ICAS 2021 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

Aerodynamics Characteristics Study on A Nature Laminar Flow Airfoil of Near-space Vehicle at Low Reynolds Numbers

CUI Fei[1], ZHANG Hongkun[2]

[1]Innovation & Research Institute of HIWING Technology Academy, Beijing 100074, China

[2]HIWING Technology Academy, Beijing 100074, China

E-mail: 381343120@qq.com Tel: 010-88532646

Abstract. In order to develop high attitude and low speed UAV, numerical computations of airfoil were used to analyze the aerodynamic characteristics of high-lift airfoil with high camber in a range of low Reynolds number. The coupled method with boundary layer transition model and CFD method based on RANS were carried out to study the aerodynamic performance of the foil. Results indicate that with the increase of attack angle, the transition point moves from the trailing edge to leading edge. The comparison of e-N method, γ-Reθt transition model method and experimental results were performed to illuminate the influence of transition location on aerodynamic analysis of natural laminar flow airfoil.

1. Introduction

Because of the low air density and low flight dynamic pressure in high altitude, the aircraft is required to have a high cruise lift coefficient. Because of long-distance flight, it is necessary to require a small cruise drag coefficient, that is, the aircraft must have a high cruise lift-drag ratio. The performance of its airfoil, to a large extent, determines the advanced nature of the aircraft. Through the design of the natural laminar airfoil and the wing, it is important to delay the occurrence of the transition, enlarge the laminar flow area of the airfoil, and realize the natural laminar flow, which is an important measure to reduce the friction of the aircraft and increase the lift-to-drag ratio. Based on this, a wide range of studies have been carried out on natural laminar airfoils.

In this paper, the aerodynamic characteristics of natural laminar airfoil are studied by combining numerical simulation with wind tunnel experiments. The boundary layer coupling calculation method combined with e^N method[1-3], the numerical simulation method based on two-dimensional N-S equation and γ-$Re_{\theta t}$ transition model[3], were used to simulate the boundary layer flow of NLF1214 high lift natural laminar airfoil, and the transition positions of the upper surface boundary layer of airfoil under different Re conditions were obtained. In addition, the aerodynamic performance verification experiments of fixed transition and free transition of the airfoil under variable Reynolds number were carried out in the NF-3 wind tunnel of Northwest Polytechnic University. The transition positions of boundary layer on the upper surface of the airfoil were measured by the pulsating pressure method [4-5]. At last, the results of calculation and experiment are compared.

2. Characteristics of airfoil design for high altitude long-endurance flight

The Reynolds number of cruising flight of high altitude long-endurance aircraft is generally low. For example, at the altitude of 20000m, the typical Reynolds number of cruising flight is about 1 million, which belongs to the low Reynolds number range.

The design characteristics and requirements of high lift natural laminar flow airfoil are presented as follows:

(1) Design condition: $Re = 1.1\times10^6$;

(2) The lift coefficient of airfoil design ranges from 1.1 to 1.2. Under the design lift coefficient, the decrease of lift coefficient in turbulent state is not more than 10% of that in free transition state;

(3) The maximum lift coefficient is more than 1.4 in free-transition, and more than 1.4 in full turbulence;

(4) The pitch moment coefficient of airfoil $C_{m,\ c/4}$ is more than -0.15 to reduce lifting loss of whole machine leveling;

(5) The maximum thickness of the airfoil is not less than 14%;

(6) The airfoil stall type is trailing edge stall, and the stall characteristic is gentle.

2.1. Experimental method

The airfoil experiment was completed in the NF-3 low speed direct current airfoil wind tunnel of the National Key Laboratory of Science and Technology on Aerodynamic Design and Research, Northwest Polytechnic University. The binary experimental section used in the experiment is rectangular section with length * width * height = 8m * 1.6m * 3m; maximum wind speed $V_{\max}$ = 130m/s; wind tunnel contraction ratio is 20; turbulence degree is less than 0.045%; maximum experimental Reynolds number is more than $6 * 10^6$.

The high lift natural laminar airfoil model is 1.6m in length and 0.8m in chord length. The inner part of the airfoil model is made of steel frame, and the outer part is made of wood material. The surface of the airfoil model is smoothed. The airfoil is parallel to the symmetrical plane of the upper and lower walls. The pressure measurement holes are arranged along the airfoil surface to measure the static pressure on the airfoil surface, and the wake pressure of the airfoil is measured by the tail rake. In addition, the transition position is measured using the pulsating pressure method [4-5]. The time domain signal of the pulsating pressure on the surface of the model is measured by the dynamic pressure measuring system. Figure 1 shows the installation of the experimental model in the wind tunnel.

