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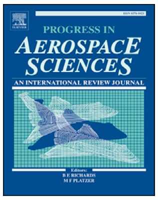

Three-dimensional turbulent near-wall flows in streamwise corners: Current state and questions

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ABSTRACT

Current advances in experimental and computational studies of three-dimensional (3-D) near-wall turbulent flows in streamwise corners (SC) including the boundary-layer transition are reviewed. The focus is the structure, properties and main regularities of such flows in a wide range of variable conditions and basic parameters. A variety of different kinds of near-wall streamwise corner flows is displayed. Analysis of approaches for modeling of the near-wall corner flow in laboratory experiment is given. The problem of simulation of such flows where some ambiguities remain is discussed. The main factors on the structure of the flow in streamwise corners are analyzed. Also, the effectiveness of flow control by streamwise vortices in the junction regions of aerodynamic surfaces is shown. Finally, some important properties of the modified near-wall turbulent corner flows which have been revealed experimentally, in particular, for the flow near the wing/body junction (WBJ), can be used as an attractive alternative for real applications.

1. Introduction

A challenge for both theoretical and practical aerodynamics is the further perfection of aerodynamic assemblies to advance the design of new-generation aircraft. From the application viewpoint, this problem includes the determination of the optimal shape of junctions of aerodynamic elements of, for example, wing/fuselage type to provide minimum aerodynamic drag of the aircraft and to improve its lifting properties. From the fundamental viewpoint, this problem is reduced to studying the physical properties and regularities of corresponding three-dimensional (3-D) flow to develop effective computational techniques. The flow even in a simple streamwise corner (SC) formed by the intersection at right angles of flat or curvilinear surfaces can mimic many features of the flow in real practical cases. The similar geometrical configurations are wide-spread in applications and common for the test-sections of wind tunnels [1], in which the aerodynamic assemblies are actually tested. The applied aspects of these problems are of similar importance for turbomachinery [2–4], as almost every basic part of the turbines, pumps, compressors, and fans contains SC-shaped elements, for example by the junction of the blades either with the bushing (axial machines) or the side disks (closed centrifugal impellers and stationary parts of the turbine setting).

Quite often, the 3-D flows in the streamwise corners depend on many complicating factors such as:

– the essential effect of turbulence. Though the laminar form of motion does not occur frequently in nature and technology, it is even less frequent in corner flow, observed only at very low subsonic velocities in very limited regions [5–15]. Thus, the flows under consideration are turbulent in most practical cases;
– the flow prehistory (“memory”) [16–22] caused either by the local pressure gradient [23] at the leading edges of the intersecting plates formed the streamwise corner or by a disturbance source located in front of the flow region under study [24–33]. This problem takes place for example in heat-exchanger channels, in which two-dimensional (2-D) disturbance sources as steps, wall fences, obstacles, etc., installed on the perimeter of the channel covering the corner regions [34] are used for heat exchange intensification;
– presence of the streamwise pressure gradient [35,36]. Such flows appear usually at different junctions as well as in ducts with noncircular cross sections containing the SC-shaped elements [37–42]. Note that the 3-D boundary layer formed in the corner region is more prone to separation than the plane one, therefore a very complex cross-section flow pattern may occur;
– presence of the longitudinal or spanwise curvature of the intersecting surfaces [43–50]. In this case, the 3-D flow near the corner line is developed with an additional effect of the centrifugal force. The existing concepts of the corresponding processes are inspired mainly by the results obtained in curved ducts [51–56]:

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Nomenclature

b_w	wing root chord
C, m, n	empirical constants
C_f	local skin-friction coefficient, $\tau_w/0.5\rho_\infty U_\infty^2$
C_x	drag coefficient, $X/0.5\rho_\infty U_\infty^2 S$
D	cylinder diameter
G	Clauser equilibrium parameter, $\sqrt{2/C_f}(H-1)/H$
H	boundary-layer shape factor, $H = \delta^*/\delta^{**}$
q	dynamic pressure, $0.5\rho_\infty U_\infty^2$
R	leading-fairing radius (in plan view); radius of the curvilinear wall
r	fillet radius
Re_x	Reynolds number based on U_∞ and x
U, V, W	mean velocity components in the x, y, z directions, respectively
u'	rms streamwise velocity, equal to $(\overline{u^2})^{1/2}$
v', w'	rms spanwise velocities
$u'v', u'w', v'w'$	turbulent shear stresses
x	streamwise coordinate along the corner line
y, z	spanwise coordinates along the corner plates
α	angle of attack
δ	boundary-layer thickness
δ^*	boundary-layer displacement thickness
δ^{**}	boundary-layer momentum thickness
θ	setting angle of an aerodynamic element
ν, ρ	kinematic viscosity and density
τ_w	wall shear stress

