FLUCOME 2009
10th International Conference on Fluid Control, Measurements, and Visualization
August 17–21, 2009, Moscow, Russia

ACTUAL PROBLEMS OF THE SUBSONIC AERODYNAMICS
(prospect of shear flows control)

Viktor Kozlov[1]

ABSTRACT

Scientific problems related to modern aeronautical engineering and dealing with basic properties of shear flows and the associated fluid mechanics phenomena are emphasized. In this context some recent experimental results on subsonic aerodynamics are considered.

Keywords: hydrodynamic instability, flow laminarization, flow control, MEMS - technology.

INTRODUCTION

Optimization of aerodynamics of modern and perspective air vehicles needs the solution of several fluid mechanics problems. They are related to studying the flow phenomena occurring close to a body surface with further elaboration of new methods to control local and global flow characteristics. As a result, it becomes possible to increase lift of wings, reduce drag of the vehicles and their acoustic radiation. As a whole, flow control is aimed at improvement of economy and operational functionality of air vehicles of different destination.

A phenomenon which is crucial for the near-wall flow pattern is hydrodynamic instability one can observe in two- and three-dimensional attached and separated boundary layers. Amplification of the laminar flow disturbances results, finally, in transition to turbulence, generation of vortex structures close to the body surface, and has a strong effect on formation of separated flow regions.

Thus, solution of the aerodynamic problems is integrated to studying various aspects of flow instability. In what follows, exploration results obtained recently on this topic are discussed from the standpoint of the main, by the author sight, problems of fluid mechanics involved in progress of commercial aviation.

1. FLOW LAMINARIZATION ON LIFTING SURFACES

In laminar boundary layers the skin friction is much smaller than that in turbulent layers which is the reason for flow laminarization. Maintenance of the laminar flow over an extended part of the wing is obviously appropriate for fuel savings and increasing efficiency of the aircraft.

Basically, the problem is approached through current knowledge on transition to turbulence in boundary layers at a low level of the external flow perturbations. Normally, the process of laminar-turbulent transition is subdivided into several main stages including generation of the boundary layer disturbances, their subsequent amplification at small amplitudes of the exited oscillations, and nonlinear interactions of the perturbations prior to onset of the turbulent motion, Fig. 1. Accordingly, the methods of transition delay utilize reduction of the initial amplitudes of the laminar boundary layer

---

[1] Corresponding author: Khristianovich Institute of Theoretical and Applied Mechanics, SB of Russian Academy of Sciences, e-mail: kozlov@itam.nsc.ru

disturbances and modification of its stability characteristics, see [1–3]. To date, the linear theory of hydrodynamic stability, dealing with exponentially growing (damping) wavy disturbances in two- and three-dimensional boundary layers, has been verified in a large number of experiments. The methods of laminarization employing stability solutions are well substantiated so that some of them are in use in engineering applications.

