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A Study of Pulsed Blowing Effect on Flow Separation over Flap

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ABSTRACT

A model with main wing and flap which is based on NACA0025 airfoil is used in this paper to study the pulsed blowing effect on flow separation over flap. The effects of average blowing momentum coefficient and Stroul number on flow separation over the flap have been discussed at first. Furthermore, thecontrol effect of this pulsed blowing technique under different deflection angle of flap isdiscussed to make sure whether the control effect of pulsed blowing can meet the needs under different deflection angle of flap. All the research works have been finished by numerical simulation method under conditions of 0deg angle of attack of the main wing.

NOMENCLATURE

Cl	average lift force coefficient of flap in apulsed blowing period
Cu	average blowing momentum coefficient in apulsed blowing period
Cp	pressure coefficient
m_j	mass flux rate (kg/s)
V_j	velocity of blowing jet (m/s)
ρ	density of free stream (kg/m^3)
V_∞	velocity of free stream (m/s)
S	reference area (m^2)
Str	Stroul number / non-dimension frequency
f	frequency of pulsed blowing (Hz)
L	reference length (m)
δe	deflection angle of flap (deg)
ΔCl_{max}	maximum increment rate of average lift force coefficient of pulsed blowing compared with case of no blowing
Re	Reynolds number based on chord length of flap

1 INTRODUCTION

Tailless flying wing aerodynamic configuration has been adopted in the modern aircraft design on account of its high aerodynamic performance, such as high lift-drag ratio and stealth[1-3], as is shown inFig.1. However, for example, as bomber B-2 inFig.2, the control efficiency of the flaps will reduce rapidly due to the flow separation under high deflection angle. This leads the lack of its longitudinal yawing and rolling stability and limites the application of tailless flying wing aerodynamic configuration.

Fig.1X-47B

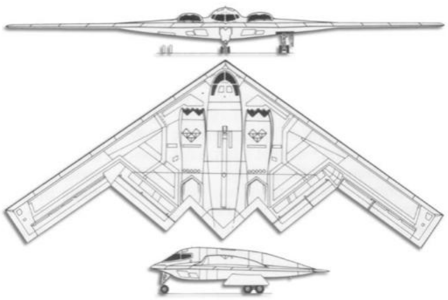


Fig.2 Bomber B-2

Therefore, for tailless flying wing aerodynamic configuration, improvement on flow separation over flap become a key point to enhance the control efficiency of flap and hencethe yawing and rolling stability can also be improved. Therefore, various of active flow separation control techniques are used[4-6].In 1960s and 1970s, blown flap or jet flap techniques are used by PollDI and Rober JE[7-8] to achieve the goal of enhancing aerodynamic characteristics of flap. However, there is a disadvantage of these techniques that all of them need a large number of gas. It limites the application of these techniques in engineering.In order to find a more efficiency technique, K. McManus and J. Magill[9-10] paid attention to pulsed jet technique to control flow separation over wing. However, it is still difficult to be adopted in engineering.

This paper pay attention to a innovative active flow control technique by pulsed blowing from leading edge of flap to eliminate the flow separation over flap, and the effect of its parameters on aerodynamic characteristics of flap is discussed.

2 PHYSICAL MODEL AND COMPUTATIONAL METHOD

2.1 Physical Model

A 2-D model based on NACA0025 airfoil is used in this paper which is shown inFig. 3.The model is separated into two parts: the main wing and the flap.The length of the whole model is 600mm and the length of the flap is 206mm. There is a gapwith a width of 0.5mm between main wing and flap.A blowing slot with the width of 0.5mm is set to the upper surface of the flapto provide stream-wise jet.In this paper, the attack angle of main wing is fixed to 0deg and Reynold number based on chord lengthof flap is fixed to 8e+5. The position of blowing slot is near the flow separation point on the upper surface of the flap.

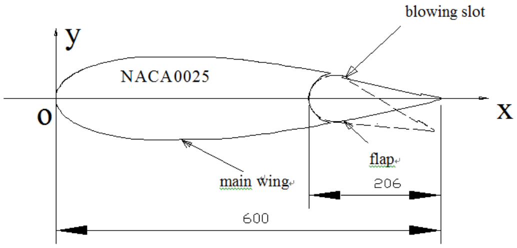


Fig.3 The sketch of the model

Fig.4 gives out the grid used in this paper. The thickness of the first layer of grid near the wall is set to 0.02mm and y+ = 0.1~1 to simulate boundary layer flow precisely.Furthermore, grid refinement is used near the blowing slot to ensure enough calculation precision.The far field of calculation is 20 times the chord length away from the model.

