TRANSITION MECHANISM AND ITS CONTROL IN BOUNDARY LAYERS UNDER CENTRIFUGAL FORCES

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ABSTRACT

Interaction of centrifugal and viscous forces results in developing streamwise vortices that represent an inherent feature of boundary-layer flows over concave surfaces. This very feature was analyzed to reveal most efficient ways to control such flows. Natural and forced evolution of the vortical structure was studied experimentally and numerically on a basis of the Goertler stability theory and receptivity approach. A gentle and flexible technique to generate and maintain streamwise vortices with a given scale was developed and tested for transitional and turbulent boundary layers. It was realized through the imposed boundary condition in a form of a *z*-regular surface temperature variation. Generated strictly according to basic flow parameters, the vortices were shown either to stabilize the flow situation (extending a stage of the laminar-turbulent transition) or to intensify mixing processes near a wall depending on their scales and growth rates.

PROBLEM DEFINITION AND INVESTIGATION APPROACH

Longitudinal vortical structure typical for a vast variety of flows evinces common mechanisms controlling this motion and consequently, its importance both for fundamental and applied research (Yurchenko, 2000-1). In particular, a group of flows affected by body forces enables more rigorous analysis that brings to a conclusion about the nature of streamwise vortices intrinsic to these flows. This basic problem appears to be directly connected with practical requirements to control boundary layers under buoyancy or/and centrifugal forces, i.e. flows over curved walls with a temperature different from that of the fluid.

Thus, a key interest of the present investigation is focused on streamwise vortices, their natural formation and evolution, their forced development with a given scale as well as the search of favorable conditions to intrude into the boundary layer for most efficient generation of this structure.

Flow control similarity principle was formulated as a basis for optimal management of boundary-layer characteristics: generation of a vortical structure type similar to one intrinsically dominating in the flow with parameters correlated with basic flow parameters as well as with set objectives and expected results of a flow control task.

It is supposed to provide an optimal surface-flow interaction from a viewpoint of energy outlay as well as convenience and flexibility of the "least-violent" flow control. Practically, it means two consequent steps:

(1) to establish typical features and scales of a vortical motion naturally developing in a flow of interest;

(2) to generate the vortical motion of a similar type but with scales and intensity best fitting problem parameters and anticipated outcome.

Combined experimental and numerical studies were based on the Goertler instability theory (Saric, 1994; Yurchenko & Delfs, 1999) and receptivity approach (Yurchenko, 2000-2).

DNS code developed for modeling of the laminar-turbulent transition in compressible subsonic boundary layers was applied here with the inclusion of body force terms into the Navier-Stokes equations and, in case of the forced vortex generation, specification of a constant boundary condition in a form of *z*-periodic wall temperature $T(z)$ (Yurchenko & Delfs, 1999). The fundamental in the spanwise direction was taken to be $\Lambda=\lambda_g^{3/2}U_0\nu^{-1}R^{-1/2}=236$, i.e. corresponding to the region of most amplified nondimensional wavelengths according to the Goertler diagram. The second mode, $\Lambda=84$, stayed in the domain of amplified wavelengths, while all the other ten numerically considered harmonics were linearly damped (see Figure 1).

To match experiments with the computations in part of generation of streamwise vortices, the mentioned boundary condition was realized using flush-mounted electrically heated longitudinal strips 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 $\Delta T\approx 60°C$.

Besides, for comparison, transversely installed arrays of mechanical vortex-generators were used. The Goertler stability diagram, Figure 1, was used as a reference to chose scales of the generated flow structure. Experimentally, the streamwise vortices were generated with λ_g scales varied stepwisely in a range from neutral to most amplified wavelengths.

