulence occurs after the emergence of secondary vortices, which are superimposed on the primary stationary vortices and propagate along the latter [26, 27]. The primary instability generated by stationary vortices is considered as the necessary condition for generation and development of secondary vortical disturbances on them. Transverse modulation of the flow by vortices results in the appearance of a local inflection on the instantaneous velocity profile in the boundary layer, which is unstable (as many researchers believe) to high-frequency secondary oscillations of the flow (concept of secondary instability of a locally inflectional profile) whose spatial evolution is the reason for the onset of turbulence [28]. Most studies offer mainly qualitative characteristics (visualization pictures) of the disturbed flow in three-dimensional boundary layers. Nevertheless, to analyze the transition processes in them, one needs quantitative information on the generation and evolution of disturbances under conditions of transverse modulation of the flow. Such information can be obtained under controlled test conditions, which allows one to study in more detail the mechanism of this or that “natural” (uncontrolled) phenomenon, which normally occurs simultaneously with processes of different physical nature.

Streamwise vortices seem to be first studied under controlled conditions in the experiment of [29], where the boundary layer was modulated by a number of small wings located in the transverse direction in the undisturbed flow, which changed the boundary-layer thickness on the model. Travelling waves were excited by a vibrating ribbon at frequencies within the range of instability of the Tollmien–Schlichting waves. It was found that stationary modulations of velocity lead to significant changes in the characteristics of flow instability.

Kachanov and Tararykin [30] developed and applied a method for simulation of a three-dimensional stationary distortion of a laminar boundary layer. An important result obtained in that work for travelling waves should be noted: the growth rates of amplitudes of disturbances in a modulated boundary layer are smaller than in the case of a flat plate; hence, a steadily disturbed boundary layer is more stable to the action of the Tollmien–Schlichting waves than an undisturbed layer. In the presence of stationary vortices, there is no dispersion (dependence of the phase velocity of the waves on the angle of their propagation). It should be noted that the study [30] was performed to investigate the development of disturbances only in the linear region at low Reynolds numbers and low intensities of both the primary disturbance and travelling waves.

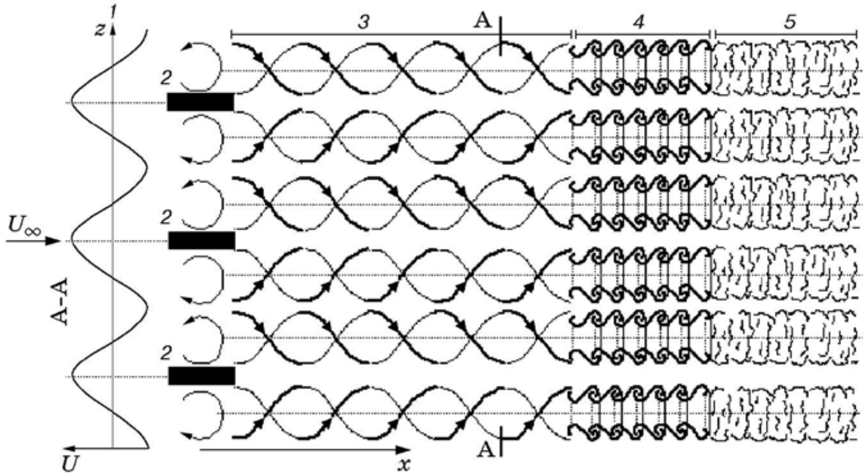

Fig. 1. Schematic of the laminar–turbulent transition in a flat-plate boundary layer modulated by stationary streamwise Görtler-like vortices [32]: 1) transverse modulation of the flow; 2) roughness elements; 3) stationary streamwise vortices (primary instability); 4) travelling waves (secondary instability); 5) turbulent boundary layer.

In the experiments [31], the vortices in the boundary layer were generated by roughness elements located periodically on a flat plate along the z axis (Fig. 1). In this formulation, the experiment "models" the transition in the flow above a concave surface. The transition inside the stationary vortices is caused by amplification of low-amplitude waves generated by the vibrating ribbon. The resultant travelling disturbances have an inviscid nature and are associated with sinusoidal-type instability [9]. Since the flow is rather simple, it was possible to study the wave characteristics and transition to turbulence in much detail.

A similar mechanism of breakdown of a high-intensity stationary streamwise vortex generated in the boundary layer on a swept wing by roughness elements was studied in [33]. A packet of waves travelling on stationary vortices was found in the boundary layer of a swept wing under "natural" conditions [34]; the development of this wave packet led to turbulence. It was shown that an acoustic field with a frequency corresponding to the "natural" wave packet excites travelling disturbances that grow and shift the laminar–turbulent transition upstream. The process of generation of higher harmonics of the fundamental frequency was registered at the nonlinear stage of evolution of travelling waves. Based on these results, the basic pair of "natural" low-intensity stationary vortices on a swept wing was "modelled," and the characteristics of development of the vortices themselves and secondary high-frequency disturbances travelling on them were studied [35]. In this case, streamwise vortices of low intensity and weak vorticity were streaky structures. It was found that the growth rates of travelling disturbances that develop on stationary structures I and II (Fig. 2) are rather different. The secondary disturbances develop more intensely on structure I due to the greater instability of the separated flow in the region of the backward-facing step relative to the crossflow, and the transition of this flow to a turbulent state occurs much earlier than that on structure II, where the separated flow on the forward-facing step is more stable to the action of the transverse flow (Fig. 2a and c). The transverse distributions of the mean velocity (Fig. 2*b*) and the fluctuating component of velocity are also different for each structure. The range of linear development of secondary disturbances was determined, and their characteristics were studied. By varying the length of the roughness element in the transverse direction, it was found that the short distance between the vortices leads to their interaction.

It was experimentally established that the evolution of disturbances on a single vortex is similar to the instability growing on a set of vortices with a large period along the transverse coordinate. The mutual influence of the vortices becomes significant with decreasing distance between them: the smaller the distance, the smaller the growth rates of the travelling waves. This is explained by the distributions of the longitudinal and normal components of velocity in the vortices. The greatest wave amplitude in all the cases considered was observed near the maxima of velocity shear (gradients) in the transverse direction. This indicates that the behaviour of disturbances can be determined by the mechanisms of inflectional (inviscid) instability.