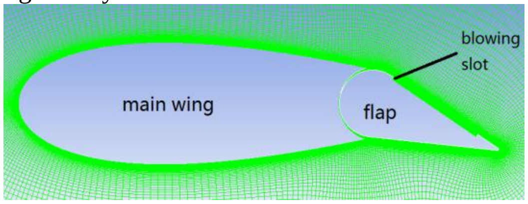


Fig.4 Grid used for calculation

2.2 Computational Method

The k-omega SST turbulence model is used in simulation. As the aspect-ratio of gridis large, double precision solver is employed to ensure the stability and convergence of numerical discretization. Second-order upwind scheme is adopted for the convection terms of all solution equations, central difference scheme is used for diffusion terms and coupled algorithm is employed for pressure-velocity coupling.

For the numerical simulation, mass flow inlet boundary condition is used to simulate the jet from blowing slot and pressure far-field boundary condition is used to simulate the free stream from far away. The surface of the model is set to fit nonslip boundary condition. The waveform of pulsed blowing is a square with duty cycle of 0.5, which is shown as Fig.5

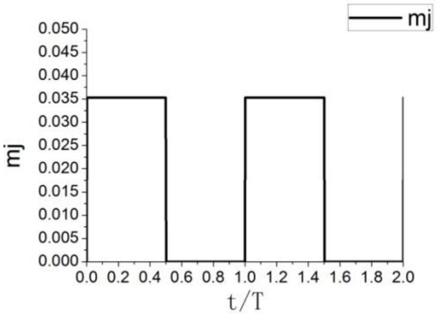


Fig.5Sketch of waveform of pulsed blowing

2.3 Parameter Calculation and Definition of CoordinateSystem

In this paper, the following parameters arementioned:average blowing momentum coefficient, Stroul number, average lift force coefficient of flap, pressure coefficient of flap etc.

Average blowing momentum stands for the quantity of blowing jetand can be expressed as follow:

$$Cu = \frac{m_j * V_j}{\frac{1}{2}\rho V_\infty^2 S} \quad (1)$$

Stroul number represents the non-dimensional pulsed blowing frequency and can be expressed as follows:

$$Str = \frac{fL}{V_\infty} \quad (2)$$

Pressure coefficient of flap represents the non-dimensional pressure on surface of model. Coordinate system used for pressure distribution in this paper is shown in Fig.6. The origin of coordinate is the forefront of flap. The x-axis is in the symmetry plane of flap and directs at the trailing edge of flap. The y-axis is perpendicular to x-axis and directs to the upper surface of flap

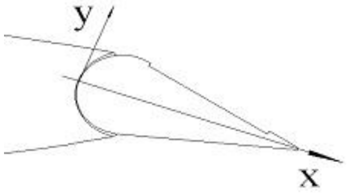


Fig.6Sketch of coordinate systems used in drawing pressure distribution

2.4 Validation of Computational Method

The pressure distribution on the flapwith a blowing momentum coefficient of 0.055 under continuous blowing is given in Fig.7, in which the dash line stands for experimental result and the solid line stands for computational result.In this case, the attack angle of main wing is 0deg and deflection angle of flap is 20deg under condition of Re number 8e+5. It can be knownfrom Fig.7that the main difference of pressure distribution between experimental result and computational result is on the fore part of flap which is covered by main wing.In fact, it is very difficult to measure the precisely width of gap between main wing and flapin the experimental case. Therefore, although the width of gap between main wing and flap is set into theoretical value of 0.5mm in experiment, the real width of gap is deviated from 0.5mm. This is the reason why pressure distribution between experimental result and computational result cannot keep overlap on the fore part of flap which is covered by main wing.时 Based on the discussion above, the computational result is proper and believable.

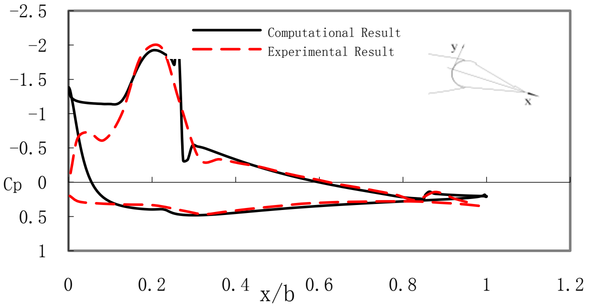


Fig.7Comparison of pressure distribution on flap between computational and experimental result under continuous blowing

(a=0° , δe =20° , Re=8e+5, Cu=0.055)

3 RESULTS AND DISCUSSIONS

Obviously,the non-dimension blowing frequency (Str) and non-dimension blowing flux (Cu)of pulsed blowing are the two important parameters for pulsed blowing control technique.The effects of these two parameters on flow separation over the flap need to be discussed at first.After that, the control effect of pulsed blowing under different deflection angle of flap needsto be discussedto make sure whether the control effect of pulsed blowing can meet the needs under different deflection angle of flap.

