Large eddy simulation – overview

The pragmatic objective of LES is to provide flow quantities of interest in various physical situations with the comparable accuracy as DNS but at a significantly reduced computational cost. LES shares this objective with RANS approaches, which computationally are even more efficient, but may fail in certain situations. For instance, Medic, Joo, Kalitzin, and Sharma presented results for compressor simulations that demonstrated superior performance of LES over RANS for flows with transition and separation effects. Research projects during the Summer Program contributed to the stated goal of LES by (i) introducing and investigating new SGS models for momentum, mixing, and heat transfer; (ii) developing wall models for LES for boundary layer flows; (iii) assessing and using LES capabilities for specific flows where RANS techniques are inadequate, specifically for flows and heat transfer for turbine blades and flows with separation, laminar, transitional, and turbulent regions; (iv) exploiting particle methods as a complementary approach to LES for increasing computational efficiency for turbulence simulations.

Cadieux *et al.* considered a boundary layer flow at moderate Reynolds number with a laminar separation bubble that transitions to turbulence and develops into a turbulent boundary layer after reattachment. This is a challenging situation for LES because of the presence of separation, and of laminar, transitional, and turbulent regions in the flow. Results from two different codes, one using structured meshes and the other using unstructured meshes, confirmed that accurate LES for such flows are possible using on the order of 1% of the DNS resolution.

Garcia-Mayoral *et al.* investigated the possibility of developing off-wall boundary condition for LES of turbulent boundary layers using DNS databases for transitional flows. The concept is based on the observation that statistical properties of turbulent spots in boundary layers with bypass transition are remarkably like those in developed turbulent boundary layers. Using this observation, they extract a lower dimensional space-time representation of the flow at the top of a minimal flow unit taken from DNS of the transitional flow and use it to create boundary conditions at the top of the buffer layer for LES of turbulent boundary layers.

Three projects investigated new SGS models. Balarac *et al.* introduced a regularized gradient model for heat transfer where the regularization is achieved by retaining in the model expression only a term that corresponds to the forward transfer. This functionally simple model was shown to perform very well in LES of a passive scalar in homogenous turbulence. Bose *et al.* applied the Dynamic Full Linear Tensor-Diffusivity SGS Heat Flux Model to a heated cylinder case for which experimental results for the Nusselt number at the cylinder surface are available for comparison. This model belongs to a class of models that attempt to represent the physics of SGS interactions better than the classical eddy viscosity models. Specifically, in the model considered the SGS scalar flux is not aligned with the scalar gradient, allowing for backscatter. The model in the same spirit for SGS stresses, the Dynamic Nonlinear SGS Stress Model, was also investigated by Saeedi *et al.* in a priori tests using as a prognostic quantity Euler angle, which characterizes misalignment between the rate-of-strain and SGS stress tensors.

Hickel *et al.* investigated wall models for large-eddy simulations of realistic problems at high Reynolds numbers. In the framework of approaches that directly model the wall shear stress, the motivation is to fill the gap between models based on wall-normal ODEs that assume equilibrium and models based on full PDEs that do not. Novel wall models based on wall-normal ODEs, which incorporate non-equilibrium effects such as strong pressure-gradient effects, are developed and tested using two databases: an adverse pressure-gradient turbulent boundary-layer and a shock/boundary-layer interaction problem, both of which lead to separation and re-attachment of the turbulent boundary layer.

Maheu *et al.* focused on the LES modeling of boundary layer flows and conjugate heat transfer (CHT) in the context of a low-Mach number turbine blade. To this aim, a numerical database of highly refined LES, counting up to 18 billion cells, and CHT simulations is built. The database is complemented by an uncertainty quantification analysis of the blade cooling system to help understand some discrepancies between LES and experiments. This comprehensive database is then used to validate both a priori and a posteriori a novel tabulated wall model for the wall friction and heat flux, which takes into account the effect of the pressure gradient on the boundary layer.

Medic *et al.* performed LES to predict flow and heat transfer in a turbine cascade with high levels of free-stream turbulence. For this configuration, it was shown experimentally that free-stream turbulence had a dramatic impact on the location of transition on the suction side. LES show that it is critical to match the experimentally observed characteristics of the turbulent flow at the measurement station just upstream of the leading edge of the vane. Similarly, the importance of maintaining sufficient grid resolution both upstream of the leading edge, and along the vane surface, has also been illustrated.

The work of Venugopal *et al.* was dedicated to the LES modeling of self-noise from a wind turbine airfoil at high angle of attack. The objective is to quantify the flow of well-documented airfoil under near-stall conditions and to compare the LES to experimental results. Structured and unstructured hybrid grids and mesh adaptation were used to obtain a suitable grid in the near-wall region. LES results are compared to experimental data and to the predictions of a well-calibrated tool based on a panel method.

The two last projects concern complementary approaches based on particle methods. The motivation of these works is to deal with some cases which are not easily handled with a classical LES approach. For example, some applications require an explicit determination of small-scale dynamics and micro-mixing. In this case, LES cannot be used and another approach allowing use of DNS with a reasonable computational cost must be proposed. The approach proposed by Lagaert *et al.* consists of coupling a standard pseudo-spectral code to solve the momentum equation with a remeshed particle method to solve the scalar dynamics. This approach allows the scalar dynamic to be solved on a finer grid without the associated time-step constraint due to the CFL condition. Adami *et al.* investigate a fully Lagrangian SPH method. This method provides a unified model for various fluid phases and structures in complex geometries. The standard SPH method is known to overestimate the dissipation. In this context, Adami *et al.* propose a correction for the particle trajectories used by the SPH method, in order to improve performance in 3D turbulent flows.

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