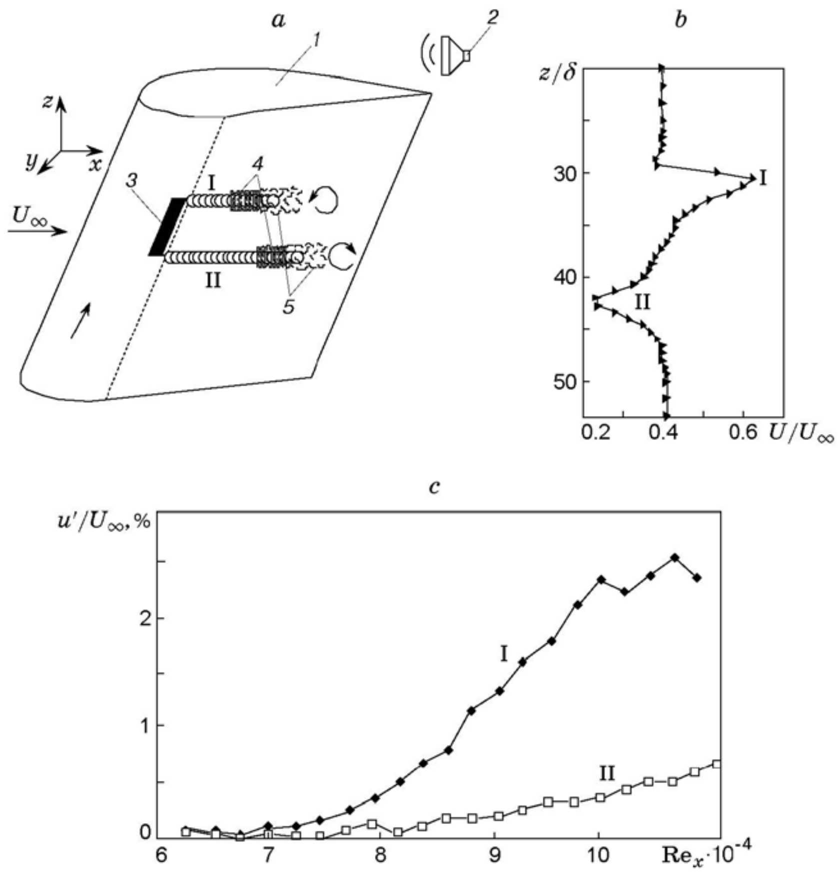

Fig. 2. Laminar–turbulent transition on a swept wing (u' is the root-mean-square fluctuations of velocity, δ is the boundary-layer thickness, and Re_x is the Reynolds number based on the downstream distance) [35]: (*a*) scheme of secondary high-frequency breakdown of crossflow streaky structures (1 is the airfoil, 2 is the generator of secondary disturbances, 3 is the roughness element, 4 is the secondary disturbances, and 5 is turbulence; streamwise structures are marked by I and II; the arrow indicates the crossflow direction); (*b*) transverse distribution of the mean velocity in the region of development of streamwise structures; (*c*) disturbances on stationary streaky structures.

Nonstationary Streamwise Vortices. We consider the transition in the boundary layer, which is initiated by a roughness element on the surface of a flat plate. In this case, a number of important quantitative characteristics of disturbed motion have been obtained. The flow around a single roughness in the form of a hemisphere placed onto the model surface has been considered in many papers. The structure of the disturbed flow is determined by the large-scale vortex that rolls up behind the hemisphere and stretches downstream. Flow visualization [36, 37] showed that the transition is initiated by horseshoe vortices in the wake behind the hemisphere. The beginning of the transition depends significantly on the place of origination of such vortices. Later, Klebanoff et al. [38] found that the secondary instability is related to vortices periodically generated by the roughness element. Having studied the dependence of the shedding frequency of these vortex structures on the size of the roughness elements, their shape, and Reynolds number, Klebanoff et al. concluded that the vortex shedding frequency normalized to the displacement thickness and local mean velocity near the roughness is 0.3. For most flows, this value corresponds to the frequency much greater than the frequency of unstable Tollmien–Schlichting waves.

In a flat-plate boundary layer, localized three-dimensional disturbances generated by roughness elements [37, 38] or various transient (according to Breuer) disturbances [39–41] lead to the formation of streamwise vortices that change locally the transverse flow structure and create conditions for secondary instability. As was noted above, nonstationary localized disturbances include also the Λ structures of the nonlinear stage of the classical transition. Experimental investigations on modelling of a solitary Λ structure in the boundary layer on a flat plate showed [10] that both decaying and growing Λ structures may exist, depending on the amplitude of the introduced disturbance. If a high-frequency wave with intensity lower than 1% is superimposed onto a decaying Λ structure, the

