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Numerical aspects and implementation of a two-layer zonal wall model for LES of compressible turbulent flows on unstructured meshes

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A B S T R A C T

This paper focuses on numerical and practical aspects associated with a parallel implementation of a two-layer zonal wall model for large-eddy simulation (LES) of compressible wall-bounded turbulent flows on unstructured meshes. A zonal wall model based on the solution of unsteady three-dimensional Reynolds-averaged Navier–Stokes (RANS) equations on a separate near-wall grid is implemented in an unstructured, cell-centered finite-volume LES solver. The main challenge in its implementation is to couple two parallel, unstructured flow solvers for efficient boundary data communication and simultaneous time integrations. A coupling strategy with good load balancing and low processors underutilization is identified. Face mapping and interpolation procedures at the coupling interface are explained in detail. The method of manufactured solution is used for verifying the correct implementation of solver coupling, and parallel performance of the combined wall-modeled LES (WMLES) solver is investigated. The method has successfully been applied to several attached and separated flows, including a transitional flow over a flat plate and a separated flow over an airfoil at an angle of attack.

1. Introduction

Large-eddy simulation (LES) is widely used for study of turbulent flows, and the method has well demonstrated its predictive capability over the last two decades. In LES, the low-pass filtered Navier–Stokes equations are solved for the resolved flow motions, while the smaller subgrid-scales (SGS) and their interactions with the resolved scales are modeled. It is often argued that the geometry-dependent large-scale eddies, which contain most of the turbulent energy, should be treated directly, whereas the small scales which tend to be more universal and isotropic are more amenable to phenomenological modeling. One of the key elements of LES is the employment of dynamic SGS closure models, where model coefficients are dynamically computed based on the information extracted from the solution itself, without having to tune them *a priori* [1–3]. The ability to predict turbulent flows accurately without tuning renders LES a predictive methodology, as opposed to traditional Reynolds-Averaged Navier–Stokes (RANS) techniques which require flow-dependent tuning of model parameters.

However, despite its favorable features, LES in fact has been used sparsely for practical engineering applications due to prohibitive resolution requirements. The basic premise of LES that energy-containing and dynamically-important eddies are

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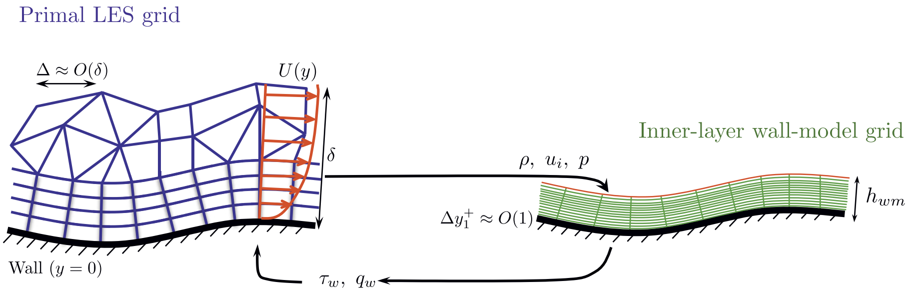

Fig. 1. Sketch of the wall-modeling procedure. Wall shear stress (τ_w) and heat flux (q_w) required to advance highly under-resolved LES are obtained from the solution of the full 3D RANS equations defined on a separate near-wall grid. The wall model is driven by the LES data imposed on the top boundary, and no-slip condition is applied on its wall.

resolved by the underlying grid is hard to meet in the near-wall region. This is because the size of near-wall "large" eddies becomes very small compared to the size of large-scale eddies in the outer portion of boundary layers. This scale separation becomes more prominent at high Reynolds numbers, and the cost of wall-resolved LES (WRLES) becomes comparable to that of direct numerical simulation (DNS), requiring $O(10^6)$–$O(10^9)$ CPU core hours to run a single LES calculation of practical aerodynamic flows. This restricts the routine use of LES in industry, where a short turnaround time is needed for parametric studies in the design/optimization cycle. As a result, the vast majority of industrial computational fluid dynamics (CFD) analyses still relies on low fidelity RANS calculations. It is forecasted in NASA's recent CFD Vision report that this situation will continue until the notional year 2030 [4].