3.1 Effect of Average Blowing Momentum Coefficient on Aerodynamic Characteristics of Flap

Fig.8 gives out the effect of average blowing momentum coefficient on the average lift force coefficient of flap under different Stroul number when attack angle of main wing is 0deg, deflection angle of flap is 20deg and Reynolds number is 8e+5. For continuous blowing (dash line), lift force coefficient of flap increases slightly with the increasing of blowing momentum coefficient at first, then increases rapidly. When blowing momentum coefficient is higher than a critical value, the lift force coefficient of flap won't change largely with the increasing of blowing momentum coefficient.The blowing momentum coefficient at whichthelift increasing rate $\Delta C_l \,/\, \Delta C_u$ is lower than 5% is defined as critical blowing momentum coefficient.In thiscontinuous case, the critical blowing momentum coefficient is 0.0589.

In addition, it can be found fromFig.8that when the lift force coefficient of flap is the same, average blowing momentum coefficient with pulsed blowing needed is almost half of that with continuous blowing.

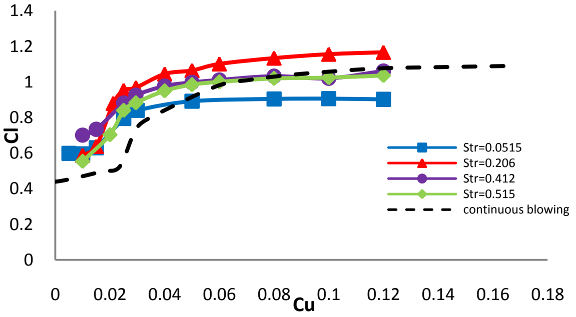
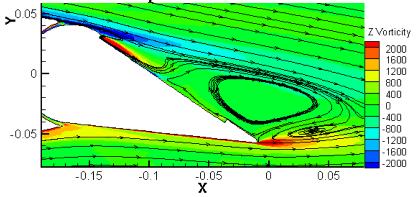


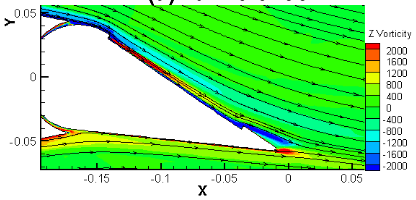
Fig.8 Effect of average blowing momentum on aerodynamic characteristics of flap under different Stroul number

(a=0° δe=20° , Re=8e+5)

Fig.9gives out the flow field over the flap under conditions of continuous blowing momentum coefficient 0.0236 and 0.06. It can be observed that when blowing momentum coefficient is higher than critical blowing momentum coefficient 0.0589, the separated flow over the flap will reattach.



(a)Cu = 0.0236



(b) Cu = 0.06

Fig.9Flow field over flap with continuous blowing under different blowing momentum

(a=0° δe=20° , Re=8e+5)

It can also be found from Fig.8that the average lift force coefficient of flap increases rapidly with the increasing of average blowing momentumcoefficient whenthe Str is 0.0515 (line with square mark). When average blowing momentum coefficient keep increasing and is bigger than 0.025, the growth rate of average lift force coefficient of flap will slow down and turn to 0 at last. Compared with that of continuous blowing (dash line), it can be found that when average blowing momentumcoefficient is bigger enough, the average lift force coefficient of flap of continuous blowing is even higher than that with pulsed blowing. WhenStrnumber is 0.206 (line with triangle mark), the effect performance due to average blowing momentum is similar and average lift force coefficient of flap with pulsed blowing is always higher than that with continuous blowing. On the other hand, when Str is higher than 0.412 (line with circular mark), the average lift force coefficient of flap with pulsed blowing is higher than that with continuous blowing only when Cu is lower than 0.0589.In addition, we also give out the definition of critical average blowing momentum under pulsed blowing as mentioned above for continuous case. It can be found that the critical average blowing momentum coefficient of pulsed blowing is almost half of that with continuous blowing.

