Fixed Boundary transition effect on transport aircraft aerodynamic characteristics under different Reynolds numbers

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Abstract. Scale differences between test models and real aircraft result in Reynolds number effect, which made it impossible to simulate boundary layer conditions and obtain accurate aerodynamic characteristics of vehicles, especially of transport aircraft, by wind tunnel tests. Normally, laminar flow would exit over super critical wing during wind tunnel tests. Fixed transition effect on super critical wing aerodynamics characteristics was investigated in traditional wind tunnels. The relative experiments were conducted in a transonic wind tunnel. Force/moment and surface pressure distribution were measured with a full model and a half model respectively. Test Mach number ranged from 0.7 to 0.86, and Reynolds number ranged from 3.3 million to 16.5 million. Experiment results showed that surface pressure distribution would be changed significantly by fixed transition when shock wave and induced boundary layer separation appeared on upper surface. With the increasing of test Reynolds numbers, its effect became weakened, and the effect was ignorable when test Reynolds number exceeded 15 million. To obtain credible wind tunnel results, fixed boundary layer transition of super critical airfoil were recommended when test Reynolds numbers were less than 15 million.

1. Introduction
Complicated flow structure, such as boundary layer transition, separation, shock/boundary layer in interference over critical wing, would appear during transport aircraft flight. And the structures would be changed clearly with the Reynolds number changing. For transport aircraft, predicting the aerodynamic characteristics under flight Reynolds number is very important. Wind tunnel test is the most important methods for vehicle aerodynamic characteristics prediction. Because of the model scale, traditional wind tunnel test Reynold numbers are much lower than flight Reynolds numbers. There would be much difference between flow structures obtained in wind tunnel test and in flight, and incorrect aerodynamic characteristics were measured resulting in huge risk in aircraft design. So much research of Reynolds number effect on transport aircraft aerodynamic characteristics was conducted in traditional wind tunnels. Zhang hui, Macwilkinson, etc. conducted the correlation of full scale drag prediction with flight and found that the longitudinal characteristics, pitch moment, pressure center were much different from that of flight. For example, the difference of minimum drag coefficient obtained between wind tunnel test and flight was 0.005 which was 50 times than aircraft design requirements,
which would lead to additional fuel consumption or flying range decrement. Karl Pettersson, Curtin, conducted series of research on wind tunnel scale correlation, and found that increasing Reynolds number would reduce drag coefficient and cruise angle, raise drag divergence Mach number [1, 2] European institute presented large number of research plan, such as REMFI, HiReTT, HiRETT, EUROLIFT, to study Reynolds number effect on aircraft aerodynamic and its mechanism on flow structure [3~7].

In essence, Reynolds number effect is a boundary layer issue. When aircraft aerodynamic characteristics were measured in traditional wind tunnel, the correlation of boundary development over wind tunnel test wing and real flight wing must be faced. Effect of boundary transition on super critical wing aerodynamic characteristics obtained in traditional wind tunnel should be paid more attentions.

2. Research Methods

2.1. Model
Two test models were applied in this research. The full model was a wing-body configuration of a transport aircraft reference model for force measurement. The half model was designed from the same reference model to obtain wing surface pressure distributions under higher Reynolds number. There were 12 orifice tapes along the wing with about 500 pressure orifices. Relative position of the half model in the wind tunnel test sections could be seen in Figure 1.

![Figure 1. Relative position of the half model in the test section](image)

2.2. Wind tunnels
All the tests were conducted in a transonic wind tunnel, Mach number of which ranged from 0.3 to 1.3. It is a half return circuit transient transonic wind tunnel with a 2.4m×2.4m cross test section. It has the ability to change test Reynolds number by changing total pressure. Test Reynolds number based on mean aerodynamic chord of full model force measurement test ranged from 3.4 million to 8 million, and that of half model wing surface pressure measurement ranged from 3.7 million to 16.5 million.

2.3. Contents
Test parameters for force and surface pressure measurement are given in Tab. 2 and Tab. 3 respectively. Cylindrical grit strips, height of which were from 0.1mm to 0.12mm, were stuck at the position of 7% local chord on the wing for boundary fixed transition.

| Transition      | Reynolds number(×10^6) | Mach number     |
|-----------------|------------------------|----------------|
| Fixed Transition| 3.3                    | 0.74, 0.76, 0.86|
| Free Transition | 3.3                    | 0.74, 0.76, 0.86|
Table 2. Test Parameter of surface pressure measurement (Half model)

| Transition    | Reynolds number($\times 10^6$) | Mach number      |
|---------------|---------------------------------|------------------|
| Fixed Transition | 3.7,7,10,15                      | 0.4,0.76,0.79,0.82 |
| Free Transition | 7,10,15,16.5                     | 0.4,0.76,0.79,0.82 |

2.4. Instrumentation and data processing

The force data of full model was measured by an internal six-component gauge balance. Performance metrics of the balance can be seen in Tab. 3.

Table 3. Balance performance metrics

|            | Normal Force | Pitch Moment | Axial Force | Roll Moment | Side Force | Yawing Moment |
|------------|--------------|--------------|-------------|-------------|------------|---------------|
| Design loads(N·m) | 15000        | 1300         | 1400        | 600         | 6000       | 700           |
| Calibration accuracy(%) | 0.3          | 0.3          | 0.3         | 0.3         | 0.3        | 0.3           |

Wing surface pressures were measured with PSI8400DTC electronic scanning valve system, which has high measurement accuracy.

Effect of Balance/model misalignment, Model dead weight, Balance/model elastic angle on original force data obtained by the balance was corrected.

