Mechanical and Aerospace Engineering
B. Guan (Ed.)

doi:10.3233/ATDE250017

Improved Delayed Detached Eddy Simulation of the NACA0015 Airfoil Stalled Flows

Kaifang MA[a,b] and Jiasong WANG[a,b,c,1]
[a] *School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China*
[b] *MOE Key Laboratory of Hydrodynamics, Shanghai Jiao Tong University, Shanghai, 200240, China*
[c] *SJTU-Sanya Yazhou Bay Institute of Deepsea Science and Technology, Sanya, 572024, China*
ORCiD ID: Kaifang Ma
https://orcid.org/ 0009-0000-5073-6786
Jiasong Wang
https://orcid.org/0000-0001-7854-7821

Abstract. Three-dimensional numerical simulations of the flow around the NACA 0015 airfoil were conducted by using the unsteady Reynolds-averaged Navier-Stokes (URANS) and improved delayed detached eddy simulation (IDDES) based on k-ω shear stress transport (SST) turbulence model. The angle of attack range (AoA) is from 0° to 75°. The solver in this paper is developed on an in-house platform HRAPIF based on the finite volume method (FVM) with the elemental velocity vector transformation (EVVT) approach. It uses a density-based method with a low Mach preconditioning technique to accelerate convergence. The inviscid spatial discretization is the 5th-order modified weighted essentially non-oscillatory (WENO-Z) scheme. The results show that the IDDES model can effectively predict lift and drag coefficients at all the studied AoAs and has significant advantages over URANS, both in predicting aerodynamic forces and in simulating flow vortex structures at post-stall AoAs.

Keywords. IDDES, airfoil stalled flows

1. Introduction

Airfoil stall is a typical manifestation of flow instability associated with large separation. When the stall occurs, large turbulent vortex structures develop from the stall point toward the trailing edge, causing the aircraft to lose lift and potentially leading to serious accidents[1]. Near the stall and post-stall angles of attack (AoAs), very complex phenomena such as separation and unsteady large vortex shedding occur. These characteristics directly affect the lift and drag properties of the airfoil. Therefore, accurately predicting the airfoil stall phenomenon is of great significance.

[1] Corresponding Author: Jiasong WANG, jswang@sjtu.edu.cn

In the past few decades, with the significant improvement in computer hardware capabilities and the development of numerical algorithms, computational fluid dynamics (CFD) methods have been widely used for the numerical simulation of airfoils. Commonly used CFD methods include direct numerical simulation (DNS), large eddy simulation (LES), and Reynolds-averaged Navier-Stokes simulation (RANS). Among those methods, RANS has a relatively low computational cost. However, it has insufficient predictive capability for large flow separations, leading to inaccurate lift and drag coefficient predictions at post-stall conditions. DNS and LES have high accuracy and can effectively simulate airfoil stall phenomena. However, they require a large amount of computational resources, especially DNS. To balance computational efficiency and accuracy, Spalart et al[2] proposed the detached eddy simulation (DES) method, a hybrid of RANS and LES methods. DES has been used to simulate airfoil stall flows. For example, Morton et al[3] conducted numerical simulations of the stall phenomenon of an aircraft wing based on DES at flight Reynolds numbers. The research shows that DES can be used to simulate large flow separations under post-stall conditions. However, Menter et al[4] indicated that the original DES model will produce an artificial separation for airfoil simulation under certain conditions, which was referred to as Grid Induced Separation (GIS) effect. To overcome this defect, Spalart et al developed the delayed DES (DDES) model. Xu et al[5] used DDES and RANS/unsteady RANS (URANS) models to perform numerical simulations of the wind turbine airfoil S809 within the AoA range from 0° to 90°, which demonstrated that the DDES model performs better than the RANS/URANS models for airfoil stall simulation. However, there is a Logarithmic Layer Mismatch (LLM) issue for the DDES model under certain conditions. Therefore, Shur et al[6] proposed the Improved DDES (IDDES) model to overcome this problem. Yang et al[7] performed numerical simulations for stalled flows of NACA0012 at different AoAs based on IDDES and URANS models. It demonstrated that the IDDES model predicts the lift and drag of airfoil more accurately than the URANS model at higher AoAs.