Figure 1 Airfoil experiment model

2.2. Calculation method

2.2.1. e^N method

The e^N method is a semi-empirical method based on linear stability theory. The basic idea is to assume that the initial small disturbances generated by the laminar boundary layer develop downstream at a constant frequency. When the disturbances are amplified to the original e^N times, the flow transition occurs. The N factor needs to be determined by experiment or numerical simulation. In this paper, according to the relevant literature and the characteristics of the NF-3 wind tunnel, the N value is 6.

2.2.2. γ-$Re_{\theta t}$ turbulent method

In this paper, the e^N method is verified by FLUENT 13.0 software, a high-precision flow solver based on N-S equation. Transition-SST model is adopted for turbulence model, and γ-$Re_{\theta t}$ transition model is used for transition prediction.

FLUENT software adopts the γ-$Re_{\theta t}$ transition model based on the SST model developed by Menter to simulate laminar flow transition. It combines the advantages of transition empirical relationship and low Reynolds number turbulence model. FLUENT software is widely used in transition prediction in the fields of turbine and aeronautics. Wang Gang[6] et al. have made a comprehensive and in-depth study of the model.

Figure 2 shows the numerical grid of the airfoil. The height of the normal first layer of the airfoil wall is y+ < 1, the circumferential grid is 120, and the normal grid is 450.

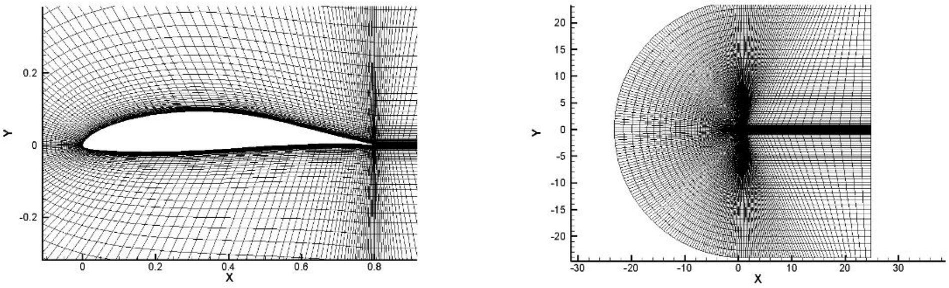


Figure 2. NLF1214 airfoil grid

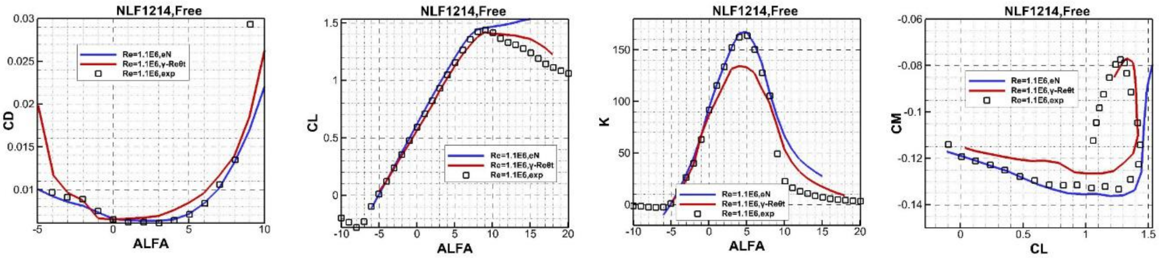
3. Results and analysis

3.1. Free transition

The airfoil characteristics under free transition conditions are compared and analyzed between the two numerical methods and the wind tunnel experimental result.

3.1.1. Design state comparison

Figure 3 shows the comparison of the aerodynamic characteristics between the calculated and experimental values for free transition, Re=1.1E6. It can be seen from the result that the airfoil drag 'pit' feature is obvious. The maximum lift coefficient of airfoil is about 1.45, the stall angle of attack is around 9 degrees, and the stall characteristic is slow when Re is1.1E6 under free transition condition. Near the designed lift coefficient (1.1~1.2), the maximum lift-drag ratio is 160, and the pitch moment of airfoil around 1/4 chord is about -0.13.It can be seen that the calculated results of LH1214 are in good agreement with the experimental values under free transition conditions, and the performance of the airfoil can meet the design requirements under free transition conditions.



