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A 3D hybrid grid generation technique and a multigrid/parallel algorithm based on anisotropic agglomeration approach

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Abstract A hybrid grid generation technique and a multigrid/parallel algorithm are presented in this paper for turbulence flow simulations over three-dimensional (3D) complex geometries. The hybrid grid generation technique is based on an agglomeration method of anisotropic tetrahedrons. Firstly, the complex computational domain is covered by pure tetrahedral grids, in which anisotropic tetrahedrons are adopted to discrete the boundary layer and isotropic tetrahedrons in the outer field. Then, the anisotropic tetrahedrons in the boundary layer are agglomerated to generate prismatic grids. The agglomeration method can improve the grid quality in boundary layer and reduce the grid quantity to enhance the numerical accuracy and efficiency. In order to accelerate the convergence history, a multigrid/parallel algorithm is developed also based on anisotropic agglomeration approach. The numerical results demonstrate the excellent accelerating capability of this multigrid method.

1. Introduction

The initial phase of any numerical simulations in computational fluid dynamics (CFD) begins with the generation of suitable mesh. Although long recognized as a major pacing item, it is still a difficult task to generate high-quality grids for three-dimensional (3D) complex geometries in CFD, especially for turbulence flow simulations with high Reynolds number. In order to deal with this problem, many grid generation techniques, such as multi-block composite or patched structured grids,[1,2] overlapping or chimera grids[3] and unstructured grids,[4] have been proposed in the last decades. More recently, mixed or hybrid grids including many different cell types have gained popularity,[5] because they integrate the advantages of both structured and unstructured meshes to improve efficiency and accuracy. For example, hybrid prism/tetrahedral grids,[6,7] mixed grids including tets/prism/pyramid/hex cells,[8] and adaptive Cartesian grid methods,[9,10] Cartesian/tetrahedral/prismatic grids[11] have been used in many applications.

It is relatively easier to use unstructured grids over complex configurations, even for viscous flow simulations, where the anisotropic tetrahedrons are used in boundary layer.

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Generally, the anisotropic tetrahedrons can be automatically generated by an advancing front method.[12] However, the enormous total grid number will reduce the efficiency of the viscous flow simulations over complex geometries. More importantly, the forfeiture of orthogonality will influence the simulation accuracy of boundary layer. Therefore, the prism grids, even unstructured hexahedral grids, may be a better choice in the boundary layer. The traditional prism grid generation method is the advancing layer method,[6,7] in which the prism grids are generated layer-by-layer in the normal direction from the surface triangular grids on the solid wall. Alternatively, the idea of solving the hyperbolic equations to generate structured grids has been introduced to generate prism grids.[13,14] However, for some real-world configurations, these methods will fail in the concave and/or convex regions, because the marching vector may be invisible from some of the nodes in its node-manifold.[15] Examples include the trailing edge of an airfoil, the tip of a sharp nose, the wing-body conjunction, the tail of a store and the nacelles of aircraft. So it is still difficult to automatically generate viscous grids in the boundary layer. Since the anisotropic tetrahedrons can be generated fully automatically, we can agglomerate them into prisms in the boundary layer and then improve the grid quality of the pure anisotropic tetrahedron grids. That is the basic idea of present work.

On the other hand, the computation efficiency is another key issue for turbulence flow simulations over complex configurations, because the total grid number may be several ten millions, even up to hundreds of millions, for a real-life aircraft. The high aspect ratio grids in boundary layer will bring about very strong stiffness during time-iteration, resulting in lower converging efficiency. The multigrid algorithm is an effective method to improve the efficiency. After Fedorenko's development of the method in the 1960s, [16] it was discovered, further developed and popularized by Brandt in the 1970s.[17] Multigrid was applied to the transonic small-disturbance equation by South and Brandt[18] and to the full potential equation by Jameson.[19] Subsequently, the idea of agglomeration multigrid has been extended to unstructured grids (Smith,[20] Lallemand et al.,[21] Venkatakrishnan and Mavriplis[22]; see also Mavriplis[23,24]). Despite considerable progress towards improving the convergence performance of multigrid algorithm based on cell-vertex finite volume schemes, the performance of these methods for viscous flow simulations is not satisfying for cell-centered finite volume schemes. The key issue is how to generate high-quality coarser grids using the agglomeration approach. In other words, how to ensure the "convex" property for the coarser grids, especially in the boundary layer. The work of Refs.[25–27] gave us some inspirations. They agglomerate the grids in boundary layer with a normal-direction restriction. This idea can be extended to improve the coarser grid quality in boundary layer.

In this paper, a hybrid grid generation technique is presented for turbulence flow simulations over 3D complex configurations, which is based on an anisotropic agglomeration of pure tetrahedral grids. Firstly, pure unstructured grids are generated over a given complex geometry, and anisotropic tetrahedral elements with high aspect ratio are adopted in the boundary layer. Then, the anisotropic tetrahedrons are agglomerated to generate the prismatic grids in the boundary layer, while the isotropic tetrahedrons in the outer flow field keep alone. To validate the method, the hybrid grids over some complex geometries are generated, including the DLR-F6 wing-body configuration, a fighter and a human body, which demonstrate the robustness of the present hybrid grid generation technique.

Furthermore, a multigrid computing algorithm based on semi-structured agglomeration method is developed to improve the convergence performance and couple with the parallel computing based on computational domain decomposition. The semi-structured agglomeration means that the agglomeration is mainly limited to the normal direction of the solid wall to keep the orthogonality of hybrid grids in the boundary layer. This multigrid computing algorithm matches the present hybrid grid generation technique, because both of them are based on the anisotropic agglomeration approach. Some typical cases are tested to validate the robustness and efficiency of the present multigrid computing method for viscous flow simulations over complex geometries. The numerical results are compared with the experimental data and other numerical results, which demonstrate the efficiency and accuracy of the present method.

The remainder of this paper is organized as follows. In the next section, a hybrid grid generation technique based on anisotropic agglomeration approach is discussed for 3D complex configurations, together with illustration examples. After that, a multi-level coarser grid generation method based on semi-coarsening method in the boundary layer is developed in Section 3 to improve the multigrid method. In Section 4, applications for several typical configurations are carried out. Conclusions from this study are summarized finally in Section 5.

2. Hybrid grid generation technique based on anisotropic agglomeration approach

As mentioned in the introduction, despite considerable progress towards facilitating the grid generation process itself, the high-quality grid generation over 3D complex real-world configurations, especially for turbulence flow simulations, is still an open issue for producing accurate CFD solutions and, thus, require further attention. Fortunately, the unstructured grid generation method is currently at a stage of maturity that allows discretization of complex, 3D, real-world configurations with relative ease and a reasonable amount of time and effort. Generally, the pure unstructured grids mean triangles in 2D and tetrahedrons in 3D. Thanks to many advances by a number of researchers in the science/art of grid generation, this crucial step no longer represents an obstacle for the routine use of CFD in the context of large-scale (industrial) applications. Some pieces of commercial grid generation software are available in the market, such as Gridgen, ICEM-CFD, etc. Also, there are some in-house grid generation software, such as VGrid in NASA and Centaur in Europe. The unstructured grids can be generated by the advancing front method,[12] Delaunay method[28] and/or the modified Quadtree/Octree methods.[29] Actually, in the commercial grid generation software, the integrated strategy is adopted to improve the grid quality and the grid generation efficiency.

For viscous flow simulations, the anisotropic tetrahedrons are generally adopted in the boundary layer. However, the enormous total grid number will reduce the efficiency. More importantly, the forfeiture of orthogonality will influence the simulation accuracy of boundary layer. A possible better