Large eddy simulation in support of RANS modelling

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Abstract

The focus of this paper is on the increasingly important role played by highly-resolved LES in supporting the development, improvement and validation of statistical RANS closures. This is illustrated by way of four recent studies by the writer's group, directed towards separation from curved surfaces, the interaction between structurally disparate shear layers, bypass transition and active flow control of separation.

Keywords: LES; RANS; Turbulence modelling; A-priori testing; Non-linear eddy-viscosity models; Reynolds-stress models

1. Introduction

Whatever the future holds for large eddy simulation (LES) as a practical prediction tool, it certainly plays an increasingly important role in the development and validation of Reynolds-averaged Navier–Stokes (RANS) models, at a cost significantly lower than direct numerical simulation (DNS). The important constraint to respect in its exploitation to this end is that the filtered-out motion and the subgrid-scale stresses must not affect the accuracy of the simulation, to the extent that the second and third moments are returned with sufficient accuracy within the primary regions of interest. If this is done, LES can provide extremely useful results for model validation, including budgets for the Reynolds-stress components. In fact, such data are potentially even more useful than experimental measurements, because the conditions at the boundaries of the simulation domain can be controlled more carefully than in experiments. Thus, if statistical spanwise homogeneity (i.e. 'perfect' statistical two-dimensionality) is desired, periodic conditions can be applied to a sufficiently wide spanwise slab. Streamwise periodicity – for example, in the case of a nominally infinite streamwise sequence of obstacles – can similarly be prescribed virtually perfectly.

Over the past few years, the author's group have undertaken a range of highly resolved large eddy simulations for flows which, although geometrically simple, feature complex physical interactions. The results have been used, on the one hand, to elucidate the turbulence interactions at play and, on the other hand, to examine the realism of RANS closures, the latter especially facilitated by the extraction of budgets for the second moments. In this paper, four such studies are outlined for the following flows:

- massively separated flow from a curved surface in a channel constricted by periodic hill-shaped undulations on one wall;
- a developing wall jet;
- bypass transition in a flat-plate boundary layer;
- separation control with a periodic, massless slot jet in a backward-facing-step flow.

2. Computational framework

Both LES and RANS schemes used herein are in-house developments. Both are based on a general non-orthogonal, block-structured finite-volume strategy with collocated storage. The LES scheme [1] incorporates second-order (centred) approximations for convection and diffusion, fractional-step advancement in time with the Adams Bashforth scheme for the fluxes, a multigrid/LSOR pressure-Poisson solver and Fourier-based partial diagonalisation in any one homogeneous direction. The corresponding RANS scheme [2] is iterative in nature, incorporates a second-order TVD form of the QUICK approximation for convection in all transport equations and a pressure-correction algorithm to enforce mass conservation. It contains a number of non-

