ORIGIN OF TURBULENCE IN NEAR-WALL FLOWS

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The origin of turbulence in fluids is a long-standing problem being in focus of researches through decades due to its great importance in a variety of engineering applications. Meanwhile, the study of turbulence origin is a part of the fundamental physical problem of the turbulence description and the philosophical problem of determinism and chaos. This paper is concern to a review of new findings in the field of laminar-turbulent transition of near-wall flows.

1. Introduction

The complete solution of the laminar-turbulent transition problem bears substantial mathematical difficulties, being the reason to divide the process into a sequence of stages appropriate for examination by simplified models. The classical linear stability theory describes low-intensity shear-layer perturbations as the instability waves. The lack of the theory to account for origination of the latter inevitably results in the problem of their excitation by external-flow disturbances. Finally, the perturbation growth beyond certain amplitude threshold is accompanied by exchange of instability, non-linear effects as waves interactions, base-flow distortions, appearance of turbulent spots, etc.

2. Modern aspects of the linear instability

In experiments by Klingmann, Boiko, Westin, Kozlov and Alfredsson (1993) it became possible to remove the suction peak near the leading edge and to reduce the pressure gradient region. The experimental theoretical neutral disturbance data are given in Fig. 1. As seen, for the low frequencies, the difference between the theoretical curves appeared to be practically negligible. The experiments showed also that the linear parallel stability theory predicts well the distributions of amplitudes, wave numbers, growth rates and neutral stability of the two-dimensional Tollmien–Schlichting waves. The assumption of the boundary layer parallelity allows to acquire quite precise results for the disturbance growth rates, except for the most upper part of the neutral stability curve, where it is necessary to take into account the effects of flow nonparallelity which are quite small.

The classical analysis of the linear stability treats the disturbances as separate modes of the Orr–Sommerfeld and Squire 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. The phenomenon of the ‘lift-up’ effect (a redistribution of the streamwise momentum by small velocity perturbations in the direction normal to the shear) leads to a linear in time growth of kinetic energy of three-dimensional localized disturbances with $\alpha = 0$, though the viscosity effects eventually prevent the unbounded algebraic growth of the disturbance energy, i.e. it experiences a *temporary growth*.

Similarly, in experiments under natural conditions at high free stream turbulence level $\mathrm{Tu} \geqslant 1\%$, two types of phenomena are usually distinguished inside the boundary layer both of which can be responsible for the transition to turbulence (Boiko, Westin, Klingmann, Kozlov & Alfredsson, 1994): the generation of the Tollmien–Schlichting waves and the generation of the quasi-stationary longitudinal (vortical) structures or ‘streaks’, which grow downstream by amplitude and length. Their appearance is usually attributed to the lift-up effect.

Grek et al. (1985) excited the flat plate boundary layer in a control manner by a localized periodic suction-blowing of fluid of different intensities and frequencies. Additionally to the linear wave packets and turbulent spots, they found a localized structure with very specific characteristics called ‘streak’ which have many characteristic typical for that predicted by the theory of algebraic instability, Fig. 2. The structures were carefully studied in controlled experiments in the flat plate boundary layer as well as straight and swept wing models by Grek, Kozlov and Ramazanov (1991, 1991a), Bakchinov, Grek and Kozlov (1994), Sboev, Bakchinov, Grek and Kozlov (1997), Boiko, Sboev and Grek (2001). Experiments of Sboev, Grek and Kozlov (1999a, 1999b, 2000) showed, that streaks excited through a tube oriented at an angle to free stream or at swept wing, i.e. with a predominant spanwise disturbance velocity excites asymmetric streaks in the boundary layer.

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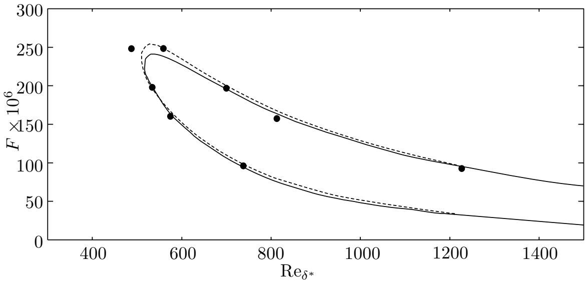

