Pulsed Jet Characteristics of Circulation Control Airfoil

Yuchang Lei1, Yanhua Zhang2*, Dengcheng Zhang2 and Guangxu Su1

1 Graduatee School, Air Force Engineering University, Xi’an 710051, China
2 Aeronautics Engineering College, Air Force Engineering University, Xi’an 710038, China

*Corresponding author’s e-mail: 1634365359@qq.com

Abstract. Compared with the steady jet, the mass flow consumed by the pulsed jet is lower, which is of great significance for solving the jet source in the circulation control technology. In order to further study the effects of different parameters on energy consumption and aerodynamic coefficient pulse in pulsed jet, based on the Reynolds average N-S equation, the aerodynamic characteristic calculation and flow field analysis of the circulation control airfoil under the action of pulsed jet are carried out, and the aerodynamic benefit is evaluated with the combination of energy consumption and aerodynamic coefficient fluctuation. The results show that: Pulsed jet is more suitable for use at high angle of attack. By using the combination of pulsed jet and steady jet, good results can be obtained in three aspects: time-averaged lift coefficient, lift coefficient fluctuation and energy consumption. The research results can be used as a reference for guiding the use of pulsed jet in circulation control technology.

1. Introduction

The circulation control technology increases the lift of the airfoil by generating a tangential jet at the trailing edge of the airfoil to increase the circulation on the surface of the airfoil.[1] After more than 80 years of development, the existing wind tunnel experiments and numerical simulations have proved its advantages in improving lift and lift-drag ratio.[2-3] However, at present, the circulation control technology has not been widely used in aircraft, because the jet generated at the trailing edge of the airfoil needs to draw air from the engine or set up additional air supply devices, this leads to thrust loss or additional energy consumption of the engine.[4] Therefore, in recent years, some scholars have gradually proposed to use pulsed jet instead of steady jet to reduce mass flow and energy consumption.[5] Previous studies have proved that the pulsed jet can greatly reduce the mass flow required by the jet while maintaining the average lift coefficient of the airfoil.[6-7] At the same time, it has excellent performance in reducing gust load, improving Aeroelasticity and so on.[8] However, because the peak velocity produced in the pulsed jet is often larger than that of the steady jet, and additional energy consumption is needed in the pulse mechanism, the energy dissipation characteristics of the pulsed jet for the circulation control airfoil still need to be further studied.

The simple pulsed jet can not be directly applied to the aircraft, because the unsteady aerodynamic coefficient under the action of the pulsed jet will lead to the severe jitter of the aircraft. In order to reduce this unsteady aerodynamic change, the aerodynamic variation and energy consumption characteristics of the circulation control airfoil are studied by the combined action of steady and pulsed jet in this paper.
2. Numerical calculation method

2.1. Computational model and grid

In this paper, the modified supercritical airfoil is used for related research. The relative thickness of the airfoil is 17%, and the chord length is \( c = 240 \text{mm} \). The radius of the Coanda trailing edge surface is \( r/c = 2\% \). The height of the jet port is \( h = 0.001c \). Figure 1 is a schematic diagram of a modified supercritical airfoil. In the calculation area, 30 times the chord length of the airfoil is selected, and the O-shaped structure grid is used in meshing. The grid height of the first layer in the boundary layer is about \( 1 \times 10^{-5} \text{m} \), and the grid height of the first layer near the jet port is \( 2 \times 10^{-6} \text{m} \). Ensure that the \( y^+ \) of the height of the first layer is less than 1 to meet the calculation requirements of the viscous bottom layer. The total number of grids is about 580000. Figure 2 shows the meshing of airfoil.

![Figure 1: Modified Supercritical Airfoil](image1.png)

![Figure 2: Computational Grid](image2.png)

2.2. Computational model and grid

The basic pulse form selected in this paper is a square wave pulsed jet with a frequency of \( T = 200 \text{hz} \) and a duty cycle of \( DC = 70\% \). The ratio of steady jet to pulsed jet is defined as \( r_{sp} \). Equation 1 represents the jet velocity of the pulsed jet in one period.

\[
V_{jet}(t) = \begin{cases} 
V_{jet, \text{max}} & t \in \left( t_{\text{open}}, t_{\text{open}}^0 \right) \\
V_{jet, \text{max}} \cdot r_{sp} & t \in \left( t_{\text{open}}^0, T \right) 
\end{cases}
\]

(1)

The momentum coefficient of jet is an important dimensionless parameter to measure the intensity of jet and characterize the momentum of airflow. Equation 2 represents the magnitude of the momentum coefficient of the jet.

\[
C_{\mu} = \rho \frac{1}{0.5 \rho_{\infty} V_{\infty}^2 S} \int_0^T \rho V_{jet}(t) h dt = \frac{T}{0} \rho V_{jet}(t) h dt
\]

(2)

\( \dot{m}_{av, jet} \) represents the mass flow through the jet outlet per unit time. It is assumed that the isentropic expansion of the air flow to the jet exit, and the static pressure of the far front flow is the static pressure of the jet outlet.

