Effects of Transition on Aerodynamic Characteristics of Laminar Airfoil Based on CFD

Yanping Zhao, Lianghua Xiao, Yao Chen, and Rui Chen

Abstract Laminar airfoil has extensive application prospect in the civil aviation area as its low drag characteristic. However, the laminar flow is too sensitive to be disturbed and then laminar-turbulent transition location will move forward, which results in a significant increase in drag. Therefore, it is meaningful to obtain the aerodynamic characteristics of laminar airfoil both under natural transition and disturbed transition conditions. This paper focuses on the aerodynamic characteristics of a laminar airfoil named NACA65(1)412. Firstly, numerical simulations of natural transition of the airfoil flow at various angles of attack were carried out using γ-Re_θ model. Secondly, forced transition simulations were taken to imitate the disturbed airfoil flow using k-ω SST model. Results show that, the transition location has a great influence on the aerodynamic characteristics of laminar airfoil, especially on the drag. For the natural transition, as the angle of attack increasing, the natural transition location on the upper surface moves upstream while the one on the lower surface moves the opposite. The upper-surface transition location moves upstream rapidly after the 4° angle of attack. For the forced transition, the drag increases approximately linearly with the transition location for both the upper and lower surface, but the upper-surface behaves much more significant. The lift changes little with the movement of transition locations.

Keywords Laminar airfoil · Aerodynamic characteristics · Laminar-turbulent transition · Forced transition · Numerical simulation

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1 Introduction

Drag reduction is so important in the civil aviation as its influence on the economy and environment pollution. Researches on modern airliners have shown that the friction drag accounts for about 50% of the total drag. So extending the laminar flow region of aircraft is one of the major measures to reduce the drag because the laminar friction drag is much less than the turbulent one. For example, laminar skin friction can be as much as 90% less than turbulent skin friction at the same Reynolds number [1, 2]. Studies have shown that, $150,000 fuel consumption will be saved if the drag reduce by 3% for a long-haul airliner per year [3]. Hence, researches of laminar airfoil/wing become the highlights in aviation field.

Laminar wing technology has been researched by not only Airbus and Boeing, but also Honda [4, 5]. However, studies mainly focus on the design and laminar flow control of laminar airfoil/wing, but rarely mention its practical application, especially the manufacture and maintenance. Roughness, bulges and steps can be found in the practical wing and can promote laminar-turbulent transition [6]. The aerodynamic characteristics would deteriorate sharply. Therefore, it is significant to obtain the aerodynamic characteristics of laminar airfoil both under natural transition and disturbed transition conditions. The study of transition is carried out in this paper, which can help to provide a guide for the design, manufacture, maintenance and flow control of laminar airfoil.

2 Computation Scheme

2.1 Governing Equation and Calculation Method

Reynolds-averaged Navier–Stokes (RANS) equations were adopted in the simulations by using Ansys Fluent (V19.2). The γ-Re_θ transition model and k-ω SST turbulence model were used in the natural transition and forced transition simulations separately. The second order upwind scheme was chosen to discretize the convection term. The diffusion term adopted the central difference scheme, and the SIMPLEC algorithm was used for pressure–velocity coupling.

The γ-Re_θ model is suitable for simulating the natural transition flow, while the k-ω SST model is generally accepted as the most accurate model for turbulent simulation. For detailed information about the calculation models, readers can refer to Fluent (V19.2) user's guides.

2.2 Research Object and Grid Generation

NACA65(1)412 airfoil, with a small leading radius, flat roof, and maximum relative thickness location near to the trailing edge, is one of the representative laminar airfoils. Figure 1 shows the geometry of airfoil and the computational grid. The *X*-axis points to the trailing edge along the chord of the airfoil, and the *Y*-axis is perpendicular to the *X*-axis and points up. The airfoil's maximum relative thickness is 12%, and locates at 40% chord. The maximum relative camber is 2.2%, and locates at 50% chord. The grid was generated by the ICEM software. The up and down boundary is 15c away from the chord. The respective distance of the front and back boundary away from the leading edge and the trailing edge is 15c and 20c. The y^+ was ensured to approximately one. The normal growth rate is 1.1 and the whole mesh contains near one hundred thousand points.

