NUMERICAL SIMULATION OF THIN AIRFOIL STALL BY USING MODIFIED DES APPROACH

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Abstract

The Detached-Eddy Simulation (DES) method was applied to calculate pre- and post-stall aerodynamic characteristics of airfoil stall. A discrepancy between numerical and experimental data was observed near the stall regime for the airfoil NACA64A-006 which is a thin airfoil stall type. The reason of this discrepancy and also possible ways for improvement of the numerical model were discussed. It has been shown that the use of the Baldwin-Lomax model in the RANS region improves the DES results in this case. With taking the factors (grid density, time step, turbulence model and so on) into account, the DES approach could reliably predict stall aerodynamical characteristics.

1 Introduction

The present study concerns simulation of the flow field around an airfoil at a low speed and a large attack angle. The question is how accurately stall characteristics can be predicted by numerical simulation of highly separated flows.

RANS models can provide accurate results for attached boundary layer flows with minimal grid spacing requirement. However, they often fail in applications to large scale separated flows that depend on geometry. Large Eddy Simulation solves large, energy containing scales by modeling smaller scales. This method requires grid spacing to be prohibitively small. In boundary layers, energy containing eddies are so small at high Reynolds Numbers that very small stream-wise grid spacing is needed.

Spalart et al. [1] proposed Detached-Eddy Simulation (DES) approach that combines the most favorable elements of RANS models with Large Eddy Simulation. It can be applied to flows at high Reynolds numbers. The DES approach has been successively applied to a delta wing vortex breakdown [2], a supersonic axisymmetric base flow [3], a circular cylinder, an airfoil pitch-up, and real configurations of several aircrafts [4], etc. It should be noted that the mentioned works focus on practical Reynolds numbers that are close to real flight conditions. In the present work, the DES method is used for the simulation of airfoils stall. In our prophase study [5], three airfoils with different stall onset mechanisms have been numerically simulated by using the DES approach and RANS approach, which are NACA63$_3$-018 as the trailing-edge stall; NACA63$_1$-012 as the leading-edge stall; NACA64A-006 as the thin airfoil stall [6].

According to results of the numerical simulations [5], for the NACA63$_3$-018 airfoil, the lift loss at the stall regime is caused by the flow separation near the trailing edge. The separation region slowly extends toward upstream as the angle of attack increases. A minor difference is observed between the RANS and DES methods. Thus, for slightly separated flows, the use of RANS models can provide reliable results. In the case of NACA63$_1$-012 airfoil, as the angle of attack increases, the flow suddenly separates in the vicinity of the leading edge. The separation region extends over all the upper surface of the airfoil. This leads to a sudden loss of lift at post-stall regimes. Before the stall, both the RANS and DES methods yield quite reliable results. However, after the stall the DES results much better agree with experimental data than the RANS those. These points to the ability of the DES method to handle massively separated flows.

For the NACA64A-006 airfoil, a difference between DES numerical results and experimental data appears yet before the stall, which becomes severe at stall and post-stall regimes. This occurs due to a bubble that is created near the leading edge. In this study, we discuss several factors that may affect the accuracy of numerical simulations and propose some modifications that can improve numerical results for unsteady regimes of thin airfoils.

2 Computational Method

2.1 Spalart-Allmaras Model

The Spalart-Allmaras one equation model solves a partial differential equation for variable $\tilde{\upsilon}$ which is related to turbulent viscosity.

$$\frac{D\tilde{\upsilon}}{Dt} = c_{b1}[1-f_{t2}]\tilde{S}\tilde{\upsilon} - \left[c_{w1}f_w - \frac{c_{b1}}{\kappa^2}f_{t2}\right]\left[\frac{\upsilon}{d}\right]^2 + \frac{1}{\sigma}\left[\nabla \bullet ((\upsilon+\tilde{\upsilon})\nabla\tilde{\upsilon}) + c_{b2}(\nabla\tilde{\upsilon})^2\right] + f_{t1}\Delta U^2 \qquad (1)$$

Then

$$\upsilon_t = \tilde{\upsilon} f_{v1}, \quad f_{v1} = \frac{\chi^3}{\chi^3 + c_{v1}^3}, \quad \chi \equiv \frac{\tilde{\upsilon}}{\upsilon}$$

υ is the molecular viscosity. The right hand side of the equation composed of production, destruction, diffusion terms, and transition trip term especially.