Although the DES model has been applied to the prediction of airfoil stall characteristics, there is still room for exploration and research in terms of spatial discretization scheme and turbulence model applicability. In this paper, the 5th-order modified weighted essentially non-oscillatory (WENO-Z) scheme[8] and the IDDES model based on the k-ω shear stress transport (SST) model[9] are employed to perform numerical simulations of the NACA0015 airfoil within the AoA range from 0° to 75°. The reasons for choosing this turbulence model and spatial discretization scheme are as follows: The SST model includes a more precise near-wall formulation, making it better suited for complex flows with significant separation; The WENO-Z scheme provides less dissipation, higher resolution, and lower computation costs than other WENO schemes.

The objective of this paper is two-fold: (1) Apply the IDDES model coupled with the k-ω shear stress transport (SST) model and the WENO-Z scheme for numerical simulations of NACA0015 airfoil stalled flows; (2) Demonstrate the IDDES advantages over URANS model for airfoil stalled flows with massive flow separation.

2. Numerical Methodology

In the present study, the governing equations are 3D compressible Navier-Stokes equations. The solver is developed on the in-house platform HRAPIF based on the finite volume method (FVM) with the elemental velocity vector transformation (EVVT) approach[10]. The objective of the EVVT method is to compute the numerical flux by utilizing the local normal and tangential velocities on the interfaces of the cell. Therefore, the EVVT method does not require coordinate transformation, resulting in relatively smaller computational effort. Besides that this solver adopts the density-based method with a low Mach preconditioning technique to accelerate convergence[11]. The inviscid flux is calculated using the Roe scheme[12]. The viscous flux is calculated using second-order-accurate central differencing. The time marching scheme is the dual time-stepping method. The grid strategy for this solver is the multi-block structured grid. Fig. 1 is the overall framework of HRAPIF.

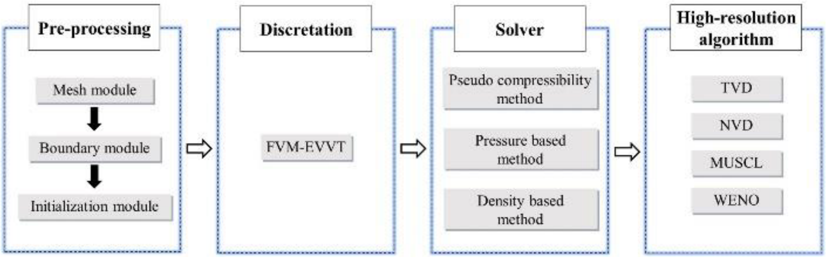


Figure 1. Framework of HRAPIF.

3. Computation Configuration

The NACA0015 airfoil experimental data, used in this paper, were tested in the Walter H. Beech Memorial Wind Tunnel at Wichita State University[13]. The airfoil chord length c is 0.1524 m, and the span is 1c for the simulations. The airfoil flow conditions: free stream Mach number is 0.1; the Reynolds number based on chord length is 3.6×105. The computation domain gird is O type, as shown in Fig. 2. The grid size is 288 (circumferential) × 122(wall normal) × 31(span), and the first grid layer height is 1.5×10-5m, corresponding to dimensionless wall distance y+ ≤ 1. The non-dimensional physical time step size is dt=0.01, where dt=ΔtU∞/c, U∞ is free stream velocity. The airfoil surface is set as the no-slip boundary. The periodic boundary condition is imposed on the span direction. The velocity inlet and pressure outlet are assigned to the inlet and outlet physical boundary, respectively.

