Adverse-Pressure-Gradient Effects in Three-Dimensional Swept-Wing Flows

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Abstract

Three-dimensional (3D) wall layers are studied by subjecting fully developed turbulent two-dimensional channel flow to mean strains characteristic of those induced by pressure gradients in boundary layers over swept wings. This is done by applying irrotational temporal deformations to the flow domain of a conventional channel direct numerical simulation code. The velocity difference between the inner and outer layer is controlled by accelerating the walls in the streamwise-spanwise plane, allowing duplication of the defining features of both the inner and outer regions. Strains imitating infinite-swept-wing boundary layers both with and without adverse-pressure-gradients (APG) are considered. We find that while both strain fields alter the structure of the turbulence, the influence of the APG dominates over that of the pure skewing.

Keywords: three-dimensional boundary layers, adverse-pressure gradient, turbulence, direct numerical simulation

Introduction and Approach

Three-dimensional boundary layers (3DBLS) can be defined as wall layers with mean velocities that change not only magnitude but also direction; they thus possess nonzero mean streamwise vorticity. Here our attention is directed toward the pressure-driven nonequilibrium case, for which the 3DBL is created by an abrupt change in the mean pressure field to which the turbulence has not yet adjusted. (See Coleman, Kim & Spalart (1996; hereinafter referred to as CKS) for a discussion of the difference between pressure- and shear-driven 3DBLS.) This choice is motivated by its relevance to many technically important flows (such as that over swept-wing aircraft), and by the fact that the physics of nonequilibrium 3DBLS is not yet well understood. Specifically, incompressible turbulent two-dimensional (2D) plane channel flow is subjected to spatially uniform irrotational strains characteristic of those induced in the outer region of engineer boundary layers by pressure gradients. We are thus able to capture the essential physics of spatially developing pressure-driven shear layers using a temporally evolving flow. Advantages of this approach, which is described in detail in CKS, and represented schematically for the case of a pure 3D-skewing strain in figure 1, include having a single well-defined initial condition (instead of dealing with the uncertainty associated with inflow and outflow boundary conditions), and being able to generate statistics by averaging over two homogeneous directions and both halves of the channel. Another is being able to use an unsteady one-dimensional problem to test and develop turbulence models for spatially evolving flows.

Solutions are obtained using direct numerical simulation (DNS), since all relevant scales of motion are resolved, no turbulence or subgrid-scale model is required. In contrast to previous DNS studies of strained flows, which assumed that both the strain and the turbulence were homogeneous (Rogallo 1981), here we apply a uniform strain to turbulence between two no-slip surfaces. The imposed strain field is given by the divergence-free irrotational deformation,

\[
A_{ij} \equiv \frac{\partial U_i}{\partial x_j} = \begin{bmatrix}
\frac{\partial U_i}{\partial x} & 0 & \frac{\partial U_i}{\partial z} \\
0 & \frac{\partial V_i}{\partial y} & 0 \\
\frac{\partial W_i}{\partial z} & 0 & \frac{\partial W_i}{\partial z}
\end{bmatrix},
\]

(1)

where

\[A_{11} + A_{22} + A_{33} = 0\quad \text{and} \quad A_{13} = A_{31}. \]

(2)

Each point of the flow volume is affected by the strain (figure 1). This amounts to distorting the entire computational domain consisting of the two walls at \(y = \pm \delta\) (where \(\delta\) is the channel half-width, which when \(A_{22} \neq 0\) will be a function of time) and the periodic boundaries in \(x\) and \(z\). The fact that the walls deform complicates the comparison between the near-wall regions of the present and actual pressure-driven boundary layers. However, since the magnitude of the irrotational outer-layer strains are typically much smaller than the mean shear near the wall, and because the appropriate behavior of the near-wall rotational gradients can be approximated in a straightforward manner (see below), the significance of this formal inconsistency is limited. It is convenient at this point to differentiate between the irrotational and vertical mean fields observed by the turbulence. The former is prescribed by imposing the various \(A_{ij}\) components in (1); the latter is due to wall-normal variations of the mean velocity \(\overline{U}_y\) between the no-slip channel walls. Note that the applied irrotational strains will affect both the turbulence and the rotational mean, since the streamwise and spanwise shear, \(\overline{\partial U}/\partial y\) and \(\overline{\partial W}/\partial y\) respectively, are the components of mean vorticity (i.e. both the perturbation and mean vorticity will be altered by \(A_{ij}\)). In order to subject the turbulence near the walls to the correct rotational mean gradient the following strategy is employed: the walls are accelerated in the \(x-z\) plane such that the difference between the mean channel centerline velocity \((\overline{u}_c, \overline{w}_c)\) and the wall velocity \((\overline{u}_w, \overline{w}_w)\) varies in time at the same rate that the outer-layer velocity in the spatial flow changes as it converges downstream. For example, when the 2D APG strain given by \(A_{11} = -A_{22} < 0\) is applied (with all other components zero), the difference between the mean streamwise velocity at the centerline and the wall, \(\overline{u}_c - \overline{u}_w\), follows \(\overline{u}_c(t) \exp(A_{11} t)\) — since we desire \(\partial (\overline{u}_c - \overline{u}_w)/\partial t = (\overline{u}_c - \overline{u}_w)A_{11}\). This accounts for the bulk deceleration caused by an APG
by diminishing the mean surface shear stress, and creates an ‘inner layer’ that propagates outward in time. In practice, instead of accelerating the walls the same result can be obtained by keeping the walls stationary and imposing a spatially uniform time-dependent pressure gradient that creates the same $\Omega(t)$ history. Since the two approaches are identical, for ease of visualization the DNS data presented below, which were generated with the moving-wall procedure, are plotted as if the nonzero pressure gradient had been used.