3.2 Effect of Pulsed Frequency on Aerodynamic Characteristics of Flap

Fig.10 gives out the influence of frequency of pulsed blowing on average lift forcecoefficient of flap under different average blowing momentumcoefficient when attack angle of main wing is 0deg, deflection angle of flap is 20deg and Reynolds number is 8e+5.It's observed that the average lift force coefficient of flap increases rapidly with the increase of Stroul number firstly and then decreases slightly. When Str is high enough, the average lift force coefficient of flap will keep constant.However, the average lift forcecoefficient of flap with pulsed blowing is higher than that with no blowing under any Stroul number.The Stroul numberat which the average lift force coefficient of flap reaches the maximum value under a constant Cu is defined as critical Stroul number. It can be known that the critical Stroul number does not change with the increase of averaged blowing momentum coefficient Cu. For the model with attack angle of main wing is 0deg, deflection angle of flap is 20deg and Reynolds number is 8e+5, the critical Str is 0.206. The highest average lift force coefficient of flap is almost twice than thatwith no blowing.

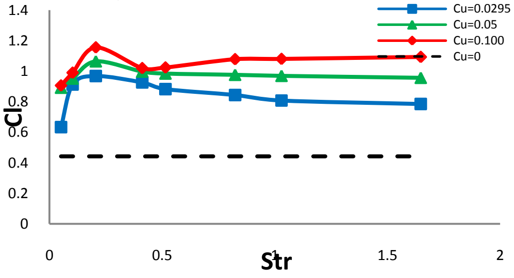


Fig.10 Effect of non-dimension pulsed blowing frequency on flow over flap under different average blowing momentum (a=0° δe=20° , Re=8e+5)

Fig.11gives out the influence of Stroul number on standard deviation of lift force coefficient of flap in a pulsed blowing period under a fixed average blowing momentum coefficient.With the increase of Stroul number, standard deviationof lift force coefficient of flap will decrease obviously. It can be found that the standard deviation of lift force coefficient of flap will decrease rapidly when Str is higher than critical Str.

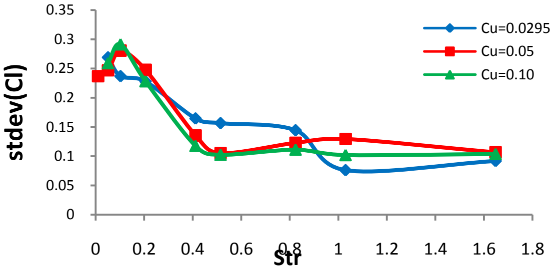


Fig.11Effect of Stroul on standard deviation of lift force coefficient of flap in a pulsed blowing period(a=0° , δe =20° , Re=8e+5)

3.3 Analysis of Control Effect of Pulsed Blowing under Different Deflection Angle of Flap

As is mentioned above, there is a critical blowing momentum coefficient (Cu_c)for continuous blowing and the flow over the flap will keep reattached onto the upper surface when the blowing momentum is bigger than it. Fig.12gives out the critical blowing momentum coefficient under different deflection angle of flap for continuous blowing cases. It can be found that with the increase of deflection angle of flap, critical blowing momentum coefficient of continuous blowing increases rapidly.It meansthat the bigger the deflection angle of flap is, the more blowing flux need and the more difficult the flow separation over the flap can be improved.

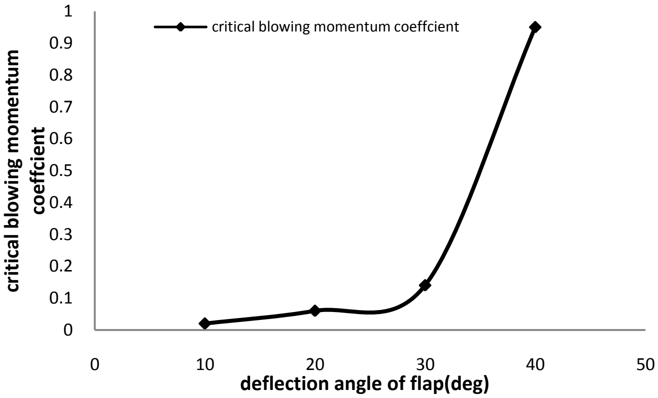
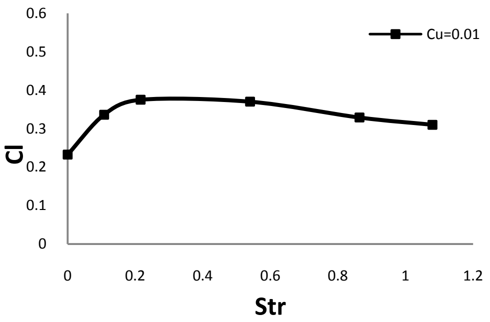
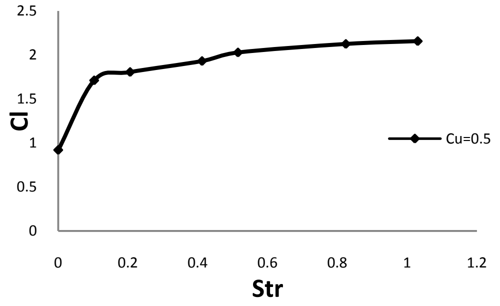