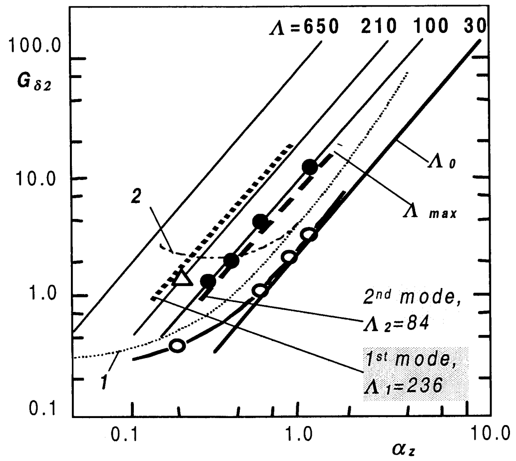

Figure 1 : Goertler diagram ($G_{\delta 2}=\delta_2^{3/2}\ U_\infty \nu^{-1} R^{-1/2}$, $\alpha_z=2\pi/\lambda_z$); neutral curves (cited by Saric, 1994) by Floryan & Saric (1982) -1, Hall (1983) –2;

$\Lambda_0 \approx 30$ and $\Lambda_{max} \approx 100$ - experimental curves for vortices with zero and maximum growth rates;

Λ_1 and Λ_2 - 1st and 2nd modes considered in the numerical simulation

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 which contained a concave section. Figure 2 shows the problem definition in graphical terms. The free-stream velocity range, U_0=0.5-50.0 cm/s, allowed to examine thoroughly the laminar-turbulent transition area up to developed turbulence. A flow field was visualized using electro-chemical Tellurium method similar to the well-known smoke-wire visualization technique in air. Together with the laser velocimetry and hot-wire measurements it gave information about the velocity distributions in a boundary layer; in addition, hot-wire signals were processed to obtain power density spectra.

Supplementary (part 2) measurements were carried out in a tripped turbulent boundary layer to estimate the efficiency and the application range of the proposed method of thermally initiated streamwise vortices (Yurchenko et al., 2000). This part of the experiments 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. Temperature and two components of velocity were measured using a thermocouple and a triple hot-wire probe.

RESULTS AND DISCUSSION

A problem of the flow control, as appeared from numerous engineering applications, naturally reduces to maintenance of a favourable vortical structure near a wall. Here, its optimized solution is proposed through the insight into the natural formation of streamwise vortices intrinsic to flows over curved surfaces. Picking out advantageous stages of their evolution must help to modify the motion scale and intensity so that to efficiently maintain it in a given range of Reynolds numbers.

The most indicative and sensitive characteristics of embedded streamwise vortices is known to be the transverse distribution of any flow quantity (like velocity or temperature) displaying its wave-like shape as shown in Figures 2, 3. Hence, if the regular temperature inhomogeneity *T(z)* applied to the smooth surface can cause flow reorganization, it should be seen in the measured or calculated *U(z)* velocity profiles.

