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Reynolds number effects of supercritical airfoil with mini-TED in transonic flow

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Abstract. In order to accurately investigate the Reynolds number influence of supercritical airfoil with miniature trailing-edge devices (mini-TED) under transonic conditions. The supercritical airfoil pressure measurement test of high Reynolds number was conducted in the European transonic wind tunnel. The reliability of the high Reynolds number numerical calculation method was validated by the wind tunnel test results. The calculation results are in good agreement with the wind tunnel test results, indicating that the high Reynolds number calculation accuracy could meets the investigation requirement. The transonic flow of supercritical airfoil with mini-TED in the range of Reynolds number 3×10^6~50×10^6 and Mach number 0.76 was simulated using the validated calculation method. Due to the existence of mini-TED, the Reynolds number influence self-adjustment range of the supercritical airfoil disappeared, while the influence magnitude and sensitivity reduced. At the same time, the supercritical airfoil's linear influence of Reynolds number effects has been changed, and the Reynolds number prediction method based on pressure distribution is no longer applicable. After considering the influence of Reynolds number, the detailed design of supercritical wing with mini-TED could be conducted to improve its reliability and economy in the application of advanced aircraft.

1. Introduction

The cruising speed of modern large aircraft is generally located in the transonic range. In order to improve the drag divergence Mach number, the supercritical airfoil is commonly applied in the aerodynamic design process. However, the supercritical airfoil has a thicker thickness, the upper surface is flat, and the trailing edge is loaded significantly. Under the transonic conditions, the aerodynamic characteristics are seriously affected by the Reynolds number. Reynolds number is the ratio of inertial force to viscous force. It is the decisive factor for complex flow phenomena such as shock wave, boundary layer transition and separation on supercritical airfoil under transonic conditions [1]. Therefore, the Reynolds number effect of supercritical airfoil must be accurately considered in the aerodynamic design process to improve the economy and safety of the large aircraft. Especially in the wind tunnel test, the experimental Reynolds number is one order of magnitude smaller than the real flight Reynolds number, so that it is necessary to conduct the Reynolds number influence correction on the test data [2]. In the main wind tunnel test organization, there are engineering estimation, numerical simulation and Reynolds number influence correction method based

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on pressure distribution, which basically meets the correction requirements of conventional airfoil's Reynolds number influence.

