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Numerical Simulation of Unsteady Separated Flow over a Delta Wing Using Cartesian Grids and DES/DDES

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Abstract

Detached-Eddy simulation (DES) and Delayed Detached-Eddy simulation (DDES) based on SA and SST turbulent models were developed by using Cartesian grids. Associating with flexible deformation dynamic grid method on Cartesian grids, unsteady Reynolds-averaged Navier-Stokes (URANS), DES and DDES methods involving moving boundaries were established. URANS, DES and DDES were evaluated for simulating the high angle of attack separated flow over a delta wing of 65 degrees swept and with sharp leading edge, showing that DES and DDES forecast the site of vortex breakdown more accurate, which means these methods are fit for simulating the large separated flow and can be adapted to the engineering applications. The study also simulated the unsteady separated flow around the oscillating delta wing. The results show that the pitching of the wing delays the flow separation and makes the flow field appearing hysteresis. It is meaningful to the design of modern astronautical and aeronautical vehicles.

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Keywords: Unsteady separated flow; Moving boundaries; Delta wing; DES; DDES; Cartesian grids

1. Introduction

New astronautical and aeronautical vehicles are required to achieve flying at high angle of attack or ultra maneuverable flight. There must be large unsteady separated flow in the flow field. To adapt the requirement of wing flat shape at different speeds, delta wing or other similar wing flat shape is generally applied in modern aircraft

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or missile design. Carrying out the study of numerical simulation applied to large separated flow is meaningful to the design of modern aircraft.

Recently, the numerical simulation of separated flow showed the interaction among every flow structure, the generation, developing and breakdown of vortex and so on. The main means contain direct numerical simulation (DNS), large-eddy simulation (LES), RANS and hybrid RANS/LES simulation. The cost of DNS and LES is too large, so they are not fit for the global engineering applications; RANS is not adapted for the simulation of large separated flow. Therefore, for the engineering applications, hybrid simulation can impose the advantages of both RANS and LES. DES is one of hybrid RANS/LES, which was first proposed in 1997 by Spalart[1]. Strelets[2] proposed DES based on the SST model in 2001. Menter[3] and Spalart[4] proposed DDES based on SST and SA models respectively. DES and DDES are popular in the applications, such as iced airfoil, landing gear, fighter and transport aircraft.

The paper aims at high angle and moving boundaries separated flow, developing DES/DDES method by using Cartesian dynamic grid strategy.

2. Numerical method

2.1. Governing equation

The time-dependent RANS equations for dynamic grids can be expressed in the integral form as

$$\iiint_{\Omega(t)} \frac{\partial}{\partial t} \mathbf{Q} d\Omega + \oiint_{\partial\Omega(t)} \left(\mathbf{F}_i(\mathbf{Q}) - \mathbf{Q}\mathbf{v}_g \cdot \mathbf{n} \right) dS = \oiint_{\partial\Omega(t)} \mathbf{F}_v(\mathbf{Q}) dS \tag{1}$$

where $\mathbf{Q}$ is the vector of conserved variables, $\mathbf{F}_i$ is the inviscid flux vector and $\mathbf{F}_v$ is the viscous flux vector, $\partial\Omega$ is the surface surrounding the control volume Ω, $\mathbf{v}_g$ is the velocity of $\partial\Omega$, $\mathbf{n}$ is the out-going unit normal of $\partial\Omega$.

The governing equations are dispersed by finite volume method. The inviscid flux is calculated using Roe method and the viscous flux using gauss method. Runge-Kutta method is used for the time integral. The thesis uses the spring approximation method to achieve moving boundaries, while the velocity of moving grids is calculated by geometric conservation.