(a) cd~α (b) cl~α (c) K~α (d) cm~cl

Figure 3. Comparison between calculation and experiment(Re=1.1E6, free transition)

Comparison of different numerical calculations and experimental results:

(1) Within the angle of attack of 8 degree, the drag coefficient and pitching moment coefficient calculated by e^N method are in good agreement with the experimental values, and the slope of lift and lift-drag ratio are slightly larger than the experimental values. But the e^N method can't predict the stall caused by separation, when the angle of attack is relatively large.

(2) The drag coefficient and pitch moment coefficient calculated by the $\gamma\text{-Re}_{\theta t}$ transition model are larger than the experimental value, the slope of lift is slightly smaller, and the lift-drag ratio is lower. But the $\gamma\text{-Re}_{\theta t}$ transition method can accurately predict the stall angle of attack.

In conclusion, the e^N method (N value 6 in this paper) is more effective than the $\gamma\text{-Re}_{\theta t}$ transition model in predicting the free transition aerodynamic characteristics of airfoils.

3.1.2. Transition position comparison

In this paper, the transition position of NLF1214 airfoil is measured by means of fluctuating pressure method and compared with two numerical values.

Figure 4 shows the comparison of the transition position between the calculated and experimental values for free transition, Re=1.1E6. It can be seen that the prediction of transition position by e^N method (in this paper, N takes 6) is in good agreement with the experiment at a small angle of attack, and that by $\gamma\text{-Re}_{\theta t}$ method at a large angle of attack, the prediction of transition position is in good agreement with the experiment.

Figure 5 is a comparison of transition positions measured in wind tunnel experiment at different Re and angles of attack. It can be seen from the figure that under the designed lift coefficient and angle of attack of 4° ~5° the transition position of the upper surface of the airfoil is between 50% and 60% of the local chord length. And with the increasing Re, the transition position of the upper surface of the airfoil moves forward.

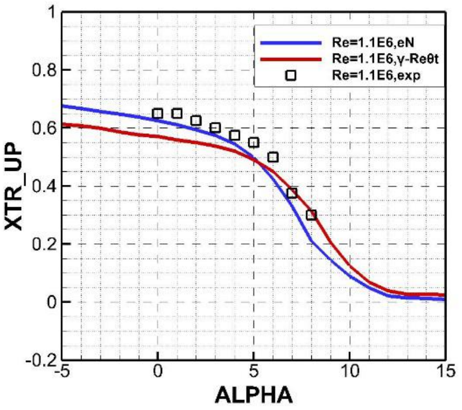


Figure 4. Comparison of transition position at different angle

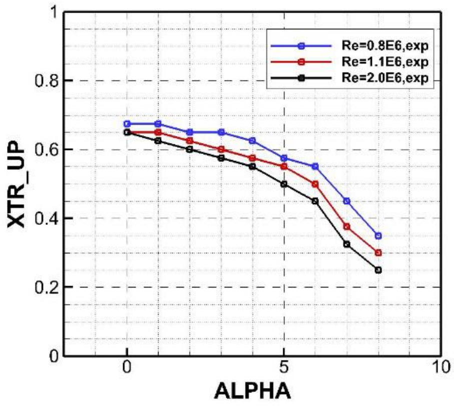
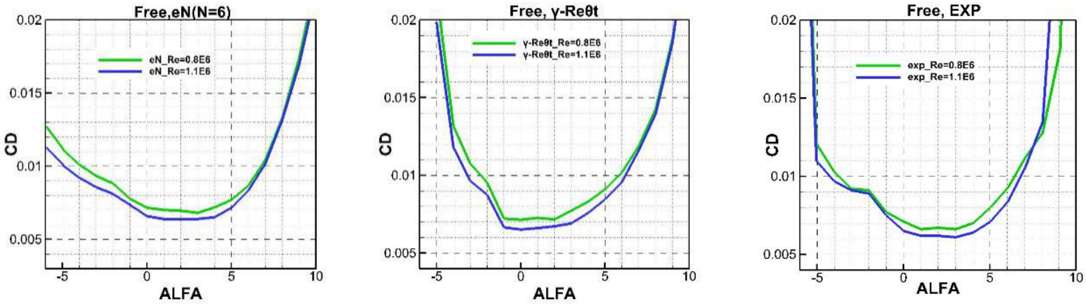