Miniature Trailing-Edge Devices (Mini-TED) is a flow control device mounted on the lower surface of the trailing edge of the airfoil. The generalized mini-TED can be divided into different types such as Gurney flaps, split flaps and divergent trailing edges. Among them, the split flap deflection angle can be adjusted according to the actual working conditions, and the application is more convenient, so that is also regarded as mini-TED in a narrow sense. The split flap length does not exceed 2% of the airfoil chord length, which is much smaller than the traditional flap size of 10% to 30% chord length. The mini-TED increases the effective camber of the airfoil, and the Kutta condition of the trailing edge is changed, so that the higher lift and lower drag could be realized under certain conditions. Due to its lower energy input, smaller space size requirements and lighter weight, it has broad application prospects in the advanced aircraft aerodynamic design. Numerous researchers have conducted multifaceted investigation on mini-TED. Chu Hubing calculated the influence of geometric parameters such as mini-TED installation position, length and deflection angle on the lift-drag characteristics, and summarized the design principles of geometric parameters [3]. Shen Dong numerically calculated the influence law and mechanism of the position, height and angle of mini-TED on the lift/drag of airfoil [4]. Xia Jun conducted the wind tunnel test of mini-TED airfoil and obtained the difference in aerodynamic characteristics of the NACA23012 airfoil using mini-TED [5]. Zhou Hua numerically simulated the change of aerodynamic performance of NACA0012 airfoil with mini-TED, and analyzed the mechanism of the lift increasing [6]. By optimizing the installation angle of mini-TED, Huang Wei has increased its application range in improving the aerodynamic characteristics of the aircraft [7]. Wei Chuang used genetic algorithm to optimize the geometric parameters such as height, thickness, installation position of mini-TED, and obtained a geometric configuration with higher lift coefficient [8]. Wang Chen also conducted the optimization design of the height and width of mini-TED design for the NACA0015 airfoil [9]. Hak-Tae Lee [10] used CFD method to simulate the steady and unsteady flow of Gurney flaps with different heights, and discussed its application in aeroelastic stability control. Li Zhi's calculations show that mini-TED can suppress shock oscillation, and reduce or even eliminate separation bubbles, which improve the RAE2822 airfoil's chattering boundary [11]. Rao Pan also obtained the conclusion that mini-TED can improve the RAE2822 airfoil buffeting lift coefficient under transonic conditions [12]. In the AWIATOR project, Airbus explored the application prospects of mini-TED in reducing aircraft aerodynamic noise and delay chattering, and conducted flight test verification on the A340-300 prototype [13]. Thiel [14]、Matalanis [15] combine numerical calculation and wind tunnel test to study the application prospect of mini-TED on propeller rotor airfoil. Richter [16] combined wind tunnel test and calculation methods to study the steady aerodynamic characteristics of supercritical airfoil with mini-TED under transonic conditions, and systematically summarized the results near Mach 0.7. The research results include the influence law of geometric parameters, analyze the working principle of mini-TED, compare the control effect difference with traditional flexible trailing edge, and also obtain the influence of the flow parameters such as Mach number. The study concluded that mini-TED can be used as an effective wing control surface after verification by the Reynolds number effect. In summary, the current research of mini-TED mainly focuses on the influence of geometric parameters, working mechanism, application effect and parameter optimization design. There are few studies on the Reynolds number effect of supercritical airfoil with mini-TED under transonic conditions. Mini-TED changes the pressure distribution, flow separation and vortex at the trailing edge, which affects the position and intensity of the shock wave on the upper surface of airfoil. If the Reynolds number effect is not accurately considered in the design process, the difference of above complex flow will cause the mini-TED actual application effect to deviate from the theoretical design and the maximum benefit cannot be obtained. In severe cases, the correction accuracy of the supercritical airfoil Reynolds number effect is reduced, which directly affects flight safety.

In this paper, the transonic flow field under different Reynolds numbers of supercritical airfoil with and without mini-TED is simulated, and the influence of the Reynolds number of aerodynamic characteristics is obtained. In the European transonic wind tunnel (ETW), the variable Reynolds number pressure test was conducted using supercritical airfoil without mini-TED, and the reliability of the calculation method was validated using the high Reynolds number test results. After mini-TED's installation, the sensitivity of Reynolds number effect decreased, and the Reynolds number self-adjustment area of initial airfoil disappeared. The linear influence law of Reynolds number effect is no longer valid, and the traditional Reynolds number effect correction methods based on pressure distribution are not applicable. It is necessary to consider the influence of Reynolds number during the supercritical wing's mini-TED designing, in order to improve its reliability and economy in the practical application of advanced aircraft.

2. Research methods and models

2.1. Numerical simulation method

The N-S equation was numerical solved by finite volume method：

$$\frac{\partial Q}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=0 \tag{1}$$

Where

$$F=F_I-F_V \quad G=G_I-G_V$$

$$Q=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ E\end{pmatrix} \quad F_I=\begin{pmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (E+p)u\end{pmatrix} \quad G_I=\begin{pmatrix}\rho u\\ \rho uv\\ \rho v^2+p\\ (E+p)u\end{pmatrix} \quad G_V=\frac{1}{\mathrm{Re}}\begin{pmatrix}0\\ \tau_{yx}\\ \tau_{yy}\\ \tau_{yx}u+\tau_{yy}v-q_y\end{pmatrix}$$

$$E=\frac{1}{\gamma-1}p+\frac{1}{2}\rho\left(u^2+v^2\right) \quad \tau_{xx}=(2\mu+\lambda)u_x+\lambda v_y \quad \tau_{yy}=(2\mu+\lambda)v_y+\lambda u_x$$