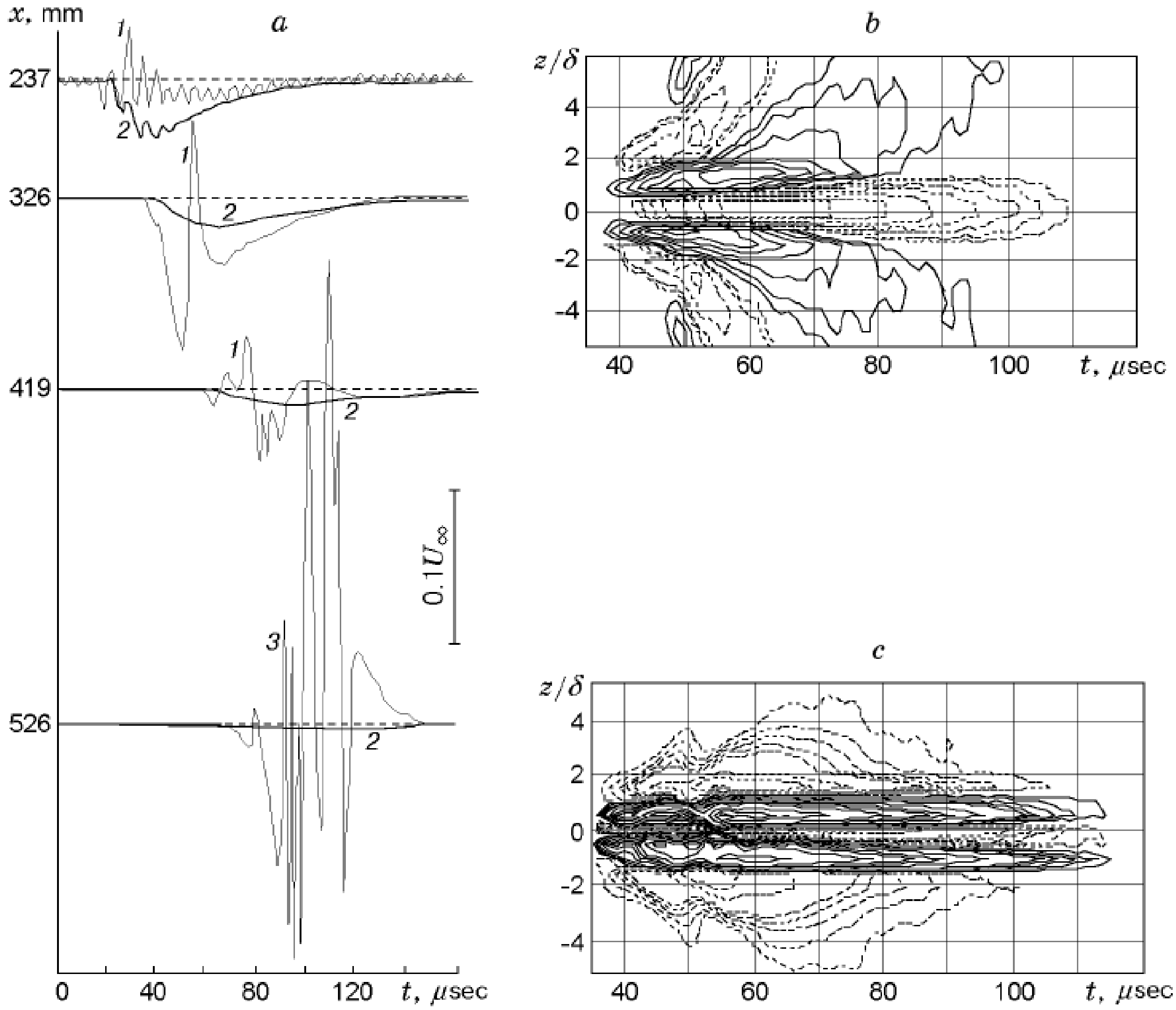

Fig. 3. Interaction of a decaying localized disturbance (streaky structure) with a high-frequency wave [9]: (*a*) traces of instantaneous velocity [f = 205 Hz, U_∞=6.6 m/s, z = 0, and y = y(u'_{max})]; test conditions with the wave (1), without the wave (2), and with the wave (appearance of a turbulent spot) (3); (*b*) isolines of velocity fluctuations of the streaky structure [x = 335 mm, U_∞=6.6 m/sec, y = y(u'_{max}), and u'_{max}/U_∞=0.03]; (*c*) isolines of velocity fluctuations of the streaky structure interacting with a high-frequency wave [f = 205 Hz, x = 335 mm, U_∞=6.6 m/s, y = y(u'_{max}), and u'_{max}/U_∞=0.38].

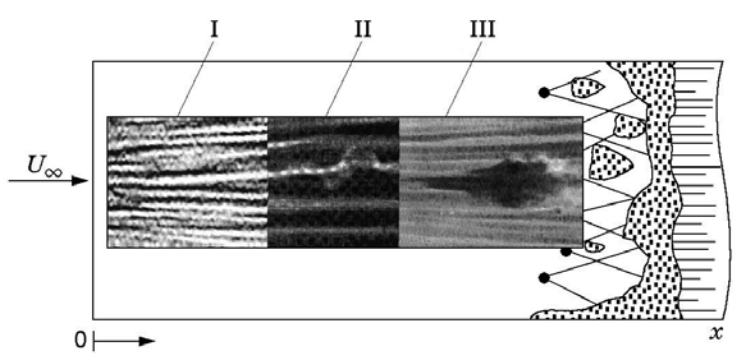

Fig. 4. Scenario of the laminar–turbulent transition at high free-stream turbulence ($u'_{max}/U_\infty \geq 0.01$) [9]: I is the region of generation and development of streaky structures, II is the region of origination and development of high-frequency wave packets and incipient turbulent spots, and III is the region of development and coalescence of turbulent spots.

disturbances interact, and a high-frequency wave packet is developed on the “legs” of the Λ structure, which leads to an increase in the localized disturbance and its transformation to a turbulent spot. Development of secondary high-frequency instability at the nonlinear stage of evolution of a two-dimensional Tollmien–Schlichting wave with three-dimensional distortion (origination of Λ structures) was studied by Klingmann [42] who justified the concept of secondary instability both experimentally and theoretically.

At high free-stream turbulence, continuous penetration of external disturbances into the boundary layer leads to excitation of streamwise structures (streaky structures) modulating locally the boundary layer [43–48]. As in the case of the transition of a three-dimensional boundary layer modulated by stationary vortices, the transition to turbulence in these flows is related to stability of streamwise vortex structures. The streaky structures are also observed in the viscous sublayer of a turbulent boundary layer. The origination of these structures is associated with the lift-up effect described within the framework of Landahl’s theory of algebraic instability [49]. In contrast to stationary vortices, streaky structures have weak vorticity; they are narrow layers of a slowly and rapidly moving fluid alternating in the transverse direction. Nevertheless, the instability of flows modulated by streaky structures is related to transverse gradients of velocity, as in the case of their modulation by stationary vortices. This statement was confirmed by controlled experiments (Fig. 3); based on the results of these experiments, a scenario of the transition at high free-stream turbulence was proposed (Fig. 4). The development of secondary high-frequency disturbances in regions of unstable profiles of the mean transverse velocity in a flow with streaky structures leads to the origination of high-frequency packets, which are transformed to turbulent spots downstream. This process may occur in the case of interaction of a streaky structure with a high-frequency wave (see Fig. 3) or as a result of increasing high-frequency component of the localized nonstationary disturbance itself [9].