For the commercial software FLUENT, the main factors that affect the calculation of unsteady aerodynamics include the number of internal iteration steps and the time step. The time step mainly reflects the change of the flow in the physical time, while the inner iterative step is mainly used to analyse the flow in each time step. Generally speaking, the smaller the time step is and the larger the inner iterative step is, the more accurate the unsteady numerical calculation is. But at the same time, the amount of computing resources consumed is huge. It takes about 120 hours to run on a high-performance computer with 40cpu when the number of internal iterations is 100 and the local time step is \( 5 \times 10^{-5} \text{s} \). Over-accurate calculation is of little significance to the analysis of the results. In the early stage, the
author has verified the irrelevance between the inner iteration step and the local time step, and finally selected the inner iteration number of 50 and the time step of $5 \times 10^{-5}$ s as the calculation condition.

3. Result analysis

3.1. The influence of angle of attack

Figure 3 shows the variation trend of the lift coefficient of the circulation control airfoil at different angles of attack. For the steady jet, the efficiency-cost ratio of the airfoil is $\Delta C_{L}/C_{\mu} = 36.9$ at 0° angle of attack and 11.9 at 15° angle of attack. With the increase of the angle of attack, the aerodynamic benefit of the steady jet decreases. Compared with the steady jet, the pulsed jet has more prominent lift performance at high angle of attack. At 15° angle of attack, the efficiency-cost ratio of the airfoil is $\Delta C_{L}/C_{\mu} = 36.7$, and the aerodynamic benefit continues to increase with the increase of the angle of attack. The steady jet has good lift characteristics at lower angles of attack, but not at high angles of attack. Pulsed jet can bring high lift benefit in a large range of angle of attack, especially it provides a better solution to aerodynamic stall at high angle of attack.

In the circulation control technology, the trailing edge jet needs to draw air from the engine or set up additional air supply devices, which requires additional energy consumption. A systematic comparison of the energy consumption and aerodynamic characteristics of pulsed and steady jets is very important to measure the effect of circulation control. The energy consumption is expressed by the power coefficient required to form the jet. It is assumed that the jet is achieved through an air pressure pump installed inside the wing, which absorbs the free flow of gas from the outside and is compressed into the jet trough to form a jet. The energy consumption power can be expressed by the change of mass flow rate and total enthalpy:

$$
P_{c, \text{jet}} = \frac{\dot{m}_{\text{av, jet}} C_{T2}}{\eta} \left[ \left( \frac{P_{t1}}{P_{t2}} \right)^{\frac{y-1}{y}} - 1 \right] \left( 0.5 \rho_{\infty} V_{\infty}^3 S \right)
$$

(3)

$P_{c, \text{jet}}$ represents the energy consumption power coefficient produced by the jet. $P_{t2}$ and $T_{t2}$ represent the total pressure and temperature of free flow. $P_{t1}$ represents the total pressure at the exit of the jet. $\eta$ represents the working efficiency of the air pressure pump, which is 0.85 in this paper. By using an oscillating blowing actuator, the stable or oscillating jet can be achieved by alternately opening and closing the connection between the air pressure pump and the injection slot, or by opening and closing the connection between the air pressure pump and the fluid suction channel. The actuator can provide a large jet momentum, which is very suitable for the circulation control technology for high-speed jet. Of course, the valve switch that drives the actuator also needs additional pressure sources, and complex piping systems will also cause pressure loss and additional energy consumption, but these consumption is obviously outside the scope of this paper.

In order to further analyse the influence of aerodynamic characteristics and energy consumption on jet control effect under the action of pulsed jet and steady jet. In this paper, the aerodynamic quality factor $AFM1$ proposed by Seifert is used to measure.[9] This index is based on the lift-drag ratio, and the jet power is converted into equivalent resistance. The higher the value, the more effective it is to provide power for the actuator than for the power plant, and it is more advantageous in increasing lift and reducing drag, and the higher the efficiency of jet control is. Equation 4 represents the aerodynamic quality factor $AFM1$.

$$
AFM1 = \frac{L/(D+P)}{(L/D)_{\text{baseline}}}
$$

(4)

Figure 4 shows the aerodynamic quality factor curves under different momentum coefficients. For the steady jet, the control efficiency decreases gradually with the increase of the angle of attack, and then remains basically unchanged. For the pulsed jet, with the increase of the angle of attack, the control
efficiency decreases at first, then increases rapidly, and gradually exceeds the steady jet. This is because at medium and low angles of attack, the lift effect of steady jet is obvious, the energy consumption is lower than that of pulsed jet, and the control efficiency is higher. With the increase of the angle of attack, the effect of steady jet on lift decreases gradually, and the airfoil enters the stall state ahead of time, and the control efficiency decreases. At high angle of attack, the lift coefficient of pulsed jet increases obviously, the stall angle of attack is delayed, and the control efficiency increases gradually.

