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Engineering Notes

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Experimental Study of Canard-Spanwise Pulsed Blowing on a Canard Configuration

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Nomenclature

C_L = lift coefficient with continuous blowing
$\bar{C}_L$ = mean lift coefficient with pulsed blowing
C'_L = instantaneous lift coefficient with pulsed blowing
C_μ = jet momentum coefficient with continuous blowing ($\dot{m}V_j/q_\infty S_c$)
$\bar{C}_\mu$ = mean jet momentum coefficient with pulsed blowing
f = pulse frequency
$\dot{m}$ = nozzle air mass flow rate
q = pulse width
q_∞ = freestream dynamic pressure
S_c = canard reference area
T_L = vortex lived time
T_P = pulse time
T_w = vortex delay time
V_j = jet velocity
α = angle of attack
Λ_c = swept angle of canard

I. Introduction

WING-SPANWISE blowing has been studied extensively [1–5]. It was considered as a hopeful technique to control wing vortex, but has not been used in practice due to demanding a mass of blowing. Previous researchers [6–12] found that a close-coupled canard configuration could increase the lift, improve the lift-drag ratio of supersonic cruise, and enlarge the angle of stall by using the favorable interaction between the canard and wing vortex. Associating with advantages of the close-coupled canard configuration and wing-spanwise blowing, an innovative vortex-control technology conception, canard-spanwise blowing, has been brought forward. Using the canard as a vortex generator, the canard-spanwise blowing can strengthen the canard vortex and control its breakdown. By making use of the advantageous interaction between canard and wing vortex, the strength of the wing vortex is enhanced and its breakdown is delayed indirectly, the lift and angle of stall are increased, and high attack angle and poststall maneuverability of the fighter are improved.

Shi et al. [13] found that on a delta wing, the leading-edge vortex with jet remained for a period of time when the jet intermitted suddenly and then came back to the breakdown state with no jet. Meyer and Seginer [14] observed a lag in response time on a delta wing with pulsed spanwise blowing. Based on the lag characteristic of the leading-edge vortex, we bring forward the canard-spanwise pulsed blowing to reduce the bleed air from the engine. A detailed experimental study will be made on the lift change with canard-spanwise pulsed blowing and on the mechanism of pulsed blowing causing highly aerodynamic performance.

II. Apparatus, Model, and Method of Experiment

The force measurement experiment was conducted in the D4 wind tunnel of Beijing University of Aeronautics and Astronautics. The D4 wind tunnel has a 1.5×1.5 m square-shaped test section with a 2.5 m length. The freestream turbulence intensity is less than 0.08%.

The model is a simple canard configuration with a 50 deg swept delta wing and a 50 deg swept delta canard, shown in Fig. 1. It is made of duralumin sheet with 4 mm thickness and the leading edge is beveled windward at 45 deg. The wing area is 0.05625 m^2 and the canard area is 0.0068 m^2. The wing and canard are coplanar and the longitudinal distance between them is zero. Two stainless steel nozzles with inner diameters of 2 mm and outer diameters of 2.5 mm are fixed over the canard surface, which are located at 30% of the canard root chord and 50% of span (corresponding to the 30% of the canard root chord). The vertical height of the nozzles is 2.5 mm, and the length is 3 mm over the canard surface. The orientation is parallel to the leading edge of the canard.

The pulse control system for this experiment is shown in Fig. 2. The pressure of high-speed air entering these nozzles is about 8 times the atmospheric pressures, and the value keeps constant in the whole experiment process. The on–off of the blowing pipeline is controlled by a pressure valve. The volume flow rate is supervised by a flow meter (the Dwyer RMB Series). To achieve the pulsed blowing, we add a solenoid valve after the flow meter and use the computer to control its on–off. The solenoid value was a MAC200, which has the open response time of 15 ms and the close response time of 5 ms, so that when the pulse frequency is below 10, the blowing can be considered as the square wave pulse.

