IMPROVED DELAYED DETACHED EDDY SIMULATION OF THE FLOWS AROUND S809 AIRFOIL FOR ANGLES OF ATTACK FROM 0 TO 90 DEGREES

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Abstract

High Reynolds number flows around airfoils involve complex phenomena at different angles of attack (AOA). In this study, improved delayed detached eddy simulations (IDDES) are carried to investigate the flows around S809 airfoil at a wide range of AOA from 0 to 90 degrees. In addition, unsteady Reynolds-averaged Navier-Stokes simulations (URANS) are adopted for a comparison purpose. Both IDDES and URANS simulations agree well with the experimental results in the attached flow regime of low AOA. However, in the mild separation and massive separation regime, IDDES simulations show better prediction than the URANS simulations. Detailed flow structures are analyzed with comparisons between IDDES and URANS simulations.

1 Introduction

Accurate modeling and simulation of high Reynolds number flow around airfoils at large angles of attack (AOA) is a challenging CFD problem of significant importance for the aerospace industry and wind energy. Although Reynolds-averaged Navier-Stokes (RANS) models have been applied successfully in many practical computations with attached flows as well as some with shallow separations, they tend to fail for high angle of attack flows with massive separation. Direct numerical simulation (DNS) resolves all scales of turbulent flows and can yield accurate predictions theoretically. However, it is computationally impractical for DNS to handle industry turbulent flows. Large eddy simulation (LES), which directly calculates the large turbulent scales with only small turbulent scales modeled, attempts to reduce the grid requirements of DNS. However, due to the high computing power requirements in boundary layers of high Reynolds number flows, LES is still too expensive for practical applications. In order to resolve turbulent flows in practical applications at an affordable computational expense, hybrid RANS/LES methods have been developed in recent years.

The first generation DES model, DES97, was proposed by Spalart et al[1]. It is defined as "a three-dimensional unsteady numerical solution using a single turbulence model, which functions as a subgrid-scale (SGS) model in regions where the grid density is fine enough for a large-eddy simulation, and as a Reynolds-averaged model in regions where it is not"[2]. A working definition is to treat the attached boundary layer with RANS and apply a LES treatment in the separated regions [3][4]. The space between these areas, known as the "gray area", may be problematic unless the separation is abrupt [5]. When the grid spacing in the attached boundary layers is decreased, it is fine enough for the DES length scale to follow the LES treatment but not fine enough to resolve internal velocity fluctuations in the boundary layer. The modeled Reynolds stress is reduced without any sizeable resolved stress to store the balance, which is referred to as modeled-stress depletion [6] (MSD). In order to solve this deficiency, delayed detached eddy simulation [7] (DDES) and Improved delayed detached eddy simulation [8] (IDDES) were developed based on some modifications in DES. DDES detects boundary layers and prolongs the full RANS mode, even if the wall-parallel grid spacing would normally activate the DES limiter. This detection device depends on the eddy viscosity, so that the limiter now depends on the solution. IDDES uses a new definition of filter length, which includes the wall distance and not only the local characteristics of the grid. The modification tends to give it a steep variation, which stimulates instabilities, boosting the resolved Reynolds stress. The philosophy of IDDES is combining DDES and wall modeled LES (WMLES), ensuring a different response depending on whether the grid resolution is sufficient to resolve dominant eddies in the boundary layer and whether the simulation contains inflow turbulence content. IDDES performs as WMLES if the grid resolution is sufficient and the simulation contains inflow turbulence, otherwise it reduces to DDES. IDDES has become popular in computational fluid dynamics (CFD) communities since it was proposed. Shur et al [9] validated IDDES method on shear flows in three cases: developed channel flow, zeropressure gradient boundary layer, and plane mixing layer. Krappel et al [10] applied an IDDES-type model to a Francis pump turbine flow simulation and validated it with experimental results. Zhao et al [11] performed IDDES simulation of flow characteristics behind the aerodynamic performance on an airfoil with leading edge protuberances.