3.2. The influence of ratio

Figure 5 shows the variation curve of aerodynamic coefficient and aerodynamic quality factor corresponding to different ratio $r_{sp}$ of steady jet part and pulsed jet part at 15° angle of attack. Figure 6 shows the variation curve of lift coefficient with time under different ratio $r_{sp}$. With the increase of the proportion of steady jet, the time-averaged lift coefficient decreases gradually, and the decreasing speed is slow at first and then fast. This shows that properly increasing the proportion of steady jet will not greatly reduce the time-averaged lift coefficient, and can effectively reduce the lift coefficient fluctuation compared with single pulsed jet. When the ratio is 0.84, the time-averaged lift coefficient is reduced by only about 12%, but the lift coefficient fluctuation is reduced by about 80%. The energy consumption of pulsed jet is higher than that of steady jet. Properly increasing the proportion of steady jet can effectively reduce the energy consumption of pulsed jet. When the $r_{sp}=0.566$, the time-averaged lift coefficient decreases, but the aerodynamic quality factor AFM1 is basically unchanged, which can achieve the best aerodynamic benefit.

In order to analyse the variation trend of lift coefficient under different $r_{sp}$, figure 7 and 8 shows the variation diagram of trailing edge flow field when the ratio is 0.566 and 0.84 respectively. When the
$r_{sp} = 0.566$, on the whole, the detached vortex in the trailing edge flow field gradually goes through the process of generation, backward movement and shedding. At this time, the proportion of the steady jet is low, and the steady jet velocity is small, which can not break through the outer side of the trailing edge and flow below the trailing edge. When high-speed pulsed jet is generated, the jet moves from above the trailing edge of the airfoil to below the trailing edge, resulting in a severe fluctuation of the lift coefficient. When the $r_{sp} = 0.84$, on the whole, the movement of the detached vortex in the trailing edge flow field is not obvious. At this time, the proportion of the steady jet is relatively high, and the steady jet velocity is larger, which has broken through the outer side of the trailing edge and flowed below the trailing edge. In the whole stage, the jet moves below the trailing edge of the airfoil, and the fluctuation of lift coefficient is weakened.

4. Conclusion
In this paper, through the numerical simulation of the circulation control airfoil under the action of steady and pulsed jet, the corresponding aerodynamic coefficient and energy consumption characteristics are analysed, and the following conclusions are obtained:

(1) For steady jet, it is more suitable to be used at lower angle of attack, and for pulsed jet, it is more suitable to be used at higher angle of attack.

(2) Compared with the steady jet, the pulsed jet consumes more energy, the aerodynamic coefficient pulsates more violently, and the energy consumption is the lowest when the aerodynamic force is stable.

(3) The combination of pulsed jet and steady jet can achieve better results in the parameters such as energy consumption, lift coefficient fluctuation and time-averaged lift coefficient, and has better aerodynamic benefits than single pulsed jet or steady jet.

References
[1] Englar R J. (1975) Circulation control for high lift and drag generation on a STOL aircraft. Journal of Aircraft, 12(5), 457-463.
[2] Jolslin R D, Jones G S. (2006) Application of circulation control technology (Progress in Astronautics and Aeronautics). USA, AIAA.
[3] Englar R J, Gregory G H. (1984) Development of advanced circulation control wing high-lift airfoil. Journal of Aircraft, 21(7), 476-483.
[4] Englar R J. (2004) Overview of circulation control pneumatic aerodynamics: Blown force and moment augmentation and modification as applied primarily to fixed-wing aircraft. Proceedings of the 2004 NASA/ONR Circulation Control Workshop, Part 1, NASA/Office of Naval Research, 37–99.
[5] Jones G, Englar R. (2003) Advances in pneumatic controlled high lift systems through pulsed blowing//21st AIAA Applied aerodynamics conference: 3411.
[6] Warsop C, Crowther W J. (2018) Fluidic Flow Control Effectors for Flight Control. AIAA Journal, 56(10), 3808-3824.

[7] Carmona H, Cházar H, Trasloscheros A, et al. (2016) CFD RANS Simulation of 2D Circulation Control Airfoil. //Recent Advances in Fluid Dynamics with Environmental Applications. Springer, Cham, 81-101.

[8] Li, Y., Qin, N. (2020). Airfoil gust load alleviation by circulation control. Aerospace Science and Technology, 98, 105622.

[9] Seifert A. (2007) Closed-loop active flow control systems: actuators //Active Flow Control. Springer, Berlin, Heidelberg, 85-102.