Lift is recorded by a strain-gauge balance tailor-made for force measurement. The freestream velocity of this experiment is 20 m/s and the Reynolds number based on the delta wing root chord is 3.6×10^5. The force experiment has a 200 Hz sample frequency and 800 sample points. The tests were conducted at 10 pulse frequencies ($f = 0.5$–0.9 Hz and 1–5 Hz), at 9 pulse widths ($q = 0.1$–0.9), at 3 blowing momentum coefficients ($C_\mu = 0.113$, 0.196, and 0.3), and at 3 angles of attack ($\alpha = 9$, 28, and 49 deg).

III. Results and Discussion

A. Force Measurement for Canard-Spanwise Continuous Blowing

The lift coefficient curves for canard-spanwise continuous blowing are shown in Fig. 3. It can be seen that the angle of stall and

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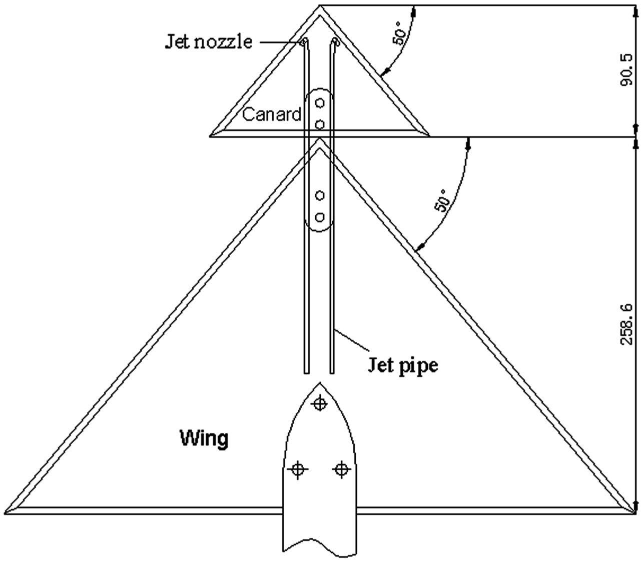


Fig. 1 Force measurement model for canard-spanwise pulsed blowing.

lift coefficients at the middle and large angles of attack (AOA) with canard-spanwise blowing are all higher than those with no blowing. Moreover, the maximal lift coefficient and the angle of stall enlarge with the increasing of C_μ.

B. Force Measurement for Canard-Spanwise Pulsed Blowing

The mean jet momentum coefficient of canard-spanwise pulsed blowing is defined by Eq. (1):

$$\bar{C}_\mu = \frac{1}{T}\int_{t_0}^{t_0+T} C_\mu(t)\,\mathrm{d}t = \frac{1}{T}\int_{t_0}^{t_0+qT} C_\mu\,\mathrm{d}t = C_\mu q \tag{1}$$

where

$$C_\mu(t) = \begin{cases} C_\mu & 0 \le t \le qT \\ 0 & qT \le t \le T \end{cases}$$

For this canard configuration, the angle of stall is about 28 deg when blowing, and so we focused our study on this degree with pulsed blowing. The research emphasis is $C_\mu = 0.3$.

1. *Effect of Pulse Frequency on Mean Lift Coefficient*

Figure 4 shows the mean lift coefficient curves with different pulse frequencies. It can be seen that when the pulse width is less than 0.8, the higher the pulse frequency, the larger the mean lift coefficient (or the mean lift coefficient increases with the enlarging of pulse frequencies). When the pulse width exceeds 0.8, the mean lift coefficient has no obvious change with the pulse frequency and it is very close to the lift coefficient of canard-spanwise continuous blowing.

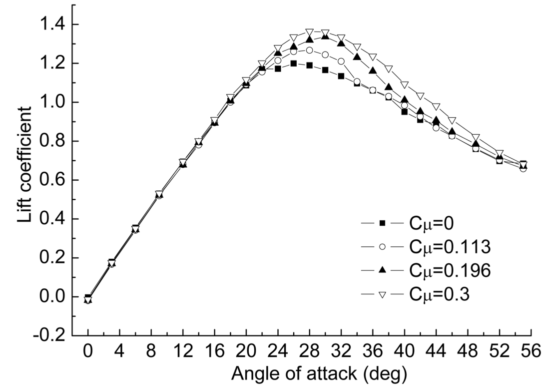


Fig. 3 Lift coefficient curves with canard-spanwise continuous blowing.

