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Advances and challenges in periodic forcing of the turbulent boundary layer on a body of revolution

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A R T I C L E I N F O

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A B S T R A C T

The effectiveness of local forcing by periodic blowing/suction through a thin transverse slot to alter the properties of an incompressible turbulent boundary layer is considered. In the first part of the review the effectiveness of the forcing through a single slot is discussed. Analysis of approaches for experimental modeling of the forcing, including those on flat plate, is given. Some ambiguities in simulating such flows are reviewed. The main factors affecting the structure of the forced flow are analyzed. In the second part the effectiveness of the forcing on a body of revolution by periodic blowing/suction through a series of transverse annular slots is discussed. The focus is the structure, properties, and main regularities of the forced flows in a wide range of variable conditions and basic parameters such as the Reynolds number, the dimensionless amplitude of the forced signal, and the frequency of the forced signal. The effect of the forcing on skin-friction in the turbulent boundary layer is clearly revealed. A phase synchronism of blowing/suction using an independent control of the forcing through the slots provides an additional skin friction reduction at distances up to 5–6 boundary layer displacement thicknesses upstream of an annular slot. The local skin friction reduction under the effect of periodic blowing/suction is stipulated by a dominating influence of an unsteady coherent vortex formed in the boundary layer, the vortex propagating downstream promoting a shift of low-velocity fluid further from the wall, a formation of a retarded region at the wall, and hence, a thickening of the viscous sublayer.

1. Introduction

Power saving is one of the most important engineering problems. It is generally accepted that the significant potential to reduce the aerodynamic drag by aerodynamic shaping and by finishing aircraft surfaces was essentially exhausted about three decades ago. Meanwhile the problem of energy saving in exploiting aircraft is still very relevant. This motivates search 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 moving objects. For example, one of the major sources of drag for the 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.

Existing data [1] indicate that all transportation systems in the United States spend up to 25% of the energy consumed to overcome the aerodynamic drag. Ground vehicles spend 27% of the total energy in this way. Therewith, 60% of the energy consumed by ground vehicles (that is, 16% of the total energy) is being spent to overcome the aerodynamic drag. Estimations show that the application of prospective technologies to reduce the drag of ground vehicles can provide an annual saving of about 20 billion dollars in the United States alone. New technologies in air transportation also promise an impressive benefit, although the situation in this case is a bit different. Unlike the ground vehicles, in which the most energy is spent to overcome the drag induced by pressure forces, up to 60% of the total drag of subsonic commercial aircraft in the cruise flight regime is the skin-friction drag, whose reduction is one of the most important problems of modern aerodynamics. For example, a 1% drag reduction of the A340–300 saves about 400,000 L of fuel per year. As the annual worldwide fuel consumption of air transport is estimated to be about 1.5 billion barrels, it is easy to imagine the benefit of the application of advanced technologies. Several years ago, Airbus announced the intention to achieve a 50% reduction of fuel consumption per passenger mile by 2020, which can be achieved with 30–50% skin-friction drag reduction.

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Nomenclature

A	forcing amplitude
C_F	streamwise-averaged skin-friction coefficient, $F/0.5\rho_\infty U_\infty^2 S$
C_f	local skin-friction coefficient, $\tau_w/0.5\rho_\infty U_\infty^2$
C_P	pressure coefficient, $(P_i$ - $P_\infty)/q_\infty$
f	forcing frequency, Hz
G	Clauser equilibrium parameter, $\sqrt{2/C_f}(H-1)/H$
H	boundary-layer shape factor, $H=\delta^*/\theta$
q	dynamic pressure, $0.5\rho_\infty U_\infty^2$, kg/m^2
L	model length, mm
Re_θ	Reynolds number based on U_∞ and θ
s	streamwise width of transverse slot (aperture), mm
T	forcing period, s
U_∞	freestream velocity, m/s
U	instantaneous velocity, m/s
$\overline{\mathrm{U}}^+$	law-of-the-wall coordinate, $\overline{\mathrm{U}}/\upsilon_*$
u'	streamwise velocity fluctuation, m/s
υ_*	friction velocity, $\sqrt{\tau_w/\rho_w}$, m/s
y	wall-normal coordinate, distance from wall, mm
y^+	law-of-the-wall coordinate, $y\upsilon_*/\nu$
δ	boundary-layer thickness, mm
δ^*	boundary-layer displacement thickness, mm
θ	boundary-layer momentum thickness, mm
ν	kinematic viscosity, m^2/s
ρ	density, kg·s^2/m^4
τ_w	wall shear stress, kg/m^2
Δx	downstream distance from the slot, mm