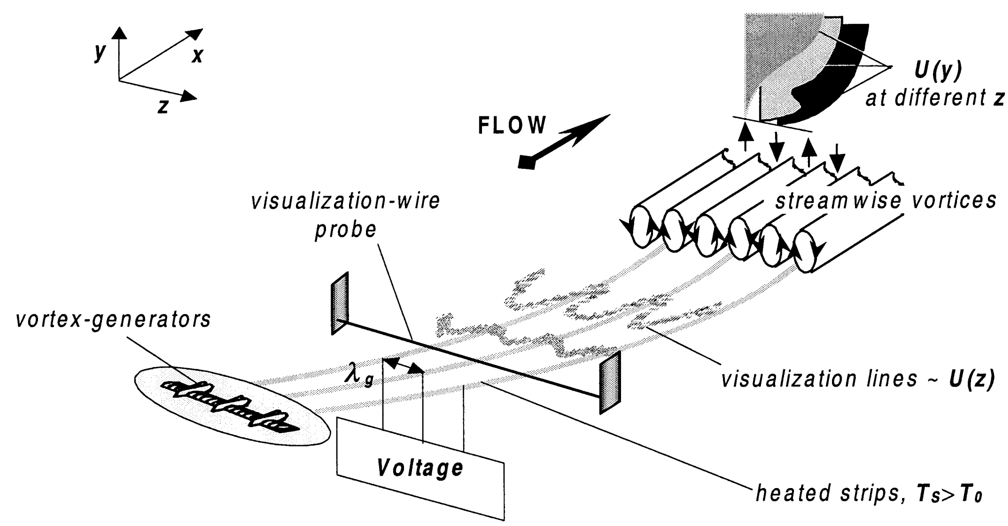

Figure 2 : Experimental/numerical scheme of the investigated problem

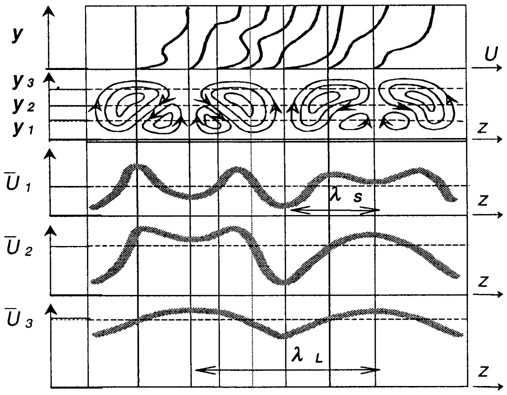

Figure 3 : Streamwise vortices embedded in a boundary layer deduced from the measured *U(y)* and typical wavy *U(z)* velocity profiles

Thus *U(z)* velocity distributions visualized in a boundary layer at three distances from a surface (Figure 3) under conditions of natural formation of a vortical structure can be interpreted as this structure pounding in the vicinity of the wall. Numerical simulation supplemented these data having brought more peculiar details for analysis. First, a sequence of events was studied in case of natural evolution of streamwise vortices over a smooth concave surface that is presented as a set of the flow field patterns in *yz*-plane (a reference case of Figure 4). Both experimental and numerical results showed that conventionally, the vortex system evolution can be divided into 4 stages (Yurchenko & Delfs, 1999): emergence, growth, distortion and breakdown (first four patterns).

The vortex growth stage is characterized by the elongation of vortices normally to the wall almost linearly in time. It creates strong shear layers between the vortices, which become a main source of instability of the organized fluid motion eventually resulting in its breakdown and establishment of the turbulent motion. During this stage, disturbance amplitudes are saturated and energy is non-linearly re-distributed between the modes. Topologically, it is seen as the formation of the mushroom-like vortical structure due to the low-momentum fluid uprising from a wall. Since this stage is presented by the well-developed and rather stable vortices, then from a viewpoint of the flow control, it looks beneficial to maintain this deterministic and inherent to given flow conditions type of motion as long as possible before its breakdown. Referring to Figure 5 that presents a refined sketch of consecutive stages of the vortical