Figure 1. Neutral stability curves: • – experimental data obtained at the inner amplitude maximum (Klingmann et al., 1993); *solid lines* – calculation for parallel flow; *dashed lines* – nonparallel theory (Gaster, 1974)

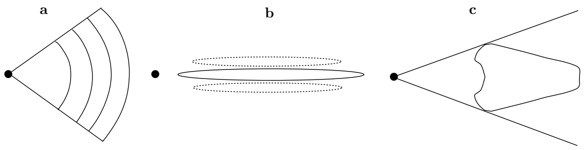

Figure 2. Three types of localized disturbances observed in boundary layer (Grek et al., 1985). (**a**) wave packet; (**b**) streaky structure (‘streak’); (**c**) turbulent spot

The investigations of (Grek, Kozlov & Ramazanov, 1987, 1989; Grek et al., 1991; Grek, Dey, Kozlov, Ramazanov & Tuchto, 1991b; Boiko et al., 1994) carried out in controlled conditions allowed to establish for the first time the possibility of existence, development and influence on transition of the Tollmien–Schlichting waves at high free stream turbulence ($1 < \mathrm{Tu} < 4\%$ of U_∞) both in gradientless and gradient flows. It was revealed that the turbulent spots appeared between the Tollmien–Schlichting waves do not affect essentially main characteristics of their wall-normal amplitude and phase profiles as well as downstream propagation velocity.

3. Receptivity of laminar near-wall flows

The receptivity problem arises when one tries to provide a reasoning for the origin of turbulence in open near-wall flows. The Tollmien–Schlichting wave receptivity is the most important for two-dimensional boundary layers, the crossflow instability is dominant in three-dimensional flows, while the stationary vortices serve as an example of the non-modal receptivity.

Flow visualizations like that of Alfredsson, Bakchinov, Kozlov and Matsubara (1996) show that the streaks start to develop at the leading edge of the plate. Experimentally, the receptivity of the boundary layer to localized free stream disturbances at the leading edge was investigated by Grek et al. (1991b). The experiments showed that the interaction of the free stream localized disturbance with the flat plate boundary layer leads to a generation of the streaks with phenomenological characteristics very similar to that of the streaks formed in the boundary layer under the effect of free stream turbulence. The same disturbances were generated in a flat plate boundary layer by blowing-suction through a hole and a slot in studies of Grek et al. (1985, 1991a).

However, the idea of the distributed receptivity mechanism is supported by the experiments of Grek et al. (1991b, 1991a), Sboev et al. (1997), Westin, Bakchinov, Kozlov and Alfredsson (1998). It was shown that the localized disturbances introduced by means of a short-time blowing through a narrow pipe placed in the free stream in front of the flat plate and a wing initiates the development of decaying streaks in all these cases is in contrast to the continuous downstream growth of the streamwise disturbance observed in the presence of FST.

A reasonable way to introduce certain controlled ‘representative’ vortical disturbances from the free stream into the boundary layer was found by Bertolotti and Kendall (1997). A model vortex in their experiment originated at the tip of a microwing positioned above a flat plate being in front of the leading edge. In the experiments of Boiko (2000), it was found that the streak introduced by this method has the same phenomenological characteristics as those which appeared in the boundary layer under the effect of high FST levels and the leading edge plays no dominant role in the streak growth.

The effect of free stream vorticity on the generation of swept-wing boundary layer structures was carried out experimentally by Boiko (2000). An isolated free stream vortex was excited behind the microwing. The presence of the forcing led to a formation of pronounced stationary disturbances in the boundary layer. Distributions of the streamwise velocity defects are presented in the Fig. 3. It is seen that the presence of the crossflow leads to a multiplication of the excited velocity defects downstream.

The multiplication of stationary vortices is a known feature specific for the development of a localized wave packet of stationary cross flow modes generated from a small-scale boundary nonuniformity due to dispersion characteristic of the vortices: the disturbances with shorter spanwise wavelengths appear on the one side of the wave packet, whereas those of longer wavelengths propagate on the other side. Spectral analysis indicates that the linear stability theory predicts in this case quite well the growth of most amplifying spectral components.