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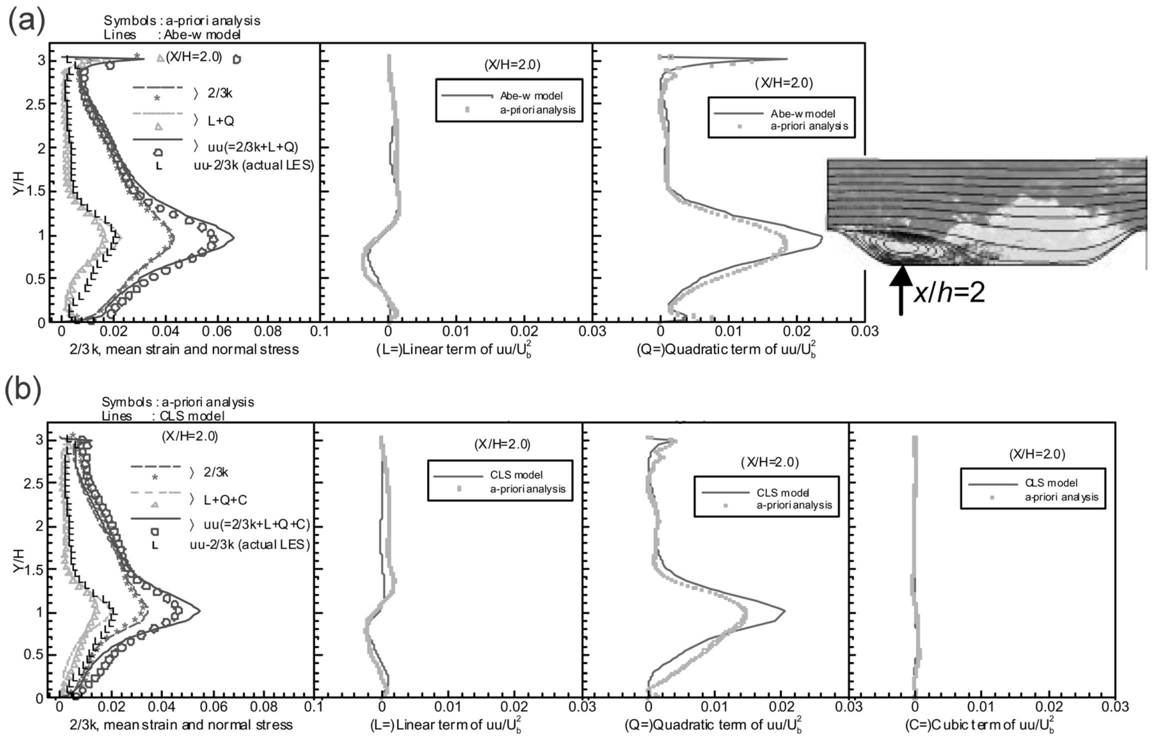

Fig. 1. Separation from a hill in a periodic channel segment. A-priori testing of the streamwise normal-stress fragments of the constitutive stress–strain/vorticity relations of two non-linear eddy-viscosity models. (a) Quadratic 2c limit EVM, Abe et al. [4], (b) cubic EVM, Craft et al. [5]. Symbols: fragments upon substitution of LES data into relations. Lines: fragments in the actual RANS computations.

linear eddy-viscosity (NLEVM) and explicit algebraic Reynolds-stress models (EARSM) and three full second-moment closures (RSM).

3. LES-supported RANS studies

3.1. Separation from hill-shaped obstructions

Separation from curved surfaces is amongst the most challenging processes for RANS schemes to predict. Unlike separation from a sharp edge, it is highly intermittent, varying rapidly in time and space, often over a substantial part of the wall. Thus, the notion of a specific separation point or line, ahead of which there exists a boundary layer which scales with wall variables, is far from reality, and this is a major root for the misrepresentation of the separation process and post-separation properties by RANS schemes.

Highly-resolved simulations with a 5-million-node mesh for the periodic channel segment shown in Fig. 1, at $Re = 21900$, are reported in [1,3]. These results were used in one of two related studies [2] to investigate several anisotropy-resolving models, mostly of the NLEVM and EARSM variety, among them a new model by Abe et al. [4], for which the simulations were instrumental in the development phase. Figure 1 gives an example of a-priori testing of the linear and non-linear fragments of the constitutive stress–strain/vorticity relations for the streamwise normal stress of two NLEVMs, one quadratic and the other cubic. These were obtained by inserting the LES mean-flow solution into the constitutive equations. Extensive model predictions, alongside a-priori tests, are given in [2].