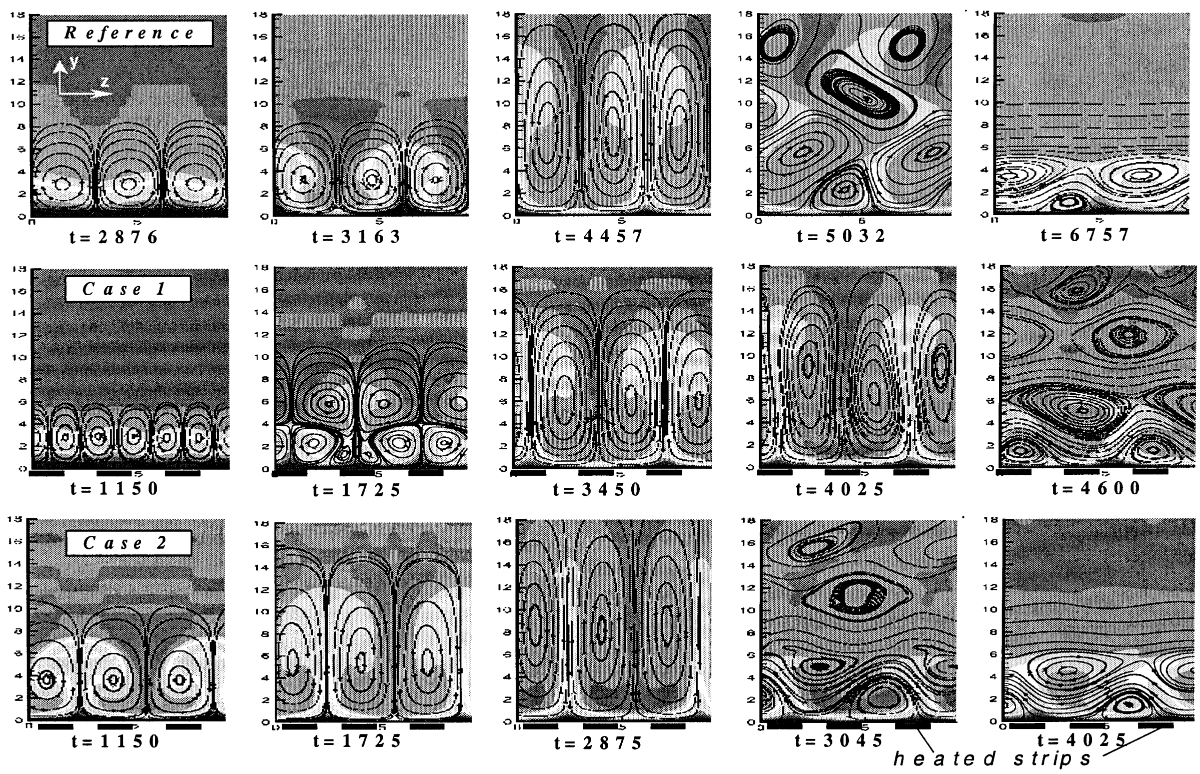

Figure 4 : Evolution of streamwise vortices in a boundary layer shown as iso-*U*-velocity and vorticity lines, G=8, M=0.8 , Pr=0.71 (air). Reference case – natural evolution during laminar-turbulent transition; Cases 1, 2 – vortices initiated thermally, ΔT=30° K, correspondingly, (1) with the regular excitation of the second Goertler mode, Λ_2=84, and (2) with irregular excitation of the second mode provided available other harmonics (i.e. when the first heated strip was slightly shifted to the right as depicted in the figure)

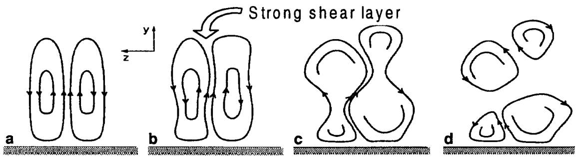

Figure 5: Summarized sequence of events in a process of streamwise vortical structure evolution from formation to breakdown

system transformation, one can clearly see that the maintenance or conservation of the organized vortical structure needs restricting the normal growth of the vortices and thus weakening the shear between them. Therefore instead of flow drastic reorganization aimed to improve its integral characteristics, the application of the formulated similarity principle offers a way requiring less energy outlay. Then the flow can be controlled with an amount of additional energy delivered into the boundary layer mainly to change and maintain the scale of motion rather than its type. Here, it is expected that self-maintenance of the vortical structure can be provided due to the special constant boundary condition.

Spanwise periodicity of the surface temperature variation *ΔT(z)* corresponding to the second Goertler mode (Case 1) shows that the initially generated vortical structure with a scale smaller than the „reference" one (above) consequently undergoes transformation to correspond to the most amplified first mode. Modeling experimental imperfection of the heated-strip system arrangement, Case 2 was considered where the generated and intended to dominate second mode admitted the appearance of other modes due to slightly shifted one of the strips. In this case, the mode competition resulted in an immediate grasp and further development of the first mode thus having shown the enlargement of the vortical structure. In both cases, the constant boundary condition imposing the permanent preference to a given vortex scale could not prevent from developing and final dominance of a larger scale vortical structure. However in Case 1, the flow structure transformation took a longer time, while in Case 2, the initially strongly prevailed second mode gave up almost immediately to the first one. Both controlled cases displayed the vortex growth stage extended by 29-47% compared to the „reference", natural evolution case.

