LIFT PREDICTION OF MULTI-ELEMENT AIRFOIL USING DES AND RANS

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Keywords: *DES, DDES, multi-element airfoil, maximal lift, separated flows*

Abstract

An algorithm is developed based on Detached Eddy Simulations (DES) and Reynolds averaged Navier-Stokes simulations (RANS). Using this algorithm, computations are conducted for the flow over ga(w)-1 multi-element airfoil at a mach number of 0.14. Comparisons of lift prediction from both computations and experiments are presented. The results support our theoretic analysis that DES (and its improved version) is superior to RANS, for multi-element airfoil lift prediction.

1 Introduction

The prediction of multi-element airfoil maximum lift is not a easy work because of its correlation with separated flows and further because of its correlation with turbulent flows. In many cases of airfoil experiment we find that, the attack angle where the lift climbs up maximum is a few degrees more than the angle where boundary layer separation arises. If the computational simulation gives premature or delayed separation, the pressure distribution on airfoil surface may be dramatically different from each other, and the resulting lift may differ a lot. So a good algorithm for airfoil maximum lift prediction is firstly an algorithm which accurately simulates separated flows. In recent years, many computational and experimental investigations show that separated flows contain a series of smaller structure with three-dimensional, time-dependent features and usually with turbulent features. Wherefore, a good algorithm for airfoil maximum lift prediction is also an accurate algorithm for turbulent flows.

As a conventional method, RANS simulations filtrate the whole flow field through Reynolds averaging, and then lost the information associated with turbulence fluctuation, and cause the closure problem [1]. One turbulence model has to be combined with RANS as both the physical reparation and the mathematical correction (make the system to be closed). Many kinds of turbulence models were developed including algebraic models, one- and two-equation models. Some of them such as Baldwin-Lomax model, Spalart-Allmaras (S-A) model [2], Wilcox k-omega model [1], Menter's k-omega SST model [3] are widely used. Although there are lots of significant achievements on turbulence models, separated flows simulation with RANS is not satisfying yet. New approaches are expected.

The first new approach is Direct Numerical Simulation (DNS), which preserves all of the turbulence fluctuations and provides both instantaneous and statistical predictions. DNS is theoretically exact [4] but so costly as to be limited to very low Reynolds numer flows at present.

The second approach is Large Eddy Simulation (LES) [4]. In LES, filtering is implemented. The large scale fluid motion are solved by the filtered Navier-Stokes equations, and a sub-grid scale (SGS) model is used to replace the effect of the small scale fluid motion on the large one. The theory of LES indicates that LES preserves much more information than RANS dose, and so it is more accurate theoretically than RANS. Unfortunately, LES is still too much costly for high Reynolds number flows in complex engineering applications.

Another one is DES [5] which is a hybrid of RANS and LES. DES gives, as does DNS and LES, both instantaneous and statistical data. DES in attached flows region solves Reynolds averaging Navier-Stokes equations with a ordinary turbulence model, and in detached flows region solves filtered Navier-Stokes equations with this turbulence model working like a SGS model. Therefore, DES has both the applicability to high Reynolds number flows as RANS, and the capability to resolve geometry dependent unsteady three-dimensional turbulent motions as LES.

DES is grid dependent. DES may exhibit an incorrect behavior when the grid close to the wall is unsuitable. When the grid spacing parallel to the wall $\Delta_{\|}$ is less than the boundary-layer thickness δ, the grid is fine enough to switch DES to its LES branch, but actually the grid is not fine enough to support LES computation. This results in smaller eddy viscosity in boundary-layer, that will be referred to as modeled-stress depletion (MSD). MSD reduces the surface friction and may lead to premature separation. A new version of DES named Delayed Detached Eddy Simulation (DDES) was proposed by Spalart [6]. Using a delay function, DDES maintains RANS behavior in boundary layers, independent of $\Delta_{\|}$.