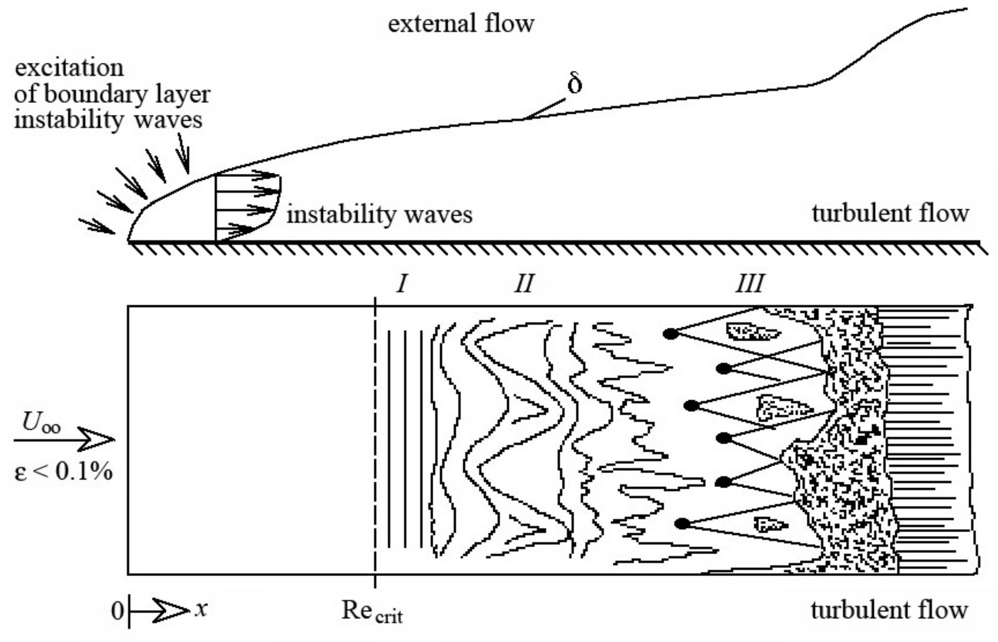

Fig. 1. Main stages of laminar-turbulent transition in a boundary layer at a low level of the external flow turbulence: I – amplification of small-amplitude perturbations (Tollmien-Schlichting waves), II – evolution of three-dimensional non-linear disturbances (Λ-structures), III – origination and interaction of turbulent spots [4].

Beyond the scope of the classic stability theory are specific localized disturbances of the boundary layer, the so called “streaky (streamwise) structures” or “streaks”, nowadays calling much interest during the research of laminar-turbulent transition, see [3–5]. Under appropriate conditions, such structures may grow in the streamwise direction initiating secondary disturbances and□-shaped vortices found at late stages of the transition to turbulence in boundary layers, Fig. 2. In this case, the effect of laminarization can be obtained through application of control techniques for modification of the origination and dynamics of the localized perturbations which are to be investigated in more details.

The streaky structures developing in Blasius boundary layer, on straight and swept wings were examined under controlled experimental conditions in a series of recent studies [7–9]. Along with determination of main characteristics of the localized laminar flow disturbances, some approaches to their control were tested. One of them is application of the surface grooves, or riblets, used for drag reduction in a turbulent boundary layer. As a result of Ref. [7], a beneficial effect of streamwise riblets on the transitional flow was observed, that is, diminution of the streaky structures magnitude, suppression of their secondary oscillations and Λ-shaped vortices, Fig. 3. Another possibility to delay the transition to turbulence caused by evolution of the streaky structures was examined in [8] where the boundary layer was controlled by flow suction through tiny holes in the surface of experimental models. This technique, similarly to the surface ribbing, was found as an effective one for damping of the streaks and their secondary instabilities. Interaction of the streaky structures generated by roughness elements on a swept wing was investigated in Ref. [9].

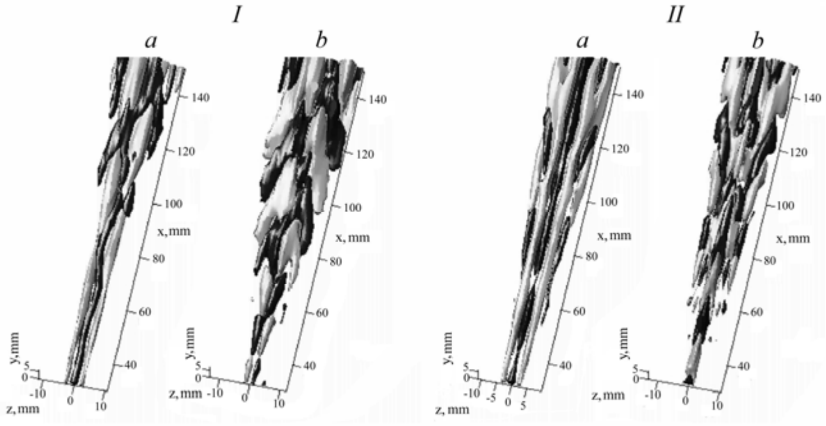

Fig. 2. Streaky structures of a laminar boundary layer with amplifying antisymmetric (I) and symmetric (II) secondary oscillations: the streamwise evolution of the secondary disturbances combined with their effect on the mean flow (a) and without it (b) (dark and light halftones indicate the regions of increased and reduced flow velocity comparing to its unperturbed values) [6].