2.2 Detached-Eddy Simulation

The DES formulation is based on a modification to the Spalart-Allmaras RANS model such that the model reduces to its RANS formulation near a solid surface and to a subgrid model away from the wall. It takes advantage of both RANS model in the thin shear layer and the power of LES to resolve geometry dependent and three dimensional eddies.

The DES formulation is obtained by replacing the distance to the nearest wall, d by $\tilde{d}$, where $\tilde{d}$ is defined as, $\tilde{d} \equiv \min(d, C_{DES}\Delta)$, where Δ is the largest one among the distances between a cell and its neighbors, and constant $C_{DES} = 0.65$. Flow field was separated into two parts by length scale, which calls as RANS region and LES region here.

2.3 Some details of numerical method

3-D and unsteady code was used for the simulation of flow field of airfoils. The free stream conditions in the non-dimension form used in present work are as follow:

$$V_\infty = 0.355$$

$$C = 1.0$$

$$T_{character} = C / V_\infty = 2.82$$

The pseudo time step [7] is employed for both Navier-Stokes equations and Spalart-Allmaras turbulence equation. The LU-SGS method [8] is used to implicitly discretize the S-A equation. The time steps for physical time are selected as △t=0.1 (3.5% of the time the free stream passes the chord length). From the calculation we can see that, △t near the value $\Delta_z * C/V_\infty$ is appropriate for the unsteady simulation of airfoils, which is in line with the advice of Spalart, P.R [9]. In present research work, an explicit local time stepping method is used for inner iterations, 20 inner time steps were used in present work.

From Fig. 1, we can see that the average lift does not converge until $T > 10 \times T_{character}$. To obtain the convergence, we integrate the lift and average it with time to get a convergent value.

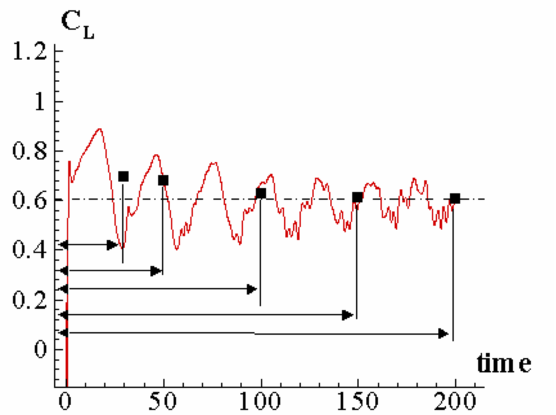


Fig.1 Average lift history

Since DES combines a property of LES, the grid density has an important effect. We increase the grid density along the span because the grid size directly affects separation between RANS region and LES region (we define the length scale as the smallest distance from the wall and the grid size, as stated above). $\triangle z=0.02$ was selected in this study.

Much more details about the numerical method can be found in reference [5]. The effect of some factors on numerical results can be concluded as Table 1.

Table 1. The effect of some factors on numerical results

Factors	Effect on numerical results
Inner iterate	Almost no when > 20
Grid density	Improve when increase in span
Time step	Almost no when < 3.5% * T character
Transition	Important
High order scheme	To be confident

3 Results and discussion

3.1 Airfoil stall

The calculations are performed for a Reynolds number of 5.8E10^6 and a Mach number of 0.3. The grid has 201 points in the stream-wise direction, 81 points normal to the wing, and 50 in the span-wise direction, respectively.

For the case of NACA63$_1$-012 airfoil, as attack angle increases, the flow is suddenly separated from the leading edge, which covers all over the upper surface of airfoil, leading to lift loss after stall. By using RANS with B-L turbulence model, we can only catch the stall angle, but the lift after stall can't be simulated. However, in the DES method, not only stall angle can be determined accurately, but also, large separated flow after stall can be simulated in detached region.

