Aerodynamic performance of three-dimensional wing tip high Reynolds number turbulence with jet control

Zizhen Huang¹, Chengyuan Luo¹, Peng Qian¹, Zhiwei Chen¹ and Minghou Liu*¹

¹ Department of Thermal Science and Energy Engineering, University of Science and Technology of China(USTC), Hefei, Anhui, 230027, PR China
*Corresponding author’s e-mail: mhliu@ustc.edu.cn

Abstract. In this paper, the wing tip jet is proposed to improve the aerodynamic performance of the three-dimensional ONERA M6 wing at high Reynolds numbers. The CFD method is used to perform numerical simulation with the SST k-ω two-equation model. To verify present numerical model, ONERA M6 wing at the attack angle(α) of 2° is selected and the simulation results are in good agreement with the experimental data. The flow around the airfoil at high Reynolds number is simulated at 0°-14° attack angle, and the critical attack angle is 11° without jet. Finally, the influence of the jet on the aerodynamic characteristics of the airfoil at different attack angle are studied and it is found that the lift coefficient and lift-drag ratio of the airfoil increase with jet.

1. Introduction
Improving the aerodynamic performance of airfoil is one of the common problems in engineering practice, such as aircraft take-off, landing, turbine engine compressor blade, wind turbine. For example, the aerodynamic performance of wind turbine blades is directly related to the power output. To find an effective method to control the turbulence of airfoil is an urgent problem to be solved[1]. Currently, active flow control technology is a research hotspot in the field of airfoil [2,3], which can significantly improve the performance of airfoil. As one of active control technologies, jet technology can significantly improve the lift of airfoil, delay laminar flow separation on upper wing surface, and increase stall attack angle of airfoil[4-6].

In this study, the jet is proposed to control the ONERA M6 wing tip flow. By comparing the calculation results with the original airfoil, the effect of the tip jet on the aerodynamic performance is concluded.

2. Mathematical and physical model

2.1. Physical model
The ONERA M6 wing is selected for three-dimensional calculation. The geometric models are shown in figure 1. Using the Cartesian coordinates, the wing extends along the Z direction, and b is the chord length of the wing. When y/b is different, it corresponds to different sections of the wing, y/b=0.44 corresponds to z=0.524094m, and y/b=0.658 corresponds to z=0.77667m. The total length of the outflow field is 285m along the X direction, 78m in the Y direction and 95.7m in the Z direction. Therefore, the boundary of the external flow field is far enough from the wing.
2.2. Mathematical model
The Reynolds number is roughly in the range of $10^6$-$10^7$, using the SST $k$-$\omega$ two-equation turbulence model[7,8] and the compressible Reynolds average N-S equation as the governing equation. The solution is based on density implicit solver and second-order upwind scheme. All relaxation factors are defined as 0.8 and the residual values are 0.00001. It can be seen from Figure 1(b) that the boundary of the external flow field is far away from the wing, therefore, the boundary is set as the pressure far field type. The boundary condition of the wing surface are set to be no slip, no penetration, and adiabatic. The Mach number is 0.8, that is, the ideal gas velocity is 272m/s, the local atmospheric pressure $p=0.99$atm, the local temperature $T=300K$, and the sideslip angle=$0^\circ$.

2.3. Model validation
In order to verify the mathematical model, the simulation results are compared with the experimental data of Schmitt et al[9]. The locally grid of the airfoil is shown in figure 2. The entire region uses hexahedral structured grid and the total number of grids is 739,750.
3. Results and Discussion

3.1. Effect of attack angle on aerodynamic characteristics of airfoil without jet

The pressure distribution contours of the upper and lower surfaces of the airfoil are compared with different attack angles (α), as shown in figure 4. The lower surface in the figure is a bottom view.
It can be seen from figure 4 that with the increase of attack angle, the pressure on the lower surface increases gradually, the high pressure area of the lower surface concentrates on the right side at the beginning and gradually transfers to the left side, and the pressure of the upper surface lower than 4000Pa gradually expands, and finally concentrates near the wing root. The pressure difference between the upper and lower surfaces, i.e. the lift force, increases continuously, which is caused by the
increase of the velocity difference between the upper and lower surfaces when the attack angle increases.

![Figure 5. Curve of lift coefficient with attack angle without jet.](image1)

![Figure 6. Curve of drag coefficient with attack angle without jet.](image2)

As shown in figure 5, with the increase of attack angle, the lift coefficient increases gradually. When the attack angle is 11°, the lift coefficient reaches 0.643 and then drops suddenly. This is basically consistent with the lift coefficient curve measured in the wind tunnel experiment. When the critical attack angle is reached, the lift coefficient reaches the maximum value, and the airfoil enters stall state.

