A 3D Anisotropic Cartesian Grid Generation Method and Its Applications in Viscosity Flows

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Abstract

In this paper, a 3D anisotropic Cartesian grid generation method is produced. With this technique, the fine parts of missiles that have small geometry scale can be described with high quality, which of course will improve the aerodynamics prediction accuracy. Viscous Cartesian grids generating of several stand missile models and simulations with finite volume method demonstrate the success of current method. It is found that the prediction accuracy of aerodynamics coefficients are greatly improved compared with results obtained with traditional Cartesian grid generation method, especially for roller moment and yawing moment.

Keywords: anisotropic Cartesian grid; aerodynamics; finite volume method; Ucart-Flow

1. Introduction

The Cartesian grid generation method has attractive advantages and being popular in nowadays computational fluid dynamics (CFD) study. The existing Cartesian grids CFD software often work with Euler and potential equations and not suitable for viscous flow [1,2]. Viscous Cartesian grid and NS equation are essential for viscous flow simulations. Traditional 3D Cartesian grid begins with isotropic mesh to do refinement, which is hard to describe fine structures and makes wasting at common flow zones, anisotropic Cartesian grid is believed to be better and it should be easy to use [2].

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Computational fluid dynamics (CFD) has got great development in the recent several decades, the importance of grid generating obtain more and more attention. Normally speaking, there are three main grid generating technique in CFD, multi-block structured grid generating technique, unstructured grid generating technique and Cartesian grid generating technique. The multi-block structured grid can have very high quality, thanks to the body fitting boundary layer grid near the wall of aircraft, with this kind of grid, people can often obtain very good numerical results that agree with experimental results in CFD. However, the generating process is often too time consuming and need a lot of labor cost, especially for complex aircraft, the grid is very hard to be generated, which greatly low down the significance of this method. For the efficiency considering, people sort to unstructured grid generating method, with this technique, the grid can be auto-generated, which will be sure generated fast and efficient. But it is a pity that this method can not give good boundary layer grid description, so it often can not give accurate simulation results in CFD simulations. The Cartesian grid, has tree structured data type, which can be visit very fast, can be auto-generated in time. In order to be used in viscous flow simulation, the near wall boundary layer grid can be generated with a projection method. After the far field Cartesian grid is generated, project the inner face of Cartesian grid into the wall of aircraft, and divide the projection into nk layers with the steps stretched outside, we will obtain the boundary layer grid, which can give good description of the boundary layer. By the way, for the sake of tree data structure, the grid can be refined easily near sharp variation range of the geometry and special flow field, such as large separation and shock wave zones. One shortage of the Cartesian grid is that, the out Cartesian grid is must isotropic, which is not easy be refined as if there are large characteristic length scale range of the geometry, and in the case of the aircraft is composed with many fine structures. To solve this problem, Wang Z.J.[3] did three dimension \(2^N\) tree refinement in Cartesian grid, the grid can be generated and refined anisotropic, which can of course low down the grid number, however, the body of the algorithm has to be complex and may logistical judgment have to be done, which destroy the simplicity of Cartesian grid generation. In this paper, we present a new three dimensional anisotropic Cartesian grid generation method, which this method, small part and small scale structures can be simulated, which will greatly increase the success of Cartesian grid generation. With several test cases, the advantages of this method are demonstrated. The paper is organized as following: the algorithm of this anisotropic Cartesian grid generation is given in part 2 in detail with simple cases, as well as the numerical method and boundary condition of viscous flow simulations are specified. In part 3, we give out the numerical simulation results with grid generated with the new method and do some simple analysis. Some conclusions and the work we will do in the next step is summarized in part 4.

2. Problem Statement

The Cartesian grid data has an oct-tree data type like fig.1 shows. At the first, the far field isotropic Cartesian grid is generated and a inner face is formed around the aircraft, then a viscous boundary layer grid need to be generated near the wall. The drawback of isotropic Cartesian grid is that it is must uniformly and isotropic distributed, which leads to the points on the wall of aircraft have to be distributed uniformly. For this reason, if there are fine structures such as the tip of a wing and small gap between structures, the grid can not descrip the body geometry clearly, and it is straight forward not suitable for the parts that need more points such as the top of aircraft.
Fig. 1. Tree data structure of Cartesian grid

To generate Cartesian grid taking small parts of aircraft into account, the original ‘father’ grid need to be carefully designed, and anisotropic original mesh will take the place of the isotropic one. The main principle of this 3D anisotropic Cartesian grid generating method is just like that: at the first, pick out the crucial points, such as tip position of the aircraft, the tip positions of wings and fins, the ends of wings and fins, the back position of aircraft; then define the grid step stretched ratio to make the Cartesian grid shrink to every crucial point with decreasing spatial steps, and then stretched out with increasing steps to an uniform step for smooth regions. With this strategy, the original father grid has the typical shape of “+” focusing on the aircraft in the center of computational domain, and the fine structures are easily to be describe and the grids are designed optimal.