For high Reynolds number flow around airfoils at large angles of attack, DES/DDES methods have been used by other researchers in the aerospace research field. For example, Im and Zha [13] presented DDES simulations of a single NACA0012 airfoil beyond stall, and the results shown that the prediction of the stalled flow using DDES with both the high-order scheme and second-order scheme is overall significantly more accurate than the URANS simulation. Morton et al. [14] conducted DES97 simulations for the massively separated flows around a full F/A-18E aircraft, demonstrating the ability of DES to accurately predict transonic nonlinear aerodynamic phenomena of abrupt wing stall. Xu et al. [15] performed DDES on the flow over S809 airfoil at a wide range of AOA from 0 to 90 degrees. Their results showed a good agreemnent with the experimental data at most AOAs, except some AOA before the stall. Further study needs to be done with an advanced model.

OpenFOAM is a C++ toolbox for the development of customized numerical solvers, and pre/post-processing utilities for the solution of continuum mechanics problems, including computational fluid dynamics (CFD) [16]. It is very popular in industrial engineering as well as in academic research. The factorized finite-volume method (FVM) is used to solve the Navier-Stokes equations in CFD solvers with a long list of numerical schemes and mathematical models. Nevertheless, in spite of many attractive features, OpenFOAM has some disadvantages. For example, (1) the absolute lack of default settings; (2) the huge amount of different numerical schemes and models (which is an advantage for the expert users); (3)the absence of a quality certification following from a lack of high-quality documentation and references. Thus, the problem of validation and verification of OpenFOAM capabilities becomes more principal and fundamental compared to other commercial CFD codes.

In this paper, IDDES simulations will be carried on the flow around S809 airfoil with angles of attack from 0 to 90 degrees. URANS simulations are adopted for comparison purpose. All the numerical results will be compared with the existed experimental results. The main objective of current work is to assese the capability of IDDES approach in prediction of unsteady flows with separations and vortex shedding.

2 Numerical Methodology

2.1 RhoPimpleFoam solver in OpenFOAM

All the simulations are carried out using the rhoPimpleFoam solver within open source code OpenFOAM 4.x. OpenFOAM employs the finite volume method for numerical representation of the equations governing fluid motion and the message passing interface (MPI) method for parallel computing.

The governing equations are generally solved using standard pressure-velocity coupling methodology- (1) momentum predictor, (2) pressure solver, (3) momentum corrector. Three different pressure-velocity coupling methods are provided for solving these equations: PISO (pressure implicit with split operator) [17]; SIMPLE (semi-implicit method for pressure linked equations) [18]; and PIMPLE, which is a hybrid of PISO and SIMPLE. The PIMPLE algorithm uses an outer correction loops cycling over a given time step for a number of iterations, and equation under-relaxation between outer correctors for stability in a certain large CFL number. The rhoPimpleFoam solver also includes dynamic time-stepping (automatic time step adjustment at a fixed CFL number) which is very useful at the beginning of unsteady simulations.

2.2 Development of DES-type models

OpenFOAM supplies turbulence models rang from RANS to hybrid RANS/LES (HRL) to LES and DNS which includes DES, DDES and IDDES models.

The DES method was pioneered in 1997 by Spalart et al. based on the Spalart-Allmaras (SA) RANS model [1]. It is referred to as DES97 model in the CFD community. The motivation and aim of DES models is to decrease the computational cost of massively separated turbulent flows compared to LES. The reduction in the cost is achieved by modeling the boundary layers using RANS model. The switching between RANS and LES models is accomplished by modification of the length scale L_{RANS} of the turbulence model. This model length scale is substituted by the DES length scale $L_{DES,}$ which is defined similar to an implicit filter in LES:

$$L_{DES} = \min(L_{RANS}, C_{DES}\Delta) \qquad (1)$$

$$\Delta = \max(\Delta_x,\ \Delta_y,\ \Delta_z) \qquad (2)$$

Further investigations on the DES97 mode showed the MSD problem which can lead to grid induced depletion (GIS) and the activation of the near wall damping terms of the underlying turbulence model in the LES regions. In order to solve the MSD problem, DDES based on SA-DES is developed by Spalart [7]. A new subgrid scale formulation is re-defined as

$$L_{DDES} = L_{RANS} - f_d \max(0, L_{RANS} - C_{DES}\Delta) \qquad (3)$$

$$f_d = 1 - \tanh([8r_d]^3) \qquad (4)$$

$$r_d = \frac{\nu_t + \nu}{\sqrt{U_{ij}U_{ij}}\kappa^2 d^2} \qquad (5)$$

$$U_{ij} = \frac{\partial u_i}{\partial x_j} \qquad (6)$$

where U_{ij} represents the velocity gradient, and κ denotes the von Karman constant.

