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Testing of Reynolds-stress-transport closures by comparison with DNS of an idealized adverse-pressure-gradient boundary layer

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Abstract

Results are used from direct numerical simulation (DNS) of incompressible plane-channel flow subjected to a uniform straining field typical of a two-dimensional adverse pressure gradient (APG) to investigate the accuracy of three second-moment closures specially designed to account for wall-bounded turbulence. Since the DNS statistics satisfy a one-dimensional unsteady problem with rigorously defined boundary and initial conditions, and since the flow contains many of the essential features found in suddenly decelerated boundary layers, this allows an efficient and straightforward but non-trivial assessment of the closures. The Reynolds-stress budgets from the DNS are used to examine the individual production/dissipation/transport terms used by each closure. This reveals shortcomings in all three schemes, especially in the near-wall behavior of their pressure–strain models. One of the major findings of this study is the degree to which the individual modeling shortcomings are offset by the tendency for them to cancel each other. The Wilcox Stress-ω model best captures the cumulative effect of the APG straining, compared to the models of Launder and Shima and So et al., in terms of giving mean velocities and the time at which the surface shear stress reverses sign that most closely agree with the DNS. However, its prediction of the streamwise $\overline{u'u'}$ and wall-normal $\overline{v'v'}$ Reynolds stresses is much less accurate than that given by the other two schemes.
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1. Introduction

This article examines the ability of second-order Reynolds-averaged Navier–Stokes (RANS) closures to predict the response of wall-bounded turbulence to two-dimensional (2D) strains associated with a suddenly applied adverse pressure gradient (APG). We compare three 'off-the-shelf' models with data from a direct numerical simulation (DNS) of a 'strained-channel' flow, a time-dependent parallel-flow idealization of the spatially developing decelerated boundary layer. This study is similar to that of Yorke and Coleman [1], who focused on the performance of popular lower-order models for this 2D APG case.

The strained-channel approach has the advantage of emulating perturbed turbulent boundary layers with a flow whose statistics depend only on time and one spatial dimension. Given the information available from DNS (such as

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Reynolds-stress budgets), this provides a rigorous but quick and efficient test for the models. Because it captures many of the essential characteristics of perturbed spatial layers (see Section 2), the strained-channel analogue provides a non-trivial modeling challenge. Yorke and Coleman [1] found that the Baldwin–Lomax (algebraic), Spalart–Allmaras (one-equation), Launder–Sharma and Menter SST (both two-equation) models each give significantly different predictions of the history of the wall-shear stress and evolution of the Reynolds-stress profiles, when applied to the APG-strained channel (Spalart–Allmaras and Menter SST give the best overall agreement with the DNS, although they leave room for improvement in their predictions of some statistics). This motivates the current examination of the Reynolds-stress transport models, which were chosen because they are relatively new and also represent distinct modeling strategies for wall-bounded flows. We will examine how well the closures reproduce the APG-induced skin-friction reversal and the finite-time lag required for the turbulence to respond to sudden mean-flow changes. Besides checking the overall model performance for low-order statistics, we also use Reynolds-stress budgets from the DNS to examine the individual production/dissipation/transport terms of the three models tested.

An overview of the strained-channel methodology and the resulting DNS benchmark is presented in Section 2, while Section 3 summarizes the three subject closures and the code used for their solution (details are included in Appendix A). Model-DNS comparisons are given in the following section, for both unstrained plane-channel flow (Section 4.1) and the idealized 2D APG (Section 4.2); a recap of the results and their implications is given in Section 4.3. We conclude in Section 5 with a summary and closing comments.

2. 2D APG strained-channel DNS

The second-order closures are to be tested by comparing them with DNS of an idealized APG boundary layer – namely turbulent plane channel flow subjected to a uniform irrotational mean strain and simultaneous time-dependent in-plane wall motion (Fig. 1). In this idealization, convective changes in the spatial boundary layer are replaced by temporal ones in the parallel-flow plane channel. An overview of this approach follows, as applied to the APG strain considered here; a fuller explanation for more general 2D and 3D strains is given in [2,3]. We also include a summary of the DNS results to which the models will be compared (some of the figures and text in this section were also used in [1]).

The objective of the strained-channel approach is to subject turbulence in the core of a plane channel to the same straining history it would experience if it were in the outer layer of an actual, spatially developing, APG boundary layer. Fully developed statistically stationary incompressible wall-bounded turbulence is subjected to a steady uniform irrotational divergence-free strain field $A_{ij} = \partial U_i/\partial x_j$ with streamwise deceleration A_{11} and wall-normal divergence A_{22}, such that

$$A_{ij} = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} \partial U/\partial x & 0 & 0 \\ 0 & \partial V/\partial y & 0 \\ 0 & 0 & 0 \end{bmatrix}, \tag{2.1}$$

where $A_{11} = -A_{22} < 0$. A simple step-function time history is applied, in which A_{ij} is zero until time $t = 0$ and then constant thereafter. The strained-channel domain is periodic in the streamwise x and spanwise z directions, and

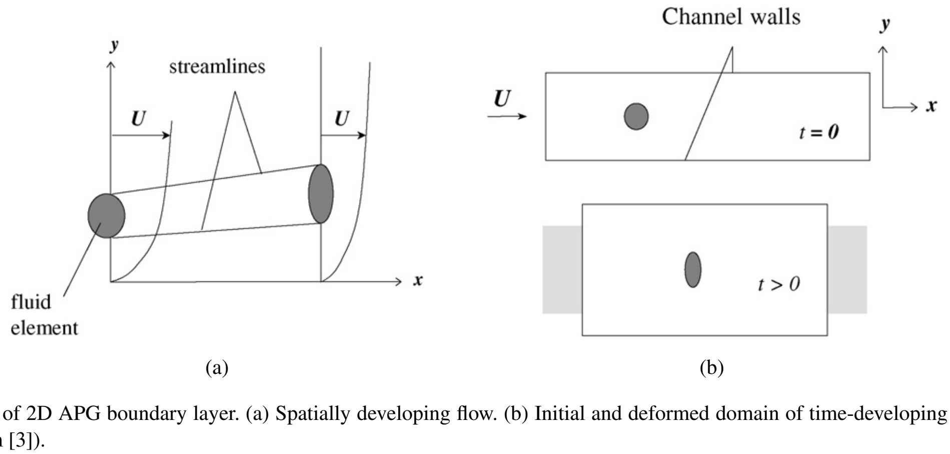

Fig. 1. Side view of 2D APG boundary layer. (a) Spatially developing flow. (b) Initial and deformed domain of time-developing strained-channel idealization (from [3]).

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