Thus, the analysis of recent experimental results shows that the transition to turbulence in boundary layers with stationary and nonstationary localized streamwise structures is related to the development of secondary high-frequency disturbances on them.

2. JET FLOWS

Round Jet. Investigations of the dynamics of a round jet whose mean and fluctuating characteristics are plotted in Fig. 5 showed that the streamwise structures localized at the jet-core periphery are generated directly at the nozzle exit due to the lift-up effect. The dynamics of evolution of these structures is similar to the dynamics of evolution of streaky structures in the boundary layer [50]. In particular, it was shown in controlled tests that secondary high-frequency disturbances may develop on these structures, which accelerates the jet-turbulization process.

“Natural” streaky structures observed near the nozzle exit for $Re \approx 10{,}600$ (Fig. 6) were artificially reproduced by roughness elements glued onto the inner surface of the nozzle (at the exit); the size of these roughness elements correlated with the scale of the “natural” streamwise structures. In this case, forced streaky structures were not subjected to the action of radial oscillations. A high-frequency disturbance was introduced into a small orifice on the nozzle surface located near the roughness element by means of suction/injection of the gas. The interaction of the streaky structure with the high-frequency disturbance leads to an increase in one of the “beams” (Fig. 7). Further downstream, the disturbance intensity increases, and the neighbouring streaky structures are involved into this process. The process of jet turbulization is accelerated. Thus, it is shown that the instability of a round jet may be related to the generation of localized streamwise disturbances (streaky structures) directly at the nozzle exit. The instability of streaky structures to high-frequency secondary disturbances favours the acceleration of the jet-turbulization process. This conclusion is in agreement with the results of investigation of the boundary-layer flow modulated by streaky structures.

Plane Jet. The studies of the near field of a plane jet [51] showed that streaky structures may also appear in this case (Fig. 8). In contrast to the round jet, the secondary disturbance is developed only on the streaky structure where it was artificially excited and does not involve the neighbouring structures into this process.

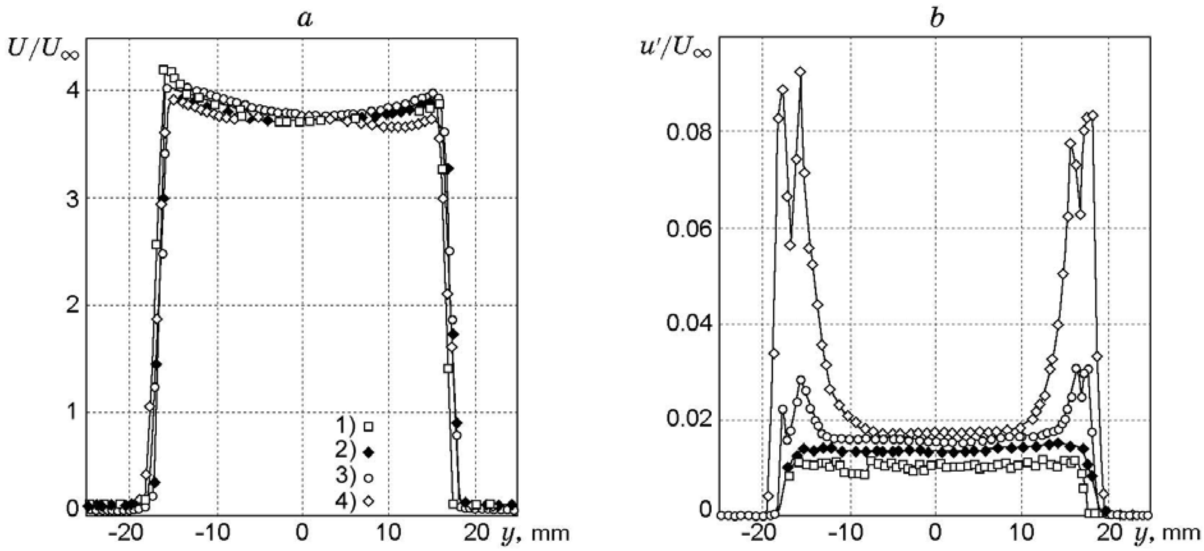

Fig. 5. Distributions of the mean (*a*) and fluctuating (*b*) velocity across a round jet at 8 (1), 12 (2), 22 (3), and 32 mm (4) from the nozzle exit (U_∞=3.75 m/s).

