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Numerical viscosity, SGS modeling and grid refinement in LES and in variational multiscale LES

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ABSTRACT

An approach to turbulence which is generally more accurate than RANS (Reynolds-Averaged Navier-Stokes equations) for flows with massive separations, as for instance bluff-body flows, is Large-Eddy Simulation (LES). However, LES is computationally more expensive than RANS. Up to now, most of the LES reported in the literature are limited to moderate Reynolds numbers and simple geometries and some open issues remain before LES can be considered a completely reliable tool for the simulation of engineering and industrial flows. The success of a large-eddy simulation depends on the combination and interaction of different factors, viz. the numerical discretization, which also provides filtering when no explicit one is applied, the grid refinement and quality and the physical closure model.

In the perspective of the application of LES in an industrial context, the use of *unstructured grids* becomes particularly attractive, because of their friendliness when applied to complex realistic geometries, although they are more demanding from the point of view of computational resources.

As for numerical discretization, although there are a few examples of numerical schemes especially developed for LES on unstructured grids, our choice was to start from an existing numerical technology for industrial application and, in particular, from a *second-order co-located scheme*. The most critical point with co-located schemes is, in our opinion, the need of *numerical dissipation*. Indeed, the classical LES approach relies on the addition to the usual Navier-Stokes equations of a sub-grid scale (SGS) term and assumes that this same term is rather optimal for both turbulence modeling and numerical scheme stabilization, i.e the damping of any high frequency component is performed exclusively by the SGS terms, which are in general second-order derivatives of the flow variables (e.g. in eddy-viscosity models). Thus, they introduce a rather violent damping, applied to some particular flow variables, which is however not adequate to stabilize the numerical scheme. In a different approach (*implicit LES*), the role of SGS terms is completely fulfilled by a purely numerical stabilization term inside the approximation. However, this family of model-free methods seems to need highly refined grids, and, thus, huge computational costs, to give accurate results. Conversely, if dissipative schemes are combined with a classical LES model, they can interact unfavorably with it, and significantly deteriorate the results. Thus, it appears that in a reasonable option, the effects of numerical dissipation and of the SGS model should be

separated as much as possible. Our proposition was to dedicate the subgrid modeling to a physics-based model and to use for numerics a second-order accurate MUSCL upwind scheme equipped with a tunable dissipation made of *sixth-order* [1] spatial derivatives of all flow variables through a flux splitting. Fourier analysis clearly shows that such a dissipation has a damping effect which is much more localized on high frequencies than the one of stabilizations based on second-order derivatives. In this way we can reduce the interaction between numerical dissipation, which damps in priority the highest frequencies, and the SGS modeling. Moreover, a key coefficient (γ_s) permits to tune numerical dissipation to the smallest amount required to stabilize the simulation.
As for SGS modeling, our first choice was to use *classical* models, viz. the Smagorinsky one and its dynamic version. As well known, we found that the dynamic model generally gives more accurate results than the Smagorinsky one. However, due to the explicit filtering required in the dynamic procedure which is highly computationally demanding on unstructured grids, the increase in computational cost for the dynamic model was found to be rather dramatic, much larger than for structured grids or spectral schemes. On the other hand, a good compromise between accuracy and computational requirements was obtained through the Variational MultiScale approach (VMS), which was found to give the same accuracy as the dynamic model at costs comparable to those of the Smagorinsky model. The main idea of VMS-LES is to decompose, through Galerkin projection, the resolved scales into the largest and smallest ones and to add the SGS model only to the smallest ones. A formulation of the VMS approach for unstructured grids and the mixed finite-volume/finite-element scheme, used in the present work, was provided in [2], in which the largest resolved scale space is defined through cell agglomeration.
The aim of the present study is to investigate the role of the previously described numerical viscosity, of the SGS modeling and of the unstructured grid resolution and quality both in *classical* LES and in VMS-LES. To this aim, we apply our *industrial* numerical set-up to an academic test-case, i.e. the flow around a circular cylinder at a Reynolds number, based on the cylinder diameter, equal to 3900, for which experimental data and the results of several *classical* LES, obtained on highly resolved structured grids, are available in the literature. A first series of simulations has been carried out on a rather coarse grid (approximately 290000 nodes) without any SGS model (*implicit* LES), with the Smagorinsky model (*classical* LES), and through the VMS-LES approach combined with different SGS models. All these simulations have been carried out with the same value of the parameter that controls the numerical viscosity (γ_s=0.3). The results, which will be discussed in details in the final contribution, show that the simulation without any SGS model gives reasonably accurate predictions, the introduction of the Smagorinsky model in the *classical* LES significantly deteriorates the accuracy, while the introduction of a SGS model in the VMS approach, thus only for the smallest resolved scales, generally leads to improved results. This is an a-posteriori confirmation that, in our approach, the numerical viscosity is indeed concentrated on the highest resolved frequencies (smallest scales) and, thus, has an effect comparable to that of the SGS model in the VMS-LES approach. Moreover, the fact of concentrating the dissipation (numerical or physical) on the smallest resolved scales seems to be an effective strategy to avoid the excessive damping introduced by *simple* SGS models, as the Smagorinsky one, in classical LES. In the final contribution the effects of decreasing γ_s will also be shown for all the previous cases and, possibly, the sensitivity to grid refinement will be analyzed.

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