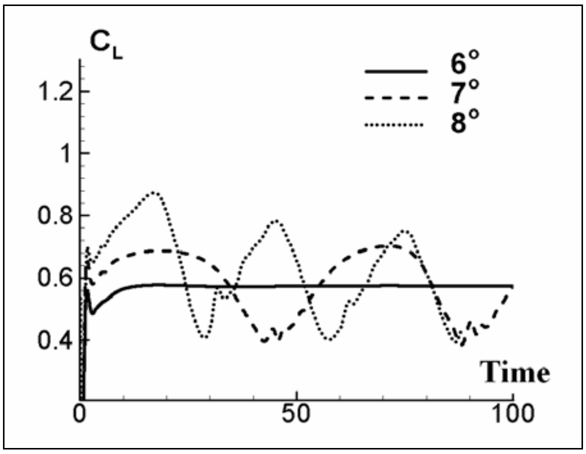
For the case of NACA63$_3$-018 airfoil, the lift loss is caused by flow separation near the trailing edge, which extends rather slowly toward the upstream as attack angle increases. No obvious differences are observed between the RANS and DES methods. This means that, for slightly separated flows, use of the RANS approach can provide reliable results.

For the case of NACA64A-006 airfoil, as the attack angle increases, a separated bubble first appears on the upper surface near the leading edge. The lift increases almost linearly for small attack angles. The first non-linearity in the lift curve appears at $\alpha = 5.27^o$, which is due to a bubble produced near the leading edge. Between 6^o to 11^o, there exit the case when the flow field appears clearly periodical phenomenon. At 6^o degree, flow field is steady and 2-D, at 7^o degree, flow field become unsteady and period phenomena exist, this phenomena become disappear from 8^o, and flow field show no disciplinarian after this attack angle. The calculations met some difficulties in the case of a thin airfoil stall type, when the bubble become unstable and shows periodical variations and extend to full turbulence flow. Much more details about the numerical analyse can be found in reference [5]. We focus to the case of thin airfoil stall in present work to found the way to improve the numerical result.

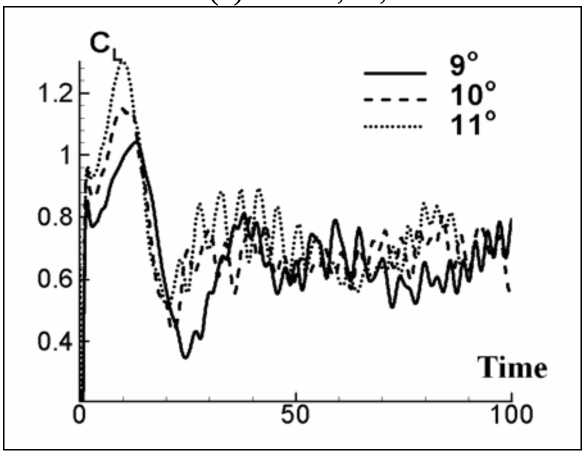
3.2 Thin airfoil stall Simulation

The NACA64A-006 with thin airfoil stall is selected for this study.

For this type of airfoil, as attack angle increases, first a separated bubble appears on the upper surface near the leading edge. This occurs at $\alpha \approx 5.27^o$ and leads to a non-linearity in the lift curve. The lift time history is shown in Figs. 2(a) and 2(b) for the attack angles $\alpha = 6^o$, 7^o, 8^o, and 9^o, 10^o, 11^o, respectively.



(a) $\alpha = 6^o, 7^o, 8^o$



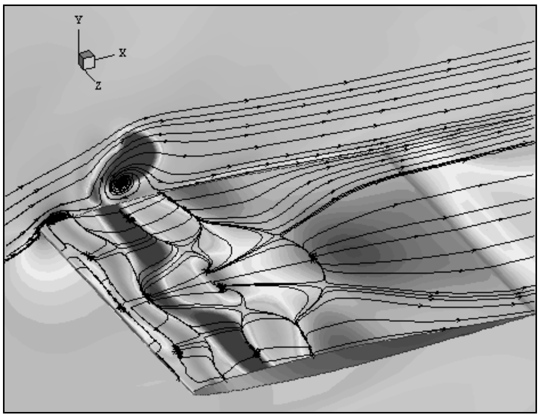
(b) $\alpha = 9^o, 10^o, 11^o$

Fig.2 Lift history for attack angles from α =7^o to α =11^o (NACA64A-006 airfoil).