Experiments showed even more slow vortical structure evolution to its breakdown if vortices were generated with a scale close to the neutral one.

Figure 6 shows visualized *U(z)* velocity profiles of a flow over a surface with longitudinal heated strips. Naturally developing *U(z)* velocity profiles are seen to be disturbed with a forced smaller scale structure in the vicinity of the wall (Figure 6, a-d). Across the overall boundary-layer thickness (Figure 6, e), the effect is displayed as an obvious stabilization of the velocity field and the deceleration of transition to turbulence on the whole.

Application of mechanical vortex-generators (shown in Figure 2), on the one hand, confirmed the capacity of the proposed thermal method for work and, on the other hand, enabled to initiate more clearly delineated and intense vortices in a boundary layer (Figure 7). Therefore it allowed to examine more thoroughly a boundary layer response to the spanwise scale λ_g of generated vortices. Depending on the correlation between values of the basic flow and control parameters, there could be observed different results. An "adequate response" was seen when a scale of generated vortices (here λ_g, a distance between neighbouring vortex generators) coincided with a scale of the vortical structure observed in the flow downstream of the vortex-generator array (i.e. a wavelength of the visualized *U(z)* velocity distribution), $\lambda_g=\lambda_z$. A subharmonic response, $\lambda_z=n\lambda_g$, as well as fast attenuation of any generated disturbances took place if scales of introduced vortices mismatched the basic flow parameters.

Both experiments and numerical simulation for conditions of small background disturbances (low free-stream turbulence, smooth leading edge and surface of a test plate) showed that the scale selection of naturally developing streamwise vortices occurs in accordance with the first, i.e. most amplified Goertler mode (λ_0 of Figure 7, a). The growth rate of vortices generated with λ_g=3.2 cm close to λ_0 appeared to be sufficient at $Re=6\cdot10^4$ for the adequate boundary-layer response (b), while the smaller-scale generated structure, λ_g=1.6 cm, (c) became apparent only farther downstream as one riding over a large-scale *U(z)* wave more proper for the given flow conditions. It can also be interpreted as a boundary-layer subharmonic response:

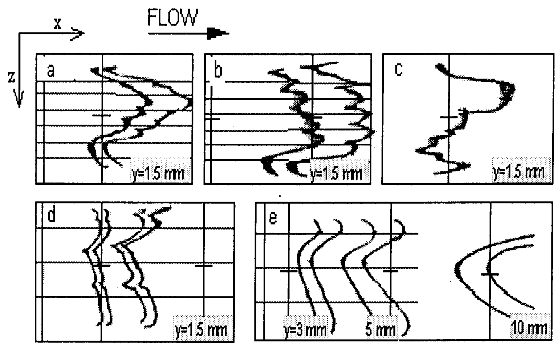

Figure 6 : Visualized boundary layer (top view) over a concave surface with a curvature radius R=12 m and 20cm-long heated strips;

a, b, c: λ_z=1.2cm; $Re=10^5$, $1.4\cdot10^5$, $1.5\cdot10^5$ (downstream development); **d, e**: λ_z=2.4 cm; $Re\sim10^5$.

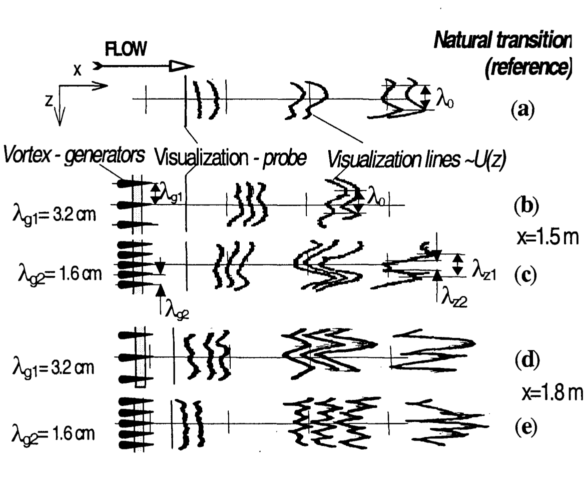

Figure 7. Boundary layer receptivity to the scale of generated streamwise vortices, visualized flow-field patterns, top view;