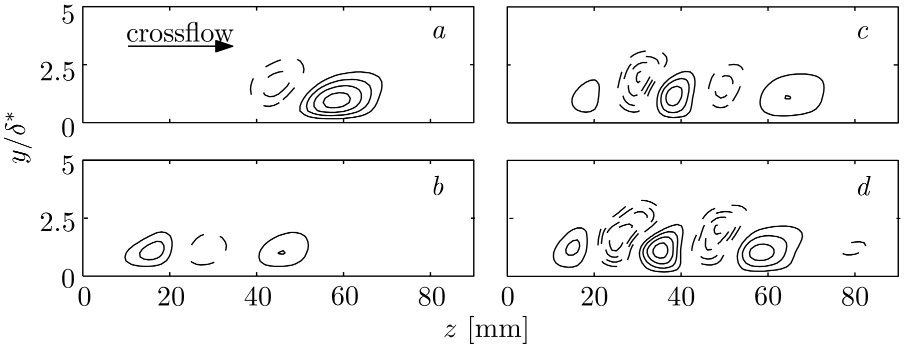

Figure 3. Development of streamwise stationary velocity disturbances in swept-wing boundary layer induced by free-stream vortex: $x/c = 0.38$ (**a**), 0.48 (**b**), 0.70 (**c**), and 0.83 (**d**). Wing chord $c = 500$ mm. Equidistant isolines from -0.130 to 0.116; $U_\infty = 5.4$ m/s (Boiko, 2000)

However, it cannot explain an amplitude maxima which appeared below the neutral spanwise number. Their origin can be attributed to the distributed receptivity due to the presence of the tip vortex along the whole model chord.

4. Late stages of transition

There is a variety of non-linear processes observed at the transition to turbulence. It stipulates to consider some specific scenarios based on the main mechanisms responsible for the formation of pre-turbulent structures. In most details only certain scenarios of the transition for the Blasius boundary layer and flat Poiseuille flow with predominance of two-dimensional instability were investigated at low free stream turbulence level: the so-called subharmonic and K regimes of the transition.

In both cases, Λ-like structures are observed. They are a pair of strong shear layers of a finite length directed under an angle to the flow, both in the streamwise and in the wall-normal directions (Kachanov, Kozlov & Levchenko, 1982, etc.). The fact that the structures were observed in different open and closed flows of the boundary layer and channel types as well as in the presence of body curvature and in separated regions indicates the universality of the mechanisms of their formation.

The Λ-like vortices can appear also without previous amplification of a two-dimensional Tollmien–Schlichting wave. It occurs in the course of development of an isolated wave packet or a pair of oblique waves. Experimental modeling of an isolated Λ-like vortex in the flat plate boundary layer by Grek, Kozlov, Katasonov and Chernorai (2000) showed, that depending on the amplitude of the disturbance excitation both decaying and growing Λ-like vortices can exist. In the experiments by Grek et al. (1991b, 1991a), Grek and Kozlov (1992), Grek (1994) different mechanisms of interactions between the Λ-structures and small-amplitude instability wave were revealed. The interaction of the disturbances produced a non-linear wave packet gradually developing into the turbulent spot. This process was also observed when both the model streak and the waves decayed if being generated separately.

Major aspect of the turbulization process is appearance of incommensurable frequencies by non-linear interactions, which can result in a smooth turbulent spectrum. A mechanism of a secondary flow instability is possible when the turbulization occurs as a result of a primary flow instability to smaller-scale stochastic disturbances. Since in the regions of the large-amplitude primary wave and the secondary instability development the instantaneous velocity distributions have inflection points along normal and spanwise directions such profiles can be inviscidly unstable for high frequencies.

Bakchinov, Grek, Klingmann and Kozlov (1995) in a model experiment generated the boundary layer vortices by roughness elements located periodically along the span of the flat plate. The traveling disturbances inside the vortices were excited by a vibrating ribbon. The simplicity of the flow configuration allowed to study in detail the wave characteristics and the transition to turbulence. Using a similar technique, Boiko, Kozlov, Syzrantsev and Scherbakov (1995b, 1995a) conducted an experimental study of traveling waves in a single vortex of large amplitude exited in a swept wing boundary layer.

Boiko, Kozlov, Syzrantsev and Scherbakov (1997a) proved the linearity of the traveling disturbance growth at the initial stage of their development inside the vortex. It was found, that various disturbance sources (sound and point-like blowing-suction) of the secondary disturbances generate the same traveling disturbances in the vortex. Besides, since the phase and amplitude behaviour of the waves, exited by sound and periodic suction-blowing is identical, it was concluded, that in both cases they are generated by local receptivity mechanism.