$$\tau_{yy}=(2\mu+\lambda)v_y+\lambda u_x \quad \tau_{xy}=\tau_{yx}=\mu\left(u_y+v_x\right) \quad \lambda=-\tfrac{2}{3}\mu \quad q_x=-\frac{\mu}{(\gamma-1)M_\infty^2\,\mathrm{Pr}}\frac{\partial T}{\partial x}$$

$$q_y=-\frac{\mu}{(\gamma-1)M_\infty^2\,\mathrm{Pr}}\frac{\partial T}{\partial y} \quad \mathrm{Re}=\frac{\rho_\infty u_\infty L}{\mu_\infty} \quad Ma_\infty=\frac{u_\infty}{a_\infty}$$

The subscript "I" stands for inviscid item, and the subscript "V" stands for viscous item.

The gas viscosity is calculated by Sutherland equation：

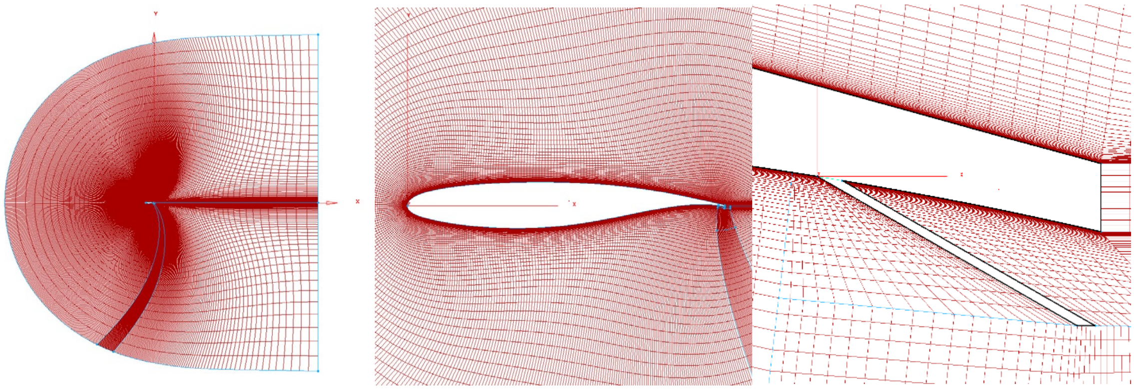
$$\frac{\mu}{\mu_0}=\left(\frac{T}{273.16}\right)^{1.5}\frac{T+110.4}{T+110.4} \tag{2}$$

μ_0 is the viscous coefficient when the temperature is 273K and the atmospheric pressure is 1.013×10^5 Pa.

The Spalart-Allmaras turbulence model was used in this paper to simulate separation flow accurately. LU-SGS and ROE scheme were selected to solve the equation, and wall and far field were defined as boundary conditions. Multigrid technology was also used in the calculation to speed up convergence.

2.2. Research model

The research model of this paper is the supercritical airfoil with mini-TED. The upper surface of supercritical airfoil is relatively flat, and the curvature of the lower surface of the trailing edge is large to compensate for insufficient lift. A typical supercritical airfoil was chosen as the initial configuration and mini-TED was added to the trailing edge (shown in figure 1).



a. computation grid b. grid distribution of airfoil c. grid distribution of mini-TED

Figure 1. Computation model and grid.

The grid is generated by the commercial software Gridgen, encrypted at the head and trailing edge of airfoil. The height of boundary layer grid meets the requirement of $y^{+}=1$.

