Blowing momentum and duty cycle effect on aerodynamic performance of flap by pulsed blowing

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Abstract: Control surface, which is often located in the trailing edge of wings, is important in the attitude control of an aircraft. However, the efficiency of the control surface declines severely under the high deflect angle of the control surface because of the flow separation. To improve the efficiency of control surface, this study discusses a flow-control technique aimed at suppressing the flow separation by pulsed blowing at the leading edge of the control surface. Results indicated that flow separation over the control surface can be suppressed by pulsed blowing, and the maximum average lift coefficient of the control surface can be 95% times higher than that of without blowing when average blowing momentum coefficient is 0.03 relative to that of without blowing. Finally, this study shows that the average blowing momentum coefficient and non-dimensional frequency of pulsed blowing are two of the key parameters of the pulsed blowing control technique. Otherwise, duty cycle also has influence on the effect of pulsed blowing. Numerical simulation is used in this study.

Keywords: Flow Control, Pulsed Blowing, Duty cycle

Nomenclature

\[ C_\mu = \text{Average blowing momentum coefficient} \]
\[ V_\infty = \text{Velocity of the freestream (m/s)} \]
\[ Re = \text{Reynolds number based on chord length of model} \]
\[ c_0 = \text{Chord length of the model (m)} \]
\[ m_j = \text{Mass flow rate of blowing (kg/s)} \]
\[ V_j = \text{Jet velocity from the blowing slot (m/s)} \]
\[ S_e = \text{Reference area of the flap (m}^2\text{)} \]
\[ S_j = \text{Area of the blowing slot (m}^2\text{)} \]
\[ f = \text{Frequency of pulsed blowing (Hz)} \]
\[ Str = \text{Non-dimensional frequency of pulsed blowing} \]
\[ h_j = \text{Width of the blowing slot (mm)} \]
\[ C_p = \text{Pressure coefficient} \]
\[ C_L = \text{Average lift coefficient of the flap} \]
\[ c = \text{Chord length of flap (m)} \]
\[ \rho_\infty = \text{Density of free stream (kg/m}^3\text{)} \]
\[ \alpha = \text{attack angle of main wing (°)} \]
\[ \delta = \text{deflect angle of flap (°)} \]
\[ t = \text{time (s)} \]

1. Introduction

In modern aircraft designing, the attitude control of an aircraft is still relies on traditional control surface such as flap, which is often located in the trailing edge of wings. However, the efficiency of the control surface declines severely under the high deflect angle of the control surface because of the flow separation. This condition leads to the penalty of attitude control and limited aerodynamic performance of an aircraft. In order to improve the efficiency of flap, flow control is necessary. In the past decades, scientists have exerted considerable effort to develop flow control techniques. Moreover, various flow control techniques \([1]\) has been used to suppress flow separation such as moving surface control technique \([2-4]\), plasma flow control technique \([5-8]\) and co-flow jet control technique \([9-12]\).

Although flow separation on the control surface can be suppressed substantially by these flow control technique, the application of these techniques in engineering are limited because of complicated devices or other reasons. Relatively, the flow control technique by blowing at the leading edge of flap catch people’s eyes because of its simple device, rapidly remarkable lift increment and low gas consumption. In order to reduce the gas consumption further, pulsed blowing technique is taken into consideration. Study shows that lift coefficient of flap can be higher with pulsed blowing compared with that of continuous blowing.

This study introduces an flow control technique by pulsed blowing near the leading edge of the flap to suppress the flow separation over the flap that is located on the tailing edge of an airfoil. First, the effect of pulsed blowing on the aerodynamic performance of the flap is investigated thoroughly. Thereafter, the effect of cycle duty of pulsed blowing are discussed. All the results of this study is completed based on the following conditions: the angle of attack of the main wing is 0° and the deflect angle of the flap is 20°.

2. Numerical Model and Data Process

2.1 Numerical Model

The airfoil model used in the study is based on NACA0025 airfoil with a 0.6 m chord length. This model can be divided into two parts (see Figure 1): the main wing and a flap that is as long as 0.206m.

![Figure 1. Sketch of the Model](image-url)

A spanwise blowing slot with a 0.5mm height is located near the leading edge of the flap which is
selected based on the flow separation point on the upper surface of the flap (see Figure 2). Compressed air flows downstream along the tangential direction of the upper surface of the flap from the slot.

![Figure 2. Sketch of the Flap](image)

The 2D mesh of the model used in numerical simulation is as shown in. The minimum gap between the main wing and the flap is 0.5 mm, and the width of blowing slot is also 0.5 mm. An O-mesh with circle far-field, which is 20 chord length away from the model, is used in the simulation. In addition, the k-omega SST turbulence model is used. The boundary condition of the mass flow rate is used on the blowing slot. The height of the first layer of the grid is 0.02 mm, and the number of cells is 79757.

![Figure 3. Mesh Used in Numerical Simulation](image)

The pulsed blowing wave is as shown in Figure 4. The wave is a standard square wave with a duty cycle of 0.5.