R=12 m, Re=6·10^4 (**a**, **b**, **c**); Re=7.2·10^4 (**d**, **e**)

$\lambda_{z1}=2\lambda_{z2}=2\lambda_g$. At the greater Re=7.2·10^4 of cases (d) and (e), the same generated vortex scales were supported by the boundary layer having shown its adequate response, $\lambda_z\approx\lambda_{g2}$. However, judging from the *U(z)* downstream deformation and amplitude, the larger-scale structure can involve the whole boundary-layer thickness into the vortical motion (not shown here *U(z)* profiles display their wavy shape while measured at different distances from the wall), i.e. provides better mixing.

At the same time, the imposed small-scale streamwise vortices affected a near-wall region like "a freezer" restricting (or rather controlling) transverse momentum transfer that would otherwise naturally result in a meandering motion of the vortical system accelerating the breakdown process. The latter effect is similar to one displayed in the numerical simulation, Figure 4, Case 1.

Thus, choosing boundary conditions (a scale of generated streamwise vortices), one can get either the situation of a slowly developing transition to turbulence, or acceleration of its initial stages with the formation of large scale vortices assisting to enhance transport processes near a wall.

To approach requirements of practice, the applicability of the flow control method based on thermal excitation of the organized vortical structure over curved surfaces was tested for turbulent boundary layers.

First, spanwise temperature and velocity distributions were measured over a flat test plate in a wind tunnel described above (part 2 of experiments). Results in a form of typical wavy temperature and velocity profiles presented in Figure 8 confirm the available regular vortical structure stimulated near a wall. The top of the figure illustrates a probable vortical system with affiliated velocity profiles across the boundary-layer thickness which correspond to the measured *U(z)*.

Since vortex generation modifies fluid motion scales, spectra of turbulent fluctuations become one of the most important flow characteristics. It is known that large-scale vortices contribute to a long-wave part of the spectrum, and its short-wave part corresponds to dissipation scales of fluid motion, which transforms into heat due to available viscosity. Thus from a viewpoint of practical applications, flow control techniques should redistribute the fluid motion energy in favour of a long-wave part of the spectrum.

A standard procedure using fast Fourier transform was applied to hot-wire signals recorded in a water boundary layer (experimental facility 1). A legend for experimental conditions of vortex generation is given in Table 1. Here y is a distance of a hot-wire probe from a surface, y_{vg} is a normal size of vortex-generators, δ_1 is a boundary-layer displacement thickness, δ is a boundary-layer thickness. For reference, fluctuating streamwise velocities were measured in naturally developing transitional and turbulent boundary layers, i.e. without vortex generation. Results are depicted in Figure 9. Reference spectral curves are shown here both for transitional and turbulent boundary layers. The turbulent reference curve 4 obtained closer to the

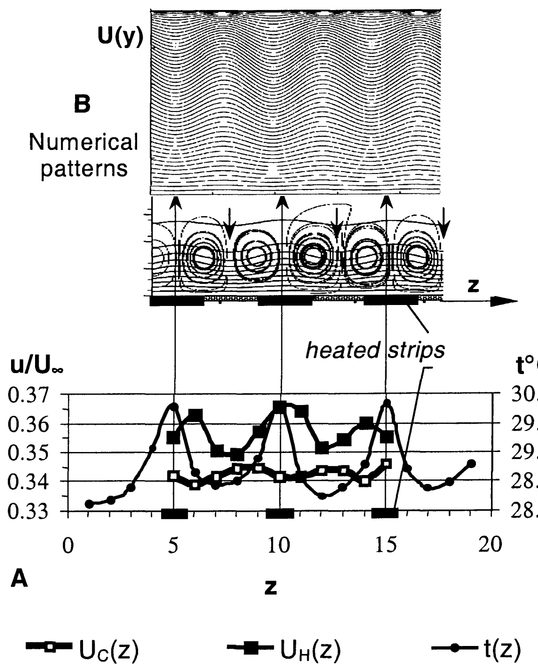

Figure 8 : **(A)** Measured spanwise distributions of temperature *t(z)* in a turbulent boundary layer at y+=5 and mean streamwise velocity component at y+=6 in the controlled case of heated strips switched on, *Uh(z),* and off, *Uc(z)*, i.e. in a reference case;
(B) Calculated topology of the flow near a wall with the *z*-regular temperature distribution (qualitative comparison)