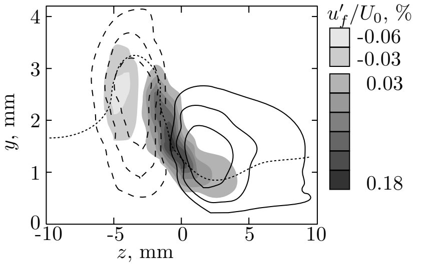

Figure 4. Isolines of disturbances in the region of localization of stationary vortices. (**a**) – $\Delta U/U_0$, (**b**) – $u'_f/U_0\%$, *dash-dotted line* – location of the 'critical layer' $U/U_0 = 0.6$ (Boiko et al., 1997a)

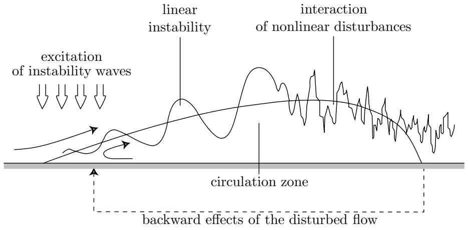

Figure 5. Aspects of laminar-turbulent transition in separation region

The validity of the local secondary instability mechanism for the case under investigation was done by Boiko et al. (1997a). The distributions of mean velocity defect and growing disturbances as well as the position of 'a critical layer' in the (y–z)-plane are shown in Fig. 4. The core of the perturbed region is always close to the 'critical layer' and the distribution of the traveling wave amplitude well correlates with the location of local maximum of the velocity gradient along the spanwise coordinate.

5. Transition to turbulence in separation bubbles

The main reason to deal with flow instability in separation bubbles is their destabilizing influence upon near-wall layers. Experimental results show that the laminar-turbulent transition in separation bubbles starts from spatial amplification of small-amplitude vortical disturbances, i.e. the transition problem for separation regions can be approached in the same way as in other convectively unstable systems, Fig. 5.

Experimental data on receptivity of separation bubbles are those of Dovgal and Kozlov (1983), Boiko, Dovgal, Kozlov, Simonov and Scherbakov (1988), Boiko, Dovgal, Kozlov and Scherbakov (1990), Dovgal, Kozlov and Simonov (1989) for excitation of the instability waves by external acoustic oscillations. Summarizing results of these studies one can distinguish between two main routes of generation, depending on conditions under which a separation occurs. One of them is the transformation of disturbances evolving in the pre-separated boundary layer into the instability waves of the separated flow and the other is excitation just at separation.

The exponential stage of amplification is succeeded by the nonlinear region with wave interactions. In separation bubbles with rather small dispersion of propagating velocities the resonant interaction may occur in a wide wave-number spectrum of two and three-dimensional subharmonic disturbances which was found in wind-tunnel studies of Boiko, Dovgal and Kozlov (1989), Boiko, Dovgal, Simonov and Scherbakov (1991a). Resonant amplification of two-dimensional waves was observed in (Boiko et al., 1989) while the results obtained in (Boiko et al., 1991a) showed that, interacting with a fundamental two-dimensional wave, both two and three-dimensional subharmonic perturbations have comparable growth rates.

Provided the amplitude of the amplifying instability waves is large enough, they modify the transition process inducing perturbations of the reattaching flow which spread all over the bubble affecting its mean and oscillatory characteristics, that breaks down fundamentals of the boundary-layer theory. However, it appears that the the mean-flow sensitivity to amplifying perturbations does not prohibit the linear-stability analysis yielding to solutions which agree with experimental data and results of direct numerical simulations (Boiko, Dovgal & Scherbakov, 1991b; Dovgal & Kozlov, 1995).

6. Flow control techniques

Following to the basic knowledge on boundary-layer transition the main control methods can be divided into the modifiers of stability characteristics of a controlled flow (shaping of a body contour, surface cooling/heating, boundary-layer suction, wall motions) and the modifiers of initial and boundary conditions (reduction of external acoustics, oncoming-flow turbulence, and surface vibrations, smoothing of the wall and protection from its contamination, waves cancellation, riblets).