The DES have been successively applied to delta wing vortex breakdown [7], supersonic axisymmetric base flow [8], airfoil flow [9] and so on. These result show the superiority of DES to RANS. In this paper DES and DDES are applied to ga(w)-1 multi-element airfoil lift prediction. RANS computation as a comparison is also implemented.

2 Numerical Method

In this section a brief description of the numerical method is provided. The multi-element airfoil used is ga(w)-1 [10] with 30% chord and 40 deg deflection flap configuration. Computational solutions are obtained for a freestream mach number of 0.14, the attack angles from 0 - 20 deg, and the Reynolds number of 2.2 million.

2.1 Governing Equations

The compressible Navier-Stokes equations can be written in integral form as,

$$\frac{\partial}{\partial t}\iiint_{\Omega} W\, d\Omega + \iint_{S} H \cdot d\vec{S} - \iint_{S} H^{V} \cdot d\vec{S} = 0 \qquad (1)$$

$$W = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho e_t \end{bmatrix} \quad H^{V} = \begin{bmatrix} 0 & 0 & 0 \\ \tau_{xx} & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \tau_{yy} & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \tau_{zz} \\ \varphi_x & \varphi_y & \varphi_z \end{bmatrix}$$

$$H = \begin{bmatrix} \rho u & \rho v & \rho w \\ \rho u^2 + p & \rho v u & \rho w u \\ \rho u v & \rho v^2 + p & \rho w v \\ \rho u w & \rho v w & \rho w^2 + p \\ \rho u h_t & \rho v h_t & \rho w h_t \end{bmatrix}$$

$$\varphi_x = u\tau_{xx} + v\tau_{xy} + w\tau_{xz} + kT_x$$

$$\varphi_y = u\tau_{yx} + v\tau_{yy} + w\tau_{yz} + kT_y$$

$$\varphi_z = u\tau_{zx} + v\tau_{zy} + w\tau_{zz} + kT_z$$

Where w is the state vector of conservative variables, H and H^V are inviscid and viscous fluxes, respectively. Discretizing above equations with the finite volume method leads to the following semi-discrete form,

$$Vol_{i,j,k} \frac{3W^{n+1}_{i,j,k} - 4W^{n}_{i,j,k} + W^{n-1}_{i,j,k}}{2\Delta t} + \sum F^{n+1}_{i,j,k} - \sum F^{V\,n+1}_{i,j,k} = 0 \qquad (2)$$

2.2 DES and DDES Based on S-A Model

Spalart proposed the original DES based on S-A turbulence model, and Strelets [11] introduced another DES based on k-omega SST turbulence model. In this investigation the first is applied. In S-A model the distance to the wall is denote by d. If d is replaced with $\Delta = max(\Delta x, \Delta y, \Delta z)$ in the destruction term, the S-A model will act as a Smagorinski SGS model. Therefore, d in S-A model is replaced by

$$\tilde{d} \equiv \min\left(d, C_{DES}\Delta\right) \qquad (3)$$

$$C_{DES} = 0.65$$

when $d < C_{DES}\Delta$ the model acts in a RANS mode and when $d > C_{DES}\Delta$ the model acts in a Smagorinski LES mode.

DDES [6] is slightly different from DES. The length scale $\tilde{d}$ is determined by

$$\begin{aligned} &\tilde{d} = d - f_d \max(0, d - C_{DES}\Delta) \qquad (4)\\ &f_d = 1 - \tanh(|8r_d|^3)\\ &r_d = \frac{\nu + \hat{\nu}}{\sqrt{U_{ij}U_{ij}}\kappa^2 d^2} \end{aligned}$$

where U_{ij} is the velocity gradient, d is the distance to the wall, the subscript 'd' represents 'delayed' and equation.4 is the so-called delayed function. Above modification ensures the model will act as S-A turbulence model in boundary layer for arbitrary grid.

