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Some advances in forcing the turbulent boundary layer

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Abstract

Forcing of incompressible flows with both the periodic blowing/suction through transverse slots and the microblowing through a cascade of finely perforate inserts to alter properties of turbulent boundary layers is reviewed. The focus is the structure, properties, and main regularities of the forced flows. A local skin-friction reduction in the turbulent boundary layer is clearly revealed. Provided the phase synchronization of the blowing/suctions, the independent control of the forcing through the slots gives an additional local skin friction reduction. The effect is stipulated by a dominating influence of an unsteady coherent vortex formed in the boundary layer on the structure of the viscous sublayer. In the case of experimental modeling of the process of air blowing into turbulent boundary layer of incompressible fluid through a series of the finely perforated walls the particular attention is paid to the analysis of the main factors responsible for the effectiveness of blowing. It is shown that the blowing through the micro-perforated inserts with low effective roughness is a quite affordable and reliable control technique for near-wall turbulent flows. This approach can provide a sustained reduction of local skin friction coefficient along flat plate, which in some cases reaches 90%.

1 Introduction

Power saving is one of the most actual engineering problems. However, it is generally accepted that significant reserves to reduce the aerodynamic drag by aerodynamic shaping and by finishing aircraft surfaces had been essentially exhausted about three decades ago. Meanwhile the problem of energy saving in exploiting aircrafts is still very relevant. This stipulates searches for new means of the drag reduction, especially of the skin-friction reduction, as frequently it reaches more than 50% in the drag balance for some moving objects. For example, one of the major sources of the drag for climb and cruise flight regimes, which accounts for almost 90% of the fuel consumption for a modern subsonic transport aircraft, is the skin friction drag.

It is generally accepted that the most successful way of obtaining turbulent drag reduction is developing an effective means to control the structure of wall turbulence. It is obvious that designing an effective method of turbulent boundary-layer control is possible only if deep knowledge on the dynamics of near-wall turbulence is available as the near-wall turbulent flows are characterized by a variety of coherent structures: the streaks (streaky structures), horseshoe vortices, large-scale and highly large-scale motions, each of which makes a relevant contribution to the process of generation and dissipation of turbulence kinetic energy.

During the last three decades, the main emphasis has been done on the development of active control methods in which energy, or auxiliary power, is introduced into the flow. One such promising approach consists of a periodic injection of a fluid into a boundary layer to generate coherent vortices at the wall to affect turbulence behavior. Effective control over these vortices can be a key element of a successful strategy for turbulent skin friction reduction. This approach deserves further study because it provides an efficient and relatively simple technique for local actuation of wall-bounded flows (see, e.g. Park and Choi, 1999; Park et al., 2001; Tardu and Sedat, 2001; Park et al., 2003; Boiko and Kornilov, 2008).

Another promising approach consists in a continuous in time gas blowing through a permeable wall (Hwang, 2004; Kornilov and Boiko, 2014a, 2016; Kornilov, 2015). However, permeable surfaces produced with traditional technology were characterized by high parasitic drag due to an apparent surface roughness. The situation changed only in the last decade with the advent of electron-beam technology that made it possible to design a finely perforated surface hydraulically smooth in a relevant range of Reynolds numbers.

The main focus of the paper is placed upon a physical modeling of the processes of boundary layer periodic blowing/suction and continuous blowing as well as a critical analysis of experimental results for