Two cases are briefly considered here, defined by the strain-rate components summarized in table 1. The DNS results are obtained using a modified version of the spectral channel code of Kim, Moin & Moser (1987). The reader is referred to Coleman, Kim & Spalart (1997) for a detailed discussion of the numerical approach, as well as a more complete presentation of the current (and other) cases.

Results

We begin by imposing the most general deformation allowed by (1). The resulting flow, denoted Case I, duplicates the full complexity of a three-dimensional (3D) boundary layer, since lateral irrotational skewing ($A_{13} = A_{31}$), streamwise deceleration ($A_{11} < 0$), lateral convergence ($A_{33} < 0$) and wall-normal divergence ($A_{22} > 0$) are all present. This strain field thus corresponds to that found in the 3D boundary layer experiments of van den Berg et al. (1975) and Bradshaw & Pontikos (1985); in the present study the initial flow direction is oriented at 45° to the principal strain axes in the $x$-$z$ plane, which imitates that instead of the 35° deg sweep angle of the ‘infinite swept wing’ experiments, the effective sweep angle is 45° deg, and $A_{11}$ and $A_{33}$ are equal.

The evolution of the Case I mean spanwise velocity is illustrated in figure 2. Two characteristics of pressure-driven 3D boundary layers can be seen: the growth of the layer thickness due to the streamwise deceleration/wall-normal divergence (i.e. the APG), and the ‘instant’ appearance of spanwise shear (mean streamwise vorticity) in the outer layer, due to the $A_{13}$-induced skewing of the mean spanwise vorticity. This latter ‘inviscid skewing’ mechanism dominates the behavior of the outer-layer mean velocity to the extent that when viewed in hodograph form (not shown) the $\overline{u}$ versus $\overline{w}$ curve is closely approximated by the Squire-Winter-Hawthorne expression (Bradshaw 1987). The strain also affects the relationship between the normal and shear-stress components of the Reynolds stress tensor. As shown in figure 3, the $a_1$ structure-parameter (the ratio of the shear-stress magnitude $\tau = (\overline{u'\nu''^2} + \overline{\nu'w''^2})^{1/2}$ to twice the turbulent kinetic energy $q^2 = \overline{u'w'}$) is uniformly decreased. The significance of this reduction is twofold. From

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Case & $A_{13}$ & $A_{11}$ & $A_{22}$ & $A_{33}$ \\
\hline
I & 0.99 & -0.99 & 1.98 & -0.99 \\
Ia & 0.99 & 0 & 0 & 0 \\
\hline
\end{tabular}
\caption{Case parameters. (Strain magnitudes given in terms of initial $u_r/\delta_0$.)}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Schematic of 3D boundary layer. Top: Spatially developing analog. Middle: Strain applied to fluid element at $x = 0$ of spatially developing flow at $t = 0$ of strained-channel DNS. Bottom: Initial and deformed domain of strained-channel DNS.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Mean spanwise velocity for Case I: ----- , $A_{13}t = 0$; ---- , $A_{13}t = 0.10$; ------- , $A_{13}t = 0.18$. Reference velocity $U_{ref} = 0.73 u_r(0)$, where $u_r(0)$ is the surface friction velocity of the 2D initial condition; distance from the wall $y_w = 0.10$.}
\end{figure}
a fundamental point of view it implies that the efficiency of kinetic energy extraction from the mean by the turbulence has become less efficient. From a practical point of view it indicates an inaccuracy of turbulence models that assume $a_1$ is constant for all flows.

