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INFLUENCE OF AN UNFAVOURABLE PRESSURE GRADIENT ON THE BREAKDOWN OF BOUNDARY LAYER STREAKS

V. G. Chernoray*[1], V. V. Kozlov*[2], I. Lee *[3] and H. H. Chun*[3]

*[1] Applied Mechanics, Chalmers University of Technology, 412 96, Gothenburg, Sweden, valery.chernoray@chalmers.se
*[2] Institute of Theoretical and Applied Mechanics SB RAS, 630090, Novosibirsk, Russia. kozlov@itam.nsc.ru
*[3] Naval Architecture & Ocean Engineering, Pusan National University, 609-735, Pusan, Korea.

ABSTRACT: *Breakdown of boundary layer streaks is studied experimentally and compared at zero and adverse (positive) streamwise pressure gradients on a wing under fully controlled experimental conditions. The varicose mode of streak breakdown is found to be a dominant mode in the case of the adverse pressure gradient. A strong influence of pressure gradient upon the development of the streak and the secondary instability is revealed. The unfavourable pressure gradient is shown to alter the critical streak amplitude, the dispersion properties of the streak and the secondary disturbance, as well as attained maximum amplitudes for both the streak and the secondary disturbance.*

1. INTRODUCTION

As is known[1], the laminar breakdown in wall-bounded shear flows is often associated with transverse modulations of a flow by either steady streamwise vortices (e.g., Görtler vortices, crossflow vortices) or unsteady streamwise structures (boundary-layer streaks at high free-stream turbulence, Λ-, Ω-, and hairpin vortices). These structures create spatial velocity modulations providing favourable conditions for appearance of secondary instabilities which, in turn, promote the flow breakdown and lead to turbulence in such flows. Two fundamental secondary instability modes of the flows modulated by the streaky structures are the varicose mode (also symmetric, horseshoe, or '*y*'-mode), and the sinusoidal mode (antisymmetric, meandering, '*z*'-mode). It is agreed that the reason for the secondary instabilities is an inviscid local mechanism caused by the inflections in the instantaneous velocity profiles both in the wall-normal (varicose mode) and in the transverse directions (sinusoidal mode). For example, such two different modes were observed in flow visualizations of Görtler vortex breakdown[2], where it was shown that the secondary travelling waves are created either in the form of the periodic meandering of the vortices in the transverse direction or in the form of the horseshoe bunching. The choice of the secondary instability mode excited first and growing most rapidly depends on the stability properties of the resulted distorted flow. The strength of the spanwise and the wall-normal gradients of the streamwise velocity as well as a spacing between the streamwise perturbations are particularly important for the mode selection. Typically, the varicose instability mode prevails during the breakdown of long-wave vortices, whereas the sinusoidal mode is most often observed on short-wave disturbances[3,4].

These two modes of the streak breakdown are examined under controlled experimental conditions by Asai et al.[5] and by Chernoray et al.[6] in the Blasius boundary layer. The first of these studies is focused on the linear and weakly nonlinear evolution of the secondary instabilities, while the latter work reveals details on the nonlinear breakdown stages. In particular, Asai et al.[5] have proved that the streak width is an important parameter for the mode competition and for the growth rate of the secondary disturbances. Chernoray et al.[6] have performed detailed visualizations by hot-wires, which demonstrate that the two instability modes are remarkably similar during the late nonlinear stages of their development. Both instability modes are revealed to contribute to the horseshoe-like activity in the outer part of the boundary layer, and the generation of Λ-shaped vortices is shown to take place in both mode cases.

Current study is a natural continuation of work[6] which employs the same experimental techniques of the detailed flow mapping and visualization by hot-wires. The focus of present study is on flows with non-zero streamwise pressure gradient which are of importance in various technical applications such as, for example, turbo engines. An attempt is made to reveal how the streak breakdown is changed due to an external pressure gradient variation, aiming to deepen insight into the late stages of the laminar-turbulent transition for the flows of a practical importance. To achieve this goal, a spatio-temporal evolution of the perturbed flow was reconstructed under controlled experimental conditions and the development and dynamics of the streak breakdown was elucidated in detail.