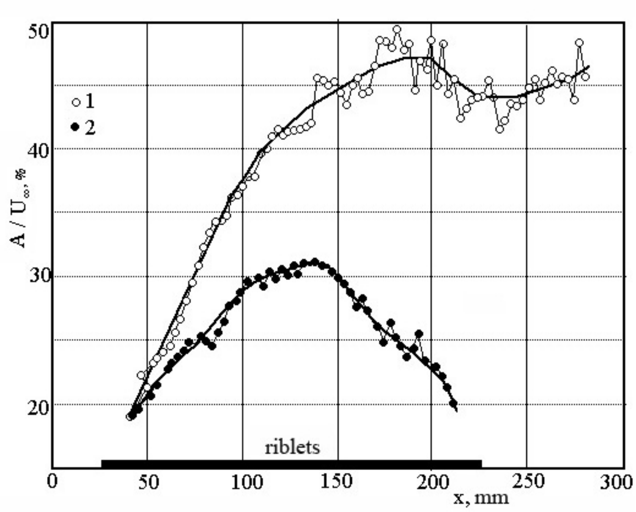

Fig. 3. Streamwise amplitude variations of Λ-shaped vortices on the smooth (1) and grooved (2) flat plates [7].

The experiments have shown that isolated stationary disturbances of the boundary layer are more prone to high-frequency secondary instabilities and the following turbulization, than the interacting perturbations evolving close to each other, Fig. 4.

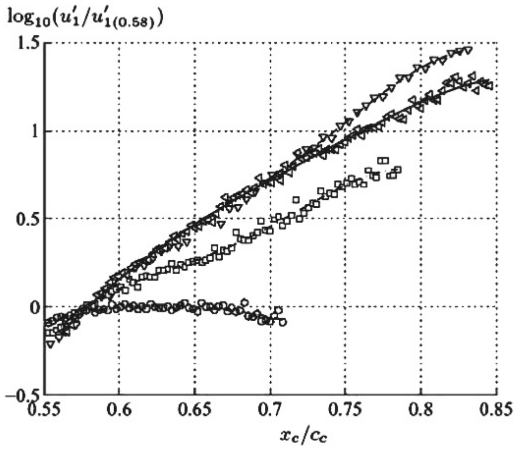

Fig. 4. Streamwise amplitude variations of the secondary perturbations evolving on the isolated (□, Δ) and interacting (○) streaky structures [9].

Thus, one expects the transition to turbulence induced by the streaky structures generated at the roughness elements can be controlled by optimization of their shape, size and the spatial arrangement.

As a whole, the results of the above studies substantiate new approaches to laminarization of the lifting surfaces in addition to the control methods inferred from the classic stability theory.

2. MODIFICATION OF TURBULENT FLOW OVER BLADES OF COMPRESSORS AND TURBINES

Normally, compressors and turbines blades are operated at high levels of the external flow vortical and acoustic perturbations, Fig. 5.

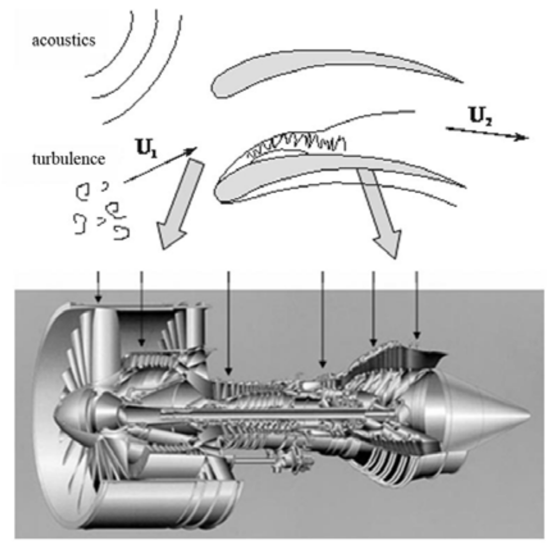

Fig. 5. Blades of engine GE CF6-50 affected by the external flow perturbations.