A temperature difference between the wall and the ambient stream produces a heat flux, modifying mean-velocity profiles and the boundary-layer stability through variation of the fluid viscosity. In a gas, which becomes more viscous with increasing temperature, wall heating destabilizes the flow while wall cooling has the opposite effect. Wind-tunnel experiments on the boundary-layer stability at wall cooling were carried out by Kachanov,

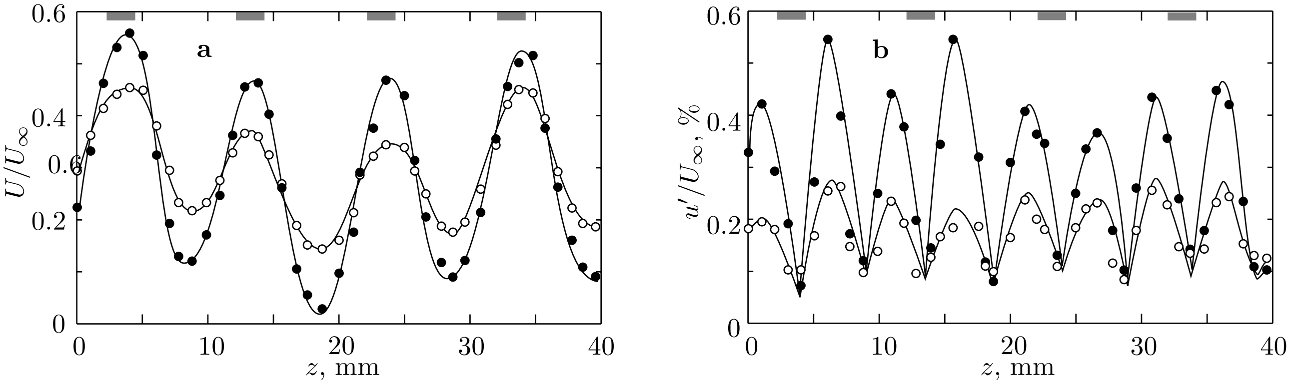

Figure 6. Effect of riblets on transitional flat-plate boundary layer modulated by stationary streamwise vortices (Grek et al., 1995). Transversal variations of the mean flow (**a**) and amplitude of natural disturbances (**b**) on the smooth (●) and ribbed (○) surfaces at $\mathrm{Re}_x = 2.5 \times 10^5$. *Grey regions* – location of roughness elements

Kozlov and Levchenko (1974). Under the control, the neutral curve moves towards higher Reynolds numbers at a reduced frequency range of amplifying disturbances.

Meanwhile, results of linear-stability calculations and experimental data indicate that at a nonuniform surface-temperature distribution the effect can be opposite (Dovgal, Levchenko & Timofeev, 1990).A local heating of a flat plate near its leading edge or its downstream sections reduces amplification of the boundary-layer oscillations and increases the transition Reynolds number. Moreover, it was found that the method can be used for laminarization of a three-dimensional boundary layer, when transition is initiated by Tollmien–Schlichting waves.

Streamwise small-size grooves on a body surface used for the boundary-layer control are known as riblets. The successful control of turbulent flows by the riblets initiated researches on the method in transitional boundary layers. Details of the transition control by riblets were elucidated through experimental modeling in a series of studies by (Grek, Kozlov, Titarenko & Klingmann, 1995; Grek, Kozlov & Titarenko, 1996a, 1996b). The wind-tunnel results have shown, that riblets mounted in a flat-plate boundary layer stimulate the transition destabilizing the flow to Tollmien–Schlichting waves, but have an opposite effect modifying evolution of Λ-structures and stationary vortices.

Another possible application of riblets is control of a boundary layer modulated by streamwise stationary vortices. This problem was explored by Grek et al. (1995) for a flat-plate flow perturbed by streamwise vortices which were generated by three-dimensional roughness elements periodically spaced across the test surface. The influence of the riblets on mean velocity and natural traveling disturbances is shown in Fig. 6. The same was observed at a control excitation of the traveling waves both inflat plate and swept wing flows (Boiko, Kozlov, Syzrantsev & Scherbakov, 1997b).

An approach to transition control which consists in manipulation of the boundary-layer disturbances without affecting the base-flow characteristics is suppression of the instability waves by external periodic forcing in an appropriate phase difference with the controlled perturbations. Gilev and Kozlov (1985) used surface vibrations and Gilev and Kozlov (1987) employed a periodic suction-blowing through a perforated wall section and a transverse slot, controlling the instability waves excited by a vibrating ribbon. In both cases the boundary-layer transition was postponed at opposite phases of the oscillations.