3.2. Wall jet

The wall jet is a generic flow that involves a strong interaction between an outer shear layer and a boundary layer. In this respect, it represents a whole range of flows in which similar interactions are important – examples being the post-reattachment region in separated flows and post-impingement regions. In the wall jet, an especially influential process is Reynolds-stress diffusion in the region in which the boundary layer overlaps with the outer shear layer. To study the ability of second-moment closure to represent this transport, highly resolved

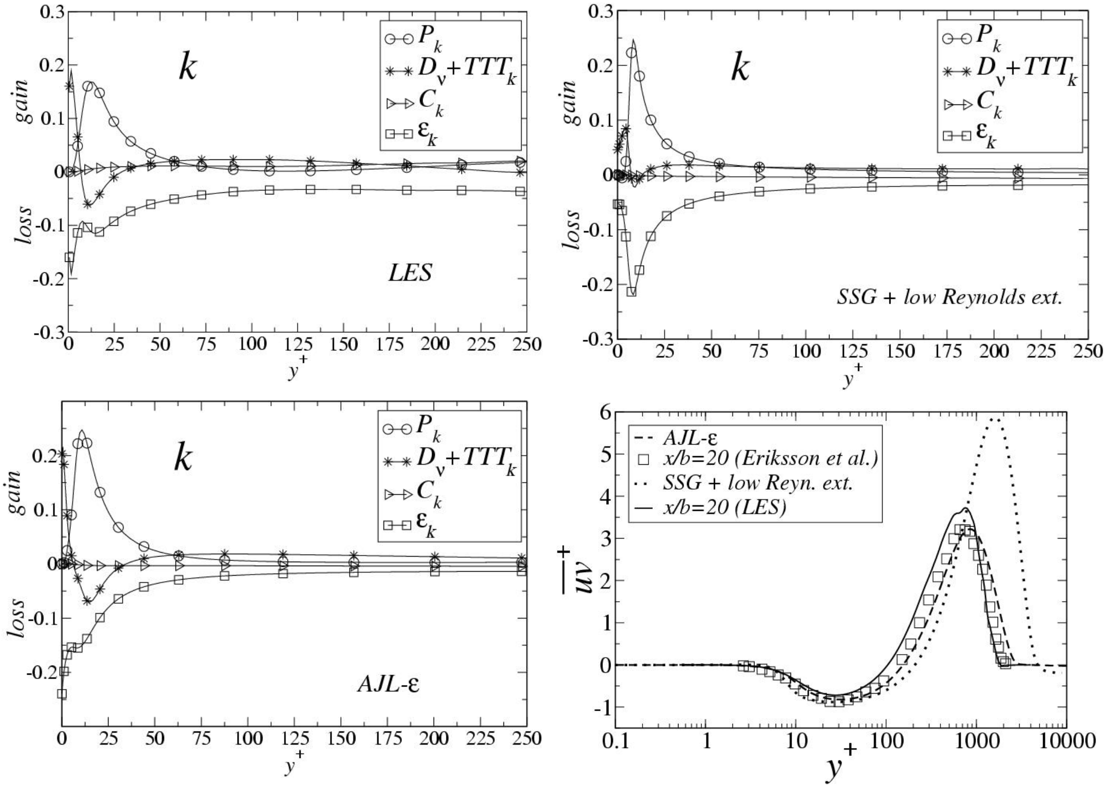

Fig. 2. Plane wall jet. Comparison of turbulence-energy budgets and shear-stress profiles in self-similar region, predicted by LES, the non-linear eddy-viscosity model of Abe et al. [4] and the SSG Reynolds-stress model.

simulations were performed [6] on a 8.4-million-node mesh, at a jet Reynolds number of 9600, for which experimental data are also available. As in the previous case, both a-priori studies and actual RANS-LES comparisons have been made, the former especially directed at stress-diffusion approximations with two second-moment closures. Figure 2 shows a comparison of turbulence-energy budgets obtained with the LES and two models. This and other results for stress components reported in [7] demonstrate two facts: first, the popular approximations of stress diffusion are seriously deficient in the case of interacting shear layers; and, second, the Speziale, Sarkar and Gatski (SSG) model gives a generally poor representation of all terms in the RSM equations. It also yields a poor result for the primary jet properties, even relative to lower-order models. Similar investigations are currently in train for a backward-facing step flow.

