Doklady Physics, Vol. 50, No. 3, 2005, pp. 147–150. Translated from Doklady Akademii Nauk, Vol. 401, No. 2, 2005, pp. 189–192.

MECHANICS

Nonlinear Sinusoidal and Varicose Instability in a Boundary Layer

Yu. A. Litvinenko[1], V. G. Chernoraĭ[1], V. V. Kozlov[1], L. Lofdahl[2], G. R. Grek[1], and H. H. Chun[3]

Presented by Academician V.E. Nakoryakov October 7, 2004

Received October 15, 2004

It is well known [1] that the laminar–turbulent transition at a low turbulence level of the free flow is associated with the development of instability waves, the so-called Tollmien–Schlichting waves. When a two-dimensional Tollmien–Schlichting wave reaches a certain amplitude at the nonlinear stage of its development, it undergoes three-dimensional distortion and, as a result, characteristic three-dimensional Λ structures arise [1]. Owing to certain features of the appearance and development of these structures, they are not only typical for the classical laminar–turbulent transition, but are also inevitable attributes of a transition to more complex flows, e.g., flows modulated with longitudinal streaky structures, such as Hertler vortices, transverse-flow vortices on sliding wings, etc., as well as flows in the viscous sublayer of a turbulent boundary layer. In these cases, they arise in particular due to the secondary high-frequency instability of such flows and may be manifested not only as Λ structures, but also in the form of horseshoe vortices (Ω structures), hairpin vortices, etc. A characteristic feature of the development of such structures, e.g., on a sliding wing, is the disappearance of one of the counter-rotating vortices due to the transverse flow, whereas the development of a classical Λ structure can be observed on a straight wing [1].

The high-frequency secondary instability of transition and turbulent near-wall flows in the presence of streaky structures is often attributed to so-called sinusoidal and varicose instability. Both instability modes were investigated under controlled conditions at the linear and initial stages of nonlinear development. When the transverse size of the streaky structure was larger than the thickness of the shear layer, growth of varicose instability was observed. At the same time, when the transverse size of the streaky structure was comparable to or smaller than the thickness of the shear layer, it became more instable with respect to antisymmetric (sinusoidal) modes than to symmetric (varicose) modes. The experiment reported in [2] clearly shows that the growth of the symmetric mode leads to the formation of hairpin vortices, which are a pair of counter-rotating longitudinal vortices that are connected by a head, i.e., a Λ vortex, while an antisymmetric mode is developed to a train of quasi-longitudinal vortices with alternating-sign vorticity. Unfortunately, the experiments reported in [2] concerned only the initial stage of the nonlinear development of disturbances, and spatial resolution was insufficiently high to reveal the structure of the flow in more detail.

In this paper, we report on our experimental investigations of the nonlinear stage of the varicose and sinusoidal instability of the streaky structure in the Blasius boundary layer. In contrast to the experiment reported in [2], the study is more detailed (thermal anemometer measurements of the longitudinal velocity component and velocity pulsations in space (*xyz*) at 5×10^4 points) in order to reveal the features of the dynamics of the appearance, development, and internal structure of coherent formations up to the later stages of their nonlinear development.

The experiments were carried out under controlled conditions in a low-turbulent wind tunnel. A plane plate 14 mm in thickness, 1000 mm in width, and 2000 mm in length was placed in parallel in the operation part of the tunnel. The streaky structure was generated by means of a cylindrical roughness element, which had a height of 1.1 mm and a diameter of 5.8 mm and was placed in the center of the plate at a distance of x_0 = 438 mm from the fore. The velocity of the flow was equal to U_∞ = 7.8 m/s, and the turbulence level was no higher than 0.04%. In the absence of the roughness element, the laminar boundary layer was developed without any waves and the velocity profile was close to the Blasius profile. A roughness-element height of h = 1.1 mm is close to the thickness of the displacement of

[1] *Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences, ul. Institutskaya 4/1, Novosibirsk, 630090 Russia*
e-mail: kozlov@itam.nsc.ru

[2] *Charmers University of Technology, S-41296 Göteborg, Sweden*

[3] *Pusan National University, 609-735 Pusan, Korea*

1028-3358/05/5003-0147$26.00 © 2005 Pleiades Publishing, Inc.