2.2. DES/DDES method

DES/DDES based on SA model modify the variable of length. The transition of RANS and LES regions is

$$d = \min\left(d, C_{DES}\Delta\right) \tag{2}$$

In the near wall region, SA turbulent model is used. Other region, LES model is used. To avoid the Modeled-stress depletion, the functions are used to turn off the LES in the near wall region.

$$d = d - f_d \max\left(0, d - C_{DES}\Delta\right), f_d = 1 - \tanh\left(\left|8r_d\right|^3\right), r_d = \frac{\mu_l + \mu_t}{\rho\sqrt{U_{ij}U_{ij}}\kappa^2 d^2} \tag{3}$$

DES/DDES based on SST turbulent model change the dissipation of turbulent kinetic energy[5].

$$S_{D,k} = \beta^* \rho k\omega \cdot F_{hybrid}, F_{hybrid} = \max\left[\frac{\left(1 - F_{SST}\right) l_{RANS}}{l_{LES}}, 1\right], l_{RANS} = \sqrt{k} / \left(\beta^* \omega\right), l_{LES} = C_{DES}\Delta \tag{4}$$

When F_{SST}=0, l_{RANS}>l_{LES}, it is similar to LES model, otherwise, it is SST turbulent model. To avoid the Modeled-stress depletion, F_{SST}=F_2, in the transition region between RANS and LES, 0<F_2<1, so the transition is delayed.

3. Grid generation strategy

In this study, Cartesian grids approach is used to discrete an computational domain. Flexible deformation dynamic grid method on Cartesian grids is established by using spring analogy, which treats every edge of grid cell as spring. The stiffness of the each edge is related to the length of the edge. When boundaries move, the grid points on the boundaries move to the new positions, the positions of the other grid points are defined by solving the balance equation of spring system[6].

4. Results and discussion

4.1. High angle of attack separated flow over a delta wing

The geometry of Chu and Luckring[7] using in the NASA NTF wind tunnel was adopted, which was a delta wing of 65 degrees swept and with sharp leading edge, shown in Fig. 1(a). The grid is comprised of 4 million elements, which is shown in Fig. 1(b) and was generated by Cartesian grids. Calculations were performed at a freestream Mach number of 0.85 and at an angle of attack of 24.6 deg. The Reynolds number based on the chord is 6.0×10^6.

a b

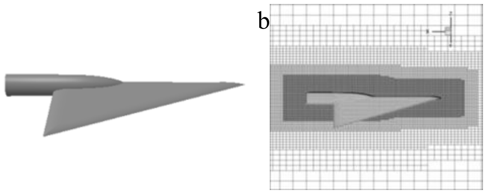


Fig.1 (a) Computational geometry; (b) Computational grids.

The pressure coefficients distribution is compared with the wing sections located at x/c=0.4, 0.6, and 0.8 shown in Fig. 2. At x/c=0.4, the pressure coefficients of all methods match the experiment well. At x/c=0.6, the results with URANS show great difference from those of experiment, while the pressure coefficients of DES and DDES match the experiment well, indicating that the site and value of the main vortex' peak. At x/c=0.8, the results of experiment show no peak, indicating the vortex has broken down. The pressure coefficients of URANS, DES and DDES show difference from those of experiment, while the results of DES and DDES showing no peak, predicting the breakdown of vortex. URANS predicting no breakdown of vortex. DES/DDES predict the site of vortex breakdown more accurate and can give more reliable surface pressure distribution than URANS.