3.3. Bypass transition

Bypass transition is a key process in turbomachine aerodynamics, especially in low-pressure turbine stages of gas and steam turbines. The challenge is twofold: first, to represent transition induced by free-stream turbulence and, second, to resolve the unsteady transition arising from passing wakes produced by upstream blades. Extensive RANS studies are being pursued by the writer's group [8] to investigate the ability of low-*Re* anisotropy resolving closures to represent wake-induced unsteady transition.

One process which no ordinary RANS closure is able to capture is the substantial build-up of 'turbulence' activity in transitional boundary layers subjected to a turbulent free stream well ahead of the transition location, identified by the sudden rise of skin friction and heat transfer coefficient. While this pre-transitional 'turbulence' does not comply with the fully-established 3D state normally associated with turbulence, its prediction is important, as it modifies the transport properties in the boundary layer, especially in respect of heat transfer. An extension of the Abe et al. NLEVM, aimed at the pre-transitional regime, is reported in [9]. This is based on an earlier model which rests on the physical notion that production by shear strain/stress is zero and that the turbulence activity in the shear layer is driven by pressure-diffusion processes. To investigate this, LES of transition was performed, subject to free-stream turbulence. This enabled the extraction of

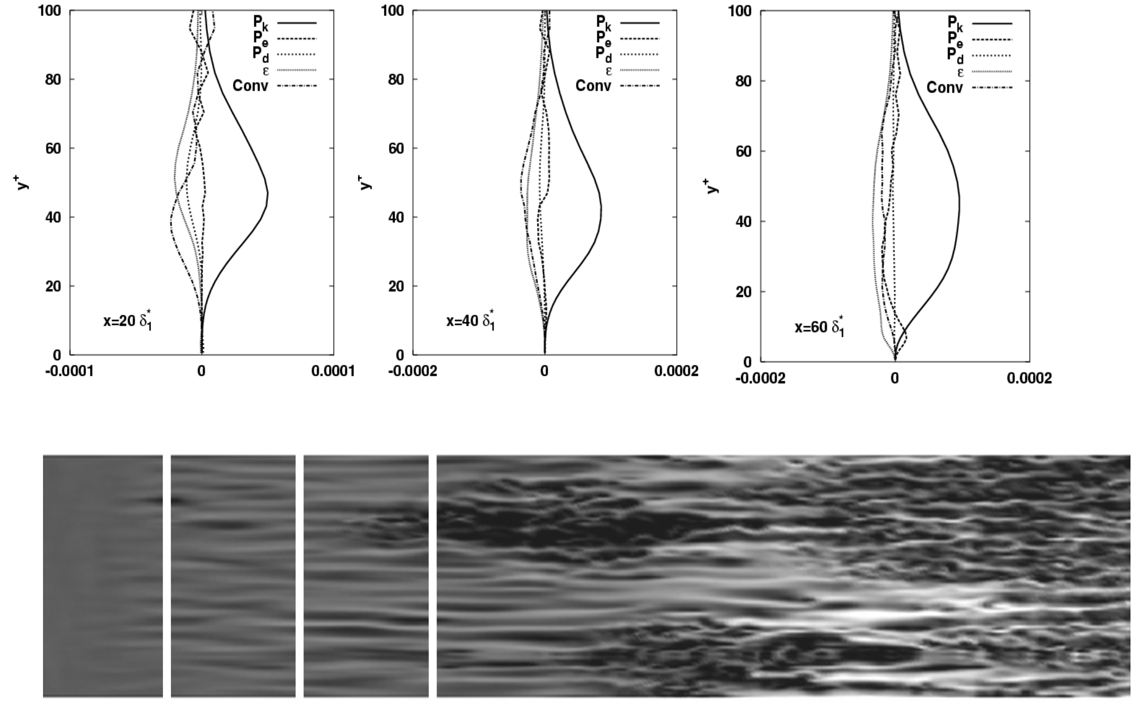

Fig. 3. LES of bypass transition with free-stream turbulence intensity of 4%. Turbulence-energy budgets used to investigate the validity of a model for pre-transitional 'fluctuation energy'.