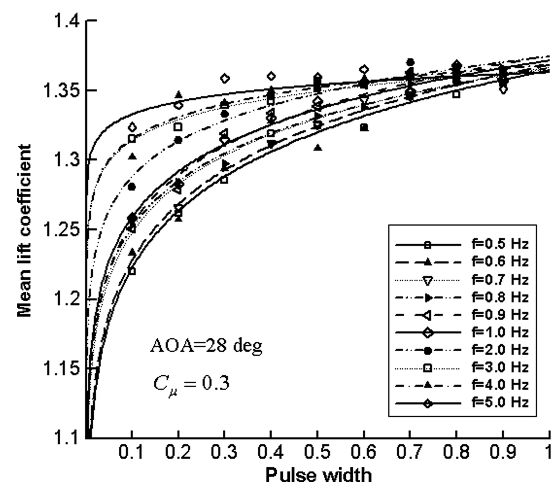


Fig. 4 Mean lift coefficient curves with different pulse frequencies.

2. *Effect of Pulse Width on Mean Lift Coefficient*

The mean lift coefficient curves with different pulse widths are shown in Fig. 5. It shows that the mean lift coefficient increases with the enlarging of pulse widths.

3. *Effect of Jet Momentum Coefficient on Mean Lift Coefficient*

Figure 6 shows the mean lift coefficient curves with $C_\mu = 0.3$ and 0.196. The data points are given by $\bar{C}_L/C_L$. If the ratio comes up to 1, we can consider that the effect of pulsed blowing is the same as continuous blowing. On the condition of a fixed C_μ, carrying out the canard-spanwise pulsed blowing, the $\bar{C}_L$ can exceed the C_L that the C_μ is less than this fixed value; the $\bar{C}_L$ can be reached the C_L at this fixed C_μ.

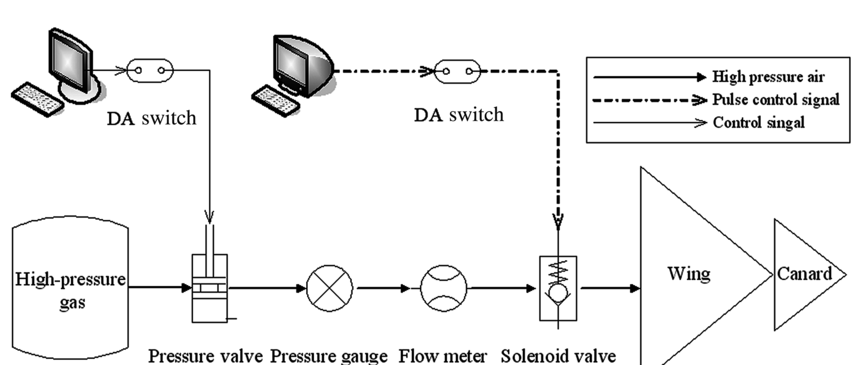


Fig. 2 Pulse control system for force measurement.

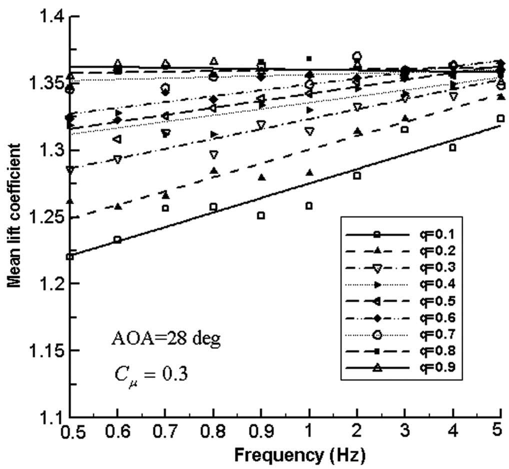


Fig. 5 Mean lift coefficient curves with different pulse widths.

