12th International Couette-Taylor Workshop, September 6-8, 2001, Evanston, IL USA

CONTROL OF STREAMWISE VORTICES IN THE FRAMEWORK OF THE GOERTLER INSTABILITY APPROACH

N. Yurchenko

Institute of Hydromechanics, National Academy of Sciences,
8/4 Zheliabov St., 03057 Kiev, UKRAINE

Abstract

Streamwise vortices are studied as a dominant structure for various types of flows affected by body forces. A boundary layer over a concave surface was investigated experimentally and numerically as a prototype problem on basis of the Goertler instability theory and the receptivity approach. Sequences of spanwise profiles together with the developing vortical flow topology showed a possibility to influence vortex dynamics owing to varying boundary conditions. The latter was realized using regular surface temperature distribution in a form of T(z) wave with a given spanwise scale λ_g of generated vortices. Varying λ_g periodicity and T(z) amplitude, one can obtain different boundary layer response that could be predicted and analyzed in terms of the Goertler diagram. Measured and calculated velocity fields evidence that, generated with a certain scale in accordance with basic flow parameters, streamwise vortices can either delay transition to turbulence or intensify mixing processes near a wall.

Introduction

Flows under body forces (i.e. with rotation or under buoyancy) are known to manifest similar features associated with self-organization of free-stream oriented vortices. Streamwise vortices developing in boundary layers precede the transition to turbulence and therefore are of primary interest from the viewpoint of fundamental knowledge and its practical applications related to control of large-scale coherent structures [1, 2]. Although the nature of forces and instability mechanisms are similar, for instance, in curved channel and boundary-layer flows, centrifugal instability in the second case displays itself only far downstream from its initiation. Therefore disturbance amplitudes are important to be analyzed for the boundary-layer problem.

At the same time, the sensitivity of flow dynamics both to disturbance amplitudes and spanwise scales gives a key to use this very feature to control vortical motion through an imposed boundary condition. This idea was realized in a form of a z-regular surface temperature variation with a given variable step, λ_g [2, 5]. A problem of natural and forced evolution of streamwise vortical structure under various boundary conditions is rigorously formulated for transitional boundary layers affected by centrifugal forces. In this case, the fluid motion can be analyzed in the frame of the well known Goertler stability theory describing growth and decay of vortices depending on the boundary-layer flow parameters [2, 3].

The **objective** of the present work is to reveal control peculiarity of a flow where streamwise vortices are an inherent and dominating structure, i.e. in a boundary layer under centrifugal forces.

Methods

The work was implemented experimentally and supported with details obtained from direct numerical simulation. First, the natural evolution of streamwise vortices in boundary layers over a concave wall was considered. Then a flow reaction to an array of generated counter-rotating pairs of streamwise vortices was studied.

The main (1) part of experiments was carried out in a low-turbulent water channel in a boundary layer over its bottom 25 x 300 cm with a concave section, R=12 m, at free-stream velocities within 0.05-0.2 m/s. Electro-chemical Tellurium-method (similar to the conventional hydrogen-bubble technique) was used to visualize a flow field. It gave information about velocity fields in a boundary layer and, together with hot-wire measurements, about its spectral characteristics.

Streamwise vortices were induced in a boundary layer with a given spanwise scale λ_g using two methods [1, 2]: mechanical (application of vortex-generator arrays placed on a surface) and thermal (temperature distribution over the surface regularly varied in the spanwise, z, direction (Figure 1). The thermal-control method was realized using flush-mounted electrically heated longitudinal strips

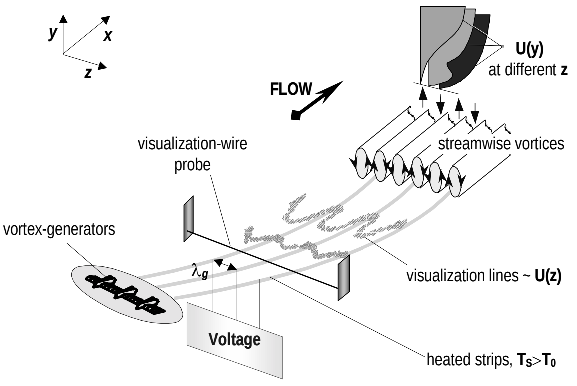

Figure 1: Sketch of the problem

regularly spaced in a spanwise direction at a λ_g distance from each other. Thermally and electrically insulated test plate provided a driving z-periodic temperature gradient $\Delta T(z)$ on the surface. Changing the applied voltage in experiments, one could control the impact: from $\Delta T=0$ (no special influence) to $\Delta T\approx 60°C$.

