Adverse pressure gradient effect on nonlinear varicose instability of a streaky structure in an unswept wing boundary layer

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Nonlinear varicose instability of a streaky structure is experimentally investigated in a wing boundary layer. Spatial evolution of the streaky structure perturbed by high-frequency traveling waves is compared at zero and adverse streamwise pressure gradients. The process of streak multiplication and generation of Λ-shaped vortices is under examination. Results obtained testify to the strong influence of pressure gradient upon the breakdown of the streaky structure due to its varicose instability. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2140287]

Laminar-turbulent transition in boundary layers is caused in many instances by the breakdown of longitudinal streaky or vortical structures, such as Görtler vortices, crossflow vortices, longitudinal structures caused by roughness elements, etc. An important factor that affects this mechanism is the strength of the spanwise and normal-to-wall gradients of mean velocity in the boundary layer, i.e., the normal and spanwise vorticity, respectively. The instability of spanwise mean velocity profiles results in the sinuous mode of flow perturbations while the instability of normal-to-wall profiles results in the varicose mode. Recent experimental and numerical studies[1–4] show that the flows perturbed by longitudinal structures are unstable with respect to high-frequency traveling waves that can cause rapid transition to turbulence. Studies[2–4] demonstrated clearly that the growth of the varicose instability mode results in the formation of hairpin or Λ vortices, whereas the sinuous mode evolves into a wave train of quasistreamwise vortices with the vorticity of alternating sign. However, experiments on the late stage development of nonlinear sinusoidal and varicose instabilities in a flat plate boundary layer[3] indicated that, finally, in both cases the Λ vortices are produced with their further multiplication. The objective of present Brief Communication is the investigation of the pressure gradient effect on the nonlinear varicose instability of a streaky structure in the unswept wing boundary layer. The spatiotemporal evolution of the perturbed flow is reconstructed through detailed hot-wire measurements, and the generation and dynamics of coherent structures initiated by the varicose instability is elucidated.

Present experiments are performed in a subsonic low-turbulent wind tunnel. In the test section of the facility a wing model with the cord length, c, of 500 and 1000 mm span was mounted (see Fig. 1). Measurements are conducted at two different angles of attack. The streamwise pressure gradient was nearly zero along the test surface of the wing in the range $x/c \approx 0.22-1.0$ at a negative angle of attack, with adverse pressure gradient being established as incidence increased. A stationary streaky structure was generated in the boundary layer via air blowing through a hole of 1.5 mm in diameter arranged on the wing surface at $x/c=0.248$, with the blowing controlled by a fan. High-frequency traveling waves were excited through the same hole of a frequency $f=150$ Hz by a loudspeaker, which was connected by a pneumatic line with the blower. The excitation frequency was chosen for the highest streaky structure receptivity to nonstationary perturbations. The experimental runs were carried out with the oncoming flow velocity $U_\infty=8.35$ m/s and the turbulence level u'/U_∞ being no larger than 0.04% of U_∞. In what follows, x is the streamwise distance measured from the leading edge of the wing, z is the spanwise coordinate, and y

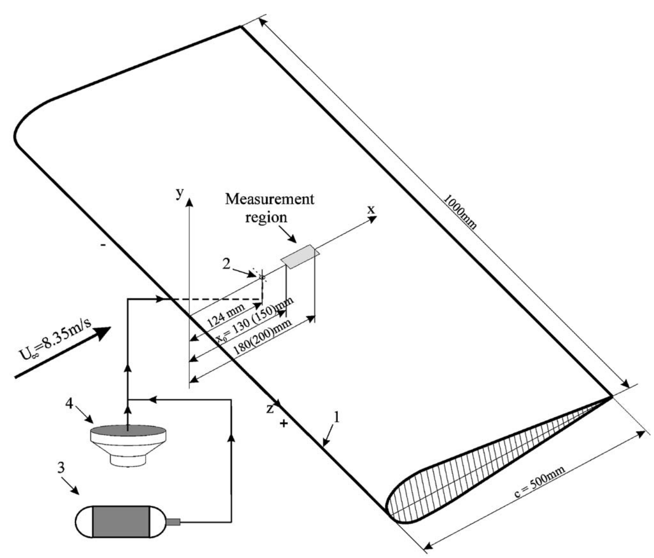

FIG. 1. Experimental setup: (1) wing model, (2) hole for injection of controlled boundary layer disturbances, (3) blower for streaky structure generation, (4) loudspeaker exciting high-frequency traveling waves.