C. Mechanism Achieving Highly Aerodynamic Performance by Canard-Spanwise Pulsed Blowing

Previous studies have shown that at the larger angles of attack, the improved or delayed leading-edge vortex by blowing does not come back to the state of no blowing immediately, but persists for a period of time [13]. We define this period of time as the vortex delay time and denote it with T_w. In this Note, we discuss the effect of q, f, C_μ, α, and Λ_c on T_w.

1. Effect of Pulse Width on Vortex Delay Time

Select $f = 0.5$ Hz to investigate the effect of pulse width on the vortex delay time. The instantaneous lift coefficient curves with $q = 0.5$ are shown in Fig. 7. We define T_L as the vortex lived time (the time interval that the instantaneous lift coefficient suddenly increases until it comes back to the value of without blowing) and define T_P as the pulse time. There is $T_w = T_L - T_P$. In Fig. 7, the T_L is about 1385 ms and the T_P is 1000 ms, so the T_w is 385 ms. For other different pulse widths, the pulse time and the vortex lived time are shown in Fig. 8. It is obvious that the linear fit curve of the T_L almost parallels with the curve of pulse time, which indicates that the vortex delay time is irrelevant to the pulse width, and it is about 380 ms.

2. Effect of Pulse Frequency on Vortex Delay Time

Select $q = 0.5$ to investigate the effect of blowing frequency on the vortex delay time. Figure 9 shows the pulse times and the vortex lived time for different blowing frequencies. The linear curve of the vortex lived time almost parallels with the curve of pulse time, which indicates that the vortex delay time is a constant and is about 380 ms.

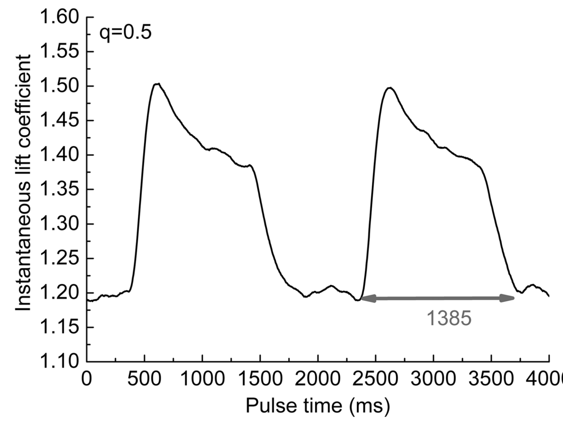


Fig. 7 Instantaneous lift coefficient curves with $q = 0.5$.