Thus, aerodynamic characteristics of the blades are dominated by the structure of the strongly disturbed near-wall flow and, basically, can be optimized employing boundary-layer control. In turn, to choose properly an effective control technique, more details on the boundary layer subject to high amplitude background perturbations are necessary.

Research data on laminar-turbulent transition indicate that under such conditions it is essentially different from that at a low level of environmental disturbances and is associated with the above streaky structures. As an illustration, in Fig. 6 results of the boundary-layer visualization obtained at variation of the external flow turbulence are shown.

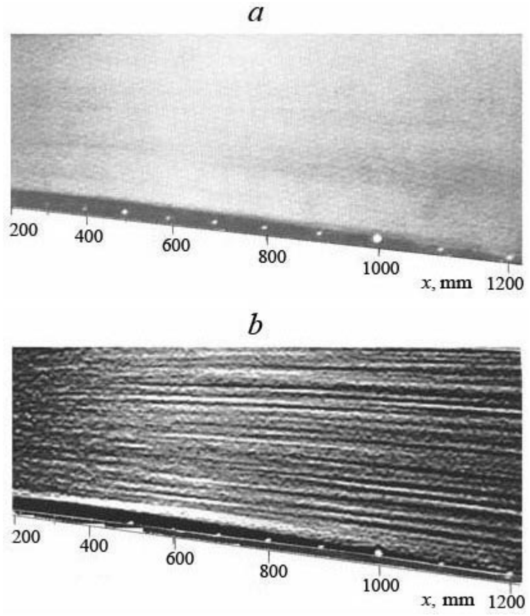

Fig. 6. Smoke visualization of the circular jet (a) and its vortex structures at different streamwise distance from the nozzle exit (b–h) [4].

The streaks generated in the near-wall region have a pronounced effect upon the flow characteristics inducing, in particular, transverse oscillations up to 20 per cent of the local heat transfer coefficient [13].

Generation of the streaky structures in boundary layers by the external turbulence was studied in Refs. [13, 15, 16] where the flow was perturbed by turbulizing grids placed in the upstream part of the wind tunnel test section. Experimental data were obtained at low subsonic velocities for both a wing and a wedge flows. At variation of the external flow turbulence level up to 1.8 per cent, the streaky structures were observed exceeding in their transverse spacing several times the boundary layer thickness. It was found that the spanwise scale and spatial arrangement of the structures near the surface are given by the grid turbulence. Through analysis of the wind tunnel results it was shown that the streaks excitation was called by vorticity stretching. Also, a possibility to modify the streaks scale and arrangement by a small amplitude acoustic forcing in the range of linear shear layer instability was clarified.

It is expected that to modify the streaks induced in the boundary layer by external flow turbulence the methods mentioned in the first section of this paper, which were tested at controlled excitation of perturbations on the surface of experimental models, can be used as well. In this case, identification of the streaky structures occurring in random way should be foreseen in the flow control system.

3. CONTROL OF INSTABILITY AND ACOUSTIC RADIATION OF JETS

Mixing in jets is of importance for combustion, acoustics of aircrafts and other air vehicles, design and construction of nozzles and combustion chambers. To a great extent gas mixing in jets depends on the flow turbulization, origination and dynamics of large scale energetic vortex structures. Those are quasi two-dimensional vortices induced by the Kelvin-Helmholtz instability and the streamwise structures, the latter generated by a special configuration of the nozzle or by secondary instabilities of the jet. The streamwise vortices interacting with the Kelvin-Helmholtz ones are involved, for example, in jet combustion and its stabilization.

There are a number of methods which are in use to control jets including acoustic forcing, generation of backflow close to the nozzle exit, excitation of streamwise vortices and shocks interacting with the mixing layer at supersonic flow velocities. A control approach coming from the concept of hydrodynamic instability is to affect directly the oscillatory flow component, that is, linear or nonlinear wavy disturbances amplifying in the shear layer at the jet periphery and coherent vortex structures. Implementation of this idea needs investigation of the fine structure of the disturbed flow and its dynamics.