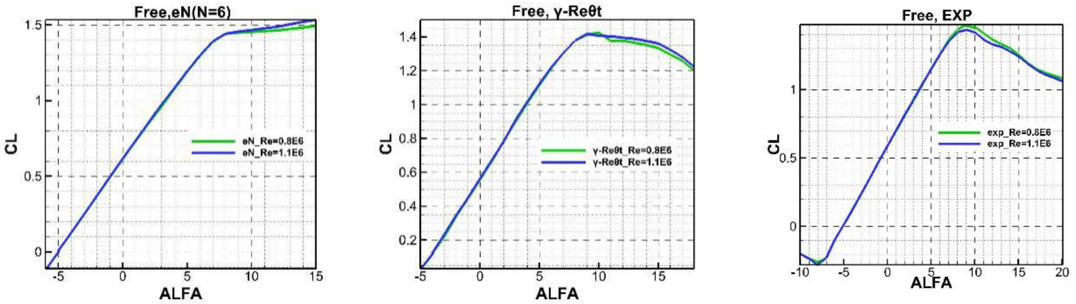
Figure 5. Comparison of transition position at different Re

3.1.3. Research on the influence of Re

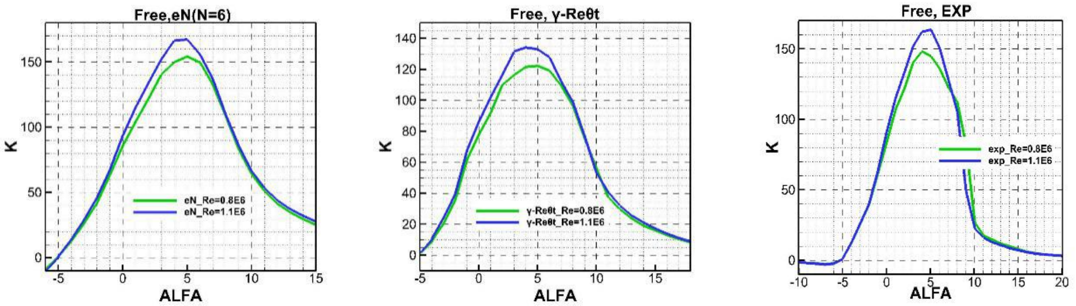
Figure 6 is the comparison of the calculation and experiment results of aerodynamic characteristics of airfoils with free transition, different Re conditions. It can be seen from the figure that the law of variation of drag coefficients of e^N method, $\gamma\text{-Re}_{\theta t}$ method and experiment is consistent, that is, with the increasing Re, the drag coefficient decreases. In terms of lift coefficients, the three methods are consistent with Figure 3 above. With the increase of Re, the maximum lift-drag ratio obtained by the three methods increases.



a. cd~α



b. cl~α



c. α~cl/cd

Figure 6. Comparison at different Re number (free transition)

3.2. Fixed transition

A comparative analysis of airfoil characteristics between two numerical calculation methods and wind tunnel experimental results under fixed transition conditions is given below. In the wind tunnel test, laminar transition belt was attached on the leading edge of airfoil to make laminar flow forced transition.

3.2.1. Design state comparison

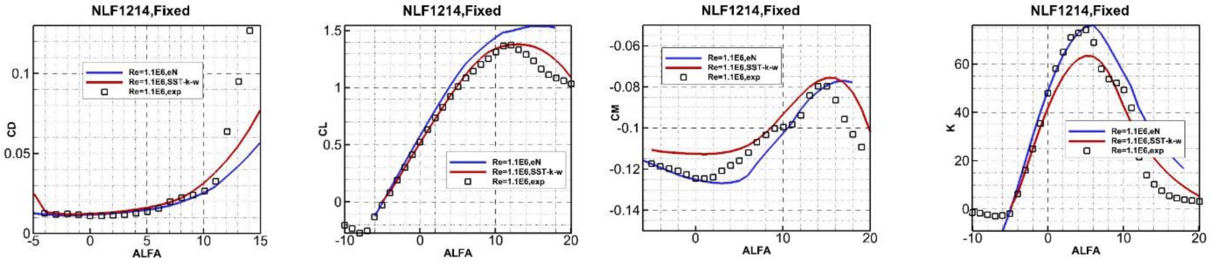
Figure 7 shows the calculated and experimental results of the aerodynamic characteristics of the airfoil with fixed transition/full turbulence and design state Re=1.1E6.