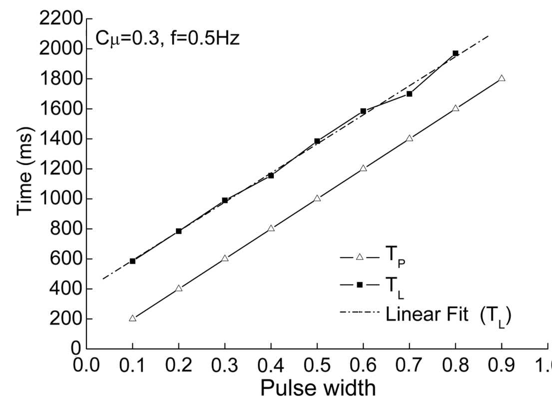


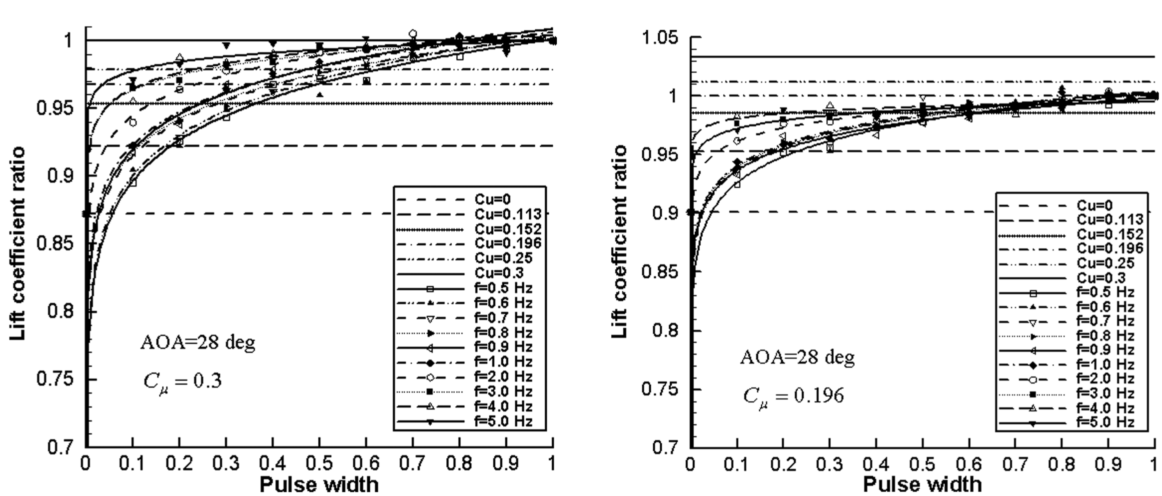
Fig. 8 Curves of the pulse times and the vortex lived times with different pulse widths.

3. Effect of Jet Momentum Coefficient on Vortex Delay Time

Select $f = 0.5$ Hz to study the effect of C_μ on T_w. The vortex lived times for different jet momentum coefficients are shown in Fig. 10. The coincidence of curves is very good. It is obvious that the vortex delay time is independent of jet momentum coefficients. The vortex delay time is about 380 ms.

4. Effect of AOA on Vortex Delay Time

In addition to the 28 deg AOA, we also select 9 deg and 49 deg to study the effects of AOA on vortex delay time. Figure 11 shows the curves of vortex lived times for different AOA when $f = 0.5$ Hz. It can be seen that the vortex delay time is relative to AOA. The vortex delay time is 230 ms at 9 deg and is 280 ms at 49 deg, which are



a) $C_\mu = 0.3$ b) $C_\mu = 0.196$

Fig. 6 Mean lift coefficient curves with different jet momentum coefficients.

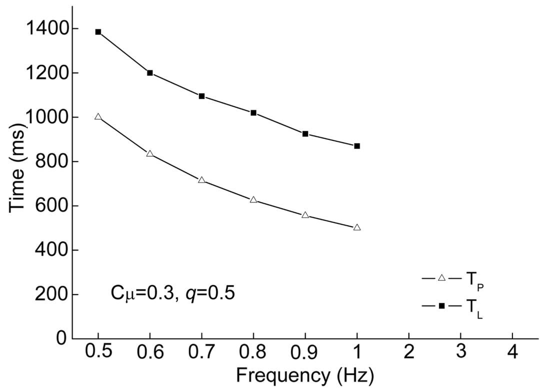


Fig. 9 Curves of the pulse times and the vortex lived times with different pulse frequencies.

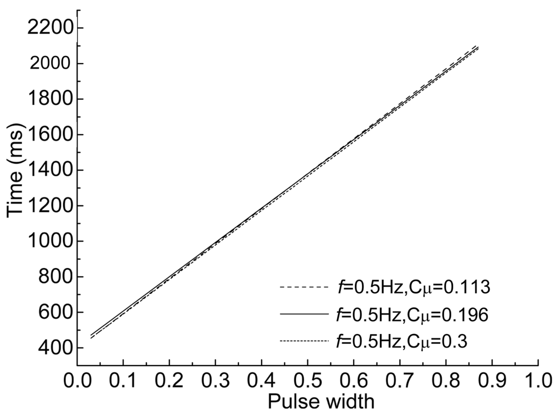


Fig. 10 Curves of the vortex lived times with pulse widths for different jet momentum coefficients.