Fig.12Effect of deflection angle of flap on critical blowing momentum coefficient (a=0° , Re=8e+5, continuous blowing)

In order to investigate the control effect of pulsed blowing under different deflection angle of flap, the change of average lift force coefficient of flap with Stroul number under a fixed average blowing momentum coefficient, which is half of critical blowing momentum coefficient in case of continuous blowing,are shown in Fig.13.Fig.13(a) shows the influence of frequency of pulsed blowing on average lift force coefficient of flap with an average blowing momentumcoefficient of 0.01 when attack angle of main wing is 0deg, deflection angle of flap is 10deg and Reynolds number is 8e+5.It is observed that the effect characteristics due to Stroul number is similar as that when deflection angle of flapis 20deg(in Fig.10). With the increase of Stroul number, the average lift force coefficient of flap increase rapidly and then decrease slightly.Fig.13(b) shows the influence of frequency of pulsed blowing on average lift force coefficient of flap with an average blowing momentum coefficient of 0.5 when attack angle of main wing is 0deg, deflection angle of flap is 40deg and Reynolds number is 8e+5.It can be found that when Str is higher than critical Str, the average lift force coefficient keep constant and the efficiency of pulsed blowing is twice ofthat under continuous blowing.



(a)δe=10deg



(b)δe=40deg

Fig.13 Effect of non-dimension pulsed blowing frequency on aerodynamic characteristics of flap under different deflection angle
(a=0° ,Re=8e+5)

Table 1 gives out themaxium increment(Δ Cl_{max}) oflift force coefficient of flap and the corresponding critical blowing momentum coefficient of Cu_cin case of continuous blowing under different deflection angle of flap. In addition, the average blowing momentum coefficient at which the same lift increment as that of continuous blowing can be reached under different deflection angle of flap are also given out in Table 1.It can be observed thatthe average blowing momentum coefficient needed under pulsed blowing is almost half of that with continuous blowing when the same increment of Cl is reached. Namely, the blowing flux can be saved nearly half of that with continuous when the pulsed blowing is adopted. However, with the increasing of deflection angle of flap, the average blowing momentum coefficient required for keeping reattached flow over flap increases rapidly.

Table 1 Increment of Cl under different deflection angle of flap

δe	10deg		20deg		40deg	
Blowing pattern	continuous	pulsed	continuous	pulsed	continuous	pulsed
Cu_c	0.02	0.01	0.0589	0.0295	0.95	0.5
$\Delta Cl_{max}/Cl_0$	62%	61%	122%	120%	207%	199%

4 CONCLUSIONS

(1) Under fixed flap deflection angle 20deg, the aerodynamic performance of the flap is influenced greatly by average blowing momentum coefficient of pulsed blowing. With the increase of the average blowing momentum coefficient, the average lift force coefficient of the flap will increase rapidly until average blowing momentum coefficient reached the critical value. Furthermore, the average lift force coefficient of the flap will keep constant when the average blowing momentum coefficient is high enough. In addition, average lift force coefficient of the flap with pulsed blowing is higher than that with continuous blowing under any average blowing momentum coefficient only when the Stroul number is higher than critical Stroul number. When Stroul number is lower than critical Stroul number, lift force coefficient of flap with continuous blowing is higher than that with pulsed blowing if average blowing momentum coefficient is higher enough. In addition, compared with lift force without blowing, the biggest increment of average lift force of the flap under pulsed blowing is over 150%.

(2)The aerodynamic performance of the flap can also be influenced greatly by the Stroul number of the pulsed blowing. With the increase of the Stroul number, average lift force coefficient of the flap increases. However, there is a critical Stroul number that average lift force coefficient of the flap will reach the maximum and standard deviation of lift force coefficient of flap is low. When the Stroul number is bigger than it, lift force coefficient of the flap will decrease slightly.In this paper, the critical Stroul number is 0.206 and average lift force coefficient of the flap is almost twice than that without blowing.

(3)Thirdly, the pulsed blowing effect on flow over flap under different flap deflection angle has also been given out. Under condition of different flap deflection angle, the effect performance due to Stroul number is similar. To reach the same increment of Cl, the average blowing momentum coefficient needed in case of pulsed blowing is almost half of that with continuous blowing. However the critical average blowing momentum coefficient increases rapidly with the increasing of the flap deflection angle.

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