3 Numerical Method Validation

A laminar-flow airfoil, the S809, for horizontal-axis wind-turbine applications, has been designed and analyzed theoretically and verified experimentally in the low-turbulence wind tunnel of the Delft University of Technology Low Speed Laboratory, by Somers [7]. Its results have been widely used for the validation of transition prediction [8]. This paper takes advantage of part of its results to validate. The calculation was simulated at Mach number of 0.107, 0° angle of attack, and Reynolds number based on airfoil chord of 2,500,000.

Figure 2 is the skin friction coefficient (C_f) of S809 airfoil. Taking the upper-surface curve as an example, the C_f becomes negative at the chord location of 50%, which means flow separation. Then the C_f goes to positive again at 56%c, which indicates the flow reattachment. And then the friction drag increases sharply. Combined with the contour of turbulent kinetic energy of upper surface shown in Fig. 3, the transition happens at the 55%c. The flow at the separation point is laminar, and the

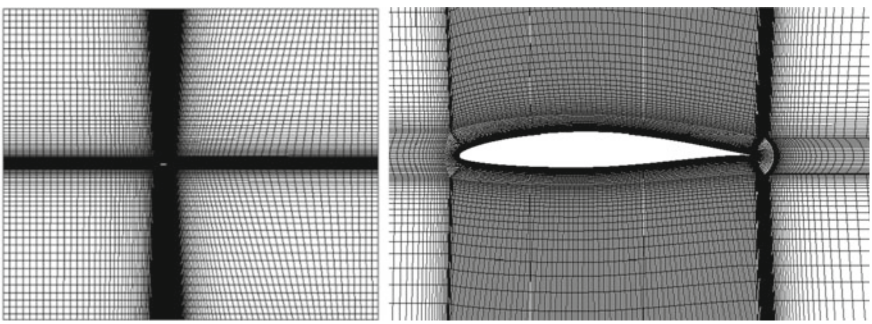

Fig. 1 View of computational grid and geometry of NACA65(1)412 airfoil

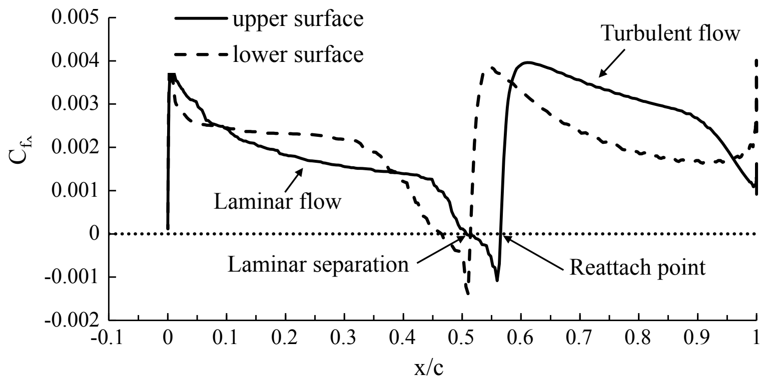

Fig. 2 Skin friction distribution of S809 airfoil

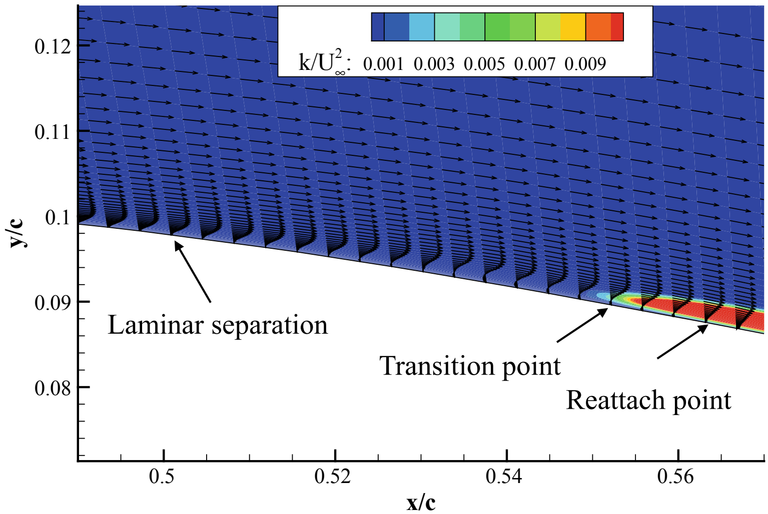

Fig. 3 Contour of turbulent kinetic energy of upper-surface

laminar separation bubble results in the instability of flow, and transition occurs. The boundary layer flow alters from laminar flow to turbulence. The reattachment happens quickly after the flow changing to turbulence. Since the turbulent friction drag is much more than the laminar one, the C_f rises rapidly exceeding the value before separation point. Similarly, the lower-surface transition location is at 50%c.

