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Adaptation for Scale-Resolved Turbulence

Anca Belme, Jeroen Wackers

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In numerical simulation for fluid flows, mesh adaptation, i.e. the automatic modification of the mesh during a simulation to suit the needs of the flow, is reaching maturity. Today, adaptation is able to handle complex flows which include shock waves, two-phase flows, and Reynolds-averaged Navier-Stokes (RANS) modelled turbulence. Mesh adaptation packages are being distributed to groups of users that are far bigger than the team of developers, and even find industrial applications. Thus, mesh adaptation is no longer only an objective in itself, but becomes a means to enable other fields of research.

As such, the application of mesh adaptation to scale-resolving turbulence, is the next targeted step. Scale-resolving turbulence models such as Large-Eddy Simulation (LES) or hybrid RANS/LES models, which represent the largest turbulent eddies in the simulated velocity field and model only the smallest turbulent scales, are promising approaches for complex-flow simulation where RANS is unable to represent the physics. However, these time-dependent simulations require heavy computational resources, so efficient computation is essential to allow the simulation of realistic flows. Also, the behaviour of these models is very sensitive to the mesh size. Therefore, precisely controlling the mesh is of the highest importance, which favours adaptive meshing.

And yet, adaptation for scale-resolved turbulence is only in its early stages. Is this because it is a particularly difficult subject? Was the maturity of mesh adaptation a prerequisite to even consider application to resolved turbulence? In any case, adaptation for turbulence is today a quickly evolving field with rapid progress but also many open questions.

Assuring the accuracy of turbulent solutions on adapted meshes is a challenge. Scale-resolved turbulence consists of many small-scale structures whose energy needs to be conserved to represent the flow physics. This requires high accuracy for the discretization of the flow equations. A first approach to obtaining the required accuracy is high-order methods, such as Discontinuous Galerkin. These methods enable new types of adaptivity, like adjusting the order of the discretization (p -refinement) or combined element size and order (hp) adaptation, and provide estimations of the local high-order contributions as indicators to guide adaptation. In this Special Issue, *Chapelier and Basile* and *Dolesji et al.* study such indicators for hp -adaptation, with *Dolesji et al.* proposing a fully implicit time-adaptive approach coupled with the anisotropic hp one, while

Naddei and De la Llave Plata as well as *Noventa et al.* consider p -adaptation, the latter comparing with an adjoint indicator based on spurious entropy production. *Liapi et al.* propose a similar indicator for a higher-order finite-volume discretization as well as an algorithm for the adaptive period control based on the error evolution between two successive time-intervals.

However, other meshing approaches to increase the solution accuracy exist. Notably, standard second-order discretization schemes perform particularly well on structured, regular grids, which are well suited for preserving the kinetic energy. Thus, mesh adaptation can be used to create such regular grids. In this issue, *Oberoi et al.* use Riemannian metric adaptive techniques, which were developed for unstructured tetrahedral meshes, to create block-structured grids. Average-based refinement criteria (see below) are used to create unstructured grids with large zones of uniform cells.

Thus, a major topic of research is where and how the meshes should be refined for resolved turbulence, which is related with the definition of refinement criteria. One of the main questions in this context is, if the mesh should be continuously adapted to follow unsteady turbulent structures or not. Several researchers in recent years have argued that the best results are obtained on stationary meshes with uniform cell sizes, which improve the accuracy of the schemes while eliminating interpolation errors during mesh adaptation. This implies that the refinement criteria are averaged in time to capture the flow at all instants. In this issue, *Liapi et al.* study average-based refinement criteria to resolve vortical flows and discuss automatic strategies to determine the frequency of refinement and criterion averaging. *Noventa et al.* and *Visonneau and Guilmineau* also use averaged criteria.

Sevilla et al. address machine learning to produce adaptation criteria for mesh refinement around wings and aircraft. The motivation for their work is that, if simulations are started on coarse meshes, standard refinement criteria do not detect the flow features which the coarse mesh cannot resolve. Thus, they may never be resolved, even in the final adapted mesh. A mesh that is adapted by a neural network trained on similar flows, is the best guarantee that major flow features are captured. A broader conclusion from this paper is that, since AI methods have seen such rapid progress today, they potentially have benefits for mesh adaptation and turbulent flows. The best ways to make use of these new powerful tools can, and should, be investigated.

Finally, the availability of adapted meshes encourages research on turbulence modelling. For example, adapted meshes change the resolution of the flow equations, so turbulence models on adapted grids may not behave in the same way as on non-adapted grids. For scale-resolving turbulence, modifying the cell sizes shifts the balance between resolved and modelled turbulence in hybrid RANS-LES models. *Monot et al.* propose local injections of turbulent velocity fluctuations to reduce the effect of any variations in the distribution of resolved and modelled turbulence. And the low numerical errors make adapted meshes ideally suited to evaluate the behaviour of turbulence models. Thus, *Visonneau*

and Guilmineau compare RANS and hybrid turbulence models for vortex-vortex interaction on a simplified fighter aircraft, while *Alauzet and Spalart* present a new variant of the well-known Spalart-Allmaras model with rotation and curvature correction which is coupled with anisotropic adapted meshes to study the non-trivial flow over this generic military aircraft at various angles of attack.

Overall, there is not yet a consensus on the optimal way of using adaptation for scale-resolving turbulence, but a wealth of research is emerging about this type of adaptation and its use for complex flow simulations. Our goal with this Special Issue is to provide a snapshot of current research, which can hopefully serve as an inspiration for further progress towards powerful, universally applicable mesh adaptation for scale-resolving simulation of complex flows.

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