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Large Eddy Simulation — overview

Large-eddy simulation (LES) has emerged during the past several decades as a computationally tractable approach to the simulation of turbulent flows. Increasingly, LES is being utilized as a means to provide quantitative insights into unsteady, multi-physics engineering applications, including guidance during the engineering design process. Resolution requirements associated with nonlinear scale separation, coupled with the desire to perform numerous calculations to estimate uncertainties or explore design space, have placed increasing emphasis on the modeling of unresolved, subgrid-scale phenomena. Furthermore, the continued efficacy of LES for engineering applications places stringent requirements on the accuracy of the LES closure models. These challenges are, perhaps, most pronounced in the modeling of the near-wall eddies in turbulent boundary layers that dictate engineering quantities of interest (e.g., skin friction, wall heat transfer, surface loading), although these eddies will remain unresolved given foreseeable computational capabilities. Lastly, relevant engineering applications require the simulation of complex effects (e.g, surface roughness, flow separation, shock-boundary layer interaction) in increasingly geometrically complex environments. The ability to perform successful simulations in these environments additionally requires suitable numerical (and geometric) discretizations of the governing equations and the corresponding closure models.

In an attempt to address some of these challenges, the projects in this group can be classified into three broad categories: i) subgrid-scale model development, ii) novel approaches for wall-modeled large-eddy simulation, and iii) numerical method developments and applications of LES for complex applications. These approaches and the results of these investigations are briefly summarized below.

i) Subgrid-scale model development. While traditional, phenomenologically motivated dynamic subgrid-scale models have helped predict various turbulent flows, the need for increased model accuracy at coarser resolutions has warranted the systematic derivation of new approaches. Silvis *et al.* extend the family of eddy viscosity models that provide the minimum dissipation necessary to prevent energetic accumulation at the grid length scale to rotating turbulent flows and non-uniform grids. Parish *et al.* derive the formally coarse-grained Navier-Stokes equations following the approaches of Mori and Zwanzig; this formulation results in a model form where finite time convolution integrals describing the non-local effects of the unresolved scales must be modeled. Finally, in search of lower complexity models for turbulent flows that are more computationally feasible for control or optimization studies, Ran *et al.* consider methods of stochastically forcing linearized governing equations to recover statistical characteristics of transitional and turbulent boundary layers.

ii) Novel approaches for wall-modeled LES. Numerous investigations over the past fifty years from increasingly resolved numerical simulations and experimental measurements have advanced our understanding of the structure of near-wall turbulent eddies. Two projects (Sayadi *et al.*, Rosenberg *et al.*) now attempt to leverage knowledge about the particular structure of the near-wall region to rigorously synthesize LES wall models from low-rank dynamical systems in zero pressure gradient turbulent boundary layers. This is in contrast to the more common approach to LES wall models that relies on phenomenological models to describe the equilibrium balance of momentum and energy. Recent estimates on the computational cost of wall-modeled LES have also shown that the resolution of thin laminar boundary layers (particularly near leading edges) are significant drivers of the overall cost of the simulation. Marques *et al.* attempt to overcome this and the more general challenge of computing an accurate wall stress when insufficient resolution of the entire boundary layer is provided via integral boundary layer approaches.

iii) Numerical method development and complex applications of LES. The fidelity of LES (and its corresponding subgrid-scale and wall models) on unstructured grids (that are a necessity in the simulation of industrially relevant geometries) are assessed in a series of complex flows. Iyer *et al.* evaluate the performance of equilibrium and non-equilibrium wall models on flows with mild adverse pressure gradients (to predict trailing edge separation on an NACA 4412 airfoil) and strong adverse pressure gradient effects present in shock-boundary layer interactions (in the case of the Bachalo & Johnson bump). Lehmkuhl & Park also assess prediction of the flow around the NASA Common Research Model that contains much of the geometric complexity and scale of full aircraft (e.g., fuselage, multi-element wing). Lastly, Joo *et al.* predict the onset of boundary layer separation due to the presence of surface roughness on a prototypical compressor blade. The final two projects concern the discretization details of discontinuous Galerkin (DG) numerical schemes applied to two canonical uses of large-eddy simulation: wall-modeled LES and shock-turbulence interaction. Discontinuous Galerkin schemes have received recent interest due to their higher-order accuracy on general, unstructured grids. Carton de Wiart *et al.* extend the formulation of the dynamic slip boundary condition for wall-modeled LES to variational multiscale methods and compressible flows, while Hillewaert *et al.* investigate the interaction between the numerical discretization/shock capturing, resolution, and closure modeling in DG schemes for canonical shock-turbulence interactions.

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