Figure 4 shows the comparison of the simulated natural transition locations with the experimental data in different angles of attack. As the angle of attack increasing, the natural transition location on the upper surface moves upstream, especially in the vicinity of 6° angle of attack where moves rapidly to the leading edge. The natural transition location on the lower surface moves downstream along with the increasing

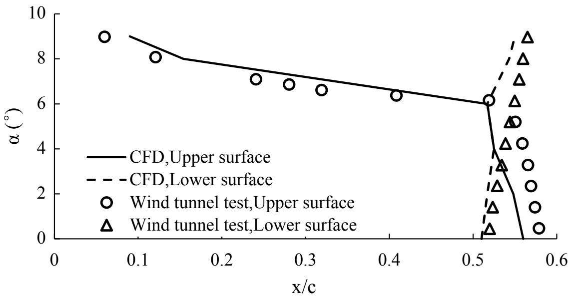

Fig. 4 Comparison of the simulated natural transition locations with the experimental data

of angle of attack, and the total movement is smaller. The simulation results display slightly ahead and are consistent with the experimental data.

Figures 5 and 6 illustrates the comparison of the calculated aerodynamic characteristics including the lift and drag forces with the experimental data of the airfoil, using γ-Re_θ model and k-ω SST model respectively. The drag obtained by γ-Re_θ model is much more accurate than that by k-ω SST model, and the lift is closer with the experimental data. Computation scheme and numerical method conducted by this paper can capture the transition locations precisely, and are reasonable.

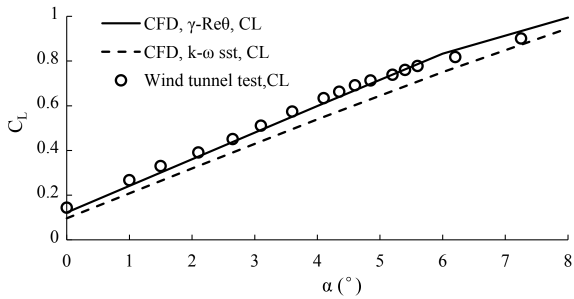

Fig. 5 Comparison of the simulated lift with the experimental data

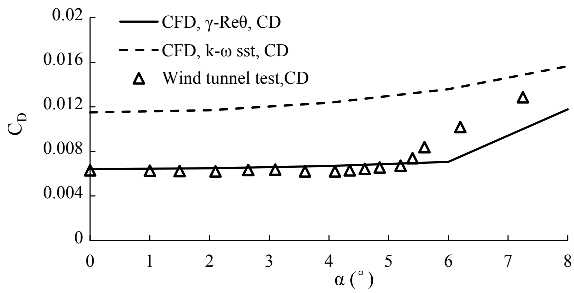

Fig. 6 Comparison of the simulated drag with the experimental data

4 Results and Analysis

4.1 Effects of Natural Transition on Aerodynamic Characteristics of NACA65(1)412 Airfoil

Numerical simulation of natural transition of the NACA65(1)412 airfoil at various angles of attack was carried out, using γ-Re_θ model. The calculation condition is the same as the numerical method validation example.

Figure 7 exhibits the natural transition locations shifting along with the increasing of angles of attack both in upper and lower surfaces of airfoil. At the 0° angle of attack, both the locations are near the 70% chord. As the angle of attack increasing, the upper-surface transition location moves upstream, and the movement speeds up suddenly at 4° angle of attack. The transition location reaches rapidly to the leading edge at the 6° angle of attack, which indicates the boundary layer flow is almost all turbulent. The lower-surface transition location moves downstream slowly along with the increasing of angles of attack, and gets to the trailing edge at the 8° angle of attack, which means no transition occurring and the boundary layer flow is all laminar.