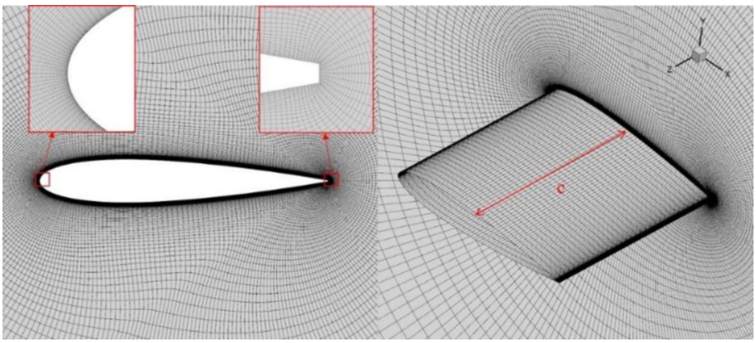
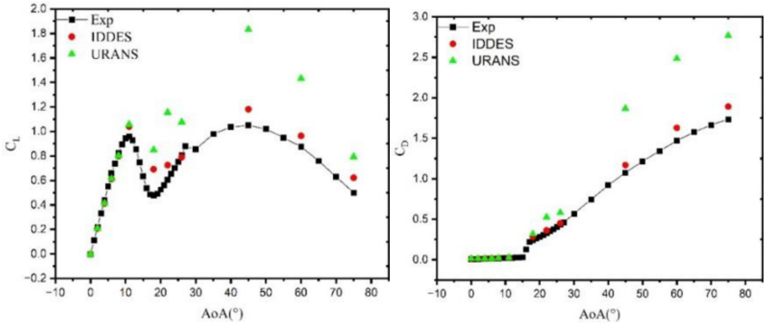


Figure 2. Schematic diagram of structured grids.

4. Results and Discussions

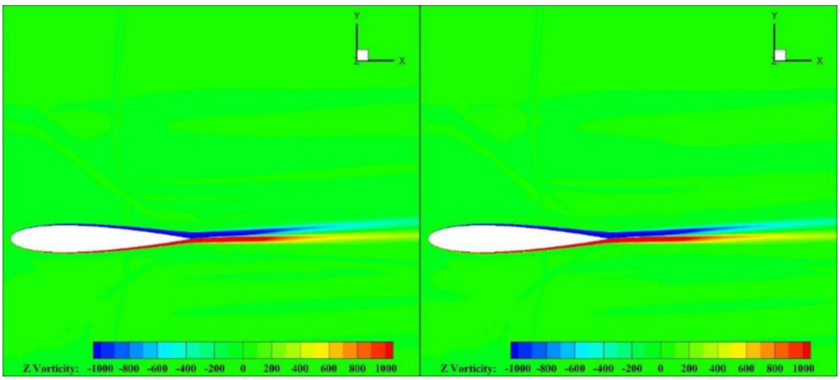
4.1. Lift and Drag Coefficients

To verify the predictive capability of the IDDES model for the aerodynamic forces on the NACA 0015 airfoil and its advantages over the URANS method, numerical calculations of the lift and drag coefficients were conducted using both the IDDES and URANS models within the AoA range from 0° to 75°. Fig. 3 shows the results of the time-averaged lift and drag coefficients versus AoA for the experiment, IDDES, and URANS models. As can be seen from this figure, when the AoA is below the stall angle (11°) of the airfoil, both the URANS and IDDES models yield lift and drag coefficients that are in good agreement with the experimental values[13] measured in the wind tunnel. However, the IDDES model performs better than URANS at post-stall AoAs. This is because, as shown in Fig. 4, when the AoA is relatively low, flows are attached to the surface of the airfoil, and the URANS model can simulate it well. Nevertheless, when the AoA is relatively high, flows begin to exhibit large-scale flow separation due to the strong adverse pressure gradient, and the URANS is unable to resolve such massively separated flows. By comparing the lift and drag coefficients, the capability of the IDDES model in predicting the aerodynamic forces on the airfoil was validated, along with its advantages over the URANS model at post-stall AoAs.

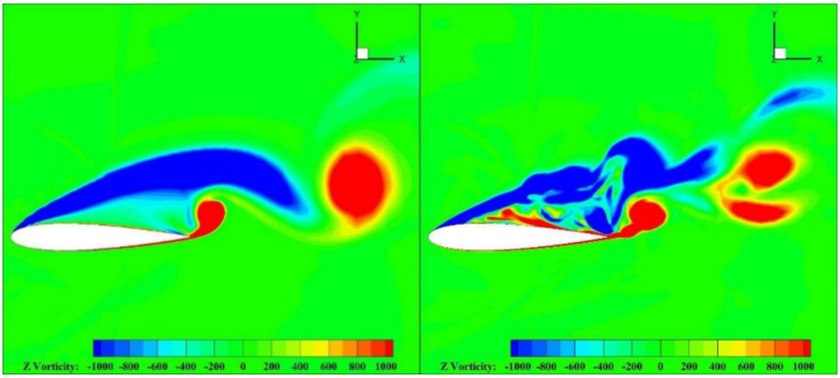


(a) Lift coefficient (b) Drag coefficient

Figure 3. Comparison of lift and drag coefficients predicted by IDDES and URANS models.