2.3 Time Advancement and Spatial Discretization

DES and DDES require time-accurate computations. A dual-time method [12] is used and gives the following form,

$$\begin{aligned} &Vol_{i,j,k}\left(\frac{1}{\Delta\tau} + \frac{3}{2\Delta t}\right)\left(W^{m+1}_{i,j,k} - W^{m}_{i,j,k}\right)\\ &+ Vol_{i,j,k}\frac{3W^{m}_{i,j,k} - 4W^{n}_{i,j,k} + W^{n-1}_{i,j,k}}{2\Delta t} \qquad (5)\\ &+ \sum F^{m+1}_{i,j,k} - \sum F^{V\,m+1}_{i,j,k} = 0 \end{aligned}$$

where $\Delta\tau$ is the dummy time step, Δt the real time step. Sub-iteration about dummy time is implemented by lower-upper symmetric-gauss-seidel method [13]. Inviscid fluxes are discretized with ausm+up [14] scheme, and viscous fluxes are discretized with 2nd-order central differences.

3 Results and Discussion

RANS ,DES and DDES are implemented on both point-to-point matched multi-block grid and overset grid. The Fig.1 and Fig.2 show x-y plan of the grids. Extruding the grid on x-y plan along z direction gives the three-dimensional grid which contains about 2.5 million grid points. All cases in this study are time-accurate, and the predicted lift values are time-averaged values. The numerical results for the lift are compared with experimental results. Fig.3 and Fig.4 show the results by DES, DDES, RANS and experiments.

RANS predicts a much higher maximum lift Cl_{max}, and a larger corresponding attack angle $\alpha_{cl\max}$. Flow visualizations illustrate the reason: RANS in this investigation predicts delayed and shallow separation regions relative to DES or DDES. When the attack angle is deg, there is still no visible separation (Fig.5). With point-to-point matched grid, both DES and DDES give much improved results: the little higher Cl_{max} and $\alpha_{cl\max}$ than experiments.

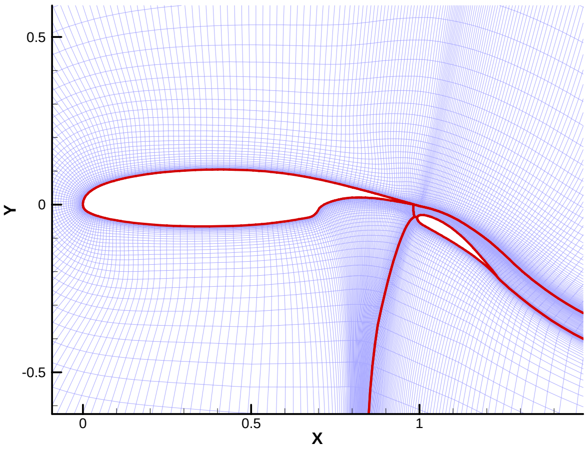

Fig. 1. Point-to-Point Matched Grid X-Y Plan

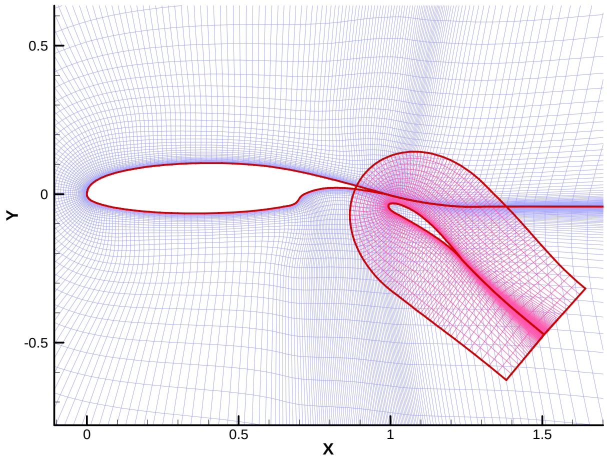

Fig. 2. Overset Grid X-Y Plan

However when using overset grid, the results are worsen. DES, DDES and RANS on overset grid give lower Cl_{max} than they do on point-to-point matched grid. Checking the holes in overset grid (Fig.6), the hole boundary in main airfoil grid is too close to the flap in region A and B. Especially in region B, cells of main airfoil grid are too much larger than those of flap grid, and so the interpolation is not accurate enough. It is a possible explanation to this problem. The results are improved slightly by artificially adjusting the grid density and the location of holes.