Subscripts

b	body
e	at the boundary-layer edge
eq	conditions of equilibrium
f	fillet
lf	leading fairing
w	wing
0	bisector-plane conditions; circular cylinder position
2	two-dimensional conditions
∞	freestream conditions

Superscripts

$'$	fluctuating quantity
羊	time average

- presence of shear flow asymmetry. The asymmetry occurs when the boundary layers with different prehistory interact. In particular, it occurs in the corner regions formed by the intersecting surfaces with the leading edges shifted in the streamwise direction relative to each other [57–63]. The junction formed by a wing profile (a flat plate in the limit case) mounted on the wall of wind-tunnel test section is a typical example [64–70]. The generated vortex systems and their evolution along the junction region are quite specific in this case due to the complicated effect of the leading edge geometry;
- occurrence of an additional effect due to interaction between an externally-generated oblique shock wave and 3-D turbulent flow in a streamwise corner [71–84]. In this case, the flow structure is characterized by a complex spatial system of impinging and reflected shocks, which interact with the initial 3-D boundary layer in the corner and may cause an undesired flow separation under certain conditions.

The present paper reviews the results of investigations concerning the near-wall turbulent flows as the dominating form of motion in the corner configurations. It is directed mainly to the classical cases of turbulent flows in the streamwise corners, which are highlighted only partly in available publications. For this reason, U-bends, rotating flows, blading corner flows, etc. are not reviewed here, although they are important for aero/mechanical-engineering applications. The problems of boundary-layer transition modeling are considered only briefly as they were not the main goal of the paper.

Here, turbulence means as usual the physical phenomenon widespread in nature and technology. In general, we keep the common definitions and concepts which characterize this phenomenon though, owing to the extreme complexity of its internal structure, there is apparently no single definition of the term. Let us refer to one such definition [85], which is quite complete from the physical point of view:

> "*The phenomenon observed in very many swirled flows of fluids and gases, both in nature and engineering devices is advisable to refer the turbulence; its idea is in the fact that thermodynamic and hydrodynamic characteristics of such flows (velocity vector, temperature, pressure, admixture concentration, medium density, sound velocity, electric conductivity, refractory index, etc.) undergo chaotic fluctuations resulting from multiple vortices of various size in these flows, thus these characteristics change extremely irregularly in space with time; plus, in the spatial distributions of these characteristics, the Fourier components with fixed wave vectors correlate with wide frequency ranges (i.e. there are no single-value dispersion relations), whereas the phase differences between the fluctuations of different characteristics in the fixed points of the space change chaotically along with the frequency of such fluctuations*".

The near-wall flow means the shear layer that, in contrast to the unbounded flows (as jets, wakes, and mixing layers), develops at one or two steady boundaries. The wall may be flat or curved, permeable, compliant or solid, i.e. there is no major restriction to its properties. The main attention is paid to the so-called equilibrium near-wall flows characterized by the balance between generation and dissipation of turbulence energy in each section along the streamwise direction. This means that the mean velocity profiles in the boundary layers are self-similar in different cross sections along the streamwise coordinate. Only statistically stationary flows will be considered. Thus, the time average at a fixed point in the flow-field will be used as the statistically mean value. The terminology, physical and mathematical concepts and definitions follow established convention (see, *e.g*, Refs. [86–88]).

2. Fundamental concepts and definitions

2.1. Classification of 3-D flows

Increasing interest of researchers and implementers to the 3-D flows is provoked by two basic factors: prevalence of such flows in various engineering devices, and permanently rising requirements to the accuracy of calculation of such flows during the design and implementation of new aerospace vehicle, concepts as well as improvement of units of thermal-engineering and power-engineering equipment. The simplest 3-D flow arises in the case when the initially 2-D boundary layer developing on the surface (plane (x, z)) deviates in the lateral direction under the action of the pressure gradient $\partial P/\partial z$, which normally hardly changes in the axial direction, so z-gradients of velocity remain low in comparison with the y-gradients. Essential peculiarity of the 3-D boundary layer lies in the presence of transverse (secondary) flows, and the streamlines of the main flow are curved as a rule. This definition is however incomplete without conventional classification of 3-D flows, nor without major mechanisms decisive to the 3-D character of the flows; first of all it is necessary to