Figure 8 and 9 shows the comparison of the lift and drag curves simulated by γ-Re_θ model and k-ω SST model. It can be seen that, for the k-ω SST model, which

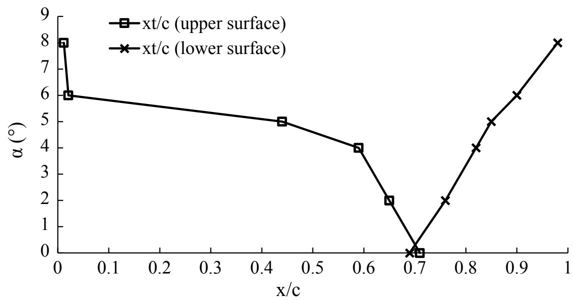

Fig. 7 Natural transition locations of NACA65(1)412 airfoil

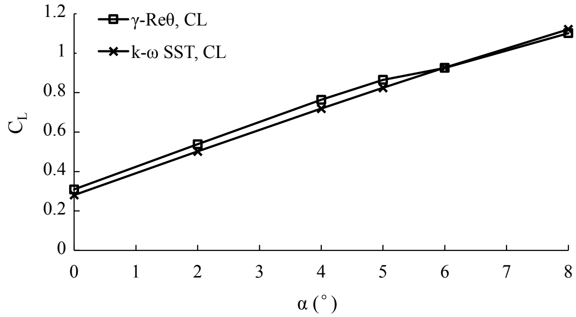

Fig. 8 Comparison of the lift curves of the airfoil simulated by two models

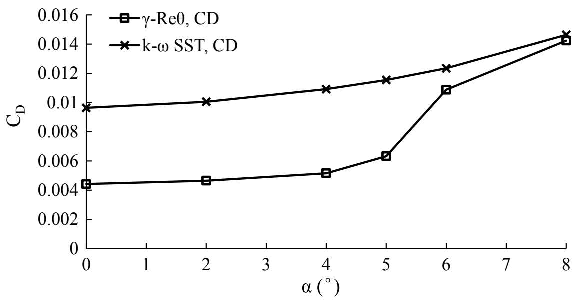

Fig. 9 Comparison of the drag curves of the airfoil simulated by two models

simulates the turbulence, the lift changes linearly with the angle of attack, and the drag varies with the angle of attack in a quadratic curve. For the natural transition simulation, the lift curve is linear in the small angles of attack before 4°. After that the increments of lift slow down and the curve becomes nonlinear, with the rapid rises of drag after the 4° angle of attack. According to the transition locations, the changes of the lift and drag characteristics is caused by the nonlinear forward movement of the transition location on the upper surface after the 4° angle of attack. In fact, the jump of upper-surface transition location will lead to the alteration of boundary layer flow situation, so as to the nonlinear phenomenon of lift curve and a sharp increase of drag.

4.2 *Effects of Forced Transition on Aerodynamic Characteristics of NACA65(1)412 Airfoil*

Introduction. In engineering, the transition location of airfoil/wing may move ahead by various disturbances. By means of forced transition, the aerodynamic characteristics of disturbed airfoil flow were simulated. The calculation condition is the same as the numerical method validation example, at 0° angle of attack. All simulated transition locations are before the 70%c, as the upper and lower surface natural transition locations of NACA65(1)412 airfoil are both near the 70%c at 0° angle of attack.

Effects of the upper-surface transition. Effects of the upper-transition on aerodynamic characteristics were carried out, while the lower-surface boundary flow is all turbulent. Figure 10 illustrates the lift and drag changing with upper-surface transition locations. As the transition location moves upstream, consequently, the laminar flow region becomes smaller, and the lift decreases as well as the drag rises. In addition, there is a linear relationship between the lift or drag with transition location. The 10% chord movement to the leading edge of upper-surface transition location results in the 1.6% reduction of lift and 7% increase of drag, roughly.

Comparisons of the results of upper-surface transition location at 0% (case 1) and 50% (case 2) chord are demonstrated. Figure 11 shows the comparisons of skin friction coefficient of the two cases. Since the turbulent friction drag is much more

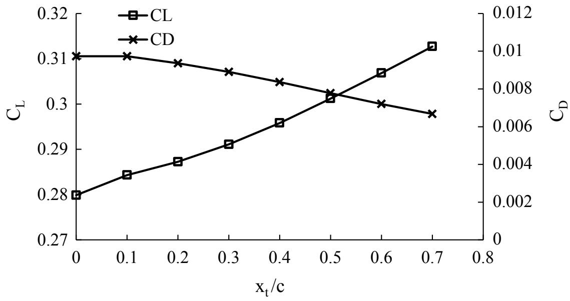

Fig. 10 The lift and drag changing with upper-surface transition locations

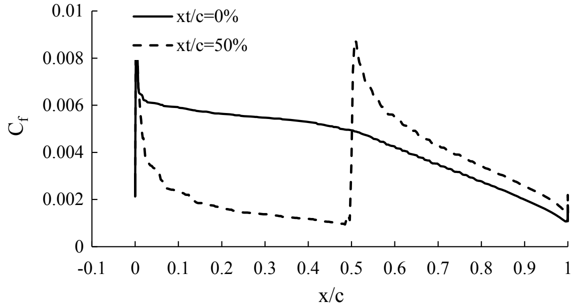

Fig. 11 Comparisons of skin friction coefficient of $x_t/c = 0\%$ with $x_t/c = 50\%$

