Effect of suction and blowing control on NACA 0012 airfoil at low Reynolds number

Zhiyong Zhang*, Tuantuan Wang, Yafei Wang and Hao Guo
Jiangsu Automation Research Institute of CSIC, Lianyungang, China

*Corresponding author e-mail: zhangzh900720@163.com

Abstract. To control the separation of flow past an airfoil with a simple jet mechanism, based on the Large Eddy Simulation from Favre, a suction-blowing combined jet is studied with holes placed on a NACA0012 airfoil’s upper surface and \( Re = 10^4 \), attack angle \( \alpha = 6^\circ \). The results show the control mode of front-hole suction and back-hole blowing is effective. It can suppress the disturbance in the flow field and increase the lift-to-drag ratio of the airfoil at the same time.

1. Introduction
Eliminating the flow separation around airfoil under low Reynolds number has great influence on engineering application of MAVs (Micro Air Vehicles). With \( Re \) decreasing, the viscosity effect becomes stronger, the boundary layer becomes thicker and shedding vortex becomes bigger [1]. With \( Re \) being between \( 10^4 \) and \( 10^5 \), the aerodynamic performance of the wing drastically deteriorates, including the drop of lift coefficient, the rapid increase of drag coefficient, and the poor stability and maneuverability [2].

Mueller and Delaurier [3] have found with \( Re \) decreasing to \( 5 \times 10^4 \), the laminar separation bubble occurs. Ye et al. [4] have applied high precision finite difference scheme to simulate the two-dimensional airfoil flow field with Mach number \( Ma = 0.5 \), \( Re = 1 \times 10^4 \) and the attack angle \( \alpha = 3^\circ \). The results show the effect of adverse pressure gradient causes the fluid boundary layer separate, and thus leads to periodic vortex shedding. The vortex structure is formed by resident vortices, exfoliated vortices and secondary vortices. Wang and Song [5] have calculated the flow field around NACA0012 airfoil with \( Ma = 0.1 \), \( Re = 1 \times 10^5 \), and \( \alpha = 0^\circ \). The results display Karman Vortex Street is formed at the empennage. This makes the velocity field no longer symmetric and the lift begins to fluctuate. The disturbance in the flow field affects the flight stability of the wing. How to control the flow field structure and improve the aerodynamic characteristics of the aircraft have become the hot research direction.

Currently jet control is a mature and effective technology, such as suction or blowing jet [6, 7], synthetic jet [8] and distributed jets [9]. However, most studies are carried out under higher Reynolds number, and single suction jet or blowing jet is difficult to achieve in MAVs. It is necessary to find a high efficiency control with a simple mechanism for micro-body at low Reynolds number.

On the basis of previous studies [10-12], this paper further discusses the effect of suction and blowing jets on NACA0012 airfoil with \( Re = 1 \times 10^4 \), \( \alpha = 6^\circ \) and \( Ma = 0.2 \). In this paper the suction-blowing combined jet is applied at low Reynolds number. The control method can be implemented in the micro airfoil. The control parameters of the jet are simulated and analyzed. The results show an effective control method at low Reynolds number is found.
2. Numerical method

The compressible LES equations can be obtained by Favre filtering the corresponding Navier-Stokes equations in the Cartesian coordinate system.

\[
\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_j)}{\partial x_j} = 0
\]  

(1)

\[
\frac{\partial (\bar{\rho} \bar{u}_i)}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{1}{Re} \frac{\partial (\bar{\tau}_{ij} + \bar{\tau}_g)}{\partial x_j} + \frac{1}{Re\delta_{ij}} \frac{\partial (\bar{\tau}_{ij} + \bar{\tau}_g)}{\partial x_j}
\]  

(2)

\[
\frac{\partial (\bar{\rho} \bar{E})}{\partial t} + \frac{\partial (\bar{\rho} \bar{E} + \bar{P}) \bar{u}_j}{\partial x_j} = \frac{1}{Re} \frac{\partial (\bar{\tau}_{ij})}{\partial x_j} - \frac{1}{Re(\gamma - 1)Ma_c^2} \frac{\partial \delta_{ij}}{\partial x_j} \left[ q_j + Q_{ij}^{SGS} \right]
\]  

(3)

The subgrid stress tensor and thermal flux are given by

\[
\bar{\tau}_{ij}^{SGS} = \frac{1}{3} \bar{\tau}_{kk}^{SGS} \delta_{ij} = 2\mu^{SGS} \bar{S}_{ij} - \frac{2}{3} \mu^{SGS} \bar{S}_{kk} \delta_{ij}
\]  

(4)

\[
Q_{ij}^{SGS} = -\frac{\mu^{SGS} C_p}{Pr_f} \frac{\partial \bar{T}}{\partial x_j} = -\frac{\mu^{SGS}}{(\gamma - 1)Ma_c^2 \text{Re}_c Pr_f} \frac{\partial \bar{T}}{\partial x_j}
\]  

(5)

Where \( Pr_L \) and \( Pr_T \) are laminar and turbulent Prandtl numbers, respectively. \( \gamma \) refers to the specific heat of gases.

