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The Numerical Study on Separation Flow field around Iced Airfoil under Stall Conditions with Hybrid RANS/LES Methods

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The improved delayed detached eddy simulation (IDDES) is applied in the comprehensive analysis of the unsteady separation flow field under stall conditions caused by a typical horn-type ice on the leading edge of GLC305 airfoil. The capability of the method for detailed simulation of the complex flow is verified by comparing with the experiment results. Numerical results of the stall process indicate that the unsteady shedding of shear layer from the ice tip determines the basic properties of the separation flow field. For the shedding angle of shear layer increases with the angle of attack, the transport process of the vortex toward the wall is delayed progressively until the ranks of vortex completely move into the wake flow region. As a result, the geometrical scale of separation bubble is gradually increased and the reattachment region shifts backward continually until the disintegration of the flow structure.

Introduction

Ice accretion can significantly alter the shape of airfoil leading edge. The unsteady flow separation caused by the horn-type ice will severely impact the aerodynamic performance of the airfoil, especially lead to the complete change of stall characters. But at present the details of the complex flow field dominated by vortex shedding and movement can not be considered as well understood. Moreover, the numerical investigation about iced airfoil flow field mainly focus on the pre-stall conditions, the whole process of stall especially characters of post stall flow field is less concerned. And the relative work might provide some knowledge to the physical nature for the stall process of iced airfoil.

With the development of the hybrid RANS/LES methods, the detailed numerical investigation of iced airfoil flow field with acceptable computation costs is feasible now. The improved delayed detached eddy simulation (IDDES) which combines DDES with WMLES is formulated by Travín[1] with defining a new sub-grid length scale and a new empirical function. Xiao[2] has carried out a series of outstanding numerical research
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with this method. These achievements prove that the method has the potential to be extended to the analysis for the separation flow field of iced airfoil.

In the current work, IDDES based on SST model was applied to the simulation of the GLC305 airfoil with a typical dual horn ice shape. The critical stall condition was chosen firstly to examine the reliability of the method. Then the method was employed for the simulation under post-stall conditions. The effect of vortex shedding and movement in the stall process was analyzed and some basic features of the separation flow field were summarized.

**Numerical Methodologies**

**a. Computational configuration and grids**

The computational configuration for numerical study is the GLC-305 airfoil with a 22.5 min horn-type ice (ice shape 944) [3]. Computational domain and the multi-block structured grids are shown in Fig 1. The spanwise of the domain is 0.5c and the size of cells in the focus region after the ice is 1/5 of the horn height (0.5%c) corresponding to 1.6x10^7 nodes in total.

![Computational domain and grids](image)

**b. Numerical implementation**

To provide a initial flow field for the IDDES computations, the unsteady RANS calculations were performed firstly. Then IDDES computations were carried out next. The nondimensional time step was
chosen as $\Delta^t = U_o \Delta t / c = 0.003$. The time average process was performed on the basis of fully developed IDDES.

**Results and discussion**

**a. Result of critical stall**

The experiment of this state has been performed in the NASA Glenn Icing Research Tunnel (IRT) by Broeren\(^3\). The experimental conditions are given as follows: $Ma=0.12, Re=3.5 \times 10^6$ based on chord length of 0.9144m, $\alpha=6^\circ$. Both the experimental data and the numerical results of DHRL\(^4\) (Dynamic Hybrid RANS/LES) method are compared with the time-averaged results of IDDES in order to provide a reliable reference for the examining of method reliability.

Fig.2 and Fig.3 gives a brief comparison of the predicted time-averaged $u$-velocity. The zero-velocity contour line illustrates that the time-averaged reattachment line locates at 50% chord approximately. Characters of the separation bubble including location and size are described well by IDDES while the reattachment location is captured precisely. The fact can be reflected from the predicted velocity profiles near the wall.

![Fig. 2 Comparison of time-averaged u-velocity contours](image)

a) IDDES  

b) EXP

**Fig. 2** Comparison of time-averaged $u$-velocity contours

![velocity profiles](image)

a) $x/c=0.15$  

b) $x/c=0.40$
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**Fig. 3** Comparison of time-averaged velocity profiles at different stations near the wall

Fig.4 and Fig.5 provide the results of the predicted RMS of the fluctuations in the u-velocity component. IDDES results have good consistency with PIV especially after the reattachment point. But the turbulence intensity near the reattachment location is overestimated in some degree.

**Fig. 4** Comparison of the RMS of the fluctuations in the u-velocity component
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![Graphs showing RMS fluctuations in u-velocity component profiles at different stations near the wall.](image)

**Fig. 5** Comparison of the RMS of the fluctuations in the u-velocity component profiles at different stations near the wall

### b. Result of post stall

Two angles of attack, Alpha=8° and Alpha=11°, are chosen as typical conditions for the post stall study. Both the time-averaged and the transient results are given in this section for the comprehensive analysis of the flow mechanism.

Fig.6a shows even after stall point, the reattachment of separated flow can also occur in a certain range of angles of attack. The length and volume of the separation bubble increase with the angle of attack until the complete crush of the separation bubble, leading a large recirculation region as Fig.6b. The obvious phenomenon of vortex core swelling is consistent with the classical separated flow theory.

![Time-averaged u-velocity contours](image)

**Fig. 6** Time-averaged u-velocity contours

Fig.7 shows that the turbulence region gradually moves into background flow as the angle of attack increases. The decreasing of near-wall turbulence intensity reflects that the effect of the flow reattachment is gradually weakened. But it seems that the turbulence intensity of the core area remains almost unchanged. That means the strength of the vortex shedding is not sensitive to the increase of angle of attack.
Fig. 7 The RMS of the fluctuations in the u-velocity component

Fig 8 and 9 shows that though the shedding angle of the shear layer increases with the angle of attack, the separating out position of vortex remain virtually unchanged. The phenomenon is consistent with the Fig.7. It is obvious that the effects of external background flow to vortex shedding direction increase gradually. The transport process of the vortex toward the wall is delayed progressively until the rank of vortex move into the wake flow region completely. Then the structure of separation bubble is unable to maintain.

Fig. 8 Instantaneous spanwise vortices distribution of different angles of attack
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![Image](image135x586_to_460x689)

**Fig. 9** Instantaneous Q criterion of different angles of attack (Q=0.1)

**Conclusions**

In the present work, the unsteady separated flow field around iced airfoil under stall condition is investigated with IDDES method. The prediction results under critical stall conditions are consistent with the experiment and reliable numerical results. The study of stall process indicates that the shedding angle of shear layer increases with the angle of attack and the transport direction of the vortex shifts towards the background flow until the ranks of vortex completely move into the wake flow region. As a result, the geometrical scale of separation bubble is gradually increased and the reattachment region shifts backward continually, leads to the disintegration of the separation bubble.

**References**