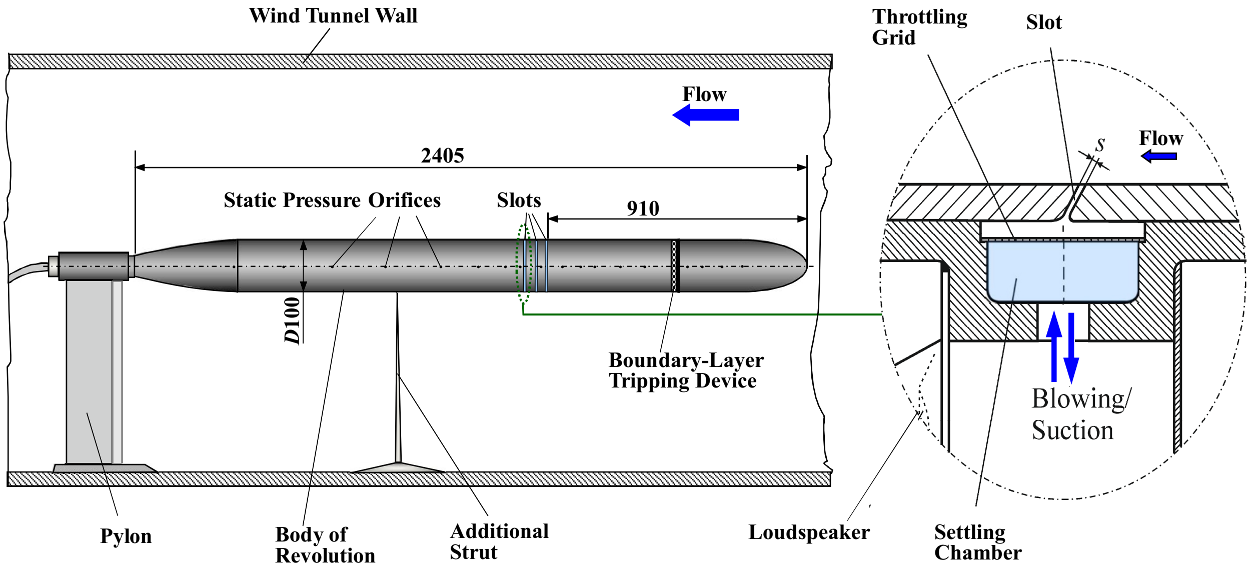

Figure 1: Body of revolution schematic and annular slot geometry, not to scale (all dimensions in millimeters).

different conditions of air blowing and elicitation of the physical mechanisms responsible for the reduction of turbulent friction at flow-exposed surfaces in the cases of application of a sequence of the control devices on plane and axisymmetric geometries.

2 Periodic blowing/suction

Experimental investigations of the effectiveness of the local periodic forcing of an axisymmetric turbulent boundary layer by means of blowing/suction through a series of transverse annular slots are of extreme interest and practical importance. Some efforts to apply the simultaneous periodic blowing/suction through a series of annular slots controlled independently to a turbulent boundary layer of an incompressible fluid on a body of revolution were undertaken by Boiko and Kornilov (2008), see Fig. 1.

The effect of the blowing/suction on the time-averaged flow characteristics and, in particular, on the boundary layer velocity profiles, when the forcing is performed through all slots simultaneously, is of a special interest. Analysis shows that in the vicinity of the slots the mean velocity gradient at the wall drops up to 80% compared with the unforced flow. The profiles clearly show the formation of a retarded flow region at the wall that can be an indication of a flow with reduced skin friction.

It is worth to note, that at the periodic forcing the maximum of the turbulent velocity fluctuations shifts to larger values of y. It could be supposed that the thickness of viscous sublayer becomes lager in this case that should promote the skin friction reduction. Meanwhile, the level of turbulent fluctuations in the presence of blowing/suction is much higher than that in the unforced case. This is related to the flow excitation in the vicinity of the slots. At the same time, an analysis of the instantaneous velocities shows that an increase in the turbulent velocity fluctuations in the examined region is also caused by the acoustic flow excitation with the dynamic loudspeakers.

One of the basic governing quantities for estimating the effectiveness of the blowing/suction is the local skin friction coefficient. Figure 2 presents the ratio of the skin friction coefficient in the presence of the forcing $C_f(\Delta x/\delta^*)$ to a corresponding value for the unforced regime $C_{f0} = C_f(0)$ (Δx is the distance from the first slot and δ^* is the displacement thickness). For comparison, averaged data for the unforced flow C_{f0i}/C_{f0} are also shown by line.