TABLE 1: Vortex-generation and flow parameters for curve 1, Figure 9

λ_g, cm	U_∞, m/s	y_{vg}/δ_1	y/δ_1	y/δ
1.2	0.56	1.22	0.615	0.091

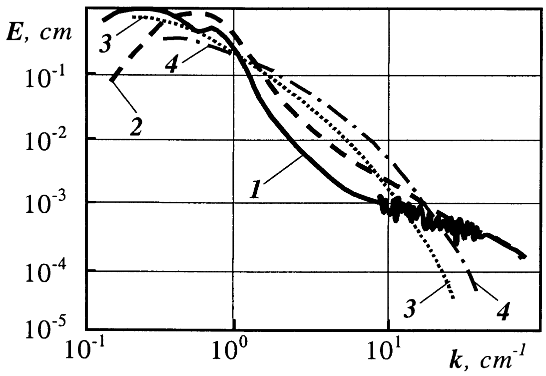

Figure 9 : Power density spectra of u'-velocity fluctuations in boundary layers,

1 – in case of generated streamwise vortices;
2 – in a reference case of natural laminar-turbulent transition, $Re\sim10^5$, $y/\delta_1=1.08$;
3, 4 – in case of a turbulent boundary layer, $Re\sim10^6$, $y/\delta=0.21$ (3), $y/\delta=0.063$ (4)

wall displays more uniform, smoothed spectral pattern than the curve 3 due to statistically dominating smaller scale vortices. Analysis of the transitional case (curve 2) brings to a conclusion that streamwise vortices naturally developing during laminar-turbulent transition result in a specific energy distribution along the spectrum characterized by a strongly pronounced long-wave interval with an amplitude peak around $k\approx0.5$.

At the same time, the large-scale motion significantly suppresses intensity of fluctuations in the inertial interval ($0.5<k<20$) but increases dissipation (spectral components of $k>10$).

The obtained results (curve 1) explicitly show that even in case of fully developed turbulent flow, generated streamwise vortices change the boundary-layer characteristics redistributing spectrum in favor of its long-wave part, i.e. approaching the transitional spectral pattern. To some extent, it can be considered as flow relaminarization with appeared deterministic vortical elements. Practically, it shows a way to change transport properties near a wall both in transitional, and in turbulent boundary layers.

Conclusions

An approach to control boundary layers affected by centrifugal forces was formulated and realized with a primary assumption to use the vortical structure (streamwise vortices) intrinsic to such flows. Goertler stability theory and receptivity methods were attracted to get an insight into the vortex dynamics and possibilities of its control in a most efficient way. The vortex growth stage was found to be preferential to intrude into the boundary layer to change its characteristics in a desirable way.

A method was developed and applied of generation of streamwise vortices with a given scale based on the application of a constant boundary condition $\Delta T(z)$. It enabled combined experimental/numerical studies of the problem. Choosing values of the control parameters correlated with the basic flow parameters, one can get either prolonged, low-rate vortex field development with stabilized smoothed velocity profiles or enforced development of streamwise vortices with a given scale, moderate long-term or well-pronounced short-term effects.

Experimental and numerical results obtained in a transitional boundary layer are in a good agreement having revealed:

- growing scales of the dominating vortical motion both downstream and normally to the surface;
- mode competition in favor of a large-scale fundamental even under condition of a constant different-scale forcing from the wall.

Experiments in turbulent boundary layers showed

- applicability of the thermal method of vortex generation;
- non-zero receptivity of a near-wall flow to induced streamwise vortices;
- power spectra redistribution in favor of a long-wave interval.

Acknowledgements

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