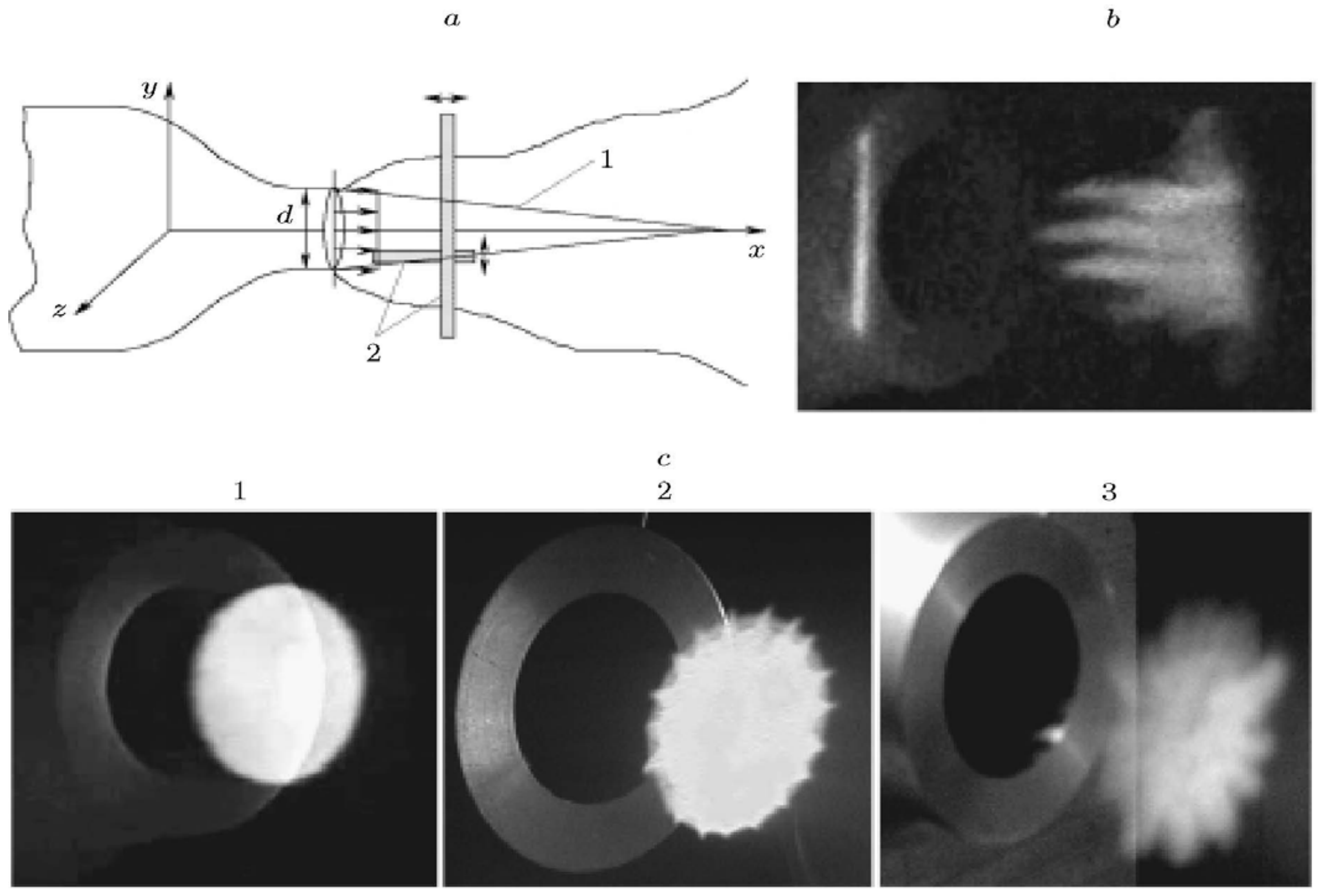

Fig. 6. Streaky structures in the near field of a round jet (U_∞= 4 m/s, nozzle diameter d = 40 mm, and Re≈10,600): (*a*) layout of the experiment (the potential core of the jet and light sheets are marked by 1 and 2, respectively); (*b* and *c*) smoke visualization of the streaky structures: streamwise section of the jet at the periphery (x/d =0.7 and z/d =0.4) (*b*) and cross section of the jet for x/d =0.4 (1), 0.68 (2), and 0.86 (3) (*c*).