In 2006, Travin et al. [12] found two stacked logarithmic layers in DES simulations of the channel flow with massively refined grids near the walls. This would cause a significant and unphysical reduction of the friction coefficient. The effect is called Log Layer Mismatch (LLM). In order to solve this problem, Travin et al. [12] presented a method based on the DDES approach and combined with the wall modeled LES. This new method is known as IDDES. In their study, IDDES showed his possibility to simulate resolved turbulent boundary layer structures in the channel flow simulations. The IDDES approach uses a more complex formulation for evaluating the grid filter Δ and for the blending of the grid filter with the RANS turbulent length scale (L_{RANS}). The grid filter depends additionally on the wall normal distance d_w and the height of the cell in wall normal direction h_{wn}:

$$\Delta = \min(\max[C_w d_w, C_w h_{\max}, h_{wn}], h_{\max}) \qquad (7)$$

$$h_{\max} = \max(\Delta_x, \Delta_y, \Delta_z) \qquad (8)$$

Here, C_w is a model constant. The blending is done by the hybrid function, f_{hyb}, that includes the functionality of the former developed DDES (f_d) with the shield function ψ and formulates the modified length scale L_{IDDES} as follows:

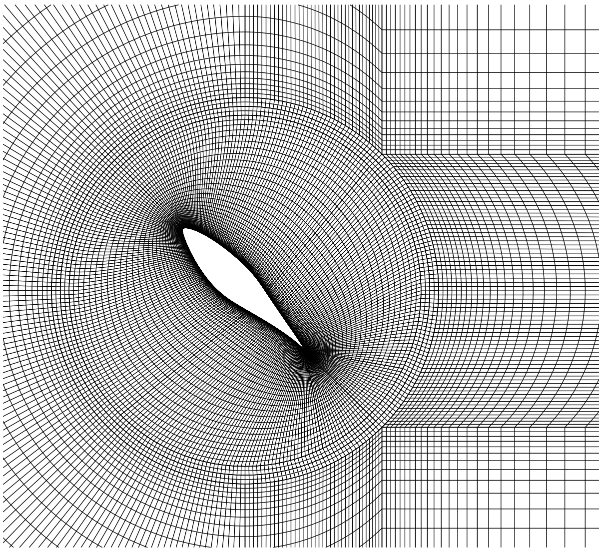
$$L_{IDDES} = f_{hyb}(1 + f_{restore})L_{RANS} + (1 - f_{hyb})L_{LES} \qquad (9)$$

$$f_{hyb} = \max\{(1 - f_d), f_{step}\} \qquad (10)$$

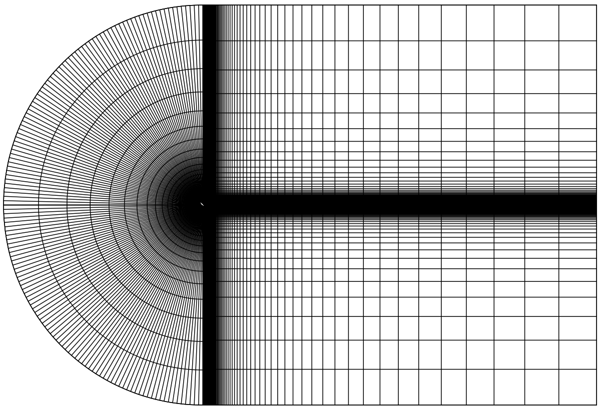
where $L_{LES} = C_{DES}\psi\Delta$. The functions f_d, $f_{restore}$, f_{step} and ψ are defined by analysis of the local boundary layer flow parameters. More details can be acquired form Shur et al.[8].

2.3 Time marching scheme and spatial discretization

In all the unsteady simulations, a standard three-level second order backward difference is used for the time marching scheme. For spatial discretization, the second order Total Variation Diminishing (TVD) scheme is used for the gradient term; the second order bounded central difference for the divergence scheme and the second order limited deferred correction scheme for the Laplacian scheme.



(a) “O-grid”



(b) “C-grid”

Fig. 1: Topology of the computational mesh.