(a) URANS at AoA=4° (b) IDDES at AoA=4°

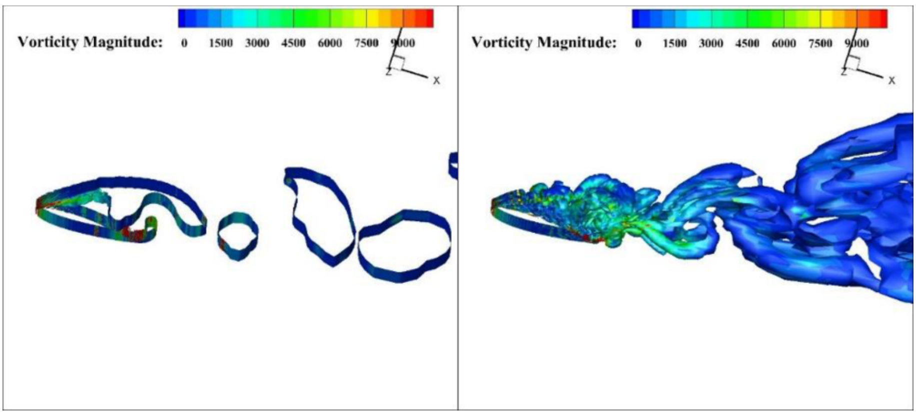


(c) URANS at AoA=18° (d) IDDES at AoA=18°

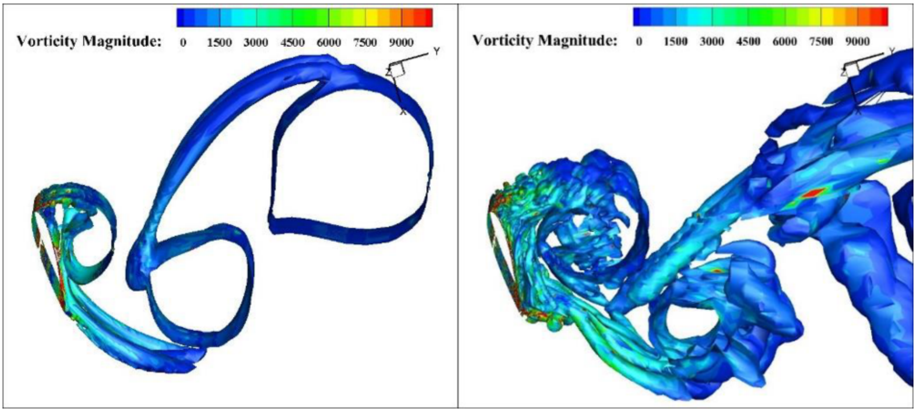
Figure 4. Comparison of transient vorticity contours at the mid-span plane.

4.2. Comparison and Analysis of 3D Vortex Structures

To analyze flow structures, the three-dimensional vortex structures were visualized based on the Q criterion[14]. Fig. 5 shows the comparison of three-dimensional vortex structures with Q=1 between IDDES and URANS models at AoAs of 18°and 75°. As can be seen from this figure, in both cases of these AoAs, there are large-scale separated flows. However, the URANS only can capture the two-dimensional large-scale vortex structures, which are organized harmonic vortex shedding. In contrast, the IDDES can capture more small-scale vortex structures and the vortex structures produced by IDDES are three-dimensional and chaotic, regardless of the streamwise, spanwise, or crossflow directions. This is mainly because, URANS is a time-averaged method that averages the flow over time, thereby missing the turbulent fluctuations and fine-scale details that characterize these structures. It cannot capture the dynamics and interactions of small-scale vortices. Therefore, compared to URANS, IDDES provides a more accurate simulation of large-scale separated flows, which is why the lift and drag coefficients calculated by IDDES are more consistent with experimental values.



(a) URANS at AoA=18° (b) IDDES at AoA=18°



(c) URANS at AoA=75° (d) IDDES at AoA=75°

Figure 5. Transient vortex structures Iso-surfaces of Q=1 (colored by vorticity magnitude).