2. EXPERIMENTAL ARRANGEMENT AND RESULTS

Experiments were performed in a subsonic low-turbulent wind tunnel at oncoming flow velocity of 8.35 m/s and the turbulence level 0.04 %. A wing model (Fig. 1) with chord length 500 mm and span 1000 mm was mounted in the middle of the wind tunnel test section. The flow Reynolds number based on the wing chord was Re = $3\cdot10^5$.

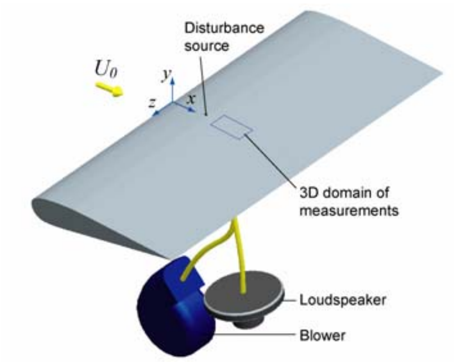

Fig. 1. Experimental setup.

Two different cases of pressure gradient, zero pressure gradient (ZPG) and adverse pressure gradient (APG) are obtained by a variation of the wing angle of attack (by about 10º). The ZPG measurements are mainly used for reference purposes. The domain of measurements was located in the diffuser area on the airfoil suction side. In this area the wing geometry is linear and nearly self-similar boundary layers are developed as a result. Details on the boundary layer characteristics for both of the base flows are presented in Fig. 2.

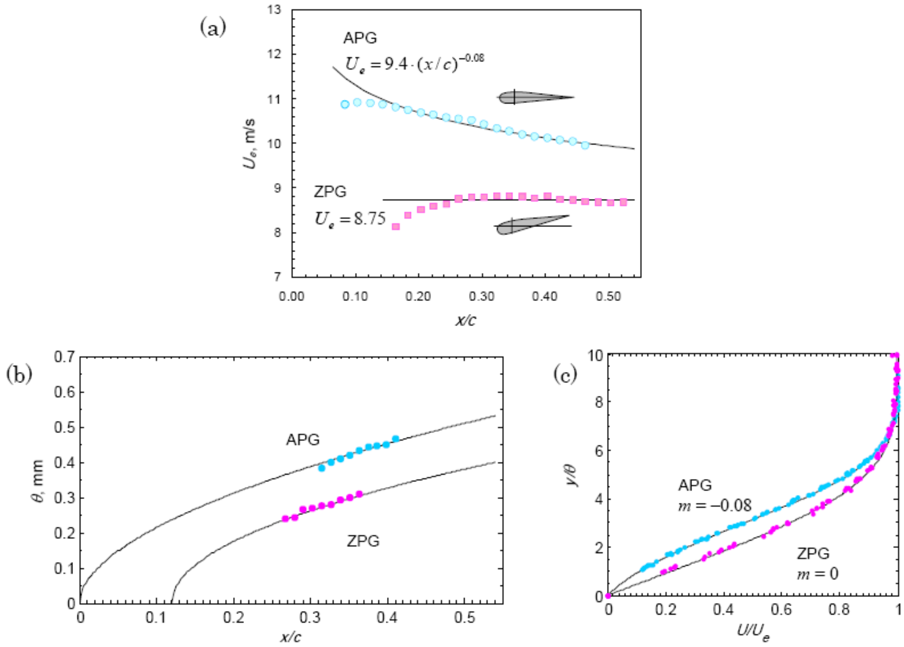

Fig. 2. Boundary layer properties for two pressure gradient cases: (*a*) external velocity variation along the boundary layer, (*b*) variation of the boundary layer momentum thickness, and (*c*) corresponding boundary layer velocity profiles. Symbols — measurements, lines — theoretical approximations.