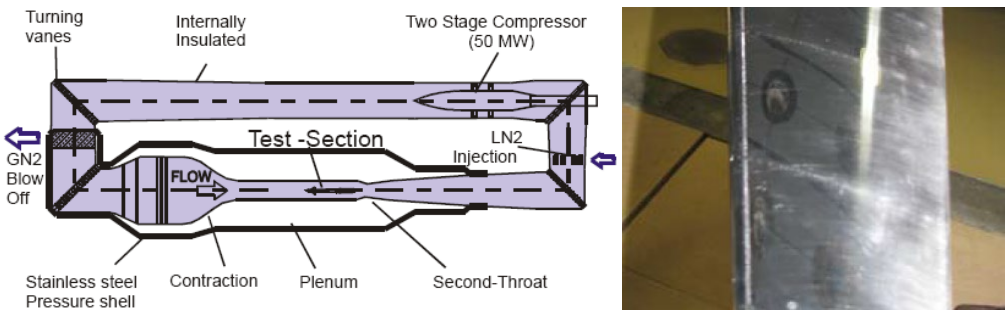
The length, position and deflection angle of the mini-TED have a serious impact on the airfoil transonic flow characteristics. This paper mainly studies the influence of Reynolds number effects, so that the geometric parameter is consistent. The length of mini-TED is 2% of the chord length of the airfoil, and is installed at the 98% C position of the airfoil with a deflection angle of 15°. The mini-TED is removed and the initial configuration grid is generated using the same mesh size and parameters to reduce the computational error of the mini-TED impact comparison.

The simulated Mach number in this paper is 0.76, the Reynolds number is 3×10^{6}~50×10^{6}, and the angle of attack is calculated to be -4°~8°.

3. Reliability validation

In this paper, numerical simulation is applied to study the influence of Reynolds number on supercritical airfoil with mini-TED. In order to ensure the accuracy of the calculation, the reliability of the CFD method must be validated. In general, the reliability validation of the CFD program is conducted by comparison with wind tunnel test results. However, there is insufficient wind tunnel with high Reynolds number test capability. Supercritical airfoil is sensitive to flow conditions at transonic speeds, making it difficult to validate CFD method without enough high Reynolds number experiment results.

The supercritical airfoil high Reynolds number verification test is conducted in European Transonic Wind tunnel (ETW). Mach number range of ETW is 0.15~1.3, and test section size is 2m×2.4m. ETW is one of the only two high Reynolds number simulation wind tunnels all around the world. The test results near the flying Reynolds number could be obtained by enhance total pressure or reduce operating temperature. The outline of the wind tunnel is shown in figure 2.



a. Outline of wind tunnel b. Test model

Figure 2. ETW test equipment and test model.

The variable Reynolds number pressure test was conducted in ETW. The profile of test model is the same as the airfoil in figure 1, but without the mini-TED (shown in figure 2b). The test Mach number is 0.4~0.86, and the Reynolds number range from 2.3×10^6 to 35×10^6. The total pressure range of the test is 124~340kPa, and the operating temperature range is 114~300K. The pressure distribution of supercritical airfoil under high Reynolds number conditions were obtained in the test, and the accuracy of test results are extremely high. The calculation results of this paper are compared with the results of ETW test. Figure 3 is a comparison of airfoil pressure distributions when Ma = 0.76, α = 8°, and Re = 30×10^6.

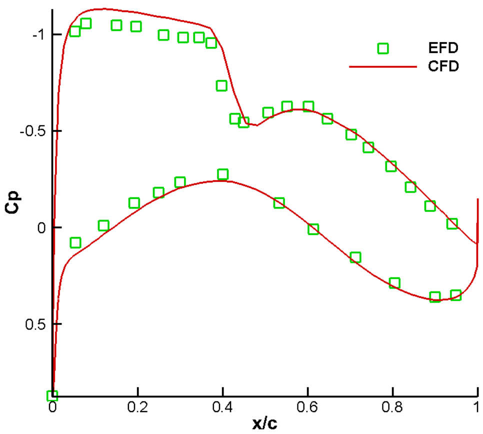
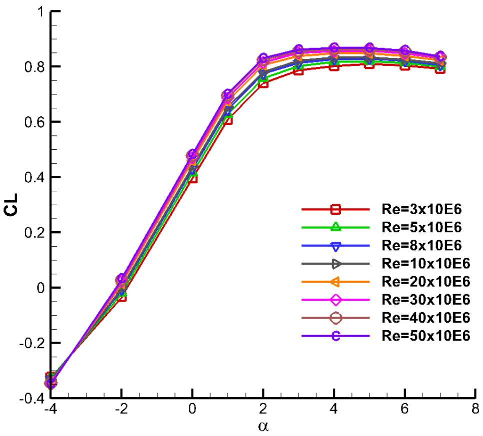


Figure 3. Comparison of CFD results with ETW results.