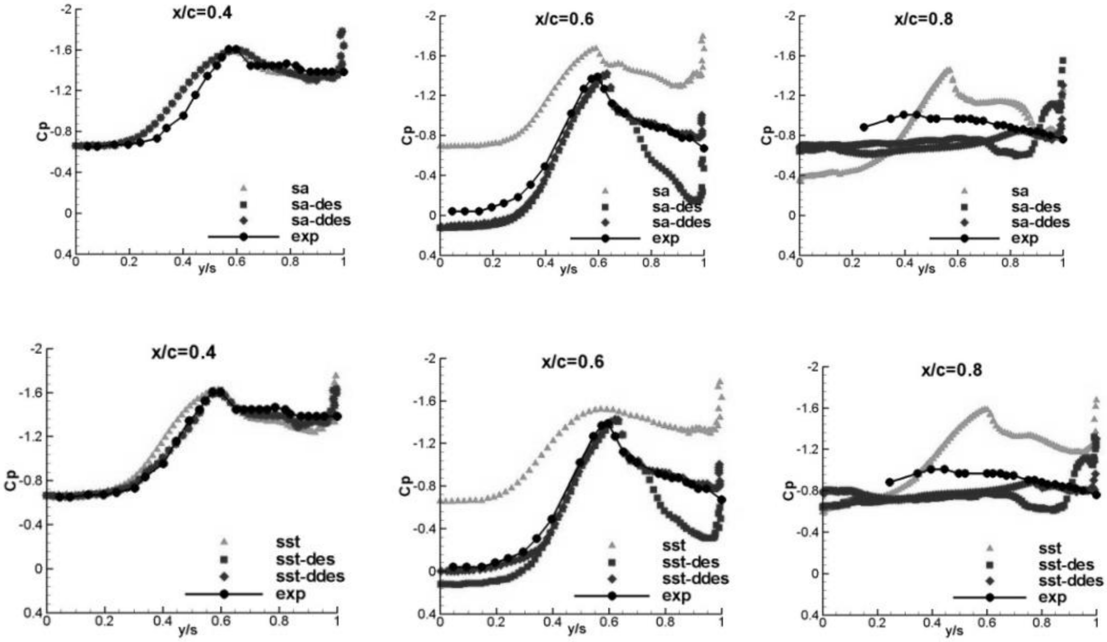


Fig. 2. Comparison of pressure with URANS, DES, and DDES methods.

4.2. Unsteady separated flow around the oscillating delta wing

The equation of the delta wing above undergoing oscillatory pitch motions is

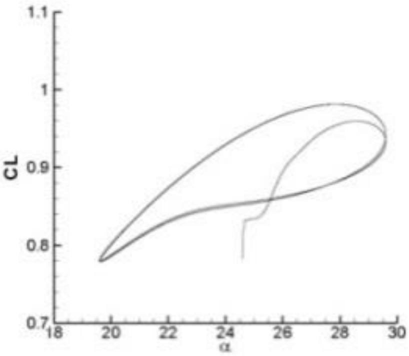
$$\alpha(t) = \alpha_m + \alpha_0 \sin(kt) \tag{5}$$

The test cases summarized in Table 1.

Table 1. Description of the test cases.

Ma	*Re*	α_m (deg)	α_0 (deg)	$k=\omega c/2u_\infty$	x_m/c
0.85	6.0×10^6	24.6	5	0.0814	0.25

The breakdown of the vortex on the delta wing vanishes because of the rising, indicating the rising motion delays the breakdown of the vortex; when the wing pitching down, the breakdown of the vortex appears in the trailing edge of the wing and moves forward. The dynamic flow structure has lots of difference from the flow field of static state at the same angle of attack, which attributes to the pitch motions of the wing. The coefficients of lift and drag represent hysteresis shown in Fig. 3.



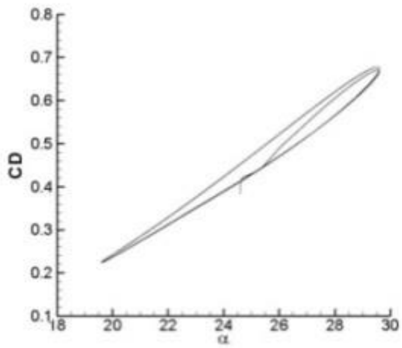


Fig. 3. The hysteresis loops of lift and drag coefficients.

5. Conclusions

DES/DDES predict the site of vortex breakdown more accurate and can give more reliable flow patterns on both the vortices structures and surface pressure distribution, while the pitching making the flow field of delta wing appearing hysteresis. It is meaningful to the design of modern astronautical and aeronautical vehicles.

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