This was in focus of Refs. [17, 18] where different flow configurations including circular, plane and near-wall plane jets were dealt with. In the experiments the natural vortex structures originating in the jets were stabilized by a forcing periodic in time combined with spatially periodic roughness elements placed near the nozzle exit. In this way, interaction of the Kelvin-Helmholtz vortices with the streamwise flow perturbations was clarified, Fig. 7.

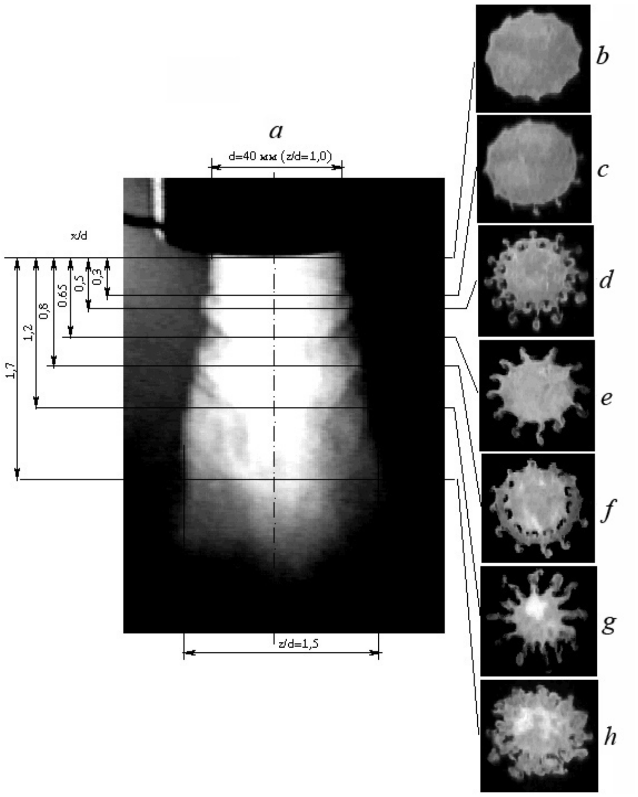

Fig. 7. Smoke visualization of the circular jet (a) and its vortex structures at different streamwise distance from the nozzle exit (b–h) [17].

Its similarity to three-dimensional distortion of two-dimensional nonlinear instability waves observed in attached boundary layers resulting in formation of the Λ-shaped vortices was found, Fig. 8.

Also, the effect of Reynolds number on transverse scale of the streamwise structures was elucidated and a possibility to modify their characteristics as well as the transition to turbulence in the jets by controlled excitation of two-dimensional waves in the jet shear layer was shown.

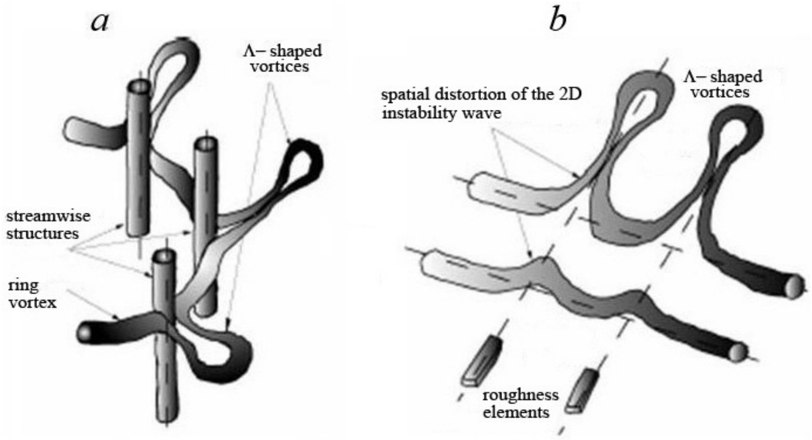

Fig.8. Scheme of the vortex structures interaction in the circular jet (a) and in the attached boundary layer (b) [17].

Most likely, perfection of the existing methods of jets control and elaboration of perspective ones are related to oncoming studies on origination and dynamics of the vortex structures dominating the perturbed flow pattern.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (grant no. 08-01-00027), the Program of Support for Leading Scientific Schools (NSh-454.2008.1), Ministry of Education and Science of the Russian Federation (project RNP 2.1.2.541).