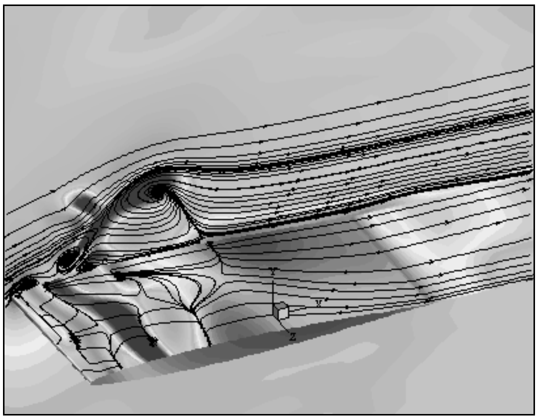
3.3 Modified DES approach

The effect of the turbulence model of the wall-adjacent flow was taken into account in present work. We examine a different turbulence model in the RANS region, to be exact – the Baldwin-Lomax model, which is known to give very good results for attached wall confined flows. Thus the turbulence model to be used in this section is a modified DES approach, where the Spalart-Allmaras equation with the modified wall distance parameter $\tilde{d}$ is used for the LES region, while the Baldwin-Lomax model is utilized in the RANS region.

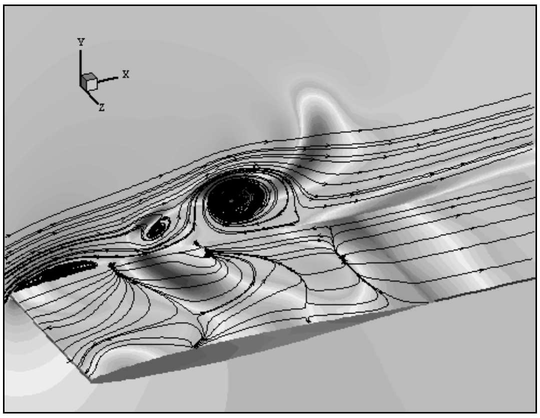
The calculations are performed with the grid of Δz =0.02. Figure 3 displays the flow field for 4 different instants at $\alpha = 8^o$ as a typical state near the stall. The bubble near the leading edge is not stable in this case; it breaks into smaller bubbles, and then the flow almost reattaches the upper surface. After this the flow separation begins again with the formation of a new leading edge bubble. This process is periodically repeated.



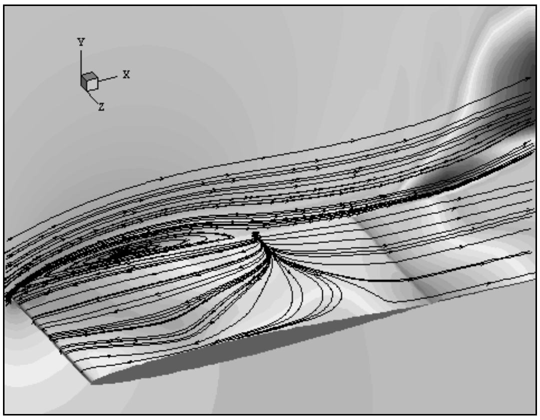
(a) $t = t_1$



(b) $t = t_2$



(c) $t = t_3$



(d) $t = t_4$

Fig.3 Pressure contours and streamlines at different instants for α =8^o (NACA64A-006).

The lift time histories for the attack angle α =8^o are presented in Fig. 4, which correspond the DES model based on entirely the Spalart-Allmaras model and on the Spalart-Allmaras model implemented with the Baldwin-Lomax model for the RANS region, respectively.

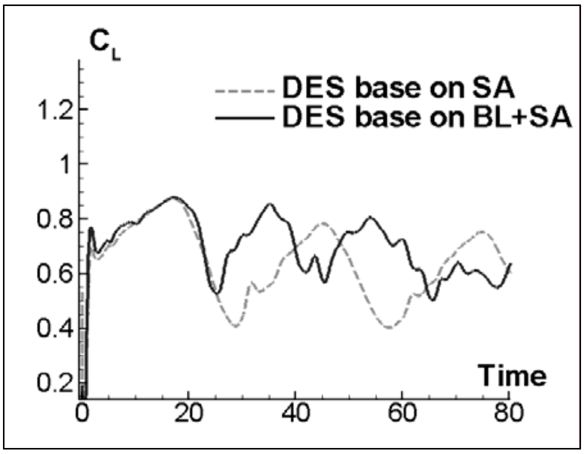


Fig.4 Effect of the model used in RANS region.