Boiko, Kozlov, Syzrantsev and Shcherbakov (1999) applied the method for suppression of secondary instability in a boundary layer modulated by stationary streamwise vortices. In their experiments the traveling waves developing on the vortices were modeled by external acoustic excitation and the controlling disturbances were generated by periodic suction-blowing through a hole on the test surface. As a result, they managed to reduce the amplitude of secondary perturbations within the vortex which was above the source of oscillations. Further extension of the idea to postpone onset of turbulence by injection of controlled boundary-layer disturbances is reported by Bakchinov, Katasonov, Alfredsson and Kozlov (2000). When turning to by-pass transition they delayed the laminar-flow breakdown, affecting three-dimensional localized nonlinear boundary-layer disturbances by impulsive suction and blowing.

A problem concerning engineering applications of the above results obtained by modeling of disturbances interactions is that during natural transition to turbulence, normally, a broad spectral band of oscillations grows. It is believed that identification of the fine structure of boundary-layer perturbations and their selective control can be achieved through the progress in micro-electro-mechanical systems (MEMS). To realize this concept of control a number of problems are to be dealt with concerning micromechanics of solids and fluids as well as organization of the distributed control circuit.

References

Alfredsson, P. H., Bakchinov, A. A., Kozlov, V. V. & Matsubara, M. (1996). Laminar-turbulent transition at a high level of a free stream turbulence. In P. W. Duck & P. Hall (Eds.), *Nonlinear Instability and Transition in Three-Dimensional Boundary Layers* (Vol. 35, p. 423-436). Manchester: Kluwer Academic Publ.

Bakchinov, A. A., Grek, G. R. & Kozlov, V. V. (1994). Experimental investigation of localized disturbances inlaminar boundary layer. *Thermophysics and Aeromechanics*, *1*(1), 51-58.

Bakchinov, A. A., Grek, H. R., Klingmann, B. G. B. & Kozlov, V. V. (1995). Transition experiments in a boundary layer with embedded streamwise vortices. *Phys. Fluids A*, *7*(4), 820-832.

Bakchinov, A. A., Katasonov, M. M., Alfredsson, P. H. & Kozlov, V. V. (2000). Control of streaky structures by localized blowing and suction. In H. F. Fasel & W. S. Saric (Eds.), *Laminar-Turbulent Transition* (p. 161-166). Berlin: Springer-Verlag.

Bertolotti, F. P. & Kendall, J. M. (1997). *Response of the boundary layer to controlled free-stream vortices of axial form* (AIAA Paper No. 97–2018).

Boiko, A. V. (2000). *Receptivity of boundary layers to free streamaxial vortices* (IB No. 223–2000 A10). Göttingen: German Aerospace Center (DLR) – Institute for Fluid Mechanics.

Boiko, A. V., Dovgal, A. V. & Kozlov, V. V. (1989). Nonlinear interactions between perturbations in transition to turbulence in the zone of laminar boundary-layer separation. *Soviet J. Appl. Phys.*, *3*(2), 46-52.

Boiko, A. V., Dovgal, A. V., Kozlov, V. V. & Scherbakov, V. A. (1990). Instability and receptivity of a boundary layer close to 2D surface imperfections. *Izvestiya Sibirskogo Otdeleniya Akademii Nauk SSSR, Seriya Tekhnicheskikh Nauk*, *1*, 50-56. (In Russian)

Boiko, A. V., Dovgal, A. V., Kozlov, V. V., Simonov, O. A. & Scherbakov, V. A. (1988). *Laminar flow separation at 2D bumps in a boundary layer* (Preprint No. 7–88). Novosibirsk: RAS. Sib. Branch. Inst. Theoret. Applied Mech. (In Russian)

Boiko, A. V., Dovgal, A. V. & Scherbakov, V. A. (1991b). *An effect of small-amplitude disturbances on a laminar separation bubble* (Preprint No. 5–91). Novosibirsk: RAS. Sib. Branch. Inst. Theoret. Applied Mech. (In Russian)

Boiko, A. V., Dovgal, A. V., Simonov, O. A. & Scherbakov, V. A. (1991a). Effects of laminar-turbulent transition in separation bubbles. In V. V. Kozlov & A. V. Dovgal (Eds.), *Separated Flows and Jets* (p. 565-572). Berlin: Springer-Verlag.