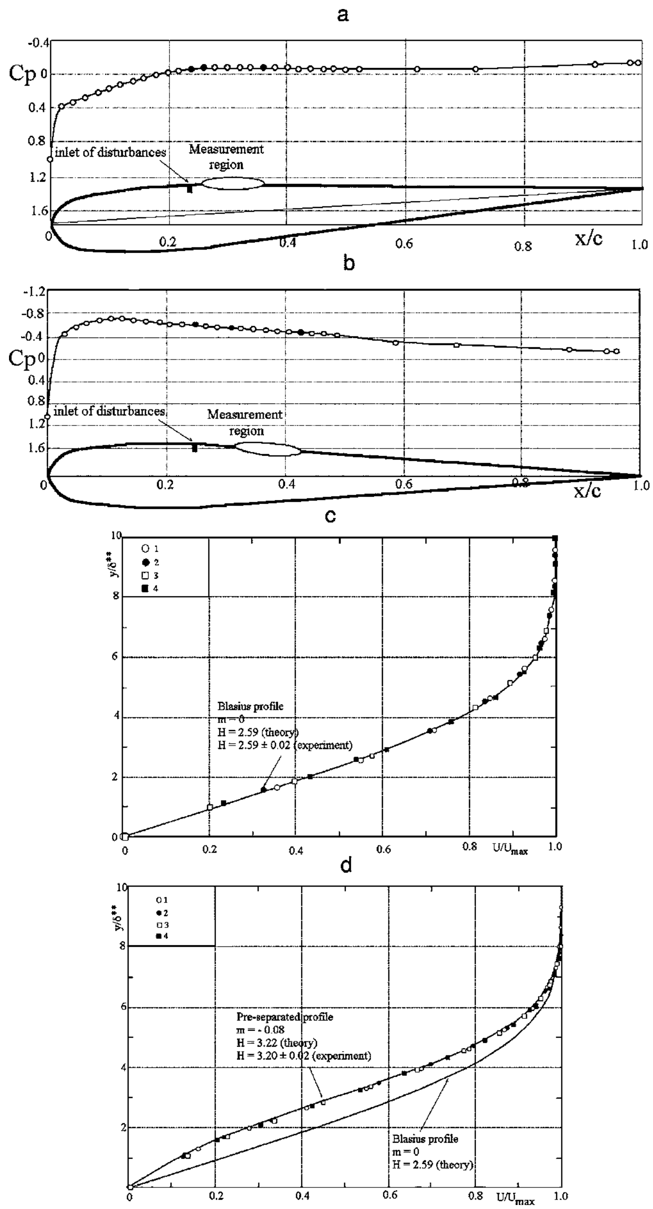

FIG. 2. Pressure distributions along the wing surface at (a) zero and (b) the adverse pressure gradient. (c) Boundary layer velocity profiles at zero pressure gradient for different streamwise stations x/c: (1) 0.26, (2) 0.29, (3) 0.32, and (4) 0.35. (d) Profiles for adverse pressure gradient at various x/c: (1) 0.31, (2) 0.34, (3) 0.37, (4) 0.40.

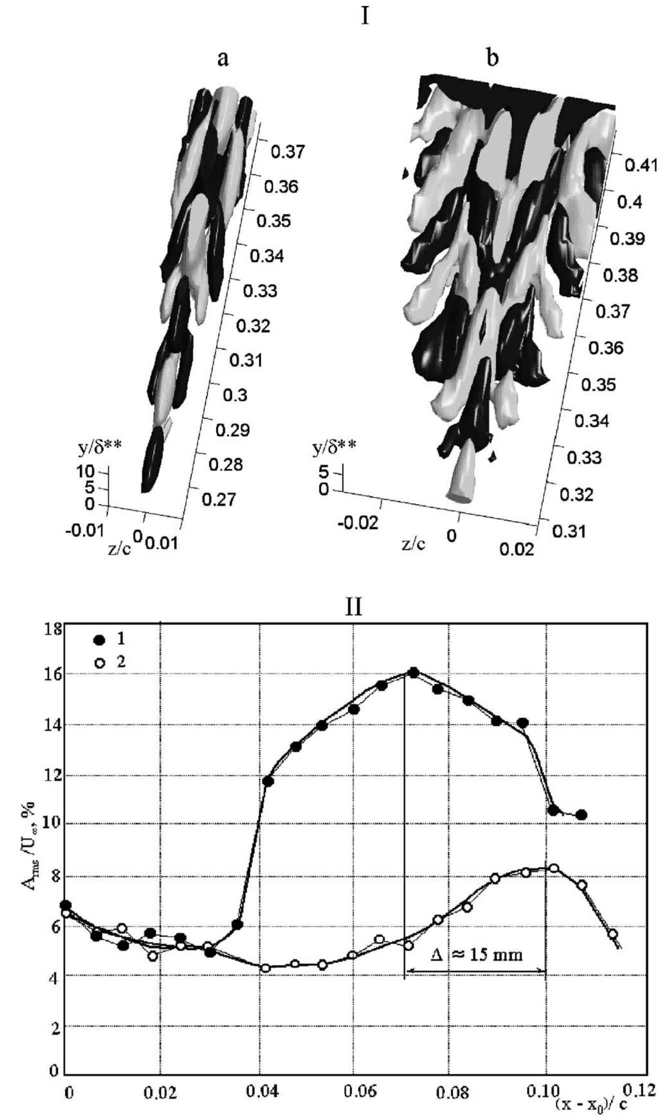

FIG. 3. Development of the high-frequency traveling waves. (I) 3D instantaneous distributions for (a) zero and (b) the adverse pressure gradient. The dark and light halftones indicate positive (0.8% of U_∞) and negative (−0.8% of U_∞) velocity deviations. (II) Streamwise variations of the amplitude for (○) zero and (●) the adverse pressure gradient.

is normal to the (x,z) plane with $y=0$ on the model surface.