3 Case Description and Grid Generation

3.1 Case description

Simulations of the flow around S809 airfoil, tested in the Colorado State University (CSU) [20], are carried out to compare the capabilities of URANS and IDDES for prediction of aerodynamic characteristics in different flow regimes including attached flow, mild separation flow and massive separation flow. The CSU experiment was done with a wide range of angles of attack from 0 to 90 degrees. The airfoil chord is 0.457m in the experiment. The Reynolds number based on the airfoil chord is 650, 000.

3.2 Grid generation

The mesh topology in the computational domain is shown in Fig. 1, which can be described as “CO-grid”. A small O-grid is generated with growing boundary layers around the S809 airfoil that can be seen in Fig. 1a. The diameter of this O-grid is three times of the chord (c) of S809 airfoil. The C-grid is on the outside of the O-grid and extended to 20D in the upstream direction and 40D in the downstream direction. Such a CO-grid can minimize the skewness of a near-wall mesh, avoid high aspect ratio of grids in the far wake and form a fine enough mesh to solve the unsteady wake flow. In the span-wise direction, CO-grid is extruded with one chord length for the 3D simulations.

In order to access the grid sensitivity, four different grids are generated at the 10° angle of attack. Their parameters are illustrated in Tab. 1 with wrap-around points on the S809 airfoil, extruded layers in the spanwise layers and total cells. Total cells between different mesh levels have a change about 2 times in sequence.

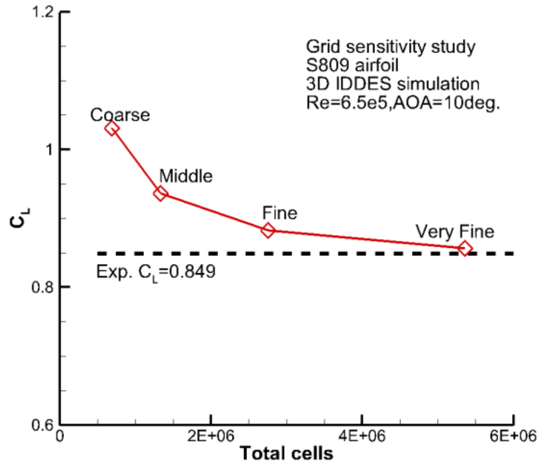
Tab. 1 Grid parameters used for grid sensitivity study

Mesh Level	Wrap-around points	Spanwise layers	Total cells
Coase	257	24	686544
Middle	361	24	1336272
Fine	513	24	2757072
Very Fine	721	24	5360592

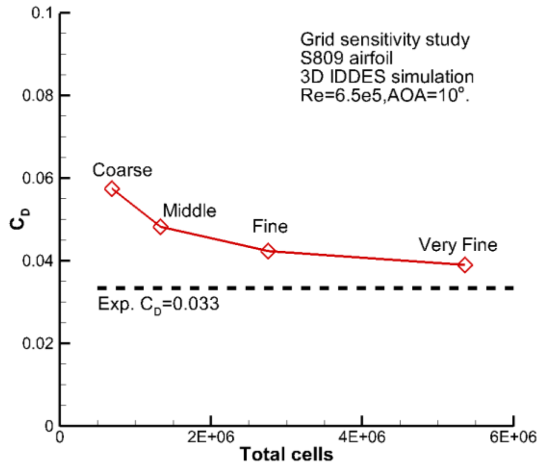
3.3 Parameters setup

The boundary condition for the S809 airfoil is no-slip adiabatic wall. The far-field boundary normal the wake flow is considered as outlet with a constant static pressure (p) at 72156.2 Pa. The other far-field boundaries are considered as velocity inlet (U_∞) with 26 m/s. The front and back boundaries are set as the symmetric boundary condition for the 3D simulations.

The time step (dt) is 0.0007 seconds in dimensional form. In order to have a convenient analysis , a non-dimensional time step is defined as $dt \times c/U_\infty$ which equals 0.04. All the unsteady simulations have been run with $40c/U_\infty$ in advance to eliminate the effect of initial conditions. Then the simulations are run by $1200c/U_\infty$ for data collection and average analysis.