Supplementary, part 2 of the measurements was implemented in a tripped turbulent boundary layer to estimate the efficiency and the application range of the elaborated method of thermally initiated streamwise vortices. It was carried out over a 50x400mm flat test plate in a wind tunnel at the free-stream velocity U_∞ = 6.3 m/s; a 2mm-diameter trip wire was placed at 10 mm from the plate leading edge [4]. Temperature and two components of velocity were measured using a thermocouple and a triple hot-wire probe.

The numerical study aimed to get specific details both of natural and forced development of the vortical structure in time. It was based on a code (for the x- and z-periodic model) developed for the direct numerical simulation of the laminar-turbulent transition in compressible subsonic boundary layers [2]. Streamwise vortices were controlled due to an imposed thermal boundary condition as the z-periodic surface temperature (the strips were heated to $\Delta T=30K$ above the (natural) adiabatic wall temperature). Simulations were carried out for a Goertler number based on the momentum thickness, G_ϑ = =8 (or one based on the Blasius reference length $d=(v_o\, x\, /\, U_o)^{1/2}$, G_d =15, and correspondingly a Reynolds number of Re_d=595). The free-stream Mach number was M=0.8, the free-stream temperature was T_o=290º K, the fluid was air with constant isentropic exponent γ=1.4 and Prandtl number P=0.71. The fundamental mode in the spanwise direction was taken to be α_z=0.66, or in terms of nondimensional wavelength of the Goertler stability diagram, $\Lambda_1=U_o\lambda_g^{3/2}/v_o\ R^{1/2}=236$, i.e. from the range of most amplified disturbance wavelengths. Given this fundamental wavelength, the second harmonic corresponded to Λ_2=84 and thus was still in the domain of amplified disturbance wavelengths, while all the other ten numerically considered harmonics were linearly damped. Twelve harmonics were found to resolve the flow patterns sufficiently for all simulations.

To match computations with the experiments in part of generation of streamwise vortices, space-scales of experimentally generated vortices (given by a distance between the neighboring vortex-generators or heated longitudinal strips, $\lambda_\mathbf{g}$, see Figure 1) covered the range from neutral to most amplified vortices according to the Goertler diagram.

Results

Typical wavy U(z) velocity profiles give a clear evidence of the developing streamwise vortices in a boundary layer as it is shown in the sketch of Figure 1. A top view of the visualized flow field (Figure 2) shows a flow receptivity to the scale of introduced vortices. It is well seen that the flow structure developing downstream of the vortex-generators depends on correlation between a spanwise scale of a disturbing factor (λ_g) and the Reynolds number, Re. It gives an idea not only about a scale but also about growth rates and intensity of vortices evolving downstream. The upper pattern displays two superimposed waves of generated small-scale λ_g and naturally developing large-scale λ_z vortices at the considered transition stage. The lower pattern demonstrates adequate reaction of the boundary layer to generated vortices due to their parameters matched with the basic flow parameters.

To show a boundary-layer response to the forced regular excitation from the surface in more detail, two thermal excitation cases were investigated numerically.

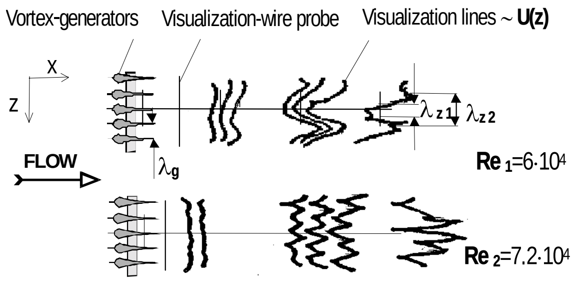

Figure 2. Boundary-layer selective response, λ_z, to vortices generated with the scale of λ_g=1.6 cm under different basic flow parameters

Case 1:

the heated strips were placed so that to ideally excite the second mode Λ_2 and higher modes according to the linear theory as a reference. The wall temperature was fixed at $\Delta T=30^{\circ}K$ above the recovery temperature of the initial, disturbance-free flow at $0<z<1.54$ and $3.08<z<4.62$ (see Figure 3). Also, a small initial wall temperature variation of about $0.3^{\circ}K$ along the spanwise direction was introduced, including components of the fundamental mode, in order to account for small imperfections.