As seen, the influence of the blowing/suction through the series of annular slots on the flow structure accompanied by the skin friction reduction is significant. First of all, the favorable effect of this control technique due to the carefully performed phase synchronization consists of a decrease of C_f/C_{f0} upstream of the slot I. The skin friction continues to drop downstream of the slot achieving at $\Delta x/\delta^* \approx 1$ its minimum value. The largest skin friction drag reduction in the analyzed case is more than 80%. Further downstream,

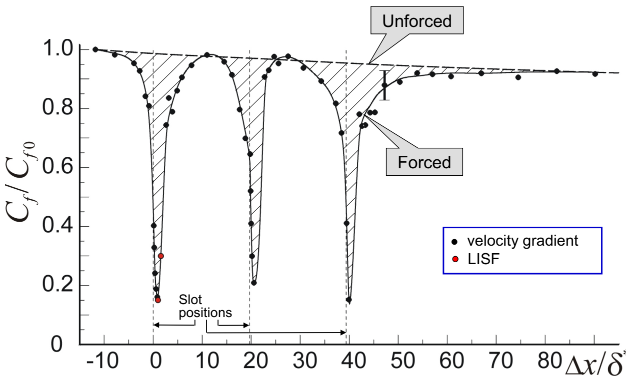

Figure 2: Local skin-friction coefficient distribution for forced and unforced (averaged data) boundary layer (Boiko et al., 2008).

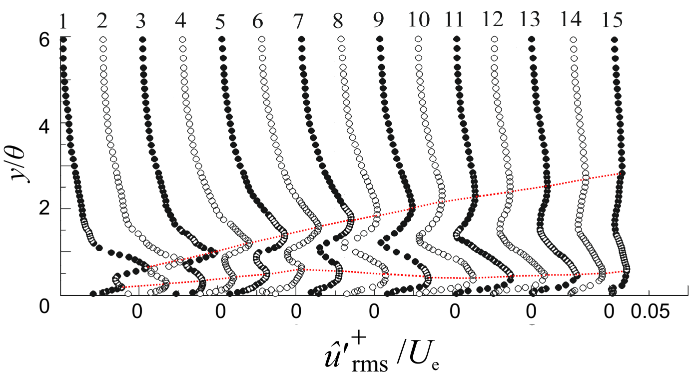

Figure 3: Profiles of root-mean-square of periodic velocity component (Kornilov and Boiko, 2018) at $\Delta x/\delta^* = 39.49$; 39.57; 39.73; 39.96; 40.24; 40.55; 40.94; 41.57; 42.08; 42.63; 43.29; 44.28; 45.25; 47.22; 50.35 (from labels 1 to 15, respectively).

C_f/C_{f0} grows at first abruptly and then gradually approaching its value in the unforced case. The situation, on the whole, being repeated at slots II and III with the only difference being that after the abrupt growth of C_f/C_{f0} at ($\Delta x/\delta^* \approx 40$–43), it gradually approaches its unforced value asymptotically.

Figure 3 presents the profiles of root-mean-square of periodic velocity component $\hat{u}'^+_{\text{rms}}/U_{\text{e}}$ at selected streamwise coordinates from a certain range of $\Delta x/\delta^*$ downstream of slot III (Boiko et al., 2008). The presence of two amplitude maxima (dotted lines) and a minimum between them is characteristic for the profiles of $\hat{u}'^+_{\text{rms}}/U_{\text{e}}$. These maxima can be attributed to a formation of an unsteady coherent structure caused by the periodic blowing/suction. It is not surprising that further downstream the amplitudes of the maxima decrease gradually. To obtain more reliable information about this issue a laser-sheet flow visualization in the vicinity of slot I was undertaken by Boiko et al. (2007). It was shown that the forcing leads to a formation of a toroidal vortex behind the slot (see Fig. 4). An interpretation of the main events demonstrating the dominating role of the vortex in the formation of the flow structure downstream of the annular slot is the following. At the blowing phase, the incoming shear flow seems to be temporarily blocked by a strong upwash jet flow directed from the wall. Then, the pressure directly downstream of the slot decreases abruptly, the mainstream flow breaks up, and a recirculation region with a reverse flow is formed. The subsequent suction phase favors a further increase in stability of the counterclockwise vortex motion being formed. As the distance Δx increases, this large-scale inclined structure gradually lifts away from the wall and dissipates to a large extent.