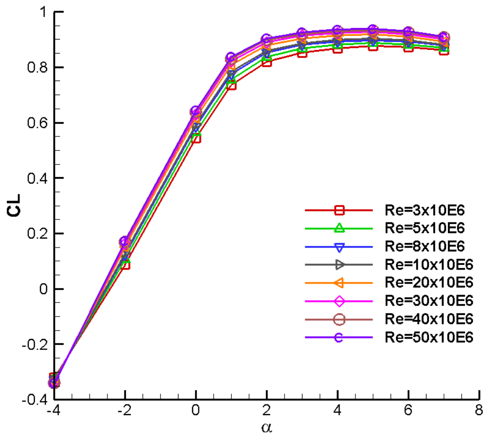
As shown in figure 3, the CFD calculation results in this paper agree well with the ETW wind tunnel test results. Typical characteristics such as upper surface pressure peak, shock position, and pressure recovery are captured accurately. The results show that the numerical method for simulating the high Reynolds number flow in this paper is reliable, which meets the research requirement.

4. Analysis and discussion

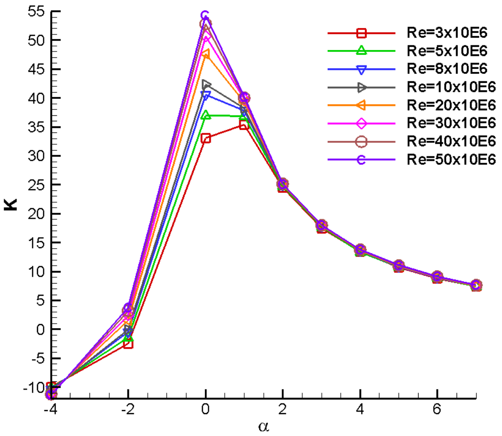
Figure 4 shows the Reynolds number influence on the lift and lift-drag ratio of the supercritical airfoil with and without mini-TED. In figure 4a/4c, as the Reynolds number increasing, the supercritical airfoil lift increases after α>-2°, and the slope of lift line increases slightly. The drag decreases significantly in the angle range of -2°~1°, which leads to an increase of the lift-to-drag ratio. After separation occurred (α>2°), the increase of lift-to-drag ratio is significantly reduced. In figures 4b and 4d, the lift line of supercritical airfoil with mini-TED is shifted upwards as a whole, and the lift coefficient is larger than the initial configuration under the same Reynolds number condition. The Reynolds number has a significant influence on the drag, which is shown in the changing of lift-to-drag ratio. Compared with initial airfoil without mini-TED, the Reynolds number influence of airfoil with mini-TED increases at α=-2°, and the influence decreases significantly at α=0°. The amount of influence is drastically reduced at α=1°, which is basically close to the influence of Reynolds number effect at a larger positive angle of attack. In general, the effect of mini-TED on the Reynolds number effect of the supercritical airfoil lift-drag characteristics is mainly concentrated on the range of sensitive angles and the magnitude of increments. Due to the existence of mini-TED, the sensitive angle range of the supercritical airfoil Reynolds number effect is reduced, and the influence magnitude decreases when α=0° and 1°.