Boiko, A. V., Kozlov, V. V., Syzrantsev, V. V. & Scherbakov, V. A. (1995a). Experimental investigation of high frequency secondary disturbances in swept wing boundary layer. *Applied Mechanics and Theoretical Physics*, *36*(3), 74-83. (In Russian)

Boiko, A. V., Kozlov, V. V., Syzrantsev, V. V. & Scherbakov, V. A. (1995b). Experimental investigation of the transition process at an isolated stationary disturbance in swept wing boundary layer. *Applied Mechanics and Theoretical Physics*, *36*(1), 72-84. (In Russian)

Boiko, A. V., Kozlov, V. V., Syzrantsev, V. V. & Scherbakov, V. A. (1997a). Investigation of influence of internal structure of streamwise vortex on development of traveling disturbances in it. *Thermophysics and Aeromechanics*, *4*(4), 1-13.

Boiko, A. V., Kozlov, V. V., Syzrantsev, V. V. & Scherbakov, V. A. (1997b). Transition control by riblets in swept wing boundary layer with embedded streamwise vortex. *European J. Mech., B/Fluids*, *16*(4), 465-482.

Boiko, A. V., Kozlov, V. V., Syzrantsev, V. V. & Shcherbakov, V. A. (1999). Active control over secondary instability in a three-dimensional boundary layer. *Thermophysics and Aeromechanics*, *6*(2), 167-178.

Boiko, A. V., Westin, K. J. A., Klingmann, K. G. B., Kozlov, V. V. & 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.

Boiko, A., Sboev, D. S. & Grek, G. R. (2001). *Linear mechanisms for evolution of streaky structures in a boundary layer.* (To be published)

Dovgal, A. V. & Kozlov, V. V. (1983). Influence of acoustic perturbations on the flow structure in a boundary layer with adverse pressure gradient. *Fluid Dyn.*, *18*, 205-209. (Transl.)

Dovgal, A. V. & Kozlov, V. V. (1995). On nonlinearity of transitional boundary-layer flows. *Philos. Trans. Roy. Soc. London Ser. A*, *352*, 473-482.

Dovgal, A. V., Kozlov, V. V. & Simonov, O. A. (1989). Acoustic excitation of a swept-wing boundary layer. *Uchenyye Zapiski TsAGI*, *20*(6), 21-26. (In Russian)

Dovgal, A. V., Levchenko, V. Y. & Timofeev, V. A. (1990). Boundary layer control by a local heating of the wall. In D. Arnal & R. Michel (Eds.), *Laminar-Turbulent Transition* (p. 113-121). Berlin: Springer-Verlag.

Gaster, M. (1974). On the effects of boundary-layer growth on flow stability. *J. Fluid Mech.*, *66*, 465-480.

Gilev, V. M. & Kozlov, V. V. (1985). Boundary-layer transition control by small-amplitude local surface vibrations. *Izvestiya Sibirskogo Otdeleniya Akademii Nauk SSSR, Seriya Tekhnicheskikh Nauk*, *2*(10), 110-115. (In Russian)

Gilev, V. M. & Kozlov, V. V. (1987). Effect of alternating injection and suction on transition in the boundary layer. *Fluid Mechanics – Soviet Research*, *16*(3), 61-68.

Grek, G. R. (1994). Laminar-turbulent transition at higher free stream turbulence and disturbances development control occurring at the present conditions. In *International Conference on the Methods of Aerophysical Research* (Vol. 1, p. 110-117). Novosibirsk.

Grek, G. R. & Kozlov, V. V. (1992). Interaction of Tollmien-Schlichting waves and localized disturbances. *Sibirskii Phisiko-Tekhnicheskii Zhurnal*, *33*, 68-76. (In Russian)

Grek, G. R., Kozlov, V. V., Katasonov, M. M. & Chernorai, V. G. (2000). Experimental study of a λ-structure and its transformation into the turbulent spot. *Current Science*, *79*(6), 781-789.