The subgrid model employs WALE (Wall-Adapting Local Eddy-viscosity) model, and the governing equations are discretized by finite element volume method. Convection items are approached with AUSM+up scheme and the second-order central difference scheme is applied for the discretization of diffusive terms. Time advance format is achieved with the second-order dual-time step LU-SGS implicit method. The accuracy and reliability of this method have been verified [14].

The NACA0012 airfoil with \( Re = 1 \times 10^4 \), \( \alpha = 6^\circ \) and \( Ma = 0.2 \) is selected as the calculation model. The C-type structure grid generated by elliptic method is applied as shown in Fig.1. Take the chord length \( c = 1 \) as reference length. The left boundary of computational domain is 4.5\( c \) away to the airfoil leading edge and the right is 9.0\( c \) away to the airfoil trailing edge. The upper and lower boundary is 6.5\( c \) from airfoil chord line. The wall distance of the first grid is 1\( \times 10^{-4} c \) and its corresponding dimensionless distance satisfies \( y^+ < 1.0 \). To accurately simulate the influence of jet on the flow field, the mesh around the jet hole is encrypted. When the width of hole is greater than 2.5\%\( c \), the lift of airfoil is no longer significantly increased [15], so it is selected as 2.5\%\( c \). Therefore, the Grid numbers in this paper are 1188\times 100.

![Figure 1. Structured grid of NACA0012 airfoil](image)

Fig.2 is the time-averaged vorticity contours around the airfoil. The separation point is after 0.2\( c \), and the breakage and shedding of the front vortex occur on the upper surface of the airfoil, which magnifies the instability of shear layer, complicates the separation flow in the boundary layer and causes...
the lift coefficient to fluctuate violently with time as shown in Fig.3. The purpose of this work is to inhibit the flow separation and reduce the disturbance in the flow field which also means increasing the lift-to-drag of the airfoil and reducing the fluctuation range of lift coefficient.

**Figure 2.** Time-averaged vorticity contours around the airfoil without jet injection

**Figure 3.** The fluctuation of lift coefficient with time

3. Results and Discuss

From the previous studies, a suction-blowing combined jet is proposed as shown in Fig.4, the blowing angle $\theta_B$ is angle between the direction of blowing jet and the normal to the jet surface. The air quality through the suction hole is the same as that through the blowing hole in unit time.

**Figure 4.** Schematic diagram of suction-blowing combined jet

**Figure 5.** The variation of airfoil time-averaged aerodynamic characteristics with the blowing angle $\theta_B$ at $V_j/V_\infty = 0.5$
Fig. 5 is the relationship between time-averaged aerodynamic characteristics and the blowing angle $\theta_B$ under suction-blowing combined control. First when $\theta_B = 0^\circ$, which is the blowing jet is vertical to the jet hole surface, the lift-to-drag ratio and lift oscillation amplitude of airfoil are all better than the base state. If the blowing jet gradually deflects downstream, the lift-to-drag ratio of airfoil under three types of combined structures increases and its lift oscillation amplitude decreases. The aerodynamic performance of airfoil develops in a better direction. In the three cases when $\theta_B$ is close to $80^\circ$, the lift-to-drag ratio reaches the extreme point and then decreases sharply. At a small blowing angle, the disturbance in the flow field is suppressed and when $\theta_B > 60^\circ$, the lift oscillation amplitude disappears, which is the flow field is completely controlled. In this example, when $60^\circ < \theta_B < 80^\circ$, the case $L_{j,s}$ (suction jet location) = 0.1$c$, $L_{j,b}$ (blowing jet location) = 0.5$c$ is better.

Fig. 6 is the time-averaged streamlines and vorticity contours around the airfoil at $V_j/V_\infty = 0.5$, $L_{j,s} = 0.1c$, $L_{j,b} = 0.5c$. Compared with the base state, when $\theta_B = 60^\circ$, the separation point is moved to about 0.75$c$ and the separation vortex completely disappears. When $\theta_B = 80^\circ$, the flow separation is eliminated.