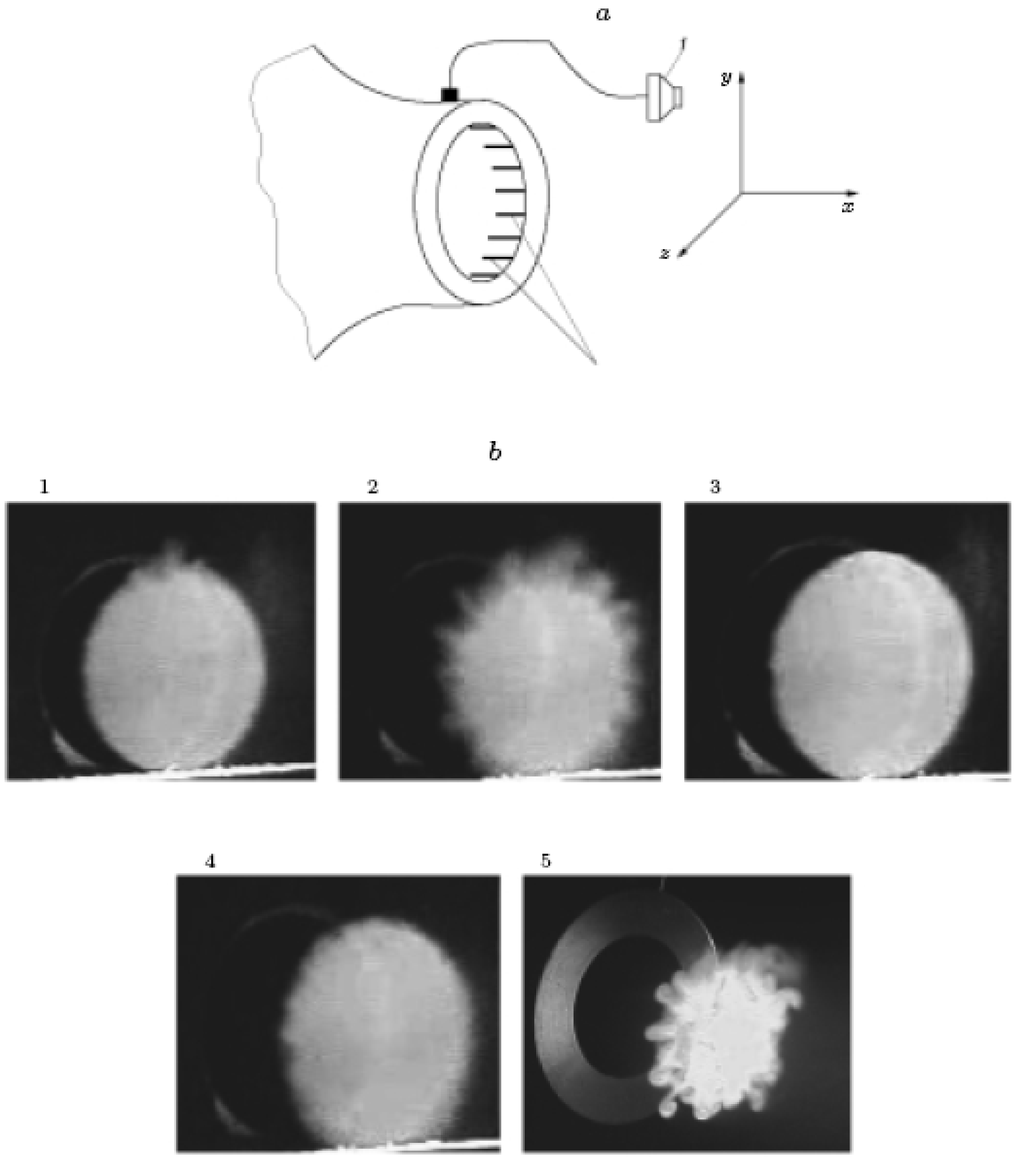

Fig. 7. Secondary instability of streaky structures with excitation of a high-frequency disturbance by injection/suction of the gas near the roughness element (U_∞= 4 m/s, d = 40 mm, and Re≈10,600): (*a*) layout of the experiment (the generator of secondary disturbances and roughness elements are designated by 1 and 2, respectively); (*b*) smoke visualization of a round jet at different distances from the nozzle exit [x/d =0.2 (frames 1 and 3), 0.4 (frames 2 and 4), and 0.68 (frame 5)]; frames 1, 2, and 5 refer to the case with generation of the secondary disturbance, and frames 3 and 4 refer to the case without generation of the secondary disturbance.

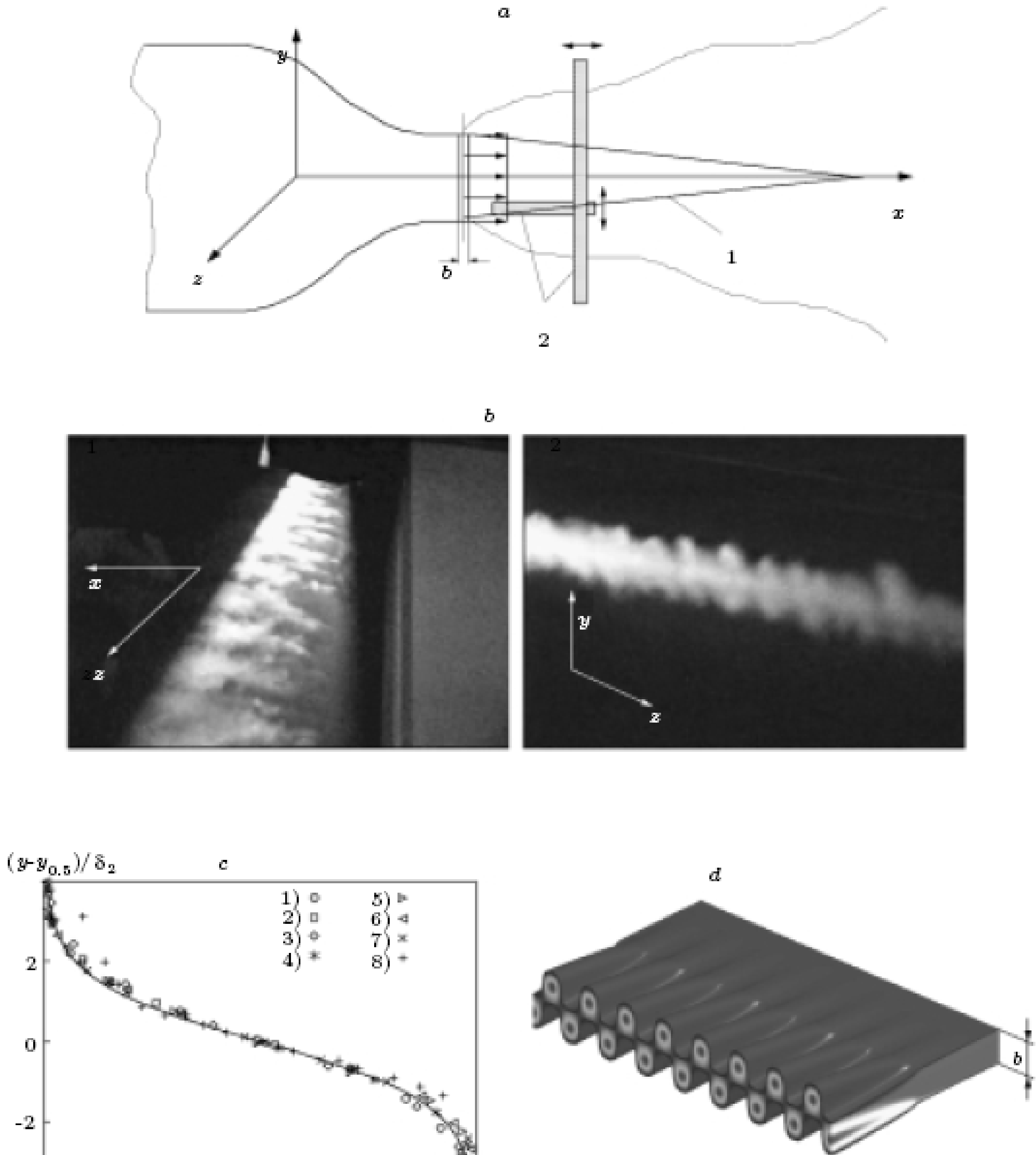

Fig. 8. Streaky structures in the near field of a plane jet (U_∞=7.3 m/s, *y/b* = 40, *b* = 12 mm, and Re≈3000): (*a*) layout of the experiment (the potential core of the jet and light sheets are denoted by 1 and 2, respectively); (*b*) smoke visualization of streaky structures [frame 1 refers to the longitudinal section of the jet (*x/b* =0.7 and *z/b* =0.4) and frame 2 refers to the cross section of the jet (*x/b* =0.4)]; (*c*) velocity profile in the shear layer [the solid curve refers to U/U_{max} =0.5 (1– tanh $y/(1.55\delta_2)$), where δ_2 is the displacement thickness of the shear layer] for *x/b* =0.2 (1), 0.4 (2), 0.6 (3), 0.8 (4), 1 (5), 1.4 (6), 2 (7), and 3 (8); (*d*) scheme of streamwise structures in the near field of the plane jet.