REFERENCES

1. Schlichting H., Gersten K. Boundary layer theory. Berlin: Springer, 2000.
2. Gad-el-Hak M. Flow control: passive, active and reactive flow management. Cambridge: Cambridge University Press, 2000.
3. Bojko A.V., Greek Г.Р., Dovgal A.V., Kozlov V.V. Physical mechanisms of transition to turbulence in open flows. Moscow - Izhevsk: Research center “Regular and Chaotic Dynamics”, Institute of Computer Science, 2006 (in Russian).
4. Boiko A.V., Grek G.R., Dovgal A.V., Kozlov V.V. The origin of turbulence in near-wall flows. Berlin: Springer, 2002.
5. Schmid P.J., Henningson D.S. Stability and transition in shear flows. Berlin: Springer, 2000.
6. Litvinenko Yu.A., Chernorai V.G., Kozlov V.V., Löfdahl L.L., Grek G.R., Chun H. Nonlinear sinusoidal and varicose instability in the boundary layer (review) // Thermophysics and Aeromechanics, 2004, vol.

11, no. 3, pp. 329-353.

7. Litvinenko Yu. A., Chernoray V.G., Kozlov V.V., Löfdahl L., Grek G.R., Chun H.H. The influence of riblets on the development of a Λ-structure and its transformation into a turbulent spot // Doklady Physics, 2006, vol. 407, no. 1-3, p. 144.
8. Litvinenko Yu.A., Kozlov V.V., Chernoray V.G., Grek G.R., Löfdahl L. Control of spanwise flow instability of a swept wing by suction // Thermophysics and Aeromechanics, 2003, vol. 10, no. 4, pp. 541–548.
9. Kozlov V.V., Chernoray V.G., Dovgal A.V., Löfdahl L. Experiments on secondary instability of streamwise vortices in a swept wing boundary layer // J. Fluid Mech., 2005, vol. 534, pp. 295-325.
10. Chang P.K. Control of flow separation. Washington: Hemisphere Publishing Corp., 1976.
11. Zverkov I.D., Zanin B.Yu. Wing form effect on flow separation // Thermophysics and Aeromechanics, 2003, vol. 10, no. 2, pp. 197-204.
12. Zverkov I.D., Sboev D.S. Application of a combined method to study the separation flows on a wavy-surface wing model // Intern. Conf. on the Methods of Aerophysical Research, Novosibirsk, 2004, part 1, p. 215-219.
13. Brylyakov A.P., Zharkova G.M., Zanin B.J., Kovrizhina V.N., Sboev D.S. Steady streamwise structures in the boundary layer on a swept wing with elevated turbulence of the incoming flow // J. Applied Mechanics and Technical Physics, 2003, vol. 44, no. 5, pp. 648-653.
14. Matsubara M., V.Kozlov V., Alfredsson P. H., Bakchinov A. A., Westin K. J. A. On flat plate boundary layer perturbations at high free stream turbulence level // Intern. Conf. on the Methods of Aerophysical Research, Novosibirsk, 1996, vol. 1, p. 174-179.
15. Zharkova G.M., Zanin B.Yu., Kovrizhina V.N., Brylyakov A.P. Free stream turbulence effect on the flow structure over the finite span straight wing // J. Visualization, 2002, vol. 5, no. 2, pp. 169-176.
16. Bryljakov A.P., Zharkova G.M., Zanin B.J., Kovrizhina V.N., Sboev D.S. Effect of free-stream turbulence on the flow structure near a wedge and the windward side of an airfoil // J. Applied Mechanics and Technical Physics, 2004, vol. 45, no. 4, pp. 510-516.
17. Kozlov V.V., Grek G.R., Löfdahl L.L., Chernorai V.G., Litvinenko M.V. Role of localized streamwise structures in the process of transition to turbulence in boundary layers and jets (review) // J. Applied Mechanics and Technical Physics, 2002, vol. 43, no. 2, pp. 224-236.
18. Levin O., Chernoray V.G., Löfdahl L., Henningson D.S. A numerical and experimental study of the Blasius wall jet // J. Fluid Mech., 2005, vol. 539, pp. 313-347.