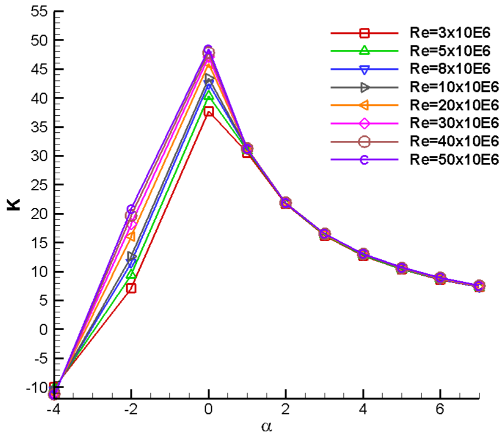
a.CL-α curves without mini-TED



b.CL-α curves with mini-TED



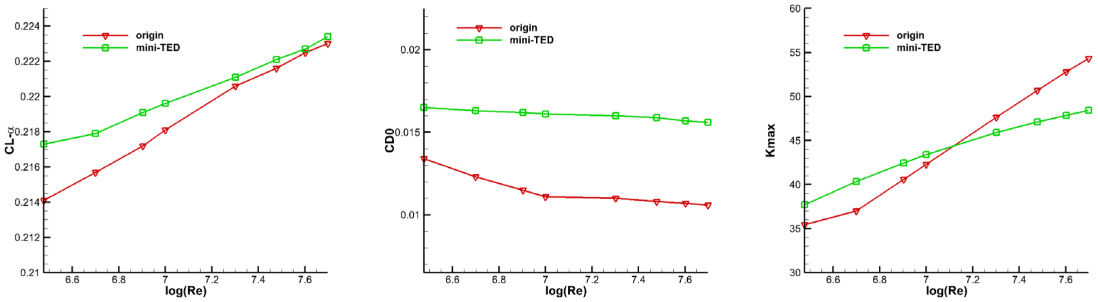
c. K-α curves without mini-TED



d. K-α curves with mini-TED

Figure 4. Lift and drag characteristics Reynolds number effects with and without mini-TED.

During the design process of aircraft, it is necessary to obtain the characteristic values such as the slope of the lift line, the zero-lift angle of attack, the zero-lift drag, and the maximum lift-to-drag ratio under different Reynolds number conditions, in order to correct Reynolds number effect. The Reynolds number effect of airfoil aerodynamic coefficient with and without mini-TED is shown in figure 5. Reynolds number effect of supercritical airfoil with mini-TED has no apparent change, but the influence difference is obviously reduced, and even the influence law of some Reynolds number range has been changed. With Reynolds number increases from 3×10^6 to 50×10^6, the slope of the initial configuration lift line increased by 41.6%, but influencing value is only 28% after the installation of mini-TED. Similarly, the Reynolds number influence of the maximum lift-to-drag ratio after mini-TED installation was reduced from 53.3% to 28.4%. In Figure 5b, the curve of zero-lift drag is changed by the effect of Reynolds number with and without mini-TED. There is a Reynolds number self-adjustment area of Re=10×10^6~20×10^6 of initial configuration, and the influence curve is divided into two sections. When the Reynolds number is smaller than the self-adjustment area, the zero-lift drag decreases linearly with the increase of the Reynolds number. After the Reynolds number exceeds the self-adjustment area, the slope of the curve decreases significantly, resulting in the drag difference does not change much and the linear law disappears. With the Reynolds number self-adjustment area completely disappeared, the drag difference is not obvious in the rest range of variation. The airfoil flow is insensitive to the Reynolds number, and the influence law is similar to the initial configuration (where exceeds self-adjustment). The disappearance of the Reynolds number self-adjustment area and linear influence law increases the difficulty of Reynolds number correction of zero-lift drag.