(a) Lift coefficient



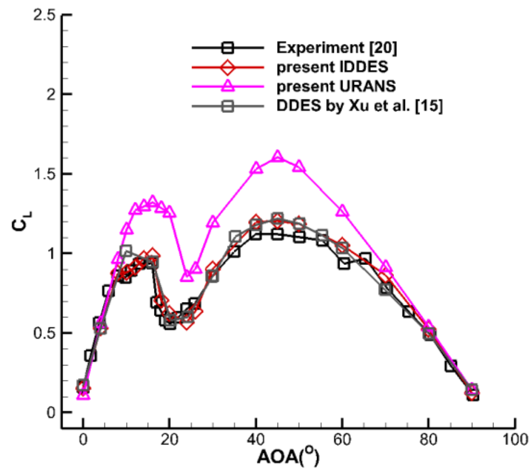
(b) Drag coefficient

Fig. 2 Grid sensitivity study in terms of lift and drag coefficients with four grids

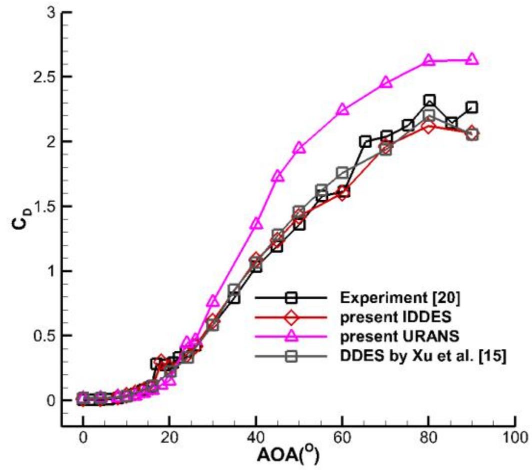
4 Results and Discussions

4.1 Grid sensitivity study

Grid sensitivity study has been done at the 10 ° angle of attack via IDDES simulations with four different grids (see Tab. 1). The results in terms of lift and drag coefficients are shown in Fig. 2(a) and (b). Both of them show a convergent tendency to the experimental data with the grid increments. It can be found that both the lift and drag coefficients decrease when the mesh is refined. Considering the requirement of huge computational resources, the fine mesh is selected for the IDDES and URANS simulations of unsteady flow around S809 airfoil from 0 to 90 degrees.



(a) Lift coefficient



(b) Drag coefficient

Fig. 3 Overall comparison of lift and dragcoefficients among different simulations

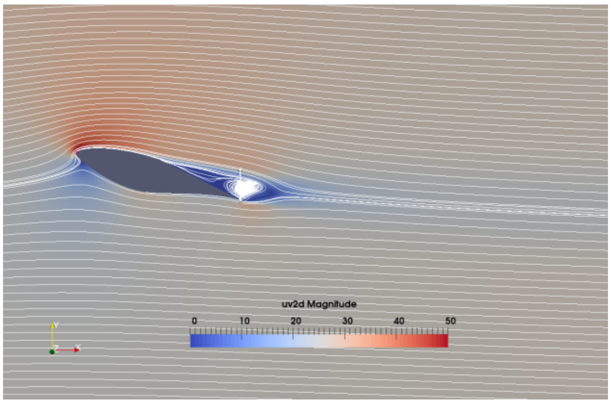
4.2 Overall comparison

The objective of this study is to verify the capability of IDDES in simulations of S809 airfoil aerodynamics with the OpenFOAM code. The AOAs ranges from 0 to 90 degrees which covers the aerodynamic characteristics of attached flow regime, mild separation flow regime and massive separation flow regime. In addition, URANS simulations are performed and compared with IDDES simulations to better understand the capability of IDDES method. Figure 3 shows the results of time-averaged lift and drag coefficients for the studied S809 airfoil obtained by present IDDES and URANS simulations, as well as DDES by Xu et al.[15] and wind tunnel experimental results obtained by Butterfield et al. [20].