![Figure 4. Sketch of Wave Form](image)

2.2 Data Process

Average blowing momentum coefficient is used to represent the gas consumption. The equation is
as follows:

\[
C_{\mu} = \frac{1}{T} \sum_{j} \frac{m_{j}V_{j}}{2\rho_{\infty}V_{\infty}^{2}S_{e}} \Delta t
\]  

(1)

where \(C_{\mu}\) represent average blowing momentum coefficient, \(T\) is the cycle time, \(m_{j}\) is the mass flow rate of the blowing jet, \(V_{j}\) is the jet velocity from the blowing slot, \(\rho_{\infty}\) is the density of freestream, \(S_{e}\) is the reference area of the flap, \(V_{\infty}\) is the velocity of freestream and \(\Delta t\) is the interval time of two adjacent time step.

The Strouhal number \(Str\) is the parameter that represents pulsed frequency. The equation of the Strouhal number is as follows:

\[
Str = \frac{f c}{V_{\infty}}
\]  

(2)

where \(Str\) is the Strouhal number, \(f\) is the pulsed frequency and \(c\) is the chord length of the flap.

Duty cycle \(dr\) is defined as the proportion of blowing time in one single cycle time.

2.3 Validation of the Numerical Simulation Results

The validation experiment is conducted in the D-4 low-speed wind tunnel of Beihang University. Figure 5 gives out the model used in validation experiment. The model has 1 aspect ratio and 0.6 m the spanwise length. The proposed model is equipped with 44 pressure taps at the longitudinal symmetric section along the upper and bottom flap. Two fiberglass plates are set on both sides of the model spanwise to simulate a two-dimensional flow in the test. DTC initium electronic scanivalve is used to measure the pressure distribution of the model with an accuracy of 0.05% and the highest sampling frequency is 650Hz.

![Figure 5. The Sketch of Model Used in Experiment](image)

Figure 6 gives out the pressure distribution on flap with a blowing momentum coefficient of 0.055 under continuous blowing. The dash line stands for experimental result and the solid line stands for numerical simulation result. The angle of attack of the main wing is 0° and deflection angle of flap is 20° with a Reynolds number of 0.8x10^6. It can be found that the pressure distribution is well coincided except the fore part of flap which is covered by main wing. In fact, the width deviation of gap between main wing and flap is the main reason of this difference between numerical and experimental result. Thus, the numerical result can be considered of appropriate and credible.
3. Results and Discussion

3.1 Effect of Pulsed Blowing on Aerodynamic Performance of Flap

Pulsed blowing at the leading edge of flap can cut the consumption of gas greatly while higher lift increment is get. Figure 7 shows the pulsed blowing effect on the average lift coefficient of the flap changing with the Strouhal number under different average blowing momentum coefficient as well as the comparison with that of the non-blowing under the following conditions: angle of attack $\alpha=0^\circ$, deflection angle of the flap $\delta_e=20^\circ$, $V_\infty=20m/s$, and $Re=0.8\times10^6$, duty cycle $dt=0.5$. The solid line with square mark represents $C_\mu=0.01$, solid line with circle mark represent $C_\mu=0.02$, solid line with triangle mark represent $C_\mu=0.04$ and dash line represent $C_\mu=0$.

When $Str=0$, the intersection of $y$ axis and three solid line, respectively, represent the lift coefficient of the flap under continuous blowing under different $C_\mu$. With the increase of $C_\mu$, the lift coefficient of the flap increase. When $C_\mu$ is 0.04, lift increment of the flap is 100% compared with the lift coefficient of the flap without blowing. When pulsed blowing is used, further increment of lift coefficient of the flap occurs. If $C_\mu$ is low (such as $C_\mu=0.01$), the flow over flap is a separated flow and pulsed blowing cannot master the flow over the flap. The evolution of lift coefficient of the flap with different Strouhal number is irregular and the lift increment is not evident enough. When $C_\mu$ is high enough (such as $C_\mu=0.02$), the lift coefficient of the flap increases rapidly with the increase of...
Strouhal number. $CL$ reaches the maximum value when $Str=0.206$. With the continuously increase of $Str$, $CL$ decrease slightly. However, the lift coefficient of pulsed blowing is constantly higher than that of continuous blowing under the same $C\mu$. When $Str=0.206$, $CL$ of pulsed blowing is $67\%$ higher than that of continuous blowing under the same $C\mu$.

3.2 Effect of Duty Cycle on Average Lift Coefficient of the Flap

When $C\mu$ keep constant, the duty cycle also has effect on $CL$. Figure 8 shows the $CL$ changing with $Str$ under different duty cycle and the following conditions: angle of attack $\alpha=0^\circ$, deflection angle of the flap $\delta_e=20^\circ$, $V_\infty=20\text{m/s}$, and $Re=0.8\times10^6$ and $C\mu=0.02$. The solid line with square mark represents $dr=0.25$, solid line with circle mark represent $dr=0.5$ and solid line with triangle mark represent $dr=0.75$.