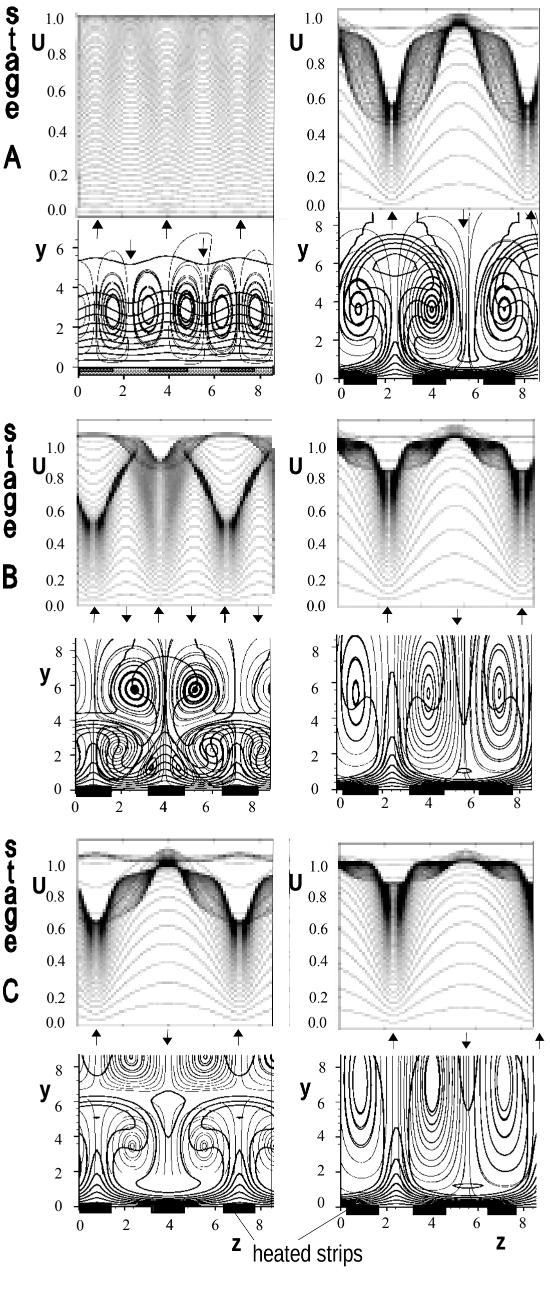

Figure 3. Streamwise velocity profiles $U(z,y_p)$ for the two cases considered at three consecutive stages of the vortical systems formation:
flow times t=1150 (stage ***A***), 1725 (stage ***B***), 2300 (stage ***C***).

Case 2:

One of the strips was slightly shifted in the spanwise direction compared to case 1, thus introducing a small but direct forcing of the fundamental mode. So the strips were placed at $0.13<z<1.67$ and $3.08<z<4.62$.

Figure 3 shows the spanwise variation of the streamwise velocity component $U(z, y_p)$ at a set of wall distances y_p coupled with the flow topology for three subsequent evolution stages (***A***–***C***) identified by the simulation time, non-dimensionalized with d/U_o, correspondingly for case 1 (left columns) and case 2 (right columns).

The calculated velocity profiles U(z) are in a good agreement with the experimental data having shown the induced vortical structure transformation from smaller to larger scales both normally to the wall and downstream (or, more generally, during the evolution process). It is especially well seen for the case of second harmonic excitation.

As displayed in Figure 3 (top left), the purely second-harmonic forcing of case 1 initially causes an adequate near-wall flow reaction in a form of the generated small-scale structure. For case 2 (top right), the “distorted” excitation introduced by the slight disorder of the heated strips appears to be crucial governing the vortex formation process due to the additionally induced fundamental mode; it is already apparent from the very early stages of the vortical structure evolution. Later stages are shown in the center and bottom parts of Figure 3. However even under conditions of the purely second-harmonic forcing in case 1, there occurs the transformation of the flow structures to larger scales, corresponding to the fundamental wavelength as also described in the experiments [5].

Since equal simulation flow times are considered for the two cases, it can be conjectured, that there is a strong influence of the excitation scheme on the near-wall region and on the early vortex formation (or shortly downstream in the spatial experimental tests). Besides, arrangement of the heated strips, or a type of forcing, strongly affects the rate of the vortex formation process.

Preliminary simulations using strips of half width of those considered in case 1 and 2 and operated at twice the value of ΔT, indicated no strong effects on the initial stage of the vortex formation, but considerable influence on the long-term behavior of streamwise vortices in a boundary layer.