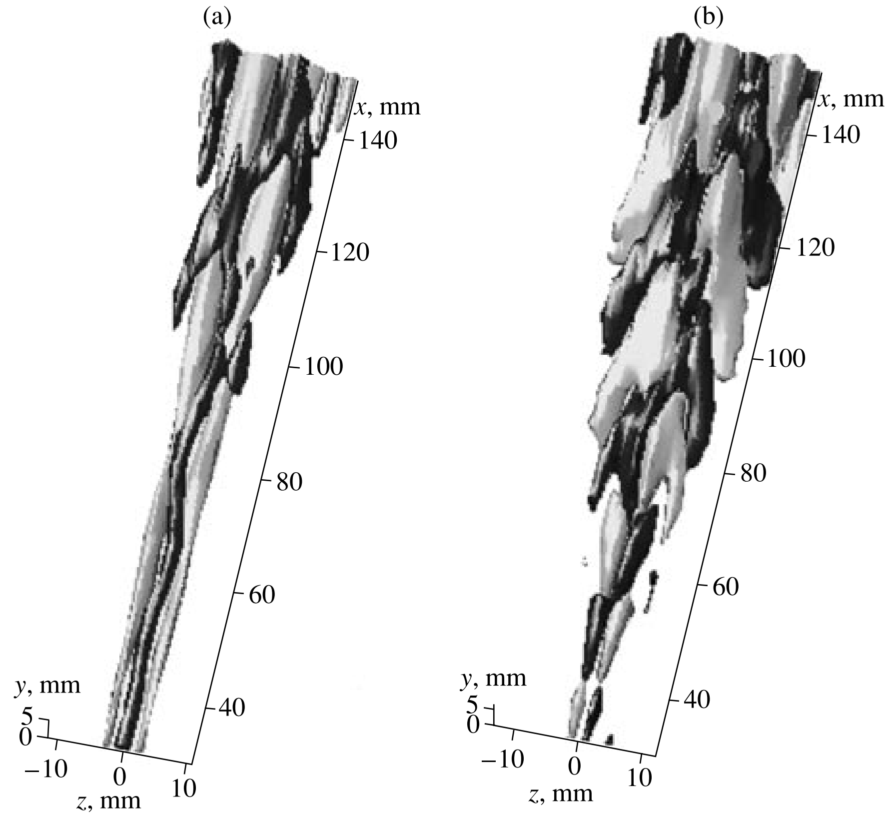

Fig. 1. Spatial patterns of the sinusoidal destruction of the streaky structure: (a) the development of the secondary disturbance jointly with its effect on average velocity (minimum pulsation level 6.4% of U_∞) and (b) the development of the secondary high-frequency disturbance (minimum pulsation level 1.3% of U_∞). Dark and light grey tones are excesses and defects of velocity, respectively.

the Blasius laminar boundary layer δ^*_B = 1.5 mm for $x = x_0$ and U_∞ = 7.8 m/s. The Reynolds number was equal to $R^* = \frac{\delta^*_B U_\infty}{\nu} = 780$ for $x = x_0$. In the absence of artificial disturbances, the boundary layer with the streaky structure remained laminar in the measured range $x - x_0$ = 30–150 mm. This circumstance enabled us to control the instability of the streaky structure by means of artificial disturbances generated by the injection–drainage of a gas through three small holes on the plate surface. One hole ($z = 0$) at $x - x_0$ = 14.5 mm was used to excite transverse symmetric disturbances, and other two holes were used to excite antisymmetric disturbances $\Delta z = \pm 4.5$ mm at $x - x_0$ = 19.5 mm. The excited frequency of the secondary high-frequency disturbance was equal to 150 Hz, which approximately corresponded to a dimensionless parameter of $\frac{2\pi f \nu}{U_\infty^2} \times 10^6 = 232$. The amplitude of the secondary disturbance reached 10% of U_∞ near the source ($x - x_0$ = 30 mm), which made it possible to study the nonlinear stage of the process that was of primary interest. The thermal anemometer measured the time-averaged longitudinal component of the velocity U and velocity pulsation u'.

We consider the flow structure at the nonlinear stage of sinusoidal and varicose instability in more detail. Figure 1 shows patterns of the sinusoidal destruction of the streaky structure. The spatial pattern of the disturbance development (Fig. 1a) shows that transverse meandering of the streaky structure is observed at the initial stage, which is typical for the development of sinusoidal instability. However, the structure of the disturbed downstream region of the flow is transformed to characteristic coherent structures similar to Λ vortices. The development of secondary disturbances is most clearly observed in the spatial pattern presented in Fig. 1b. At the initial stage of disturbance development, a pair of quasi-longitudinal, alternating-sign vortices is observed. Downstream of the flow, they are transformed to Λ structures, and the transverse scale of these coherent structures increases. Thus, detailed thermal anemometer measurements at the nonlinear stage of the development of sinusoidal instability show that the secondary high-frequency destruction of the streaky structure is associated with the formation of Λ structures, the destruction of which downstream of the flow leads to the turbulization of the flow.