than the laminar one, it is obvious that the boundary layer is all turbulent in case 1 so that its friction drag is higher than that of case 2, as well as the total drag. Figure 12 is the comparisons of pressure coefficient. The pressure distribution in case 1 contains slightly less area than that in case 2, so its lift is lower.

Effects of the lower-surface transition. Effects of the lower-transition on aerodynamic characteristics were carried out, while the upper-surface boundary flow is all turbulent. Figure 13 illustrates the lift and drag changing with lower-surface transition locations. As the transition location moves upstream, the lift is almost constant

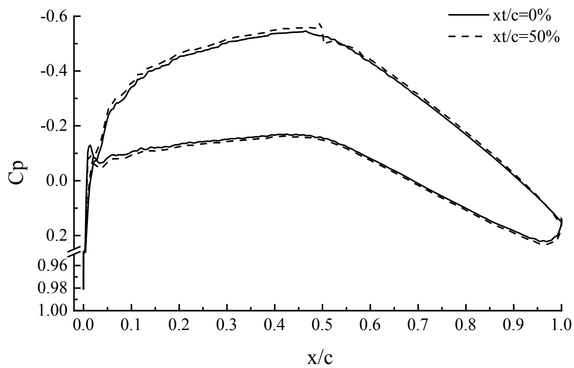

Fig. 12 Comparisons of pressure coefficient of $x_t/c = 0\%$ with $x_t/c = 50\%$

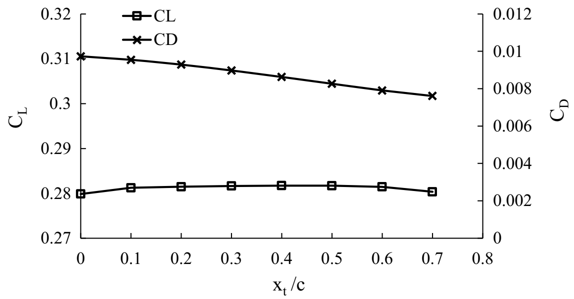

Fig. 13 The lift and drag changing with lower-surface transition locations

while the drag rises. Similarly, there is a linear relationship between the drag and transition location. The 10% chord movement to the leading edge of lower-surface transition location results in the 4% increase of drag, roughly.

In conclusion, it is apparently that the lift is greatly affected by the upper-surface transition location not the lower-surface one. The drag is affected by both the upper and lower surface transition locations in the similar way, and the influence of upper-surface transition location is bigger. Therefore, in laminar airfoil manufacture and maintenance, the surface quality should be guaranteed to avoid the transition occurring ahead of schedule, and the quality of upper-surface should be paid more attention to, particularly.

5 Conclusion

This paper focuses on the aerodynamic characteristics of a laminar airfoil named NACA65(1)412 both under natural transition and disturbed transition conditions. Conclusions can be summarized as follows.

For the natural transition, as the angle of attack increasing, the natural transition location of NACA65(1)412 airfoil on the upper surface moves upstream while the one on the lower surface moving the opposite. The upper-surface transition location will be suddenly move ahead at 4° angle of attack, which will cause the nonlinear phenomenon of lift curve and a sharp increase of drag. The lower-surface transition location moves to the trailing edge gradually and no mutation occurs within the calculated angles of attack.

For the forced transition at 0° angle of attack, as the upper and lower surface transition location moves upstream, the drag increases approximately linearly, and the influence of upper-surface transition location is bigger. The 10% chord movement to the leading edge of upper or lower surface transition location results in the 7 or 4% increase of drag, roughly and respectively. The lift decreases slightly as the upper-surface transition location moving upstream, and is almost unaffected by the lower-surface one.

In laminar airfoil manufacture and maintenance, the surface quality should be guaranteed to avoid the transition occurring ahead of schedule, and the quality of upper-surface should be paid more attention to, particularly. For NACA65(1)412 airfoil, the cruising angle of attack should not be exceed 4°.

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