As can be seen from figure 6, the drag coefficient increases as the attack angle increases. When the attack angle is small, the drag coefficient is small and increases slowly. With the increase of attack angle, the drag coefficient increases faster, because the pressure resistance on the airfoil is the dominant factor.

3.2. Effect of jet on aerodynamic characteristics of airfoil

The jet is set to shoot out from the tip surface of the wing as the figure 7 shows, the jet velocity is 1.5m/s, the boundary condition is the velocity inlet, and the other settings are the same as the one with no jet.

![Figure 7. Jet at wing tip](image3)
Figure 8. Velocity distribution contours of without jet(a) and with jet(b) at $\alpha=2^\circ$ when $x=-0.1m$.

Figure 8 shows that at the attack angle $\alpha=2^\circ$, the velocity distribution at the wing tip is different in the case of jet and without jet, and the low velocity region at the wing tip is enlarged, which is caused by the jet.

Finally, the lift of the airfoil with and without jet are compared. It can be seen from table 2 that the lift coefficient and lift drag ratio with jet are larger than that without jet at the same attack angle except for the attack angle of 0°, which indicates that the jet is effective in order to improve the aerodynamic characteristics.

| $\alpha$(°) | $C_L$ without jet | $C_L$ with jet | $C_{L}/C_D$ without jet | $C_{L}/C_D$ with jet |
|-------------|-------------------|----------------|-------------------------|---------------------|
| 0           | 0.00913           | 0.00911        | 14.53593                | 14.20693            |
| 2           | 0.18484           | 0.18490        | 15.48909                | 15.61509            |
| 4           | 0.3656            | 0.36712        | 15.88318                | 15.89756            |
| 6           | 0.53635           | 0.53856        | 11.01212                | 11.01939            |
| 8           | 0.60629           | 0.61094        | 6.87973                 | 6.93124             |
| 10          | 0.64234           | 0.64277        | 5.08256                 | 5.08868             |

4. Conclusion
In this paper, the tip jet is proposed to improve the wing aerodynamics performance. The SST K-ω two equation model is used to simulate the high Reynolds number flow around a three-dimensional ONERA M6 wing with or without the tip jet technology at different attack angles.

- In the case of no jet, with the increase of attack angle, the pressure difference between the upper and lower surfaces, i.e. the lift force, increases gradually with the increase of attack angle, which is caused by the increase of the velocity difference between the upper and lower surfaces.

- The lift coefficient increases with the increase of attack angle when attack angle($\alpha$) is between 0°-14°, which reaches the maximum lift coefficient of 0.643 at $\alpha=11^\circ$, and then drops suddenly, and the airfoil enters stall state. The drag coefficient increases with the increase of attack angle. When the attack angle is small, the drag coefficient is small and increases slowly. With the increase of attack angle, the drag coefficient increases faster, and the pressure resistance on the airfoil is the dominant factor.
The lift coefficient and lift drag ratio with jet are higher than the one without jet at the same attack angle except for $\alpha=0^\circ$. It shows that jet has favorable interference and can improve aerodynamic characteristics.

**Acknowledgments**

This work was supported by the National Key R&D Program of China [2018YFB1900602] and the Supercomputing Center of University of Science and Technology of China.

**References**

[1] Dong B G. (1993) Unsteady flow and eddy motion. National Defense Industry Press, Beijing.
[2] YouÅ D, Moin P. (2008) Active Control of Flow Separation Over an Airfoil Using Synthetic Jets[J]. Journal of Fluids and Structures, 24 (8): 1349-1357.
[3] Shaw L, Smith B, Saddoughi S. (2006) Full-Scale Flight Demonstration of Active Control of a Pod Wake[C]. Aiaa Flow Control Conference. San Francisco. 3185.
[4] Feng J, Lin Y, Zhu G, et al. (2019) Effect of synthetic jet parameters on flow control of an aerofoil at high Reynolds number[J]. Sadhana, 44:190.
[5] Wu J, Shen M, Jiang L. (2020) Role of synthetic jet control in energy harvesting capability of a semi-active flapping airfoil[J]. Energy, 208: 118389.
[6] Wang J, Wu J. (2020) Aerodynamic performance improvement of a pitching airfoil via a synthetic jet[J]. European Journal of Mechanics - B/Fluids, 83: 73-85.
[7] Abid R. (1992) Assessment of Two-Equation Turbulence Models for Predicting Transitional Flows. In: M.Y.Hussaini A.Kumar C.L.Streett. (Eds.), Springer-Verlag, New York, pp. 485-497.
[8] Menter F R. (1994) Two-equation eddy-viscosity turbulence models for engineering applications[J]. Aiaa Journal, 32.
[9] Schmitt V. (1979) Pressure Distributions on the ONERA M6-Wing at Transonic Mach Numbers, Experimental Data Base for Computer Program Assessment[J]. AGARD AR-138.