Comparison of different numerical calculations and experimental results:

(1) Before stall angle of attack, the drag coefficient calculated by e^N method is in good agreement with the experimental value, the slope of lift line is larger than the experimental value. As with free transition, e^N method does not predict stall caused by separation at larger angle of attack.

(2) The drag coefficient calculated by the $\gamma\text{-}Re_{\theta t}$ transition model is larger than the experimental value; the lift coefficient and the slope of the lift line are in good agreement with the experimental value; the drag-lift ratio of the $\gamma\text{-}Re_{\theta t}$ transition model at small angle of attack is lower than the

experimental value, but the drag-lift ratio at large angle of attack is in good agreement with the experimental value.



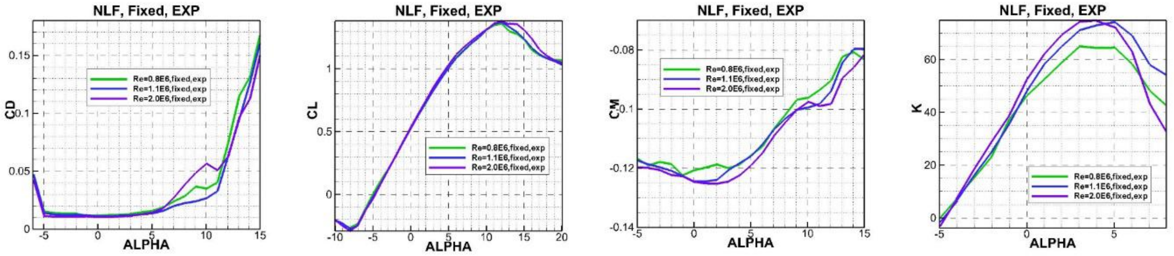
(a) cd~α (b) cl~α (c) cm~α (d) K~α

Figure 7. Comparison at fixed transition (Re=1.1E6)

Generally speaking, the γ-$Re_{\theta t}$ transition model is more effective than the e^N method in predicting the aerodynamic characteristics of airfoils under full turbulence/fixed transition conditions.

3.2.2. Research on the influence of Re

Figure 8 is the comparison of the calculation and experiment results of aerodynamic characteristics of airfoils with fixed transition, different Re conditions. It can be seen from the figure that with the increasing Re, the drag coefficient of airfoil decreases and the maximum lift coefficient increases.



(a) cd~α (b) cl~α (c) cm~α (d) K~α

Figure 8. Experimental results at different Re number and fixed transition

4. Conclusion

Aerodynamic characteristics of a natural laminar airfoil are studied by e^N method, γ-$Re_{\theta t}$ transition model and wind tunnel experiments. The results show that with the increasing Reynolds number, the transition position on the upper surface of airfoil moves forward gradually. The e^N method and the γ-$Re_{\theta t}$ transition model have their own advantages and disadvantages in predicting free transition and full turbulence aerodynamic characteristics of airfoil. The comparison method used in this paper has engineering reference value.

5. References

[1] ZHAN Hao, SI Jiang tao, BAI Jun qiang Airfoil Design of High Altitude Long Endurance Unmanned Air Vehicle. *Aeronautical Computing Technique*. 2006, **Vol 36, 82-84**.

[2] Crouch J D, Ng L L. Variable N-factor method for transition prediction in three dimensional boundary layers[J]. *AIAA Journal*, 2000, 38(2): **211-216**.

[3] Stock H W, Hasse W. Navier-Stokes airfoil computations with eN transition prediction including transitional flow regions[J]. *AIAA Journal,* 2000,38(11): **2059-2066**.

[4] Zhao Zhongfu, Teng Yongguan. The measuring and control technique of the boundary layer transition position. Aerodynamic experiment and measurement & control. 1994, **Vol 8, 10-20.**

[5] WANH Meng, GAO Yang wei and ZHU Qi liang. An Investigation on Data Processing in Transition Detection Using Surface Pressure Flutuatino. *Journal of experimental mechanics*. 2012, **Vol 27, 764-770**.

[6] WANG Gang, LIU Yi, WANG Guang qiu, SHAN Xiao wen. Transitional Flow Simulation Based on $\gamma\text{-}Re_{\theta t}$ Transition Model. Acta Aeronautica et Astronautica Sinica. 2014, **Vol 35. 70-79.**

Copyright Statement