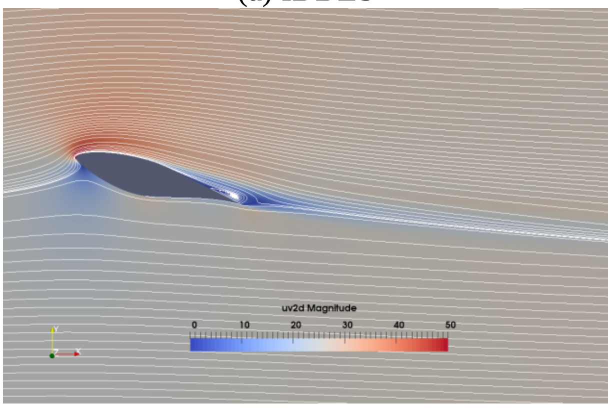
At the attached flow regime with low AOAs, it can be found that all the URANS, DDES and IDDES simulations agree well with the experimental results. At the mild separation flow regime with AOAs near the stall, present URANS simulations have a large deviation with the experimental results. Both the lift and drag coefficients obtained by URANS simulations are higher than the DDES, IDDES and experimental results. The same results can be found in 2D RANS (Zhang et al. [21] and Xu et al.[15]) and 3D URANS (Xu et al.[15]). These results from RANS and URANS simulations prove Cummings' conclusion [22] that RANS model can give accurate results for attached boundary layer flows but fail to predict the large-scale turbulence in separated flow. In contrast, both IDDES and DDES (Xu et al. [15]) simulations show better agreements with the experimental results. At the massive separation region, the deviation between URANS and experimental results becomes even larger with the increasing AOAs in terms of drag coefficients. The deviation in terms of lift coefficients increases from 24 degree to 45 degree and then decreases from 45 degrees to 90 degrees. Clearly, the deviation between URANS and experimental results is larger than DDES and IDDES. Both DDES and IDDES results show excellent agreements with the experimental results in the massive separated flow regime.

4.3 Detail comparison on the mild separation flow

The flow around S809 airfoil at 16 degree AOA is a typical mild separation flow. Figure 4 shows the comparison of mean flow velocity and streamline distribution on the middle cross section of S809 airfoil between IDDES and URANS simulations. Figure 5 shows the comparison of lift and drag coefficient histories between IDDES and URANS simulations. Figure 6 shows the comparison of Q criterion distribution between IDDES and URANS simulations.



(a) IDDES

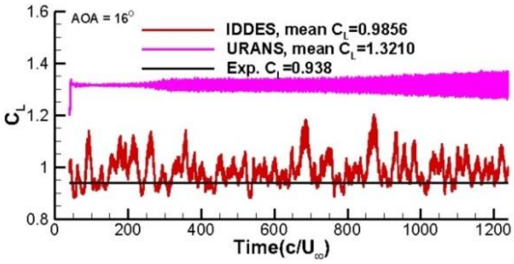


(b) URANS

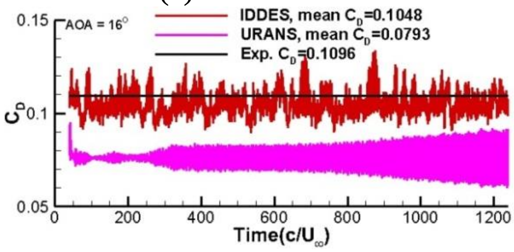
Fig. 4 Comparison of mean velocity and streamline distribution at 16 degree AOA

Both IDDES and URANS simulations show a mild separation on the trailing edge of S809 airfoil (see Fig. 4). Due to this mild separation, the lift and drag coefficients are historical unsteady (see Fig. 5). Even in the URANS simulation, the lift and drag coefficients are not fixed at constant values, but oscillating with symmetry amplitudes at certain averaged values. By the postprocessing, the mean lift coefficient is 1.3210 and the mean drag coefficient is

0.0793 in the URANS simulation of S809 airfoil at 16 degree AOA.