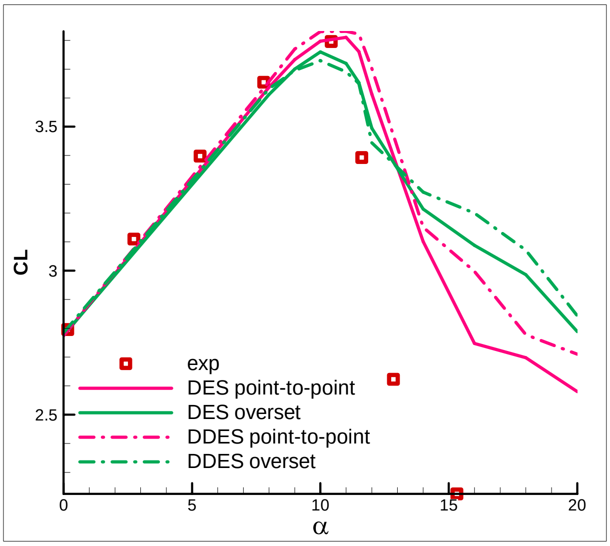

Fig. 3. Comparisons Between DES, DDES And Experiments

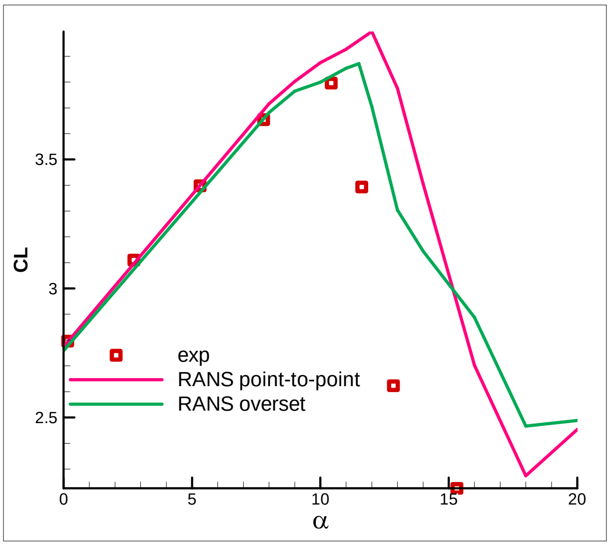

Fig. 4. Comparisons Between RANS And Experiments

4 Conclusions

In this investigation DES and DDES predicts the lift of multi-element airfoil. Although a little higher, the predicted Cl_{max} and $\alpha_{cl\,\max}$ with point-to-point match grid, are very close to experimental ones. Cl_{max} and $\alpha_{cl\,\max}$ predicted by RANS are too much higher. This shows the conclusion: DES and DDES are superior to RANS in maximum lift prediction of ga(w)-1 multi-element airfoil.

Unfortunately we do not obtain satisfying results with overset grid by both DES and DDES. The sticking point may be the inaccurate interpolation at hole boundary. The artificial adjusting of grid mentioned above is not an convenient method. An automatic adjusting method will be studied aiming at better accuracy and less manual intervention.