![Figure 6](image)

(a) baseline
(b) $\theta_B = 30^\circ$
(c) $\theta_B = 60^\circ$
(d) $\theta_B = 80^\circ$

**Figure 6.** Time-averaged streamlines and vorticity contours around the airfoil at $V_j/V_\infty = 0.5$, $L_{j,s} = 0.1c$, $L_{j,b} = 0.5c$.

In Fig. 7, $L_d$ is the distance between the suction jet hole and the blowing jet hole. And under the condition of $V_j/V_\infty = 0.5$ and $\theta_B = 80^\circ$, when the hole spacing $L_d$ increases, the lift-to-drag ratio decreases. If the suction jet hole is located at the leading edge of airfoil, this phenomenon is more obvious. As the suction jet hole moves backward, the curvature of lift-to-drag ratio decreases with the change of hole spacing $L_d$. Under the three conditions, the lift-to-drag ratio reaches the maximum at $L_d = 0.025c$, which is the blowing jet hole is close to the suction jet hole. In addition, at the same hole spacing $L_d$, the suction jet hole should be placed at the leading edge of airfoil.

At $L_d = 0.025c$ and $\theta_B = 80^\circ$, Fig. 8 shows the variation of airfoil time-averaged aerodynamic characteristics with the jet velocity $V_j/V_\infty$. It is found if $V_j/V_\infty$ is small, the variation of lift coefficient with time is still oscillating, and the disturbance in the flow field is not completely eliminated. When $V_j/V_\infty$ increases gradually, the lift oscillation amplitude decreases, indicating the flow separation is
gradually suppressed. When $V_j/V_\infty$ reaches a certain value, the flow field around the airfoil is completely controlled. In addition, with the increase of $V_j/V_\infty$, the lift-to-drag ratio of airfoil increases first and then decreases, and there exists an extremum point.

![Figure 7](image1.png)

**Figure 7.** The variation of lift-to-drag of airfoil with hole spacing $L_d$ at $V_j/V_\infty = 0.5$, $\theta_B = 80^\circ$

![Figure 8](image2.png)

**Figure 8.** The variation of airfoil time-averaged aerodynamic characteristics with the jet velocity $V_j/V_\infty$ at $L_d = 0.025c$, $\theta_B = 80^\circ$

According to the above analysis, the lift-to-drag ratio of airfoil controlled by the suction-blowing combined jet is related to a variety of control parameters. The influence of $L_d$ and $L_{j,s}$ on the lift-to-drag ratio is monotonous, but the lift-to-drag ratio has an extremum point with $\theta_B$ and $V_j/V_\infty$ as the variable, respectively. Therefore, at $L_d = 0.025c$, $L_{j,s} = 0.10c$, the blowing angle $\theta_B$ and jet velocity $V_j/V_\infty$ are selected as optimization variables to seek the optimal control parameters.

Fig.9 is the variation of airfoil lift-to-drag ratio with the blowing angle $\theta_B$ at different jet velocities $V_j/V_\infty$. At a jet velocity $V_j/V_\infty$, as the blowing angle $\theta_B$ increases, the airfoil lift-to-drag ratio increases first and then decreases, and there is an optimal value. When the jet velocity $V_j/V_\infty$ changes, there is still an optimal value but the corresponding blowing angle $\theta_B$ changes. To accurately seek the relationship between the maximum lift-to-drag ratio, the jet velocity $V_j/V_\infty$ and the blowing angle $\theta_B$, the RBF surrogate model is applied to fit the sample points at different jet velocities, and the error is checked within 5%. Otherwise, the sample pointed are expanded to re-fit. Then the fitting function is substituted into an optimization algorithm as an optimization function. The result is displayed in Fig.10. It is found as the jet velocity $V_j/V_\infty$ increases, the blowing angle $\theta_B$ should be reduced to reach the maximum lift-
to-drag ratio, which is, if the jet velocity is high, the blowing jet should be deflected upstream to attain
the maximum lift-to-drag ratio and if the jet velocity is small, the operating method is opposite.