Grek, G. R., Kozlov, V. V. & Ramazanov, M. P. (1985). Three types of disturbances from the point source in the boundary layer. In V. V. Kozlov (Ed.), *Laminar-Turbulent Transition* (p. 267-272). Berlin: Springer-Verlag.

Grek, G. R., Kozlov, V. V. & Ramazanov, M. P. (1987). *Laminar-turbulent transition at high free stream turbulence* (Preprint No. 8–87). Novosibirsk: RAS. Sib. Branch. Inst. Theoret. Applied Mech. (In Russian)

Grek, G. R., Kozlov, V. V. & Ramazanov, M. P. (1989). Laminar-turbulent transition at high free stream turbulence in gradient flow. *Izvestiya Sibirskogo Otdeleniya Akademii Nauk SSSR, Seriya Tekhnicheskikh Nauk*, *3*, 66-70. (In Russian)

Grek, G. R., Kozlov, V. V. & Ramazanov, M. P. (1991a). Laminar-turbulent transition at high free stream turbulence: Review. *Izvestiya Sibirskogo Otdeleniya Akademii Nauk SSSR, Seriya Tekhnicheskikh Nauk*, 106-138. (In Russian)

Grek, G. R., Kozlov, V. V. & Ramazanov, M. P. (1991). Study of boundary layer stability at high free stream turbulence in gradient flow. *Fluid Dyn.*, *25*(2), 52-58. (Transl.)

Grek, G. R., Kozlov, V. V. & Titarenko, S. V. (1996a). Effects of riblets on vortex development in the wake behind a single roughness element in the laminar boundary layer on a flat plate. *La Recherche Aérospatiale*(1), 1-9.

Grek, G. R., Kozlov, V. V. & Titarenko, S. V. (1996b). An experimental study on the influence of riblets on transition. *J. Fluid Mech.*, *315*, 31-49.

Grek, G. R., Kozlov, V. V., Titarenko, S. V. & Klingmann, B. G. B. (1995). The influence of riblets on a boundary layer with embedded streamwise vortices. *Phys. Fluids A*, *7*(10), 2504-2506.

Grek, H. R., Dey, J., Kozlov, V. V., Ramazanov, M. P. & Tuchto, O. N. (1991b). *Experimental analysis of of the process of the formation of turbulence in the boundary layer at higher degree of turbulence of windstream* (Tech. Rep. No. 91–FM–2). Bangalor: Indian Institute of Science.

Kachanov, Y. S., Kozlov, V. V. & Levchenko, V. Y. (1974). Experimental study on the effect of wall cooling upon laminar boundary-layer stability. *Izvestiya Sibirskogo Otdeleniya Akademii Nauk SSSR, Seriya Tekhnicheskikh Nauk*, *9*(8), 75-79. (In Russian)

Kachanov, Y. S., Kozlov, V. V. & Levchenko, V. Y. (1982). *Origin of turbulence in boundary layer.* Novosibirsk: Nauka.

Klingmann, K. G. B., Boiko, A. V., Westin, K. J. A., Kozlov, V. V. & Alfredsson, P. H. (1993). Experiments on the stability of Tollmien-Schlichting waves. *European J. Mech., B/Fluids*, *12*(4), 493-514.

Sboev, D. S., Bakchinov, A. A., Grek, G. R. & Kozlov, V. V. (1997). boundary layer receptivity to free stream vortical disturbances. In *Stability of Homogeneous and Heterogeneous Fluids* (p. 87). Novosibirsk. (In Russian)

Sboev, D. S., Grek, G. R. & Kozlov, V. V. (1999a). Experimental study of boundary layer receptivity to localized perturbations of the external flow. *TiAe*, *6*(1), 1-13.

Sboev, D. S., Grek, G. R. & Kozlov, V. V. (1999b). On the features of the inner structure of the 'streaky structures'. *TiAe*, *6*(3), 359-370.

Sboev, D. S., Grek, G. R. & Kozlov, V. V. (2000). Experimental study of swept wing boundary layer receptivity to free stream localized disturbances. *TiAe*, *7*(4), 469-480.

Westin, K. J. A., Bakchinov, A. A., Kozlov, V. V. & Alfredsson, P. H. (1998). Experiments on localized disturbances in a flat plate boundary layer. Part 1: The receptivity and evolution of a localized free stream disturbances. *EJMBF*, *17*(6), 823-846.