It is therefore clear that application of LES at realistic Reynolds numbers requires a less costly approach to account for the effect of inner-layer dynamics. In such an approach, one would compute the outer-layer using a coarse LES, while modeling the effect of momentum and heat transfer from the inner-layer to the outer-layer. This is the concept of wall-modeled LES (WMLES). A recent analysis of Choi and Moin [5] shows that $N \sim Re_L$ in WMLES and $N \sim Re_L^{1.9}$ in WRLES, where N is the number of grid points and Re_L is the chord Reynolds number of a wing. They also showed that N for the WMLES is one to three orders of magnitude smaller than that for the WRLES, in computing an attached flow over a finite aspect ratio wing at different Reynolds numbers.

Several wall-modeling approaches have been introduced in the LES literature. In one category called wall-flux modeling, the usual no-slip and thermal wall boundary conditions (BC) are replaced with stress and heat flux boundary conditions, which are provided by the wall model. The wall model in this category can be thought of as a black box which takes the LES solution at some location in the inner-layer as input, and returns the wall-fluxes needed by the base LES solver as output. The assumption underpinning the wall-flux modeling is that the imposition of correct Neumann wall boundary conditions is necessary to obtain an accurate solution on a very coarse LES grid. The models have evolved with increasing model-form complexity to incorporate more physics into the models. Algebraic wall models assume simple relations between the wall gradients and the LES data at the first off-wall cell [6–10]. Usually the law-of-the-wall that holds only in attached boundary layers is directly enforced, and its use is limited to very simple geometries. Two-layer zonal wall models, originally proposed by [11], aim at extending their applicability in complex domains by incorporating more physics. Two-layer models solve simplified or full flow equations on a separate near-wall grid, which is refined only in the wall-normal direction. A RANS parameterization is often assumed in the wall-model equation, because only the ensemble effect of near-wall turbulence can be represented on the wall-model mesh with very coarse wall-parallel resolution. Depending on the level of approximation, one can account for various non-equilibrium effects (nonlinear advection and pressure gradient) by solving unsteady three-dimensional RANS equations [12–15], or account for only the wall-normal diffusion to obtain a system of one-dimensional ordinary differential equations [16–18].

This paper details an implementation of a non-equilibrium two-layer zonal wall model in a parallel unstructured LES solver. The wall model solves unsteady three-dimensional RANS equations on a separate near-wall mesh to provide stress and heat flux boundary conditions to the LES momentum and total energy equations, respectively (see Fig. 1). Complexities of both the wall model and the base flow solver impose significant implementation overheads. We illustrate challenges and strategies in its implementation in terms of processor management in parallel architectures, LES/wall-model coupling at equation- and code-levels, verification of the coupling, and parallel performance. To authors' knowledge, this is the first implementation of a PDE-based two-layer wall model in an unstructured, parallel LES solver. This is of practical importance, since zonal models that have been designed and tested in structured mesh solvers find limited utility in engineering applications. The present wall model can be used for predicting high Reynolds number flows involving complex geometries where non-equilibrium effects are important. Validation of the combined WMLES solver is not provided in this paper, but the readers are referred to our recent publications [15,19,20] in which the present work is validated in attached boundary layers at a wide range of Reynolds numbers, and separating flows over an airfoil and streamwise-periodic hills.

The paper is organized as follows: In Sec. 2, governing equations used in the LES and the wall model are summarized. In Sec. 3, spatial and temporal discretization of the governing equations in unstructured finite-volume solvers are given. In Sec. 4, LES/wall-model coupling method is detailed in terms of parallel process management, face mapping, and interpolation