![Figure 8. Effect of Duty Cycle on Average Lift Coefficient of the Flap](image)

The tendency of evolution of $CL$ under different duty cycle is similar: increase rapidly with the increase of $Str$ and reach the maximum value, then decrease slightly. But the difference reflect in the maximum value and the corresponding $Str$. If define the critical $Str$ as the $Str$ when $CL$ reach the maximum value, then the maximum value of $CL$ increase with the increase of duty cycle. The critical $Str$ also increase with the increase of duty cycle.

Based on the study before, the mechanism of improving the lift of the flap by pulsed blowing can be divided into two components. First, blowing jet can be treated as an injector. The flow upstream of the blowing slot is injected by the blowing jet and induces a suction peak, which is the same mechanism as continuous blowing. Second, the vortex generated by the switch of blowing and non-blowing over the blowing slot induces a suction peak. Lift increment is generated by these two components of suction peak. Both the inject effect and vortex need sufficient time to develop. When $Str$ is low, the lift increment supplied by the inject effect can reach its maximum value and stability. The lift increment supplied by the vortex reaches the maximum value and decreases thereafter. A critical value of $Str$ balances the both components of the lift increment and leads their sum into maximum value. When $Str$ is higher than the critical value, the vortex generated by the switch from blowing and non-blowing cannot obtain sufficient time to develop, thereby leading to a lift increment penalty in the non-blowing period. By contrast, the blowing jet cannot induce a high speed-up in the upstream of blowing slot, thereby leading to a lift increment penalty in the blowing period. When $C\mu$ keep instant, the higher the duty cycle is, the lower the blowing momentum coefficient in
blowing-period is. Thereby, the lift increment generated by inject effect decreases with the increase of duty cycle. Meanwhile, the time of non-blowing period is decrease with the increase of duty cycle. This leads to a lower lift increment of vortex.

4. Conclusions

Based the above discussion, the following conclusions can be made:

(1) Pulsed blowing can increase the lift coefficient of the flap evidently and improve the control efficiency of the flap.

(2) The lift coefficient of the flap increase with the increase of the Strouhal number rapidly and decrease slightly if Strouhal number continuously increase. When Strouhal number is high enough, the lift coefficient of the flap will keep instant.

(3) The maximum value of average lift coefficient of the flap and the critical Strouhal number increases with the increase of duty cycle when the average blowing momentum coefficient keeps constant.

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References

[1] Sellers, W. L., III, Singer, B. A., and Leavitt, L. D. 2003 Aerodynamics for revolutionary air vehicles 21st AIAA Applied Aerodynamics Conference 2003-3785
[2] Modi VJ, Munshi SR, Bandyopadhyay G, and Yokomizo T. 1998 High-performance airfoil with moving surface boundary-layer control J. Aircraft 35(4) 544-553
[3] Asrokin A, Ramly MR, and Ahmad AH. 2013 Rotating cylinder design as a lifting generator 2nd International Conference on Mechanical Engineering Research
[4] Zhang YY, Huang DG, Sun XJ, and Wu GQ 2010 Exploration in Optimal Design of an Airfoil with a Leading Edge Rotating Cylinder 2010 J. Thermal Science 19(4) 318-325
[5] Salmasi A, Shadaram A, and Taleghani AS 2013 Effect of plasma actuator placement on the airfoil efficiency at poststall angles of attack IEEE Trans. Plasma Science 41(10) 3079-3085
[6] Wang JJ, Choi KS, Feng LH, Jukes TN, and Whalley RD 2013 Recent developments in DBD plasma flow control Prog. Aerospace Sciences 62(1) 52-78
[7] Corke TC, Enloe CL, and Wilkinson, SP. 2010 Dielectric barrier discharge plasma actuators for flow control Annual Rev. Fluid Mechanics 42(1) 505-529
[8] Houser NM, Gimeno L, Hanson RE, Goldhawk T, Simpson T, and Lavoie P. 2013 Microfabrication of dielectric barrier discharge plasma actuators for flow control Sensors and Actuators A-Phys. 201(1) 101-104
[9] Zha GC, Gao W, Paxton CD. 2007 Jet effects on coflow jet airfoil performance J. AIAA 45(6) 1222-1231
[10] Im HS, Zha GC, and Dano BPE 2014 Large eddy simulation of coflow jet airfoil at high angle of attack J. Fluids Eng. Trans. Asme 136(2) 1101-1111
[11] Wang BY, and Zha GC 2011 Detached-eddy simulation of a coflow jet airfoil at high angle of
attack *J. Aircraft* **48(5)** 1495-1502

[12] Gan WB, Zhou Z, Xu XP, and Wang R 2014 Delayed detached-eddy simulation and application of a coflow jet airfoil at high angle of attack *Adv. Computational Modeling and Simulation* **444(1)** 270-277

[13] Wu Peng, Deng Xue Ying, and Wang Yan Kui 2012 Application of pulsed blowing technique in high-lift control surface design *Adv. Materials Research* **482(1)** 121-125