Subscripts

e	boundary-layer edge conditions
max	maximum
0	no-forcing case
∞	freestream value

Superscripts

'	fluctuating value
+	wall unit value
(–)	time-averaged value

That is why the interest of finding new efficient means of turbulent shear layer control to reduce the skin-friction drag and aerodynamic forces acting on moving objects, particularly on aircraft, ships, submarines, torpedoes, and ground vehicles, is the subject of this papers. Of course, there are other means of drag reduction, such as propulsion system cycle improvements or aircraft weight reduction. The efficiency of different passive and active means of flow control, including different vibrators, actuators, microelectromechanical systems (MEMS), polymer additives, gas microbubbles, surfactants, riblets, large-eddy breakup devices (LEBU), air microblowing, and others to affect the turbulent boundary layer aiming to reduce the skin friction was reviewed in Refs. [2–4]. However, we note (omitting details) that one of the methods that probably has not been properly appreciated and completely studied is the periodic blowing/suction through a surface, as some investigators believed that the energy consumption to organize the process is too high. However, there is no complete clarity on this matter, and this topic is considered in this review.

2. Current state of studies

It is generally accepted that the most successful way of obtaining turbulent drag reduction is in developing an effective means to control the so-called coherent structures in the boundary layer [5]. Counter-rotating vortices in two-dimensional turbulent wakes, large-scale vortical structures in turbulent mixing layers as well as low-speed streaks and hairpin vortices in turbulent boundary layers serve as examples of these structures [6]. There are two principally different approaches to control the structures. The first is to prevent their formation, whereas the second one is directed at reducing their activity. 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 approach consists of the 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. In particular, according to Ref. [7] the blowing of air through spanwise slots in a surface adds energy to the near-wall part of the boundary layer, energizing the adjacent flow and enabling it to overcome a large pressure gradient. As an example of a similar approach, which currently attracts particular attention, one can use blowing/suction through a wall in the form of zero net mass flux jet. This approach deserves further study because it provides an efficient and relatively simple technique for local actuation of wall-bounded flows. Some studies (for example Refs. [8–20]), in which this approach has been used, indicate that depending on parameters of the forcing it can provide a substantial reduction of the local drag, an effective separation control, and even an improvement of airfoil lift characteristics. In particular, Park and Choi [8] showed that a stationary blowing through spanwise slot on a flat plate can reduce the skin friction and enlarge turbulence intensity, whereas a stationary suction provides an opposite effect. Park et al. [9] found that small amplitude local harmonic forcing through a spanwise slot on a flat plate reduced the drag, the forcing becoming more efficient, when the frequency was enlarged. Tardu [10] carried out wind-tunnel experiments on a flat plate to compare the behavior of periodic and steady blowing. He indicated that the wall shear stress decreases considerably until reaching the value which the laminar boundary layer would have at the same Reynolds number. In addition, he attempted to explain the response of the flow to periodic blowing in terms of physical arguments based on the vorticity dynamics near the wall. It was found that when the blowing frequency is larger than a critical value, the blowing leads to the formation of a positive near-wall vorticity layer that subsequently rolls up into a spanwise coherent structure and a negative vorticity layer that rolls up further downstream. Later Park et al. [11] found that the maximum turbulent drag reduction is achieved at the highest forcing frequency used in their study ($f^+=0.088$) at the slot angle of inclination equal to $-120°$, i.e. directed opposite to the flow. Iuso et al. [12] reported a robust drag reduction (about 18%) for a flat plate placed in a water channel by means of periodic blowing/suction through a spanwise slot. This drag reduction was accompanied by the growth of the turbulent intensity in the whole region of measurements downstream the slot. A similar effect was detected in Refs. [13,14] in applying the periodic blowing/suction through an annular slot on a body of revolution; moreover, even larger skin friction reduction was achieved.

The majority of related numerical works have been focused on studying the effectiveness of steady actuations [15–17 and others]. Investigations of Sano and Hirayama [15] and Sano [16] showed that the steady blowing reduces the drag, while the steady suction has an opposite effect. In contrast, the steady blowing increases the turbulent intensity, while the steady suction has an opposite effect. Therewith, in Ref. [15] it was demonstrated that the slot width s hardly affects both the turbulence characteristics and the velocity profiles, when $\sigma \equiv \upsilon_f U_\infty \theta$ is fixed at a constant value. Here θ is the momentum thickness of the unperturbed flow at the slot location and subscript "f" denotes forcing. Kim et al. [17] used direct numerical simulation to study the effect of three different