Structure parameter values smaller than that found in 2D layers have been observed in many 3D boundary layers – both shear- and pressure-driven, and equilibrium and nonequilibrium varieties (Bradshaw & Pontikos 1985, Moin et al. 1990, Schwarz & Bradshaw 1994, Eaton 1995, Johnston & Flack 1996). Some have proposed that this reduction is primarily a result of the spanwise shear. This hypothesis can be directly tested by comparing data from Cases I and Ia. Since the latter imposes the same skewing component upon the same initial conditions, but does so without also applying the normal components present in the Ia swept-wing strain field, the difference between the two simulations will be solely the result of non-skewing 'APG effects'. A comparison of the evolution of the structure parameter under the Case I and Ia strain fields indicates the dominance of APG strain over that of the pure-skewing effects. Figure 4 reveals only a slight change of $a_1$ due to nonzero $A_{13}$, while the change produced (after the same amount of skewing $\alpha \approx 10$ deg) by the full strain field is much more profound. We conclude that for strain magnitudes of order $u_0/\delta$ the infinite-swept-wing flow is less sensitive to pure skewing than to strains caused by adverse pressure gradients. Further support of this conclusion is given in Coleman et al. (1997).

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References


Instability of streamwise vortices over a curved wall.

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Abstract
Curved streamlines generated by Görtler mechanism produce steady vortical structure, known as Görtler vortices. The nonlinear evolution of these vortices was experimentally investigated on a concave-convex curved model. Experiment indicated that the linear state can be brief and the nonlinear regime dominates the primary instability. It also revealed that the developed mushroom-like structures are almost observed in that nonlinear stage. Hot-wire measurement of the velocity field allowed reconstruction of the vortex structure. The wall-normal and spanwise profiles of the streamwise component of the velocity showed simple and multiple inflection points. The profiles became more complex as the flow field becomes more nonlinear state. Spectral analysis of the spanwise profiles of the streamwise component show that only some modes suffice to represent the velocity field in the nonlinear regime.

Introduction
Centrifugal instability of wall shear layers, known as Görtler instability (Görtler 1954) produces streamwise vortical structures growth in a laminar boundary layer. Görtler problem has at least two particular characteristics that make it different from other instabilities. It has, usually, a curt linear regime that the vortices almost appear in the nonlinear regime. Depending on experimental conditions, the mode of the secondary instability, sinuous type or varicose type, depends upon the wavelength initially developed.

Many studies have investigated on the nonlinear evolution of Görtler instability. Most of that work presents a numerical studies, and it had been the subject of a number of investigations (Herbert 1976, Hall 1988, Floryan & Saric 1982, Sabry & Liu 1991, Lee & Liu 1992 and Li & Malik 1995).

The experimental works are less numerous (Bippes & Görtler 1972, Bippes 1978, Swearingen & Blackwelder 1987, Peerhossaini & Westfreid 1988, Kohama 1987, Peerhossaini & Bahri 1997), making the numerical-experimental comparison difficult. In this investigation we report the results of an experimental studies of Görtler instability in the linear, nonlinear regimes and especially a decomposition by spectral analysis of the nonlinear evolution.

Experimental apparatus
Experiments were run on a concave-convex model fixed in a low-speed wind tunnel with a nominal free stream velocity of 2 m/s. The model, Figure 1, consists essentially of a concave part of 65 cm radius of curvature, followed by a convex one. A flat plate tangent to the convex wall at its summit, which can pivot around the center of curvature of the convex part, completes the working surface of the model. Spanwise wavelength are triggered artificially through a 0.2 mm diameter wire grid vertically positioned at the leading edge. The wavelength is fixed to 30 mm.

Flow visualizations are performed by injecting smoke through a slit of 0.7 mm thickness inclined at 45°. The boundary layer is enlightened by an Argon laser sheet oriented normally to the wall at different streamwise positions. Görtler vortices are viewed by a camera mounted perpendicularly to the plane of the laser sheet.

Single hot-wire probe is used to measure the streamwise component of the velocity. The probe scans, at each streamwise location, the boundary layer cross-section in wall-normal and spanwise directions.

Results and discussion
Flow visualizations are performed at four streamwise positions located at x = 95, 260, 425 and 580 mm from the leading edge.

At the first location x = 95 mm from the leading edge smoke visualization don't reveal any significant rotating structure. At x = 260 mm, Figure 2 (a), a local growth "small hump" of smoke has been observed in back of each triggering wire. However, streamwise location x = 425 mm shows three pairs of developed vortices presented in Figure 2 (b).