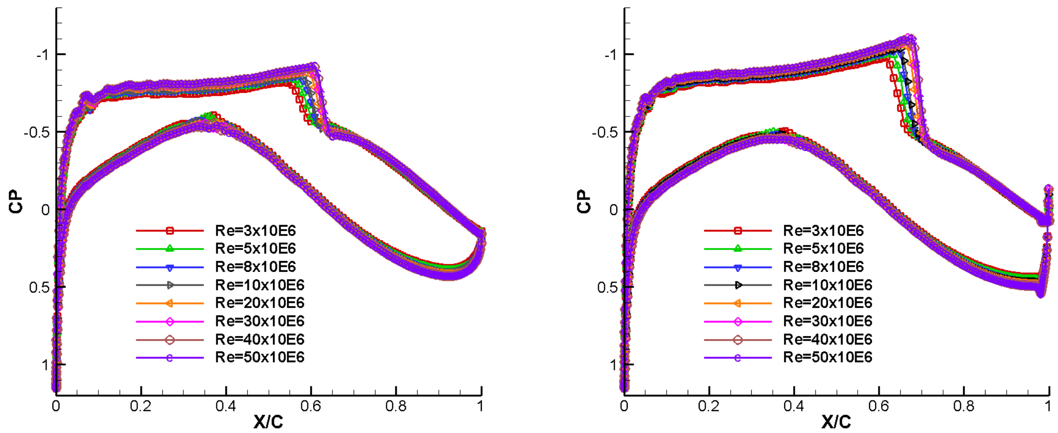


a. Results of CL^{α} b. Results of CD0 c. Results of Kmax

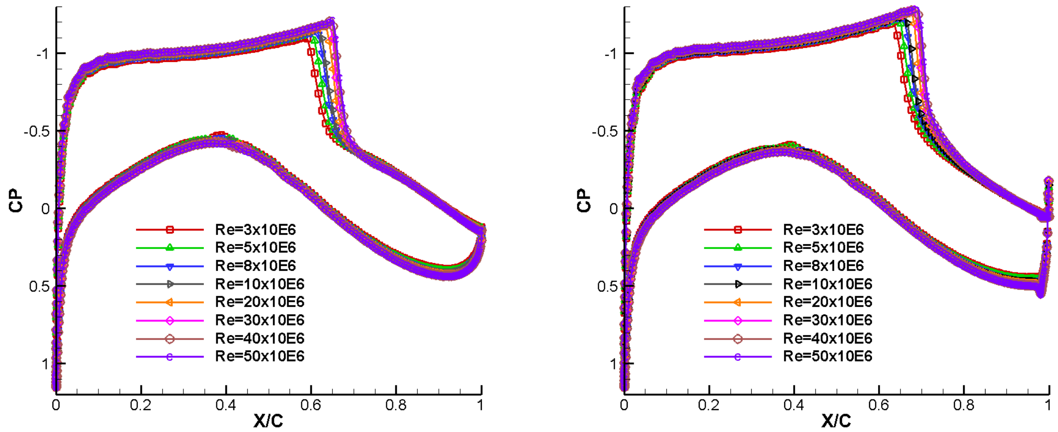
Figure 5. Aerodynamic coefficient Reynolds number effects with and without mini-TED.

Figure 6 shows the pressure distribution of supercritical airfoil and Reynolds number influence with and without mini-TED when the angle of attack is 0° and 1°. Under the same Reynolds number and angle of attack, the mini-TED make the shock wave move backward and the shock intensity is enhanced (especially at angle of attack of 0°), while the wave front pressure peak/trailing edge pressure coefficient decreases and the pressure platform at the shock wave foot disappears. The pressure near mini-TED on the lower surface is increased, and the trailing edge loading effect is more obvious. The closed area of the pressure curve increases, indicating that the lift of supercritical airfoil with mini-TED become higher (as shown in figures 4a and 4b). The increase of shock intensity is the main reason of larger drag (as shown in figure 5b).

Reynolds number mainly affecting the sensitive factors such as the shock position/intensity, pressure coefficient near the shock wave or trailing edge. When α=0°, the shock wave position moves backward after the mini-TED is added. The Reynolds number sensitive area on the airfoil upper surface is move backward from 55%~65% of the initial configuration and slightly reduced to 63%~71%. As Reynolds number increases, the difference of pressure platform (after the foot of shock wave) decreases, and the trailing edge pressure coefficient is almost independent with the Reynolds number. When α=1°, the Reynolds number influence sensitive area of the airfoil upper surface reduced after mini-TED's installation. Because of that, the Reynolds number influence of the aerodynamic characteristics in figure 4 and figure 5 is reduced.