This leads to some conclusions on the mechanisms of the skin friction reduction with air blowing/suction through the slots. In general, the obtained data show that the blowing phase reduces the skin friction drag

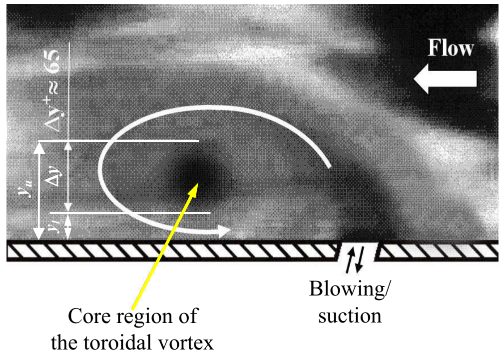

Figure 4: Formation of the toroidal vortex due to the blowing (Kornilov and Boiko, 2018).

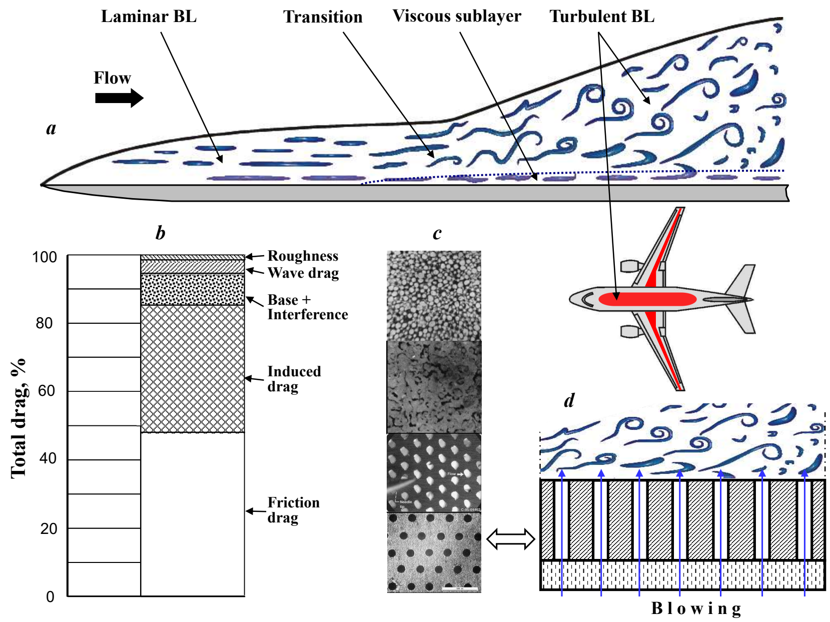

Figure 5: A conventional schematic diagram illustrating the formulation of problem and the the method of its solution).

and the suction phase increases it. The local skin friction reduction is due to the dominating influence of a formed unsteady coherent structure (toroidal vortex) in the boundary layer, in propagating downstream the vortex promoting a shift of low-velocity fluid further from the wall, a formation of a retarded fluid region at the wall, and, hence, a thickening of the viscous sublayer. Therefore, the velocity near the wall decreases, leading to a decrease in friction drag. Another reason for the skin friction reduction can be identified using a simple relation between the Reynolds stress and the skin friction for the canonical near-wall turbulent flows in a channel, a pipe and past a flat plate derived by Kasagi et al. (2009). In general, it can be concluded that the term $\sim u'v'$ in the equation characterizing the turbulent contribution is dominant in the equation. Depending on the amplitude of fluctuations, frequency, and Reynolds number, it can be either positive or negative. Thus, the suppression of the Reynolds stress near the wall is of paramount importance for effective control of drag reduction in the presence of blowing/suction.