To make the process clearly, we take a two dimensional case as an example, the geometry and mesh is shown in Fig. 2.

Step 1: Define crucial points in x and y directions: A (tip of the aircraft), B (beginning of fins), C (end of the aircraft);
Cut the field in x direction into four parts: WA (from far field to the tip of aircraft), AB (from the tip of aircraft to the beginning of fins), BC (to cover the fins in x direction) and CE (from the end of aircraft to far field);
Cut the field in y direction into six parts: S0 (far field to tip of lower fin), 01 (to cover the lower fin), 12 (to cover the lower half of the body of aircraft), 23 (to cover the upper half of the body), 34 (to cover the upper fin), 4N (from tip of upper fin to far field)

Step 2: Define the spatial step varying ratio:
For simplicity, let’s consider a line L-A-R with refinement at A as Fig.3 shows, from left side with a step $\Delta x_L$ to A, the spatial step decreases with a ratio $r_L$ to the minimum step $\Delta x_{min}$ at A, while from A to right side, the step increases with a ratio $r_R$ to $\Delta x_R$. $r_L$ and $r_R$ can be defined with given M and N.

$$
\begin{align*}
    x_{-N} &= x_w, \quad \Delta x_{-N} = \Delta x_L = \left(r_L\right)^N \Delta x_0 \\
    x_{-j} &= x_A + \left(r_L\right)^j \Delta x_0, \quad N = \log(\Delta x_L / \Delta x_0) / \log(r_L) \\
    x_j &= x_A + \left(r_R\right)^j \Delta x_0, \quad M = \log(\Delta x_R / \Delta x_0) / \log(r_R) \\
    x_M &= x_R, \quad \Delta x_M = \Delta x_R = \left(r_R\right)^M \Delta x_0
\end{align*}
$$

With this method, there is a refinement at every crucial point, such as point A, B and C. For the smooth region, a fine enough uniform grid distribution is recommended.

Step 3: Generating the out field an-isotropic Cartesian grid.

Step 4: Obtain the inner face of Cartesian grid and projecting it into the wall of aircraft to generate viscous boundary layer grid.

After the above steps, a 2D an-isotropic viscous Cartesian grid with refinements at the crucial points is generated, we can see from the figure that, there are enough points at the fine structures such as the top part of aircraft, the tips of fins. Compared with isotropic Cartesian grid, it is sure that the new method will give better numerical results. The process for 3D an-isotropic Cartesian grid is straightforward and has little difference from that of 2D.

The CFD solver used to do aerodynamics simulations is named Ucart-Flow based on finite volume method, with 2nd order in space and advanced with time with a 3rd order Runge-Kutta method. For the out field, far field boundary is used, and no-slip and adiabatic boundary are used at the wall. The generated grids are cut by Metis into zones and used to do parallel simulations.

3. Results and Discussion

To validate the new technique, we do 3D an-isotropic viscous Cartesian grid generation and numerical simulation with for two stand missile model I and II. For case I, the Mach number is $Ma=1.8$, and $Ma=2.0$ for the second case. The aerodynamic coefficients obtained with the present grids are compared with that from isotropic Cartesian grids.

Fig. 4 (a) gives the out field an-isotropic Cartesian grid for missile I, at first glance, we can see that it is alike that of structured grid, which has a “+” characteristic with refinement at the center of missile, it is reasonable. Fig.4 (b) shows the surface grid of missile I, from which we can see the variation of spatial step in three directions. From the local zoom in, we can see that more grid points are arranged to describe the thickness of fins and top of the missile, which of course will give better aerodynamic prediction. Fig. 5 gives the lift coefficient and norm force coefficient, from the figure, we can see that with an-isotropic Cartesian grid, the simulation results as the angle of attack ranges from 10 to 20 agree better with experiments than that of isotropic grid.
Missile II is another stand model, it is hard for traditional isotropic grid generation since there is a little gap between air inlet and the missile body. Fig. 6 give the generated an-isotropic viscous Cartesian grid and numerical simulation results of lift coefficient, we can see that the grid can be successfully generated with the new an-isotropic viscous Cartesian grid generating technique and the lift coefficient agrees experiment well.
4. Conclusion and Future Work

In this paper, a 3D anisotropic viscous Cartesian grid generating method is presented, the new grid generating method takes the small parts and small gap between structures of aircraft into account, with adjusting the farther Cartesian grid from isotropic into anisotropic at crucial points, the grid can descript aircraft geometry better with a “+” characteristic as structured grid, even for difficult case that traditional isotropic Cartesian grid can not define, an-isotropic Cartesian grid can still successfully generated, which will of course improve the efficiency of grid generating and simulation accuracy. From the two test cases missile I and II, we can see that the results obtained with anisotropic Cartesian grid can give better results and the aerodynamics coefficients agree experiments well.

Actually, there is no need to do refinement in outfield, which means that the current grid generating method still can be optimized, which will be our next step work.

References