Figure 2 shows patterns of the varicose destruction of the streaky structure. The spatial pattern of the disturbance development (Fig. 2a) shows that the longitu-

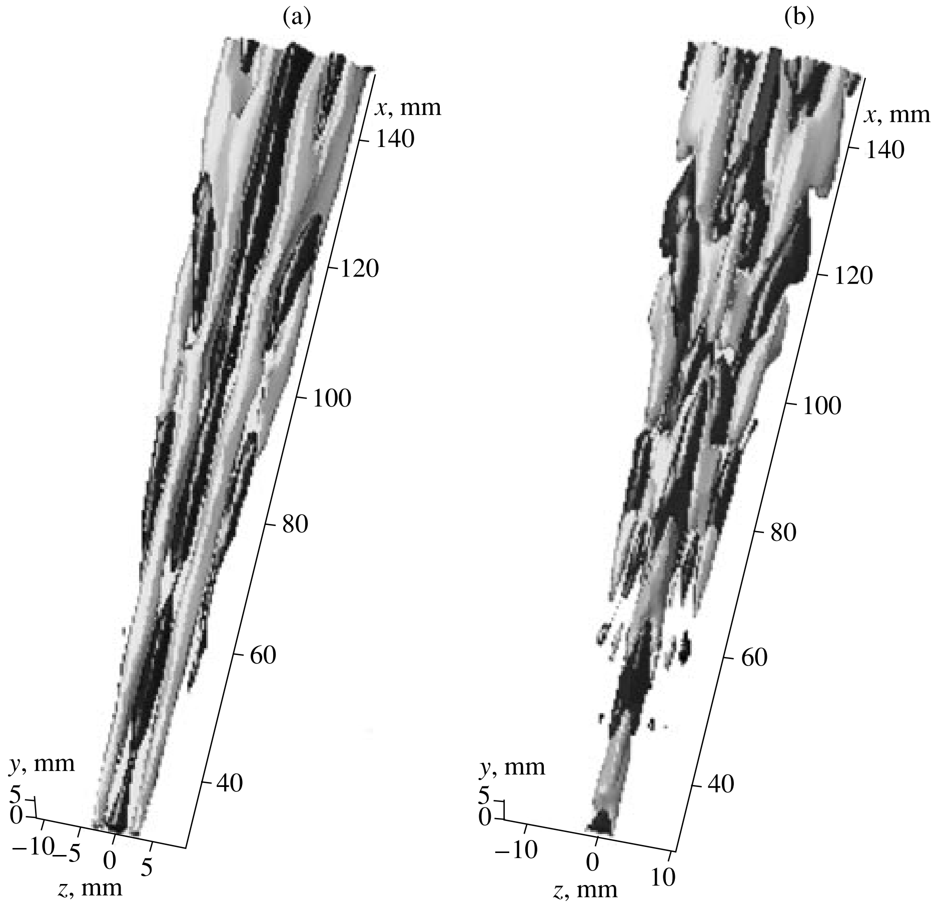

Fig. 2. Spatial patterns of the varicose destruction of the streaky structure: (a) the development of the secondary disturbance jointly with its effect on average velocity (minimum pulsation level 3.8% of U_∞) and (b) the development of the secondary high-frequency disturbance (minimum pulsation level 1.3% of U_∞). Dark and light grey tones are excesses and defects of velocity, respectively.

dinal modulation of the streaky structure by the secondary-disturbance frequency (f = 150 Hz) is observed at the initial section, which is typical of the development of varicose instability. However, the structure of the disturbed region further downstream of the flow is transformed to characteristic coherent structures similar to Λ vortices, as in the case of the sinusoidal destruction of the streaky structure. However, we emphasize that, in contrast to the latter case, Λ structures are asymmetric; i.e., the second counter-rotating vortex is at the formation stage due to weak vorticity at the transverse boundaries of the disturbance field. Below, symmetric Λ structures will be observed when considering the direct development of high-frequency disturbance.