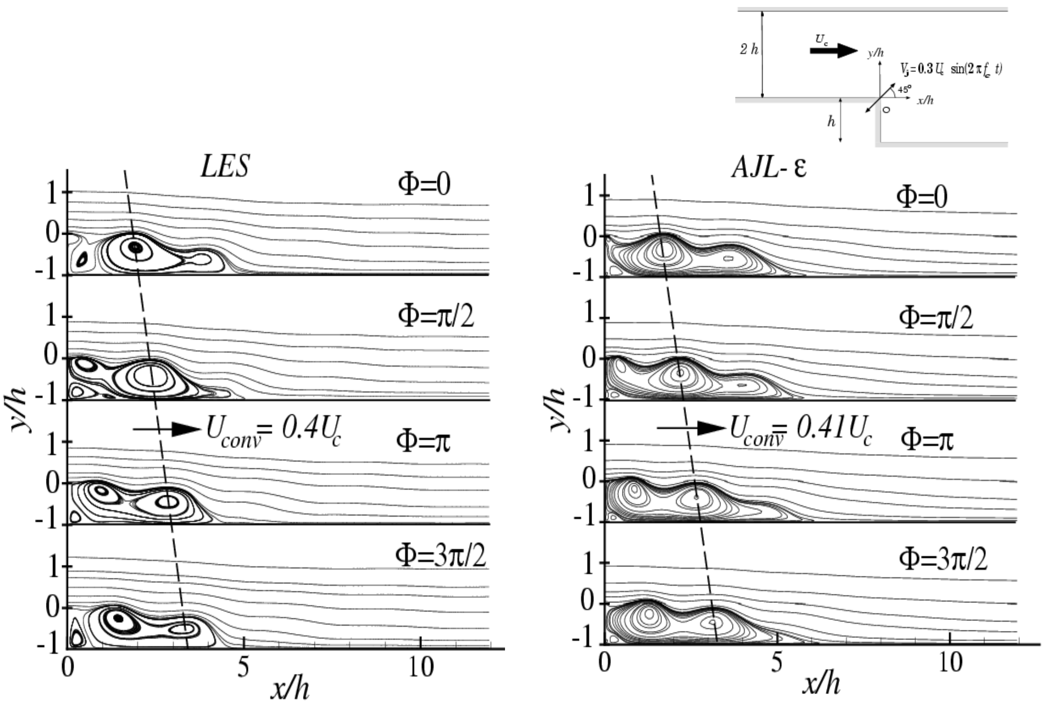

Fig. 4. Periodic jet injection into a backward-facing-step flow. Comparison of phase-averaged streamfunction contours predicted by LES and the non-linear eddy-viscosity model of Abe et al. [4].

budgets and the study of the turbulence processes. Figure 3 shows such budgets for a free-stream turbulence level of 4% generated at the inlet by a Fourier method (a kinematic simulation). The main conclusion derived from these is that the underlying conceptual proposal is wrong: transition actually arises from shear-induced production in the upper part of the boundary layer, which then progressively spreads into the near-wall region. The next step is to correct the closure model to reflect reality rather than to simply produce the desired phenomenological features.

3.4. Separation control

Experiments show that periodic perturbations, even when weak, introduced into turbulent shear flows can provoke profound changes to its properties. One such example is the period injection/suction of a thin plane 'jet' at the step edge of a backward-facing-step flow. Experiments for this case show that the reduction in the recirculation zone are quite sensitive to the frequency of injection. The mechanisms by which this occurs and the ability of RANS models to represent them have the subjects of two related studies by the writer's group [10,11]. Figure 4 shows a comparison of phase-averaged streamfunction contours obtained with a highly resolved LES relative to the Abe et al. NLEVM [4]. The plots illustrate the formation of large scale vortices within the recirculation zone, which play an important role in shortening the zone. Corresponding comparisons of phase-averaged turbulence-production rate [11] show the RANS model to give a broadly correct response of the flow to the periodic jet disturbances.

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