\[ \frac{\Delta C_L}{C_D} \]

\[ \theta_B \]

\[ \frac{V_j}{V_\infty} = 0.25 \]

\[ \frac{V_j}{V_\infty} = 0.30 \]

\[ \frac{V_j}{V_\infty} = 0.35 \]

\[ \frac{V_j}{V_\infty} = 0.40 \]

\[ \frac{V_j}{V_\infty} = 0.45 \]

\[ \frac{V_j}{V_\infty} = 0.50 \]

\[ \frac{V_j}{V_\infty} = 0.55 \]

\[ \frac{V_j}{V_\infty} = 0.60 \]

\[ \frac{V_j}{V_\infty} = 0.65 \]

\[ \frac{V_j}{V_\infty} = 0.70 \]

\[ \frac{V_j}{V_\infty} = 0.75 \]

Figure 9. The variation of airfoil lift-to-drag ratio with the blowing angle $\theta_B$ at $L_d = 0.025c$, $L_{j, s} = 0.10c$

Figure 10. The relationship between the maximum lift-to-drag ratio and its corresponding jet velocity $V_j/V_\infty$ and blowing angle $\theta_B$

4. Conclusion
The LES method is applied to simulate the flow field around the NACA0012 airfoil with suction-
blowing combined jet acted on the upper surface at low Reynolds number. It is found keeping the
direction of suction jet unchanged, changing the direction of blowing jet can control the flow separation
and enhance the airfoil’s aerodynamic performance. If the control parameters of suction jet remain
unchanged, with the direction of blowing jet gradually deflecting downstream (the increase of blowing
angle $\theta_B$), the flow separation point moves down and the lift-to-drag ratio of airfoil increases, and there
is an optimum blowing angle $\theta_B$ to maximize the airfoil’s lift-to-drag ratio.

References
[1] Lin J C M, Pauley L L. Low-Reynolds-number separation on an airfoil [J]. AIAA Journal, 1996,
34(8):1570-1577.
[2] Li Feng, Bai Peng, Shi Wen, et al. Low Reynolds number aerodynamics of micro air vehicles [J].
Advances In Mechanics, 2007, 37(2): 257-268.
[3] Mueller T J, Delaurier J D. Aerodynamics of small vehicles [J]. Advances in Mechanics, 2004,
35(1): 89-111.
[4] Ye Jian, Zou Zhengping, Lu Lipeng, et al. Investigation of separation mechanism for airfoil leading edge flow at low Reynolds number [J]. Journal of Beijing University of Aeronautics and Astronautics, 2004, 30(8): 693-697.

[5] Wang Long, Song Wenping. Applying lattice Boltzmann method (LBM) to large eddy simulation (LES) of flow around airfoil at low Reynolds number [J]. Journal of Northwestern Polytechnical University, 2010, 28(3):448-452.

[6] Li Feng, Wang Yiyun, Cui Erjie. Numerical simulation of separation control by suction [J]. Acta Aerodynamic Sinica, 1994, 12(1):36-42.

[7] Lebeau R P, Huang L, Huang P G, et al. Numerical study of blowing and suction control mechanism on NACA0012 airfoil [J]. Journal of Airfoil, 2004, 41(5): 1005-1013.

[8] Duvigneau R, Visonneau M. Optimization of a synthetic jet actuator for aerodynamic stall control [J]. Computers & Fluids, 2018, 35(6):624-638.

[9] Wahidi R, Bridges D H. Effects of distributed suction on an airfoil at low Reynolds number [J]. Aiaa Journal, 1971, 50(3): 523-539.

[10] Zhang W. Suction control and its optimization of boundary layer separation at low Reynolds numbers [D]. Nanjing University of Science & Technology, 2014.

[11] Zhang W, Tan J, Chen Z, et al. Effect of suction control on separation flow around an airfoil at low Reynolds numbers [J]. Acta Aeronautica et Astronautica Sinica, 2014, 35(1):141-150.

[12] Zhang W, Zhang Z, Chen Z, et al. Main characteristics of suction control of flow separation of an airfoil at low Reynolds number [J]. European Journal of Mechanics – B/Fluids, 2017, 65:88-97.

[13] Feng L H, Wang J J, Pan C. Effect of novel synthetic jet on wake vortex shedding modes of a circular cylinder[J]. Journal of Fluids & Structures, 2010, 26(6):900-917.

[14] Zhang Z Y, Zhang W L, Chen Z H, et al. Suction control of flow separation of a low-aspect-ratio wing at a low Reynolds number [J]. Fluid Dynamics Research, 2018, Res. 50 065504.

[15] Dannenberg R E, Weiberg J A. Section characteristics of a 10.5-percent thick airfoil with area suction as affected by chordwise distribution of permeability [J]. Technical Report Archive & Image Library, 1952.