3 Microblowing

Continuous in time gas blowing through a permeable wall (see Fig. 5) was considered in a series of studies (Kornilov and Boiko, 2014a, 2016; Kornilov, 2015). Of interest is the question of the effectiveness of the

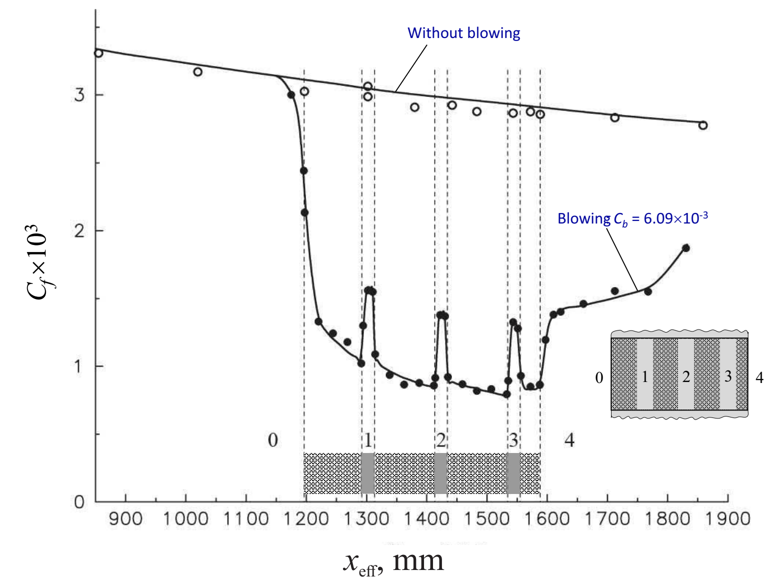

Figure 6: The skin-friction coefficient at air blowing through the wall consisting of permeable and impermeable sections in the streamwise direction (Kornilov and Boiko, 2014a).

control when the blowing intensity changes 'smartly' along the length of the plate to reduce potentially the total air supply and, hence, the energy consumption. To this end, a flat plate boundary layer along a perforated surface consisted of areas of permeable and impermeable sections along the streamwise direction was studied in detail by Kornilov and Boiko (2014a, 2016). Approximately two-thirds of each section were permeable followed by an impenetrable section. Figure 6 shows that a skin-friction reduction is observed over the permeable sections. However, a large part of the gain is maintained further over the impermeable sections, because the flow has no time to relax to the equilibrium state. Note that the region of lowered skin-friction covers not only the perforated insert, but also an extended region located downstream of it that plays an important role in the balance of the total drag.

It was shown (see Kornilov and Boiko, 2014b) that the main reason for the observed behavior of C_f lies in the sharp change of flow conditions at the boundary between the permeable and impermeable sections. Indeed, the boundary layer cannot instantly adapt to a new environment due to its memory of prehistory. Therefore, the flow reaction to such changes of the boundary conditions manifests itself in the form of a slow relaxation of the main flow characteristics (including the skin friction) to the condition of the hydrodynamic equilibrium.

4 Conclusions

In the vicinity of the slots the velocity gradient at the wall drops by dozens of percent compared with the unforced flow. The measurements clearly indicate the skin friction reduction on the body of revolution with the maximum reduction up to 80% downstream of the slots justifying that the cascade control can be an effective means of forcing the near-wall turbulence. A phase synchronization of the blowing/suctions through the slots makes it possible to achieve an additional local skin friction reduction at distances up to 5–6 boundary layer displacement thickness upstream of slot. The local skin friction reduction under the effect of periodic blowing/suction is stipulated by a dominating influence of the formed unsteady coherent vortex on the boundary layer; the vortex propagates downstream and promotes a shift of low-velocity fluid further from the wall and a formation of a retarded fluid region at the wall, and hence, leads to a thickening of the boundary viscous sublayer. Generally, by using a cascade of the slots it is possible to provide a higher effectiveness of this control technique, at least on a limited body surface. To demonstrate its effectiveness with regard of net drag reduction over the whole body surface, additional efforts are required.

It was shown that the air blowing through a series of the finely perforated inserts with low effective roughness is an effective means to influence the structure of wall turbulence. The skin-friction reduction is achieved without boundary layer separation even at high values of the blowing coefficient C_b. The formation of extended region of lowered skin friction downstream a blowing section, the length of the region being commensurate with the length of the perforated insert, is a significant reserve to reduce the total drag. Blowing through the finely perforated surface consisting of alternating permeable and impermeable regions along the plate can provide an additional reduction of the total aerodynamic drag C_x at the same amount of air expense. However, the optimal combination of permeable and impermeable areas requires additional research.

Acknowledgements

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