The varicose instability of the streaky structure was examined in both zero $(dp/dx=0)$ and adverse $(dp/dx>0)$ pressure gradient boundary layers [see Figs. 2(a) and 2(b)]. In the first case the undisturbed laminar flow in the range of measurements from $x/c=0.26$ to 0.36 is developed with mean velocity profiles close to the Blasius solution for the flat plate boundary layer. The shape factor determined in the experiment is $H=2.59\pm0.02$ (the theoretical value for the Blasius flow is $H=2.59$) and the Hartree parameter, m, is equal to zero [Fig. 2(c)]. In the second case, the velocity distributions in the testing area from $x/c=0.30$ to 0.40 were as for a preseparated boundary layer with the shape factor determined in the experiment, $H=3.20\pm0.02$. The best fit was obtained with a theoretical profile corresponding to the Hartree parameter, m, equal to −0.08 [Fig. 2(d)] and the shape factor for this profile is $H=3.22$. As is known, the boundary layer separation occurs for values of m less than −0.0904 (see, e.g., Ref. 5). The flow Reynolds number $R^*=\delta^* U_\infty/\nu$, where δ^* is displacement thickness, was within 840–1010 at $m=0$ and within 940–1106 at $m=-0.08$. Velocity profiles distorted by the streaky structure became inflexional both normally to the wall and in the transverse direction. The flow perturbed by the stationary disturbance was subjected to the high-frequency oscillations symmetric in the transverse direction. The excitation frequency, $f=150$ Hz corresponded to the normalized value $2\pi f\nu/U_\infty^2\approx200.10^{-6}$, and near the source the oscillation amplitude was higher than 10% of U_∞; thus the traveling waves were nonlinear from the very beginning.

The evolution of traveling waves for the case of $m=0$ can be seen clearly in their three-dimensional (3D) representation [see Fig. 3(I)(a)]. Initially the disturbances appear as quasistreamwise vortices at $x/c \approx 0.32$, which transform further into hairpin or Λ structures of alternating sign at each period of the excited oscillations. Notice that in experiments[2,3] on the nonlinear varicose instability of flat-plate boundary layer, very similar coherent structures were found. As in Ref. 3, the generation of new streaky structures on both sides of the initial structure is observed. Evaluations show that the perturbed flow region spreads in the spanwise direction from 2 to 5 mm approximately and the total disturbance amplitude increases from 3% to 7.5% of U_∞.

The streamwise evolution of traveling waves at $m=-0.08$ is shown in Fig. 3(I)(b). As in the previous case, the Λ structures are observed at $x/c \approx 0.34$ and further downstream with their multiplication. However, the transverse spreading of the disturbance becomes about two times faster than that for $m=0$ due to the influence of pressure gradient. The adverse pressure gradient results in rapid growth of the intensity of mean velocity distortion from 12% to 60% of U_∞ with the amplitude of the traveling waves ranging from 6–16 % of U_∞. The laminar-turbulent transition is promoted also due to significantly increased dispersion of the disturbance. The perturbed flow region spreads from 1.5 to 20 mm with associated transverse multiplication of the streaky structures and Λ vortices.

As is known,[1] the sinuous instability mode is more "dangerous" than the varicose mode, as it occurs at a lower level of primary disturbance. However, often these two instability modes take place simultaneously, and under certain conditions the varicose mode is even more dangerous than the sinuous one.[4] Let us consider the influence of adverse pressure gradient on the varicose instability in more detail. The effect of pressure gradient on transition to turbulence caused by streak breakdown is well seen in Fig. 3(II) where streamwise distributions of the rms amplitudes of high-frequency perturbations are compared for $m=0$ and $m=-0.08$. One can see that at the beginning of the testing area the disturbance amplitude decreases from 6–7 % of U_∞ to 4–5 % of U_∞ for $(x-x_0)/c$ from 0 to 0.04 in both cases. However, further downstream, the amplitude increases most rapidly in the case of $m=-0.08$, reaching about 16% of U_∞ at $(x-x_0)/c=0.07$, with further decay, which testifies to the turbulence of the flow. In the case of $m=0$, the disturbance growth is slower and transition to turbulence is fixed at $(x-x_0)/c=0.10$ for the 8% perturbation amplitude. The upstream shift of the transition point at $m=-0.08$ is approximately 15 mm. Notice, that in both cases, the maximum of $u_{\mathrm{rms}}(y)$ was correlated with the inflexion of $U(y)$ profiles induced by the streaky structure, with this being in accordance with previous results.[1,4]

Thus, in the present Brief Communication, spatial flow patterns of the nonlinear varicose breakdown of the streaky structure in the unswept wing boundary layer, with zero and adverse pressure gradients, were obtained through hot-wire visualization. It was found that transverse multiplication of the streaks and Λ structures occurred in both cases, with spanwise spreading of the disturbance at $m=-0.08$ being about two times faster than at $m=0$. In addition, it can be concluded that the streaky structure breakdown is accelerated by the adverse pressure gradient.

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