European Journal of Mechanics / B Fluids 67 (2018) 70–78

Contents lists available at ScienceDirect

European Journal of Mechanics / B Fluids

journal homepage: www.elsevier.com/locate/ejmflu

Influence of the transition of a laminar separation bubble on the downstream evolution of strong adverse pressure gradient turbulent boundary layers

M.P. Simens [a], A.G. Gungor [b,*]

[a] School of Aeronautics, Universidad Politécnica de Madrid, 28040 Madrid, Spain
[b] Istanbul Technical University, Faculty of Aeronautics and Astronautics, 34469 Maslak, Istanbul, Turkey

ARTICLE INFO

Article history:
Received 15 June 2017
Received in revised form 17 July 2017
Accepted 4 August 2017
Available online 16 August 2017

Keywords:
Adverse pressure gradient
Boundary layer
History effect
Transition
Turbulence

ABSTRACT

The evolution of boundary layers subject to adverse pressure gradient (APG) is strongly influenced by the upstream history. Hence, the detailed understanding of APG flows in general or downstream of reattachment of a separation bubble requires a clear acquaintance of the relation between the upstream flow structures and the downstream ones. In this work the results for three different direct numerical simulations (DNS) of APG flows are analyzed to scrutinize the relaxation of these flows having distinct development histories. The three cases have the same overall characteristics – laminar separation, transition, and turbulent reattachment – with respect to the imposed APG and the Reynolds number $Re_{\delta_{99}^0}$ at the inlet. However, in the first case no additional perturbations are imposed to trigger transition, in the second case the flow is tripped by a trip wire and in the third case a periodic wake is superimposed on the flow. The detailed information provided by DNS is critical to evaluate the current turbulence models and develop new ones. Hence, main points that are discussed are the Reynolds stress budgets, two-point spatial correlations, and spanwise spectra. Attention is in particular directed to a comparison between the three different cases. The most important conclusion is that the flow downstream of the reattachment decorrelates faster with the flow at the transition position if transition to turbulence completes within the separation bubble than in the case the transition completes after reattachment.

1. Introduction

It is well known that in general flows need a long decorrelation in time or length for the flow to become independent of imposed perturbations. This has been observed for example in several studies showing the long downstream effect of different types of trip wires or perturbations in boundary layers. These history effects are both present in zero-pressure-gradient (ZPG) boundary layers [1,2] as well as in mild APG flows [3]. An important difference between these studies and the present study is that the different perturbations used here are primarily meant to trigger different transition scenarios in the bubble. The effect of these different transition scenarios on the downstream flow development is being studied.

DNS studies [4–7] exist in which a turbulent boundary layer under the influence of a continuous APG is being studied. In those cases however, both the transition process and the separation bubble are obviously absent. There are several experimental and numerical studies that investigate the relaxation from a separation bubble towards a canonical turbulent ZPG boundary layer [8,9] and [10]. In these studies the separation bubble is formed due to a bump or a backward facing step and the influence of the APG is local in space.

An important example in this respect is discussed in [11] and [12] where a separation bubble is formed on the leading edge of a blunt plate. The plate is long enough to be able to study the effect of transition and reattachment on the evolution of downstream flow that develops under approximate ZPG conditions. It is shown that the flow takes at least twenty bubble lengths to relax to a more or less canonical ZPG boundary layer. This slow relaxation is hypothesized to be due to the large-scale structures that are generated as a result of the separation bubble. These large-scale structures, shed by the separation bubble resemble the structures in a mixing layer affected by the presence of the wall [11]. It is conjectured here that these large structures are more natural in APG boundary layers and therefore a relaxation to an APG boundary layer might be faster.

Studies [13–16] exist in which both the transition of the separation bubble and a subsequent downstream APG coincide, however,

* Corresponding author.
E-mail addresses: mark@torroja.dmt.upm.es (M.P. Simens), ayse.gungor@itu.edu.tr (A.G. Gungor).

http://dx.doi.org/10.1016/j.euromechflu.2017.08.004
0997-7546/

these studies are normally related to short turbine like domains and are not useful for a study of history effects.

In this work we propose to study the relaxation of the flow after transition and subsequent reattachment of a separation bubble that develops under APG. For this purpose, three different DNS data sets will be analyzed. The difference between [11] and the APG cases discussed here is that the APG extends until the end of the numerical domain. Considering a very likely shear layer type instability of the separation bubble, we expect to see the flow downstream of reattachment to correlate for long distances with the upstream flow as well as the flow downstream being influenced by the structures created at transition.

The study of the relaxation will be done by looking at spanwise spatial spectra, two-point spatial correlations and the development of components of the Reynolds stress budget terms as a function of streamwise direction.

The article will first discuss and describe the different data sets used, after which results for the Reynolds stress budgets will be discussed. This discussion is followed by results on two-point spatial correlations and spanwise spectra and the paper subsequently closes with conclusions.

2. Data and analysis

The data used for the analysis come from three different DNS's of three-dimensional boundary layers [17–19]. These three cases have the same overall characteristics with respect to the imposed APG and the Reynolds number at the inlet but with distinct transition and relaxation histories. The laminar boundary layer subjected to a streamwise APG eventually undergoes laminar separation. The reattachment of the separated boundary layer occurs due to an increase in the momentum exchange in wall-normal direction, induced through transition to turbulence. The turbulent boundary layer flow develops still subject to the APG. For completeness an overview of the most important details of these simulations are given here.

