Developing LES/DNS Simulation Capability based on Immersed Boundary Method coupled with FCAC Multigrid and AMR Techniques

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Abstract

Complex-geometry turbulence, because of the practical importance and demands, has attracted many scientists investigating its solution technologies. Modern numerical prediction methodologies, particularly the Large Eddy Simulation(LES) and Direct Numerical Simulation(DNS) with the assistance of powerful supercomputers, are still greatly challenged, since the multitude of unsteady motion scales in complex-geometry turbulence have to be accurately resolved. Over the past decade, the computing architectures, particularly the RAM size and CPU speed, have developed to a point where it permits a directly attack the complex geometry turbulence at a moderately-high Reynolds number using LES or DNS and to establish relevant physical law of turbulence, see Ref. [1, 2, 3, 4]. However, the development of the reliable software technologies, using the highly efficient grid generation strategy and the high-performance solution techniques, is somewhat lagged behind, particularly in the area of resolving the entire spectra of the multi-scales motions in turbulence.

To develop the LES/DNS simulation capability for complex geometry flow configurations, the current research proposed novel approaches to address the two critical issues in the development, i.e. the efficient grid generation for complex geometries and the high-performance flow solution techniques. The flows around complex geometry inside a computational domain were handled by the immersed boundary method through cutting the computational cells around the geometry. The grid refinement scheme was managed through utilizing the quad(2d) or oct(3d)-tree data structures organized via a hierachy of the refined levels of grids, as seen in Figure 1. These cut-cells were refined near the geometry surface via the adaptive mesh refinement (AMR) strategy with the wall-distance as the level-controlling parameter for the near-wall resolution. The approach was capable of smartly and efficiently address the issue of the near-wall grid resolution in a complex geometry LES/DNS simulation.

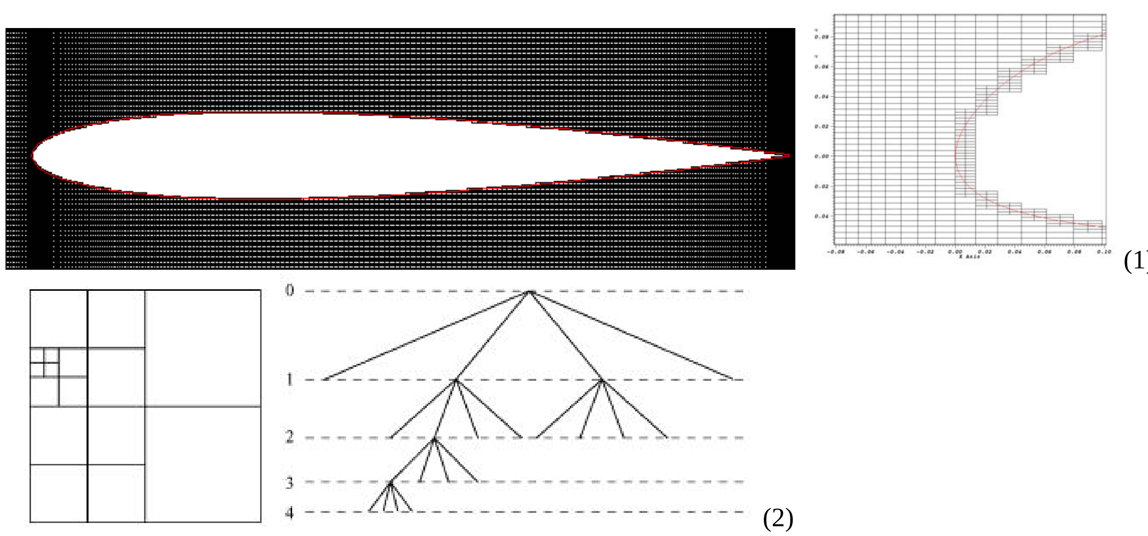

Figure 1: （1）Immersed boundary method and（2）Adaptive mesh refinement data scheme.