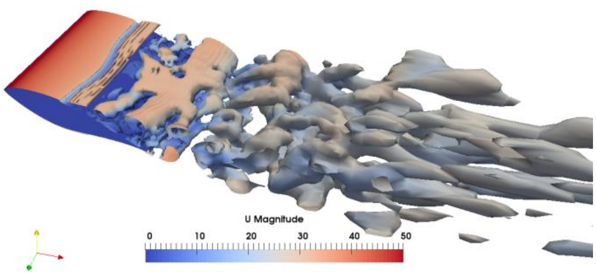


(a) Lift coefficient

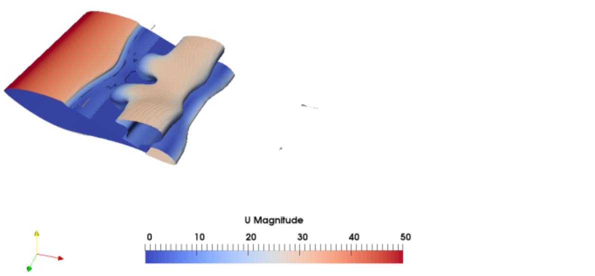


(b) Drag coefficient

Fig. 5 Lift and drag coefficient histories at 16 degree AOA



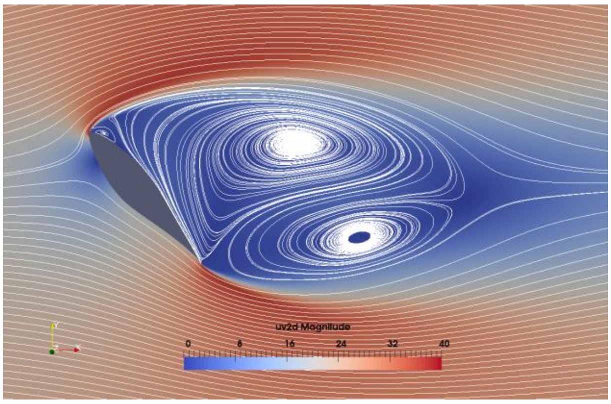
(a) IDDES simulation



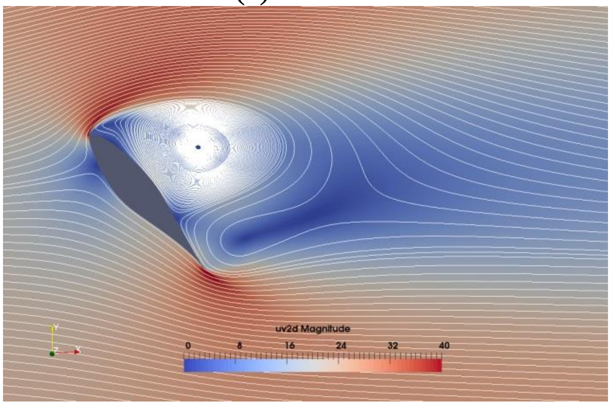
(b) URANS simulation

Fig. 6 Iso-surfaces of Q=1000 in IDDES and URANS simulations at 16 degree AOA (colored by velocity magnitude)

The IDDES simulation owns a larger separation region than the URANS simulation at 16 degree AOA (see Fig. 4). It could be explained with that more flow structures are generated in the IDDES simulation. This can also be concluded from the comparison of Q criterion distribution in Fig. 6. In the wake flow, IDDES simulation shows a larger region of vortexes than the URANS simulation at 16 degree AOA. The lift and drag coefficient histories are also effected by the chaotic motion of these turbulent vortexes in the IDDES simulation, see Fig. 5(a). The mean lift coefficient is 0.9856 and the drag lift coefficient is 0.1048 in IDDES simulation at 16 degree AOA. Both of them show better predictions with the experimental results than the URANS simulation.



(a) IDDES



(b) URANS

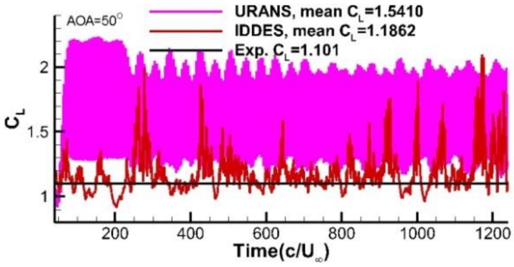
Fig. 7 Comparison of mean velocity and streamline distribution at 50 degree AOA

4.4 Detail comparison on the massive separation flow

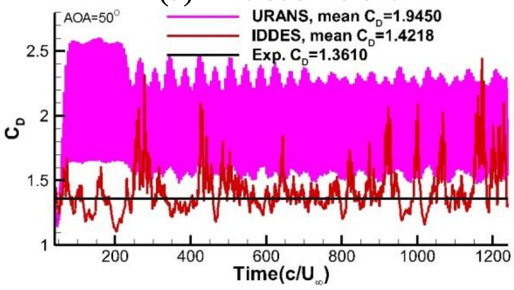
Compared to URANS simulations, IDDES simulations show much better predictions on the massive separation flows on S809 airfoil (see

Fig. 3). The flow at 50 degree AOA is a typical case.