The details of the DNS code that is used for these analysis are given in [17], including a full discussion of the numerical scheme and examples of applications to other problems. The streamwise, wall-normal and spanwise directions and velocity components are x, y, z and u, v, w, respectively, and the kinematic pressure p incorporates the constant fluid density. Upper-case letters refer to mean quantities, lower-case to fluctuations with respect to the mean and primed ones to the root-mean-squared (rms) fluctuation intensities. The brackets $\langle\rangle$ represent averaging over the periodic spanwise direction and time. The $'+'$ superscript denotes wall units defined in terms of the wall friction velocity u_τ and kinematic viscosity ν. The 99% boundary-layer thickness is δ_{99} and it is defined as the wall-normal location of 99% of the maximum velocity in the free-stream. There are more accurate ways to determine δ_{99} especially for scaling analysis for boundary layer flows with pressure gradients [20]. However, the method used here is deemed sufficient since δ_{99} is used as a length scale only and not in a scaling analysis.

In all cases, the Reynolds number based on the boundary layer thickness, δ_{99}^0, measured at the inflow and the free-stream velocity is $Re_{\delta_{99}^0} = 948$. The streamwise extent of the simulation domain is $L_x = 190\delta_{99}^0$, the vertical height is $L_y = 54\delta_{99}^0$ and the spanwise extent is $L_z = 90\delta_{99}^0$. The corresponding grid sizes N_x, N_y, and N_z are 1537, 301 and 768, which results in grid cells of the order of the Kolmogorov length scales for the whole numerical domain, except extremely close to the wall [19] at the reattachment location. The grid resolution at a streamwise location downstream of reattachment is at $x/\delta^0{}_{99} = 157$, $\Delta y^+ \approx 0.4$ (given in wall units) at the wall, and $\Delta y^+ \approx 2$ further into the boundary layer, while $\Delta x^+ \approx \Delta z^+ \approx 2$. Note that in general wall units are not the correct scaling for strong APG flows as $u_\tau \to 0$ or is zero (at separation).

The mean APG is achieved by imposing at the top boundary a stationary suction velocity, which apart from close to the inlet and exit is constant along the x direction. No-slip boundary conditions are applied on the lower wall and the spanwise direction is treated as periodic. At the outflow plane a convective boundary condition is used. A laminar Hiemenz profile [21] is imposed at the inflow to approximate u and v, and a stationary three-dimensional perturbation is also explicitly added

$$u_{pb}(y,z) = 0.038U_\infty\phi(y)\left[\frac{\sin\kappa_1 z - \cos\kappa_1 z}{2} + \sin\kappa_2 z + \sin\kappa_3 z\right], \quad (1)$$

to the streamwise velocity in all three cases as was done by [22] to assure that the flow becomes three-dimensional. The effect of this perturbation on transition has been discussed in previous studies [17,23]. Hence, in this study we will only focus on the relaxation of the flow after transition and subsequent reattachment.

In the *Smooth* case, this aforementioned perturbation is the only source to trigger the transition of the separated boundary layer. Whereas, in addition to this three-dimensional perturbation, in the *Rough* case, a two-dimensional steady trip-wire, with a height of $h_r = 0.08\delta_{99}^0$ and length of $l_r = 4.2\delta_{99}^0$ is positioned close to the inflow where the flow is still laminar and attached [19], and in the *Wake* case, an unsteady mean wake deficit is introduced as a low-frequency large-scale forcing [18]. These steady and unsteady disturbances increase the turbulent fluctuations in the boundary layer and results in different transition mechanisms and relaxation scenarios than the one observed in the *Smooth* case.

Since the transition mechanisms are different in these three cases, all resulting separation bubbles are different. In order to identify the different flow dynamics and structures in these flows, this section follows with a visual assessment of the flow in the boundary layer through the vortical structures, Reynolds shear stress contours, and turbulent statistics.

A visualization of typical instantaneous flow structures is shown in Fig. 1, which shows that in all cases, the flow field after transition is filled with three-dimensional, small-scale and apparently randomly distributed vortices. The number of vortices become less numerous close to the end of the simulation domain, probably because the smaller ones coalesce to form bigger ones. Comparing vortical structures in the *Smooth* case with those for the *Rough* and *Wake* cases, we see that more intense vortical structures occur in the transition region. For the *Rough* case, the flow after the two-dimensional trip element is still laminar, as can also be seen from Fig. 3, and perturbations due to the trip element hardly grow until the bubble starts to form. In general in all of the three cases the three-dimensional vortical structures only become apparent around the transition location and are not present before separation. It is, however, interesting to note that the structures appear upstream of the time-averaged reattachment location for *Smooth* and *Rough* cases, while in the *Wake* case the wake passing induces increased momentum transfer towards the wall, and effects the location of the reattachment point, as a result these structures appear after this location [18].

To assess the nature of the flow within the boundary layer, the streamwise variation of the boundary layer thickness δ_{99}, displacement thickness δ^*, and momentum thickness θ are depicted in Fig. 2. All quantities grow rapidly due to the laminar separation bubble formed as a consequence of the APG. However, the growth of the boundary layer is suppressed as a result of the controlled forcing for the *Rough* and *Wake* cases. Furthermore, for these two