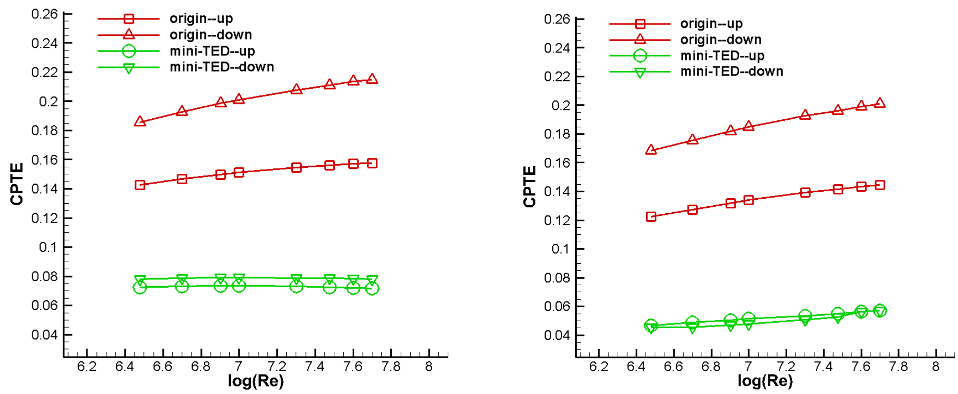
a. Pressure distribution without mini-TED（α=0°） b. Pressure distribution with mini-TED（α=0°）



c. Pressure distribution without mini-TED（α=1°） d. Pressure distribution with mini-TED（α=1°）

Figure 6. Airfoil pressure distribution with and without mini-TED under different Reynolds numbers.

The trailing edge of airfoil is completely located in the mini-TED's wake, so that its pressure distribution and Reynolds number effect are influenced by mini-TED obviously. Figure 7 shows the Reynolds number effect on the trailing edge pressure coefficient of the supercritical airfoil with and without mini-TED under different angles of attack. Before the mini-TED installation, the trailing edge pressure coefficient of initial configuration of supercritical airfoil become higher with the increasing of Reynolds number, and the pressure difference between the upper and lower surfaces increases. The influence curve has an approximate linear trend, so that the Reynolds number effect could be corrected according to this linear law. After mini-TED installation, the Reynolds number influence of trailing edge pressure coefficient changes significantly. When α=0°, the pressure coefficient of the upper and lower surfaces of airfoil and its difference are almost independent with the Reynolds number, indicating that the airfoil pressure recovery is almost the same, so that the zero-lift drag in Figure 5b hardly changing with the increasing of Reynolds number. When α=1°, the trailing edge pressure coefficient of airfoil increases slightly with the increasing of Reynolds number, but the pressure difference between the upper and lower surfaces is small. As shown in figure 7, mini-TED of supercritical airfoil reduces the sensitivity of Reynolds number influence, the Reynolds number linear influencing law of initial configuration is changed. The traditional Reynolds number effect prediction and correction method based on pressure distribution is no longer applicable.



a. trailing edge pressure coefficient，α=0° b. trailing edge pressure coefficient，α=1°

Figure 7. Trailing edge pressure coefficient Reynolds number effects with and without mini-TED.

5. Conclusion

The effect of mini-TED on the Reynolds number effect of supercritical airfoil is numerically simulated in this paper. Results indicated that:

The CFD results agreed well with the ETW high Reynolds number test results, which proved that the computing method of this paper could meet the research requirements；

After mini-TED's installation, the sensitivity of Reynolds number decreased, and aerodynamic characteristics difference influenced by Reynolds number reduced；

After mini-TED's installation, the Reynolds number influence self-adjustment range of initial airfoil drag disappeared, and zero-lift drag is not sensitive to Reynolds number changes；

After mini-TED's installation, the linear influence of Reynolds number is no longer valid; The traditional Reynolds number effect correction methods based on pressure distribution are not applicable, which increase correction difficulty of supercritical airfoil wind tunnel test；

In the future, it is necessary to consider the influence of Reynolds number during the supercritical wing's mini-TED designing, in order to improve its reliability and economy in the practical application of advanced aircraft.

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