Regarding the high-performance flow solution research, the highly efficient Flexible-Cycle Additive-Correction(FCAC)-multigrid(MG) techniques developed in Ref. [5] was coupled with the immersed boundary (IB) methods to tackle the unsteady multi-scale turbulence motions with complex geometries. The major advantage of the Flexible-Cycle(FC) over the conventional V-cycle or W-cycle in a multigrid iteration is that the computation on a given grid level always have the opportunity to move up or to go down one grid level, depending on whether the residual reduction on the current grid level is satisfied. This flexibility makes the FC iterations more efficient and smart in the corrections between the fine and coarse grids. On the other hand, the Additive-Correction(AC) scheme enables the integral conservation property being preserved on all multigrid levels which is an important nature of the Navier-Stokes(N-S) system. Therefore, as a combination of both mathematics- and physics-oriented solution strategies, the FCAC-MG acceleration technique is highly, efficient, reliable and robust making it feasible for CPU-intensive computations, such as LES and DNS. Figure 2 demonstrates the FC iterations and the FCAC MG performance in solving the discretized N-S system.

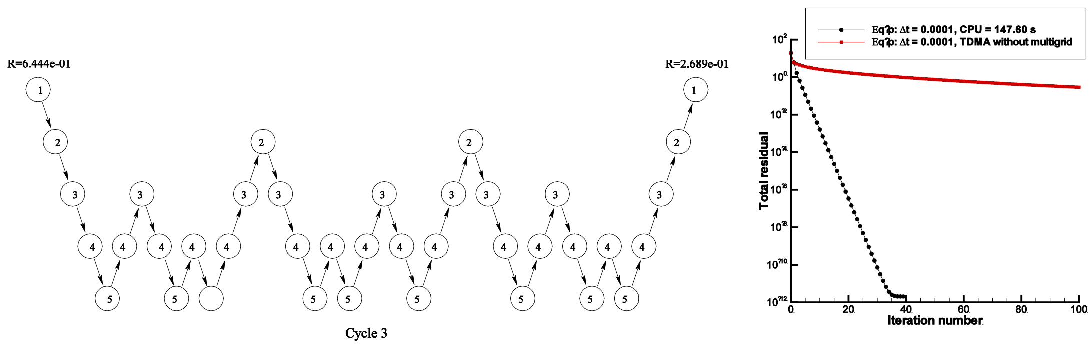

Figure 2: FCAC-MG solver performance in the LES of a confined square coaxial jet flow[4,5].

The major breakthrough of the current research is that the grid generation is no longer conducted by a stand-alone external grid generator, instead, is performed by a designed algorithm executed by a computer, which significantly (orders of magnitude) reduces the turnaround time of grid generation in the conventional CFD technologies. The more important aspect of the development is that it opens the door to enable a strong coupling of the CFD technology (as opposed to the weak coupling that the current CFD tools can best achieve) with other modules, such as Computational Structure Dynamics (CSD) and heat-transfer or icing modules, to tackle the multi-physics moving-boundary unsteady flow problems, such as helicopter rotor flow, turbine blade cooling or in-flight icing problems. The research will lead to an ultimate modeling and simulation technology which allows the fluid engineering industries to design their products based on the physically-accurate predictions of the complex unsteady flows with multi-physics phenomena (structure dynamics, heat transfer, icing and acoustics) as well as the moving-boundary configurations of a rotor blade, icing or non-fixed wing UAV.

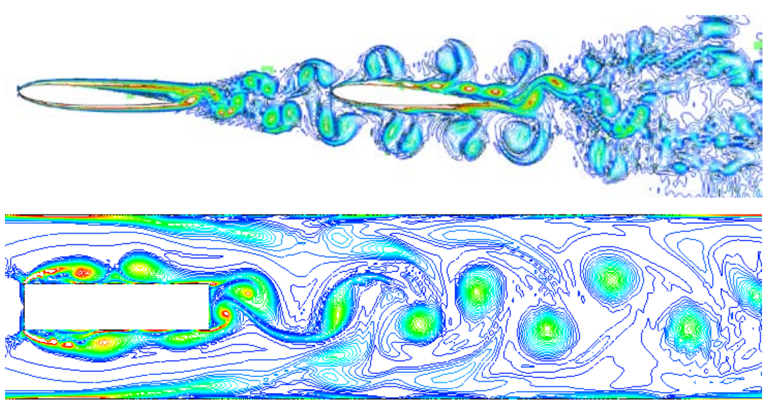

Figure 3: Vortical shedding unsteady flow past airfoils in tandem and rectangular block using IB, AMR and FCAC-MG solution technologies

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