CONCLUSIONS

The analysis of the process of transition of a laminar flow into a turbulent state showed that localized streamwise structures are observed in various shear flows, such as boundary layers and jets. The mechanism of breakdown of the laminar flow is related to secondary high-frequency instability of flows modulated by these structures. This process is qualitatively identical both for stationary and nonstationary localized streamwise structures, such as Görtler vortices, crossflow vortices on a swept wing, and streaky structures at high free-stream turbulence, and also for coherent structures of the viscous sublayer of a turbulent boundary layer. Better understanding of the mechanism of the laminar–turbulent transition and the possibility of controlling this process requires further investigations of the characteristics of development of these structures and their secondary high-frequency instability.

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REFERENCES

1. Y. S. Kachanov, V. V. Kozlov, and V. Ya. Levchenko, *Origination of Turbulence in the Boundary Layer* [in Russian], Nauka, Novosibirsk (1982).
2. P. S. Klebanoff, K. D. Tidstrom, and L. M. Sargent, "The three-dimensional nature of boundary layer instability," *J. Fluid Mech.,* 12, Part 1, 1–34 (1962).
3. Yu. S. Kachanov and V. Ya. Levchenko, "The resonant interaction of disturbances at laminar–turbulent transition in a boundary layer," *J. Fluid Mech.*, 138, 209–247 (1984).
4. A. D. D. Craik, "Non-linear resonant instability in boundary layers," *J. Fluid Mech.,* 50, 393–413 (1971).
5. J. D. Swearingen and R. F. Blackwelder, "The growth and breakdown of streamwise vortices in the presence of a wall," *J. Fluid Mech.,* 182, 255–290 (1987).
6. Y. Kohama, Y. Fukunishi, and T.-J. Wang, "The response of artificial longitudinal vortex pair embedded in the boundary layer to acoustic excitation," *JSME Int. J., Ser. B*, 36, 74–79 (1993).
7. D. I. A. Poll, "Transition in the infinite swept attachment line boundary layer," *Aeronaut. Quart.*, 30, 607–629 (1979).
8. W. S. Saric and L. G. Yeates, "Generation of crossflow vortices in a three-dimensional flat plate flow," in: *Laminar–Turbulent Transition,* Springer-Verlag, Berlin (1985), pp. 429–437.
9. A. V. Boiko, G. R. Grek, A. V. Dovgal', and V. V. Kozlov, *Origination of Turbulence in Near-Wall Flows* [in Russian], Nauka, Novosibirsk (1999).
10. G. R. Grek, V. V. Kozlov, M. M. Katasonov, and V. G. Chernorai, "Experimental study of a Λ-structure and its transformation into the turbulent spot," *Curr. Sci. India,* 79, No. 6, 781–789 (2000).
11. V. F. Kop'ev and S. A. Chernyshov, "Oscillations of a vortex ring, emergence of turbulence in it, and generation of sound," *Usp. Fiz. Nauk*, 170, No. 7, 713–742 (2000).
12. S. C. Crow and F. H. Champagne, "Orderly structure in jet turbulence," *J. Fluid Mech.,* 48, 547–591 (1971).
13. A. J. Yule, "Large-scale structure in the mixing layer of a round jet," *J. Fluid Mech.*, 89, 413–432 (1978).
14. J. C. Lau and M. J. Fisher, "The vortex-street structure of 'turbulent' jets," *J. Fluid Mech.*, 67, 299–337 (1975).
15. D. Liepmann and M. Gharib, "The role of streamwise vorticity in the near-field entrainment of round jets," *J. Fluid Mech., 245, 643–668 (1992).*
16. A. K. M. F. Hussain, "Coherent structures and turbulence," *J. Fluid Mech.*, 173, 303–356 (1986).
17. J. H. Citrinity and W. K. George, "Reconstruction of the global velocity field in the axisymmetric mixing layer utilizing the proper orthogonal decomposition," *J. Fluid Mech.*, 418, 137–166 (2000).
18. S. J. Lin and G. M. Corcos, "The mixing layer: deterministic models of a turbulent flow. Part 3. The effect of plain strain on the dynamics of streamwise vortices," *J. Fluid Mech.*, 141, 139–178 (1984).
19. M. M. Rogers and R. D. Moser, "The three-dimensional evolution of a plane mixing layer: the Kelvin–Helmholtz rollup," *J. Fluid Mech.*, 243, 183–226 (1992).
20. M. V. Morkovin, "Unstable vorticity and pressure fields near cylindrical stagnation lines," NASA Report No. 181693, Washington (1977).
21. H. I. Reed, "An analysis of wave interaction in swept-wing flows," in: *Laminar–Turbulent Transition*, Springer-Verlag, Berlin (1985), pp. 471–478.
22. W. M. Saric, "Görtler vortices," *Annu. Rev. Fluid Mech.*, 26, 379–409 (1994).
23. X. Yu and J. T. C. Liu, "The secondary instability in Görtler flow," *Phys. Fluids*, 3, 1845–1847 (1991).