The boundary layer streak was created by a steady air blowing through a 1.5-mm hole located on the wing surface at 125 mm. In addition, a loudspeaker was attached to the same pneumatic line and was used to modulate the streak by high-frequency oscillations. The excitation frequency was set equal to f = 333 Hz.

The breakdown of the boundary layer streaks is studied experimentally and compared at zero and adverse (positive) streamwise pressure gradients under controlled experimental conditions. Figure 3 shows an example of obtained disturbance visualizations.

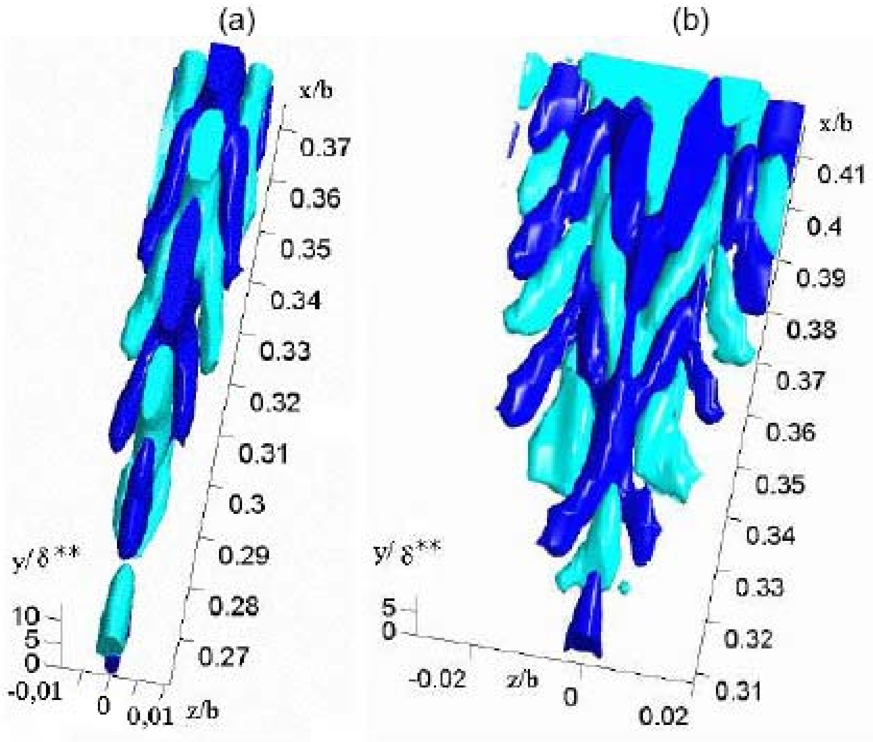

Fig.3. (*a*) Development of the varicose instability mode at zero pressure gradient and (*b*) development of the varicose instability mode at adverse pressure gradient. Isosurfaces of instantaneous time-periodic velocity.

3. CONCLUSIONS

The breakdown of the boundary layer streaks is studied experimentally and compared at zero and adverse (positive) streamwise pressure gradients under controlled experimental conditions.

Comparison of current results for zero pressure gradient case with results of Asai et al.[5], Skote et al.[7], and Chernoray et al.[6] revealed that the spatial distribution of the primary steady disturbance has a dramatic influence on the spatial topology of the secondary periodic disturbance. Depending on which, the secondary disturbance can be composed either of one or several rows of the lambda-shaped structures.

In case of adverse pressure gradient only the varicose mode was found to be unstable. Even if the sinuous mode was triggered, it decayed rapidly and transformed into the varicose mode during the streamwise development.

A strong influence of the pressure gradient upon the development of the streak and its secondary instability is revealed. The unfavourable pressure gradient is shown to alter the critical streak amplitude necessary for triggering the secondary instability. The critical streak amplitude is found to decrease to 10% of U_e in APG boundary layer (compared to 25-40% in zero pressure gradient boundary layers).

ACKNOWLEDGMENTS

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