We consider the dynamics of the direct development of secondary high-frequency disturbance generated on the streaky structure. The development of secondary disturbances is most clearly manifested in the spatial pattern shown in Fig. 2b. At the initial stage of disturbance development, a set of quasi-longitudinal vortices is observed, which is transformed downstream of the flow to hairpin vortices or Λ structures. These vortices are pronounced at z = 0 mm in the form of a pair of alternating-sign structures at each period of the secondary disturbance. As was mentioned above, Λ structures or hairpin vortices become asymmetric at $z = \pm 5$ mm (transverse boundaries of the disturbed region). Nevertheless, the structure of the second counter-rotating vortex of these coherent formations is evidently observed. We note that such coherent structures were observed in [2], where the nonlinear stage of varicose instability was studied. Investigations of the varicose instability of a single streaky structure in the boundary layer of the sliding wing [3] show that Λ vortices are transformed to asymmetric structures due to the transverse flow. Thus, detailed thermal anemometer measurements at the nonlinear stage of the development of varicose instability show that the secondary high-frequency destruction of the streaky structure is attributed to the formation of Λ structures, as in the case of the sinusoidal destruction of the streaky structure.

In conclusion, we emphasize that the scenario of classical laminar–turbulent transition at the nonlinear stage of this process is associated with the three-dimensional distortion of the two-dimensional Tollmien–Schlichting wave and the formation of three-dimensional coherent structures of the Λ-vortex type. These investigations show that there are other scenarios for the occurrence of Λ structures in the near-wall shear flows, in particular, in the process of the secondary high-frequency instability of streaky structures of the sinusoidal and varicose types. The secondary high-frequency instability of streaky structures of the sinusoidal and varicose types at the nonlinear stage was found to lead to the multiplication of new streaky structures downstream of the flow. It has been established that the mechanism of the nonlinear destruction of the streaky structure through the development of secondary disturbance in it is associated with the formation of coherent structures of the Λ-vortex type for both sinusoidal and varicose types of instabilities. Λ vortices are shown to be multiplied in the transverse direction upon the evolution of disturbance downstream of the flow. It has been shown that varicose instability can exist on the sliding wing [3], rapidly transforming under the action of the secondary flow to the superposition of structures of sinusoidal and varicose instability.

This result is important for insights concerning both a mechanism of the turbulization of flows modulated by streaky structures and mechanisms of the reproduction of turbulence in turbulent flows, where the dynamics of coherent structures of the viscous sublayer plays a substantial role. The mechanism of the transformation of a Λ structure to a turbulent spot, particularly through the secondary high-frequency instability of its components—two counter-rotating vortices (legs of the structure)—is also well known [4]. At the same time, there are various methods for controlling the development of coherent structures such as Λ vortices, hairpin vortices, streaky structures, etc. As was shown in a number of works, riblets [1, 5–8], localized and distributed drainage [1, 8], transverse vibrations of the wall [9], etc., considerably affect both the intensity of coherent structures and their secondary instability, which can be used to control sinusoidal and varicose instability.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 02-01-00006), the Council of the President of the Russian Federation for Support of Young Russian Scientists and Leading Scientific Schools (project no. NSh-964.2003.1), and Advanced Ship Engineering Research Center of the Korea Science and Engineering Foundation (KOSEF).

REFERENCES

1. A. V. Boiko, G. R. Grek, A. V. Dovgal, and V. V. Kozlov, *The Origin of Turbulence in Near-Wall Flows* (Springer-Verlag, Berlin, 2002).
2. M. Asai, M. Minagawa, and M. Nishioka, J. Fluid Mech. **455**, 289 (2002).
3. Yu. A. Litvinenko, G. R. Grek, V. V. Kozlov, *et al.*, Teplofiz. Aéromekh. **11** (1), 1 (2004).
4. G. R. Grek, V. V. Kozlov, M. M. Katasonov, and V. G. Chernorai, Curr. Sci. **79**, 781 (2000).
5. G. R. Grek, V. V. Kozlov, and S. V. Titarenko, J. Fluid Mech. **315**, 31 (1996).
6. G. R. Grek, V. V. Kozlov, and S. V. Titarenko, Rech. Aerosp., No. 1, 1 (1996).
7. G. R. Grek, V. V. Kozlov, B. G. B. Klingmann, and S. V. Titarenko, Phys. Fluids **7**, 2504 (1995).
8. V. V. Kozlov and G. R. Grek, in *Lectures Notes in Physics. Physics of Rotating Fluids*, Ed. by C. Egbers and G. Pfister (Springer-Verlag, Berlin, 2000), pp. 375–394.
9. M. M. Katasonov and V. V. Kozlov, Izv. Akad. Nauk, Ser. Mekh. Zhidk. Gaza **34** (5), 63 (1999).

Translated by R. Tyapaev