24. W. Liu and J. A. Domaradzky, "Direct numerical simulation of transition to turbulence in Görtler flow," *J. Fluid Mech.*, 246, 267–299 (1993).
25. G. Schlichting, *Boundary Layer Theory*, McGraw-Hill, New York (1968).
26. Y. Kohama, "Behavior of spiral vortices on a rotating cone in axial flow," *Acta Mech.*, 51, 105–114 (1984).
27. Y. Kohama, "Some expectation on the mechanism of crossflow instability in a swept wing flow," *Acta Mech.*, 66, 21–38 (1987).
28. Y. Kohama, W. S. Saric, J. A. Hoos, "A high-frequency, secondary instability of crossflow vortices that leads to transition," in: *Proc. of the Int. Conf. on the Boundary Layer Transition and Control*, Roy. Aeronaut. Soc., London (1991), pp. 4.1–4.13.
29. I. Tani, "Prediction of longitudinal vortices in the boundary layer along a curved wall," *J. Geophys. Res.*, 67, 3075 (1962).
30. Y. S. Kachanov and O. I. Tararykin, "Experimental study of a relaxing boundary layer," *Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk*, No. 5, 9–19 (1987).
31. A. A. Bakchinov, G. R. Grek, B. G. B. Klingmann, and V. V. Kozlov, "Transition experiments in a boundary layer with embedded streamwise vortices," *Phys. Fluids*, 7, 820–832 (1995).
32. V. V. Kozlov and G. R. Grek, "Control of secondary instability of the crossflow and Görtler-like vortices," in: *Lectures Notes in Physics. Physics of Rotating Fluids*, Springer-Verlag, Berlin (2000), pp. 375–394.
33. A. V. Boiko, V. V. Kozlov, V. V. Syzrantsev, and V. A. Shcherbakov, "Experimental study of the transition to turbulence at a single stationary disturbance in the boundary layer of an oblique aerofoil," *J. Appl. Mech. Tech. Phys.*, 36, No. 1, 67–77 (1995).
34. V. V. Kozlov, V. Ya. Levchenko, V. A. Sova, and V. A. Shcherbakov, "Effect of the acoustic field on the flow structure and laminar–turbulent transition on a swept wing," in: *Advanced Problems of Aerohydromechanics*, Proc. Symp. (Moscow, April 12–15, 1999), Vol. 2, Inst. Appl. Math., Russian Acad. of Sci., Moscow (1999), pp. 145–155.
35. V. V. Kozlov, V. A. Sova, and V. A. Shcherbakov, "Experimental study of evolution of secondary disturbances on a swept wing," *Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 5, 92–98 (2001).
36. M. S. Acarlar and C. R. Smith, "A study of hairpin vortices in a laminar boundary layer. Part 1. Hairpin vortices generated by hemisphere protuberances," *J. Fluid Mech.*, 175, 1–41 (1987).
37. M. Mochizuki, "Smoke observation on boundary layer transition caused by a spherical roughness element," *J. Phys. Soc. Jpn, 16, 995–1012 (1961).*
38. P. S. Klebanoff, W. G. Cleveland, and K. D. Tidstrom, "On evolution of a turbulent boundary layer induced by a three-dimensional roughness element," *J. Fluid Mech.*, 237, 101–113 (1992).
39. G. R. Grek, V. V. Kozlov, and M. P. Ramasanov, "Three types of disturbances from the point source in the boundary layer," in: *Laminar–Turbulent Transition*, Springer-Verlag, Berlin (1985), pp. 267–272.
40. K. S. Breuer and M. T. Landahl, "The evolution of a localized disturbance in a laminar boundary layer. Part 2. Strong disturbances," *J. Fluid Mech.*, 220, 595–621 (1990).
41. B. G. B. Klingmann, "On transition due to 3-D disturbances in plane Poiseuille flow," *J. Fluid Mech.*, 240, 167–195 (1992).
42. M. Nishioka, M. Asai, and S. Iida, "An experimental investigation of the secondary instability," in: *Laminar–Turbulent Transition*, Springer-Verlag, Berlin (1980), pp. 37–46.
43. A. N. Gulyaev, V. E. Kozlov, V. P. Kuznetsov, et al., "Interaction of a laminar boundary layer with external turbulence," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 5, 55–65 (1989).
44. V. E. Kozlov, V. R. Kuznetsov, B. I. Mineev, and A. N. Secundov, "The influence of free stream turbulence and surface ribbing on the characteristics of a transitional boundary layer," in: *Near Wall Turbulence*, Proc. of the Zorian Zorac Mem. Conf. (Dubrovnik, Yugoslavia, Sept. 14–18, 1988), Zorian Zorac Publ., Dubrovnik (1990), pp. 172–189.
45. M. Matsubara, V. V. Kozlov, P. H. Alfredsson, et al., "On flat plate boundary layer perturbations at high free stream turbulence level," in: *Proc. of the 8th Int. Conf. on the Methods of Aerophysical Research* (Novosibirsk, Sept. 2–6, 1996), Part 1, Inst. Theor. Appl. Mech., Sib. Div., Russ. Acad. of Sci. (1996), pp. 174–179.
46. P. H. Alfredsson., A. A. Bakchinov, V. V. Kozlov, and M. Matsubara, "Laminar–turbulent transition structures at a high level of a free stream turbulence," in: *Proc. of the IUTAM Symp. on Nonlinear Instability and Transition in Three-Dimensional Boundary Layers* (Manchester, U.K., July 17–20, 1995), Kluwer Acad. Publ., Manchester (1996), pp. 423–436.
47. V. V. Kozlov and G. R. Grek, "Visualization of the laminar–turbulent transition in the wing boundary layer at high free stream turbulence," in: *Proc. of the 6th Asian Symp. on Visualization* (Pusan, Korea, May 27–31, 2001), REXCO, Pusan (2001), pp. 372–377.

48. A. P. Brylyakov, V. N. Kovrizhina, B. Yu. Zanin, and G. M. Zharkova, "Spatial vortex system in the boundary layer over the windward side of wing," in: *Proc. of the 6th Asian Symp. on Visualization* (Pusan, Korea, May 27–31, 2001), REXCO, Pusan (2001), pp. 269–271.
49. M. L. Landahl, "A note on an algebraic instability of inviscid parallel shear flows," *J. Fluid Mech.*, 98, 243–251 (1980).
50. V. V. Kozlov, A. A. Bakchinov, L. L. Löfdahl, and V. G Chernorai, "Streamwise structures in boundary layers and jets," in: *Stability of Homogeneous and Inhomogeneous Liquid Flows*, Abstracts of VIII Int. Conf. (Novosibirsk, April 25–27, 2001), Inst. Theor. Appl. Mech., Sib. Div., Russ. Acad. Sci., Novosibirsk (2001), p. 84.
51. V. G. Chernoray, A. A. Bakchinov, V. V. Kozlov, and L. L. Löfdahl, "The role of streamwise structures in the near-field entrainment of plane jet," in: *Ercoftac Colloquium on Swirling Flows*, Book of Abstr. of 426th Euromech. (Bergen-Tromsø, Norway, Sept. 16–20, 2001), Norwegian Technol. Univ., Trondheim (2001), pp. 9–10.