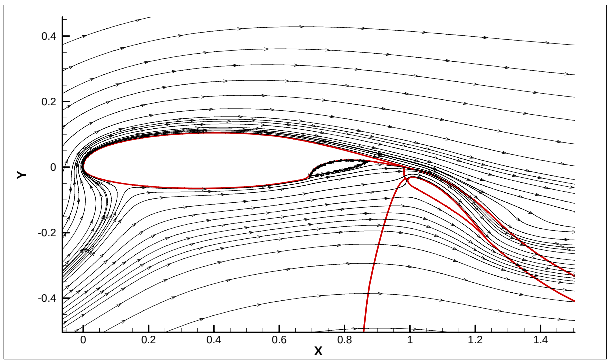

Fig. 5. RANS Results, Stream Track At Attack Angle Of 12 Deg

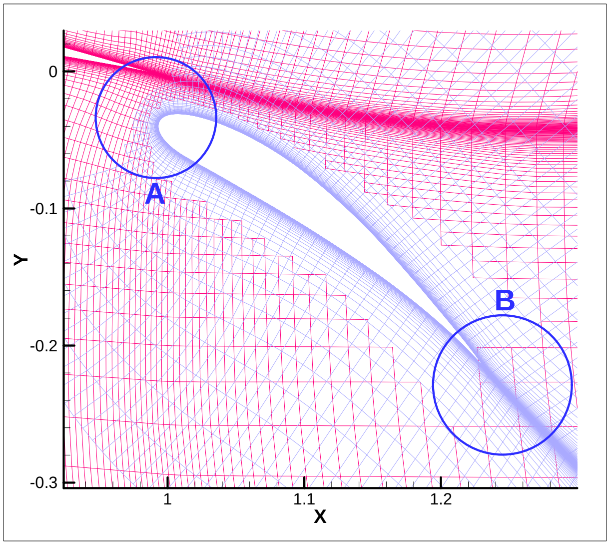

Fig. 6. Holes For Overset Grid

References

[1] Wilcox D. *Turbulence modeling for CFD,* DCW Industries, Inc., La Canada, California, 1993.

[2] Spalart P R and etc. A one-equation turbulence model for aerodynamic flows, *AIAA-92-0439*,1992.

[3] Menter F and Rumsey C. Assessment of two-equation turbulence models for transonic flows, *AIAA-94-2343*, 1994.

[4] Marcel L, Olivier M and Pierre C. *Large-eddy simulations of turbulence,* Cambridge university press, 2005

[5] Spalart P R and etc. Comments on the feasibility of LES for wings and on a hybrid RANS/LES approach, advances in DNS/LES, *IstAFOSR Int. Conf. on DNS/LES,* Greyden Press, 1997

[6] Spalart P R, Deck S, Shur M L , Squires K D and Strelets M Kh, Travin A. A new version of detached-eddy simulation, resistant to ambiguous grid densities, *Theor. Comput. Fluid Dyn.* Vol 20: 181–195, 2006
[7] Morton S, Forsythe J R, Mitchell A, and Hajek D. DES and RANS simulations of delta wing vortical flows, *AIAA-2002-0587*,2002.
[8] James R F, Klaus A H, Kyle D S. Detached-eddy simulation with compressibility corrections applied to a supersonic axisymmetric base flow, *AIAA-2002-0586*,2002.
[9] Sebastien DECK. Detached-eddy simulation of transonic buffet over a supercritical airfoil, *AIAA-2004-5378*,2004.
[10] Wentz and Seetbaram. Development of a flowler flap system for a high performance general aviation airfoil, *NASA-CR-2443,* 1974.
[11] M Strelets, Detached eddy simulations of massively separated flows, *AIAA-2001-0879*, 2001.
[12] Jameson A. Time dependent calculations using multigrid, with applications to unsteady flows past airfoils and wings, *AIAA-91-1596*, 1991.
[13] Yoon S and Jameson A. Lower-upper symmetric-gauss-seidel method for the euler and navier-stokes equations, *AIAA-87-0600,* 1987.
[14] Meng-Sing Liou. A further development of the ausm+ scheme towards robust and accurate solutions for all speeds, *AIAA-2003-4116,*2003.

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