As can be seen from Fig. 4, the lift time histories given by SA and SA+BL model deviate each from other after some initial time. The minimal lift achieved in the BL+SA simulation appears to be larger than that in the SA simulation. In Table 2 we list the values of the time-averaged lift, drag and momentum coefficients in the SA and SA+BL simulations. One can see that using of the BL model instead of SA model in the RANS region leads to higher averaged values, which much better agree with the experimental data.

Table 2. Effect of the RANS model on averaged coefficients

α =8^o	CL	CD	CM
EXP	0.76	0.098	-0.03
DES(SA)	0.604	0.085	-0.047
DES(BL+SA)	0.705	0.100	-0.066

In Fig. 5 we show the improvement that can be achieved in the DES lift prediction by means of foregoing modification.

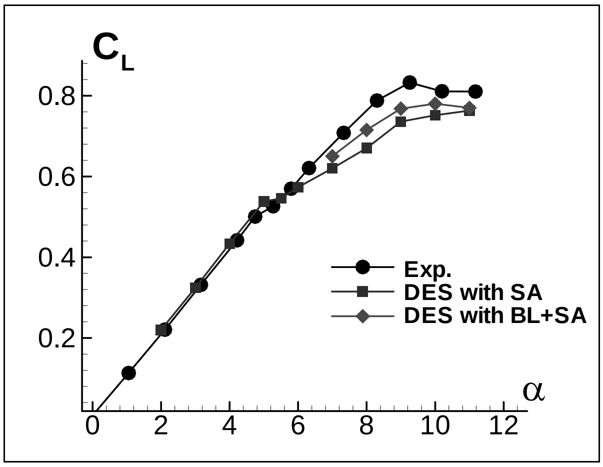


Fig.5 Lift vs. attack angle for NACA64A-006 airfoil.

4 Conclusions

For the airfoil NACA64A-006, the bubble is destabilized as the angle of attack is increased, and the flow becomes unsteady and highly turbulent. Refine the grid in the spanwise direction and so on affects the numerical results in this case and shows the trend from quasi-periodical to a turbulent behavior, however, a discrepancy between numerical and experimental data was still observed near the stall regime. It has been shown that the use of the Baldwin-Lomax model in the RANS region improves the DES results further. With taking these factors into account, the DES approach could reliably predict stall aerodynamical characteristics.

References

[1] Spalart, P.R., Jou, W.-H., Strelets, M., and Allmaras, S.R. “Comments on the feasibility of LES for wings,

and on a hybrid RANS/LES approach," 1st AFOESR Int. Conf. On DNS/LES, (1997), Ruston, LA. In Advances in DES/LES, C.Liu & Z.Liu Eds., Greyden Press, Columbus, OH.

[2] Morton, S., Forsythe, J.R., Mitchell, A., and Hajek, D., "DES and RANS Simulations of Delta Wing Vortical Flows," AIAA Paper 2002-0587, 2002

[3] Forsythe, J.R., Hoffmann, K.A., Squires, K.D., "Detached-Eddy Simulation with Compressibility Corrections Applied to a Supersonic Axisymmetric Base Flow," AIAA Paper 02-0586, 2002

[4] Squires, K.D., Forsythe, J.R., Morton, S.A., Strang, W.Z., Wurzler, K.E., Tomaro, R.F., Grismer, M.J., and Spalart, P.R., "Progress on Detached–Eddy Simulation of Massively Separated Flows," AIAA Paper 2002-1021, 2002.

[5] Li Dong, Igor Men'shov, and Yoshiaki Nakamura, "Numerical prediction for airfoil Stall," ICAS2004, Yokohama, Japan, Sep. 2004

[6] George, B. and Donald, E., "Examples of Three Representative Types of Airfoil Section Stall at Low Speed," NACA technical report, TN-2502, 1951.

[7] Arnone, A., Liou, M.S., and Povinelli, L.A., "Integration of Navier-Stokes Equations Using Dual Time Stepping and a Multigrid Method," AIAA Journal, Vol.33, No.6, June 1995.

[8] Men'shov, I. and Nakamura, Y., "On Implicit Godunov Method with Exactly Linearized Numerical Flux," Computer and Fluids, V.29, No.6, 2000, P695-616.

[9] Spalart, P.R., "Young-Person's Guide to Detached-Eddy Simulation Grids," NASA/CR – 2001 - 211032, July 2001.