Figure 7 shows the difference of mean flow velocity and streamline distribution between IDDES and URANS simulations. It can be clearly found two main vortexes in the wake flow (see Fig. 7(a)) with the IDDES simulation. However, only one vortex is found in the URANS simulation.



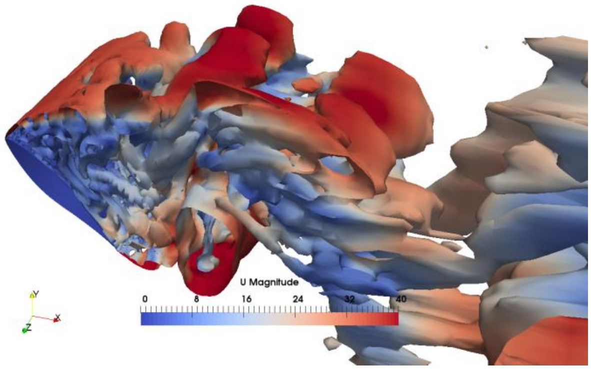
(a) Lift coefficient



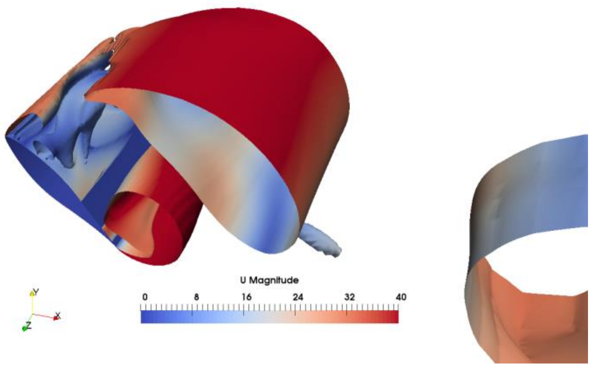
(b) Drag coefficient

Fig. 8 Lift and drag coefficient histories at 16 degree AOA

Figure 8 shows the comparison of lift and drag coefficient histories between IDDES and URANS simulations. The URANS simulation has larger oscillating amplitudes in both lift and drag coefficients than the IDDES simulation. The lift and drag coefficients of IDDES simulation are more chaotic than the URANS simulation. These differences can be explained in Fig.9. Figure 9 shows the difference of instantaneous vortexes distribution between IDDES and URANS simulations in terms of Q criterion. One big vortex is generated and moving downstream in the wake flow. The generation and motion process of this big vortex causes the oscillation of the lift and drag coefficients. In contrast, there are much more vortexes generated with different sizes in the IDDES simulation. These turbulent vortexes make the lift and drag coefficients chaotic in the IDDES simulation at 50 degree AOA. Compared to the experimental results, IDDES simulation predicts the mean lift coefficient at 1.1862 and the drag coefficient at 1.4218, which is much better than the URANS simulation.



(a) IDDES simulation



(b) URANS simulation

Fig. 9 Iso-surfaces of Q=1000 in IDDES and URANS simulations at 16 degree AOA (colored by velocity magnitude)

5 Conclusion

In this study, a numerical study of the flow around S809 airfoil has been performed with angles of attack from 0 to 90 degrees. With the use of OpenFOAM, IDDES and URANS simulations have been carried for a comparison.

A grid sensitivity study has been taken by four different grids with the IDDES simulations at 10 degree AOA. Both the lift and drag coefficients show the convergence to the experimental results. Then the fine mesh is taken for all the IDDES and URANS simulations with AOAs from 0 to 90 degrees.

At the attached flow regime with low AOAs, both URANS and IDDES simulations agree well with the experimental results. However, in the mild separation and massive separation regime with high AOAs, IDDES gives much better predictions of lift and drag coefficients than the URANS simulation. Detailed flow structures have been analyzed at certain typical AOAs in the mild separation and massive separation regime, respectively. The difference between IDDES and URANS simulations are thorough compared with mean flow structures, lift and drag coefficient histories and instantaneous vortexes.

Acknowledgments

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