5. Conclusions

In this paper, a 3D numerical simulation solver adopted the density-based method with a low Mach preconditioning technique is developed by the authors based on the in-house platform HRAPIF. The flow over the NACA0015 airfoil within the AoA range from 0° to 75° was investigated by using the URANS and IDDES models based on the k-ω shear stress transport turbulence model. The inviscid spatial discretization scheme is the5th-order WENO-Z scheme. The main conclusions are as follows: (1) When the AoA is below the stall angle (11°) of the airfoil, both the URANS and IDDES models can accurately predict the lift and drag coefficients of the NACA0015 airfoil. However, the IDDES model performs better than the URANS model at post-stall conditions. (2) For large-scale separated flows, the vortex structures computed by IDDES exhibit stronger three-dimensional effects, and IDDES captures more details of the flow field, resulting in more realistic simulations of the flow.

References

[1] H.-S. Im, G.-C. Zha, Delayed Detached Eddy Simulation of Airfoil Stall Flows Using High-Order Schemes, Journal of Fluids Engineering 136 (2014) 1-12. https://doi.org/10.1115/1.4027813.
[2] P.R. Spalart, Comments on the feasibility of LES for wings, and on a hybrid RANS/LES approach, in: 1997. https://api.semanticscholar.org/CorpusID:116820008.
[3] S.A. Morton, J.R. Forsythe, K.D. Squires, R.M. Cummings, Detached-Eddy Simulations of Full Aircraft Experiencing Massively Separated Flows (2003).
[4] F.R. Menter, M. Kuntz, R. Langtry, Ten Years of Industrial Experience with the SST Turbulence Model, Heat and Mass Transfer 4 (2003) 625–632.
[5] H.-Y. Xu, C.-L. Qiao, H.-Q. Yang, Z.-Y. Ye, Delayed detached eddy simulation of the wind turbine airfoil S809 for angles of attack up to 90 degrees, Energy 118 (2017) 1090–1109. https://doi.org/10.1016/j.energy.2016.10.131.
[6] M.L. Shur, P.R. Spalart, M.Kh. Strelets, A.K. Travin, A hybrid RANS-LES approach with delayed-DES and wall-modelled LES capabilities, International Journal of Heat and Fluid Flow 29 (2008) 1638–1649. https://doi.org/10.1016/j.ijheatfluidflow.2008.07.001.

[7] Y. Yang, G. Zha, Simulation of Airfoil Stall Flows Using IDDES with High Order Schemes, in: 46th AIAA Fluid Dynamics Conference, American Institute of Aeronautics and Astronautics, Washington, D.C., 2016. https://doi.org/10.2514/6.2016-3185.
[8] R. Borges, M. Carmona, B. Costa, W.S. Don, An improved weighted essentially non-oscillatory scheme for hyperbolic conservation laws, Journal of Computational Physics 227 (2008) 3191–3211. https://doi.org/10.1016/j.jcp.2007.11.038.
[9] M.S. Gritskevich, A.V. Garbaruk, J. Schütze, F.R. Menter, Development of DDES and IDDES Formulations for the k-ω Shear Stress Transport Model, Flow Turbulence Combust 88 (2012) 431–449. https://doi.org/10.1007/s10494-011-9378-4.
[10] J. Wang, Flow Around a Circular Cylinder Using a Finite-Volume TVD Scheme Based on a Vector Transformation Approach, J Hydrodyn 22 (2010) 221–228. https://doi.org/10.1016/S1001-6058(09)60048-2.
[11] J.M. Weiss, W.A. Smith, Preconditioning applied to variable and constant density flows, AIAA Journal 33 (1995) 2050–2057. https://doi.org/10.2514/3.12946.
[12] P.L. Roe, Approximate Riemann Solvers, Parameter Vectors, and Difference Schemes.
[13] R.E. Sheldahl, P.C. Klimas, Aerodynamic characteristics of seven symmetrical airfoil sections through 180-degree angle of attack for use in aerodynamic analysis of vertical axis wind turbines, 1981. https://doi.org/10.2172/6548367.
[14] J. Jeong, F. Hussain, On the identification of a vortex, J. Fluid. Mech. 285 (1995) 69–94. https://doi.org/10.1017/S0022112095000462.