In the middle stages of the vortical structure evolution, both experimental and numerical results showed that the thermally induced small-scale structure is observed up to $y \leq 0.4\delta$. It is seen from the transformation of the U(z) velocity profiles and from the flow topology.

A reference case of naturally evolving Goertler vortices displayed features similar to the case 2. However the duration of the vortex growth phase (establishment of the well-developed system of streamwise vortices [2]) was essentially shorter than in both controlled cases. It means that compared to the natural boundary layer development, a downstream extent of a developed and stably sustained vortical system can be extended due to the generation of vortices intrinsic to the given flow situation but having scales different from those naturally arising. This effect is especially remarkable because a weak controlling factor (ΔT) caused noticeable changes of integral boundary-layer characteristics.

Thus vortex scale transformation was observed both across the boundary layer thickness and downstream if streamwise vortices generated with a scale different from the most amplified 1st mode. It was in a good agreement with experimental visualization results.

To see how the obtained fundamental knowledge can be applied to the turbulent case, measurements were made in a wind tunnel at the Reynolds number based on the boundary-layer thickness, Re=8025. Temperature and velocity fields were registered separately. Turbulent signals were measured and processed by Discrete and Continuous Wavelet Transforms (DWT and CWT) [4].

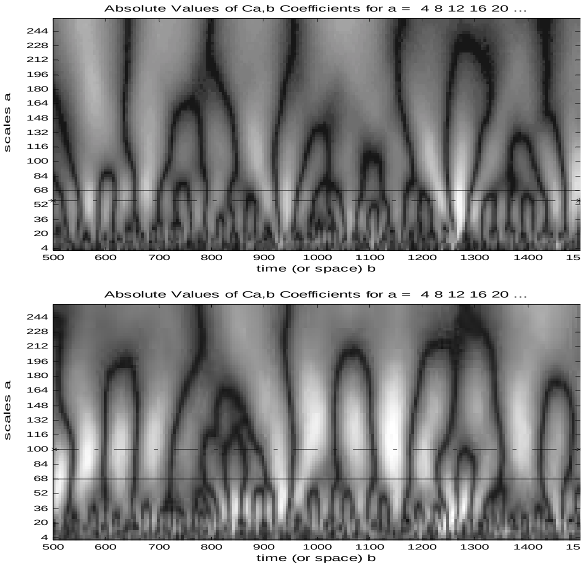

Figure 4. CWT analysis of turbulent signals at y+=23.2 in a reference (top) and controlled (bottom) cases

The CWT results are presented in Figure 4 as **E(a)** distributions where **E(a)** is the turbulence energy and **a** is a wavelet scale parameter. It shows contributions of various scale structures into the turbulence energy analyzing a signal simultaneously in temporal and frequency domains. Growth of the total energy in the controlled case occurs together with increased scales of vortices carrying maximum energy (corresponding dashed lines show scales **a**=56 and **a**=100).

Conclusions

Both experimental and numerical studies displayed susceptibility of a boundary layer under centrifugal forces to disturbances of the type inherent to this flow, i.e. to streamwise vortices. In particular, the following was shown:

selective response of the flow to a boundary condition (spanwise scale, λ_g, of generated vortices, intensity and a point of the control factor switching on) depending on the basic flow parameters;

vortex scale, λ_z, enlargement under natural and forced development of streamwise vortices, downstream and normally to the wall;

possibility to use similar principles to control a streamwise vortical structure both in transitional and turbulent boundary layers.

Acknowledgements

This material is based upon work supported by the European Office of Aerospace Research and Development, AFOSR, AFRL under the Contract F61775-99-WE075.

References

[1] Yurchenko, N., Pedishius, A., Zygmantas, G., 1989, “Boundary layer receptivity and heat transfer enhancement” (in Russian, abstract in English), Engineering-Physical J., 56: 916 - 924.

[2] Yurchenko, N., Delfs J., 1999, “Optimal control of boundary layers under body forces”, in Proc. of IUTAM Symp. on Laminar-Turbulent Transition, Sedona: 6 pages.

[3] Saric, W. S., 1994, "Goertler vortices", Annual Rev. of Fluid Mechanics, Vol. 26, pages 379-409.

[4] Y. Lian, N. Yurchenko, 2001, “Organized vortical structures in a flow over a regularly heated surface”, in Proc. Int. Conf. "Fluxes and Structures in Fluids", Moscow, 4 pages.

[5] Yurchenko, N., 2001, “Transition mechanism and its control in boundary layers under centrifugal forces”, in Proc. Second Int. Symp. On Turbulence and Shear Flow Phenomena, Stockholm: 61- 66.