Surface pressure coefficient was calculated by:

$$C_{pi} = \frac{P_i - P_{\infty}}{q_{\infty}}$$

where $i = 1, 2, \ldots, n$.

2.5. Data uncertainty

Root mean square errors of force/moment coefficient and pressure coefficient were analyzed respectively. Results showed that mean square errors of lift force coefficient, drag coefficient and pitch moment coefficient was 0.0017, 0.00012, 0.0009 respectively. And the mean square error of wing surface coefficient was 0.0028. So the wind tunnel and the instrumentations were all kept in normal condition to be used to conduct the experiments.

3. Results Analysis

3.1. Fixed transition Effect on Aerodynamic Characteristics

Aerodynamic force/moment characteristics obtained from the transonic wind tunnel boundary layer transition type were compared, as shown in Figure 2. As can be seen in the figure, when the boundary layer was fixed transition, lift coefficient (CL) of the full model would be decreased and angle at zero lift be increased. The lift coefficient slope would be kept almost constantly. While the boundary layer was fixed transition, flow separation on the upper surface would appear earlier with the maximum lift coefficient much decreased. Pitching moment (Cm) at zero lift was increased by approximate 0.018 with a slight tendency of aircraft focus moving forward at the same time. The drag coefficient (CD) curve showed that drag would be increased apparently when boundary layer was fixed transition, for example, the zero lift drag coefficient was increased by approximate 0.003. To verify this effect of fixed transition on aerodynamic characteristics of full model, extra airfoil surface pressure measurement and wake total/static pressure measurements with wake rakes were conducted. Lift/pitch moment coefficients were obtained by surface pressure integration, and drag coefficient was obtained by momentum lose integration. As can be seen in Figure 3, fixed transition effect on airfoil was almost the same with that on wing-body. But zero lift drag coefficient was nearly not increased because of the errors brought by wake rake measurements for friction drag.
3.2. Fixed transition Effect under different Reynolds numbers

Surface pressure at the local section 72.36% along the wing under different Reynolds numbers when Mach number is only 0.4, as can be seen in Figure 4. The curves show that flow did not show typical characteristics of super critical airfoil and Reynolds number had almost no effect on surface pressure distributions.

When Mach number was increased to 0.76, shock wave appeared on upper surface of wing. Fixed transition would change the pressure distribution obviously when Reynolds number was 3.3million, for example, shock wave location would be moved upward. With the increase of Reynolds number, effect of fixed transition would turn to be much weaker (Figure 5.). There was nearly no effect of fixed transition on upper surface pressure distribution when the Reynolds number was 15 million. The same phenomenon was encountered when Mach number was increased to 0.79. As can be seen in Figure 6., when Reynolds number was 2.3million, fixed transition would cause the shock wave position to be moved upward by almost 20 percent of local chord, which would cause the lift to be decreased. When the Reynolds number was increased to 15 million, fixed transition would have much weaker effect on surface distribution.

![Figure 2. Fixed Transition Effect on Aerodynamics Characteristics (Wing -Body)](image1)

![Figure 3. Fixed Transition Effect on Aerodynamics Characteristics (Airfoil)](image2)

![Figure 4. Fixed Transition Effect on surface pressure distribution (M=0.4, α=4°)](image3)
3.3. Mechanism of fixed transition effect on flow structures over super critical airfoil

Two interesting phenomena could be found from above results. One is that fixed transition had much less effect on surface pressure distribution of lower Mach numbers (Figure 4.) than high Mach numbers (Figure 6.). The other is that fixed transition caused shock wave position to be moved windward, lift coefficient to be decreased and drag coefficient to be increased, which was the effect of Reynolds number being decreased. These phenomena resulted from the interference between shock wave and the induced boundary layer separation. At low Mach numbers, there was no shock wave on upper airfoil surface and the fixed transition would mainly affect friction drag, which brought negligible effect on pressure distributions. If shock wave appeared on the upper surface, shock induced boundary layer separation would happen more easily when fixed transition made the boundary layer thicker. The shock wave would be pushed windward by the separation, and boundary layer would separate at new position near the new shock wave which changed the pressure distribution largely. The surface pressure distribution changed as the Reynolds number decreased, and the aerodynamics force/moments showed lower Reynolds number characteristics. Natural boundary layer transition would happen near the fixed grit strip with the increasing of Reynolds number resulting in stable boundary layer state and its interference with shock wave, which would not bring much effect on pressure distribution over the upper surface, as can be seen from above figures when the Reynolds number is 15 million. Natural transition boundary layer state of super critical airfoil was very sensitive to flow disturbances, and real effect of Reynolds number might be fake at lower Reynolds number ranges. So fixed transition of super-critical airfoil was suggested when wind tunnel test Reynolds number did not exceed 15 million.
4. Conclusion
Laminar flow would exit over super critical wing when wind tunnel test Reynolds number was not high enough. And if test Mach number was also low, surface pressure distribution would not be affected obviously by fixed transition. When shock wave and induced boundary layer separation appeared on upper surface, surface pressure distribution would be affected by fixed transition significantly. With the increasing of test Reynolds numbers, fixed transition effect on surface pressure distribution would be weakened, for example, the effect was ignorable when test Reynolds number exceeded 15 million. Fixed transition was used to make boundary layer stable, which could be helpful to eliminate unsteady flow disturbance effect test data quality and obtain pure effect of Reynolds number. Fixed super critical airfoil transition were recommended during wind tunnel tests when test Reynolds number were less than 15 million.

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