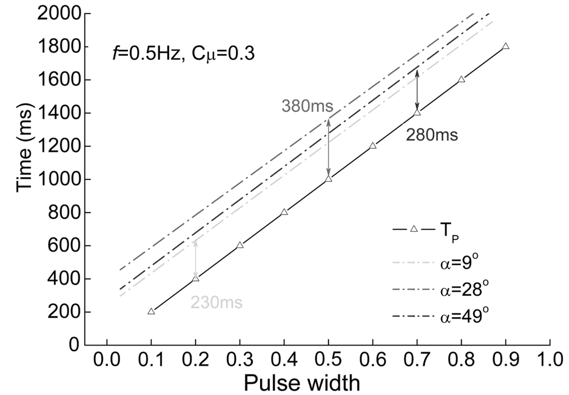


Fig. 11 Curves of the vortex lived times with pulse widths for different AOA.

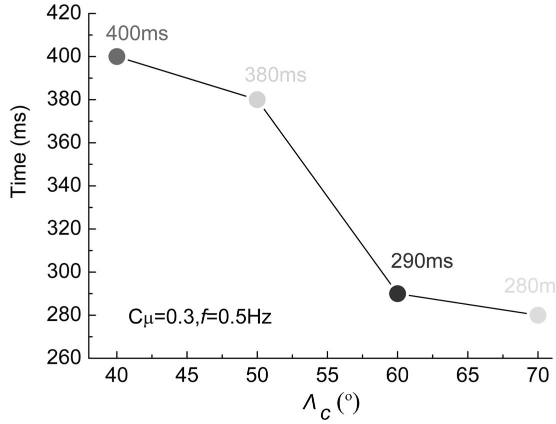


Fig. 12 Vortex delay times for different swept angles of canard.

shorter than that of 28 deg. This is because at a 9 deg of AOA, the leading-edge vortex begins to generate and the spanwise blowing is difficult to work on this stable flow. When the solenoid valve is off, the flow is easy to come back to the state undisturbed, andso the vortex delay time is shorter. At 49 deg of AOA, the leading-edge vortex has already broken down and the flow is also stable, and so the vortex delay time is also shorter than that of 28 deg.

5. *Effect of Swept Angle of Canard on Vortex Delay Time*

To study the effect of swept angle of canard on vortex delay time, we select 4 canards, and the research emphasis is $C_\mu = 0.3$ and $f = 0.5$ Hz. The vortex delay time for different swept angles of canard is shown in Fig. 12. It is obvious that the vortex delay is relative to swept angles of canard, and it is longer with the increasing of the swept angle. This is because at a 28 deg of AOA, the flow on the canard with a bigger swept angle is more stable than that with a smaller swept angle.

Combined with the effect of q, f, C_μ, α, and Λ_c on the vortex delay time, it can be concluded that the vortex delay time is relevant to the flow state but not the pulse width, frequency, and blowing coefficients.

IV. Conclusions

As a result of this study, the following conclusions can be made:

1) The canard-spanwise blowing can delay the wing vortex breakdown indirectly and increase the lift coefficient and the angle of stall.

2) On the condition of canard-spanwise pulsed blowing, the mean lift coefficient increases with the enlarging of pulse widths. When the pulse width is less than a critical value, the pulse frequency is higher and the mean lift coefficient is higher; when the pulse width exceeds a critical value, the mean lift coefficient has no obvious change with the pulse frequency and it is very close to the lift coefficient of canard-spanwise continuous blowing.

3) The pulsed blowing cannot only obtain the lift value of continuous blowing, but can also reduce the bleed air from engine. The mechanism of pulsed blowing causing highly aerodynamic performance is that the improved or delayed wing vortex does not come back immediately to the state without blowing, but persists for a period of time. This time is relevant to the flow state but not the pulse width, frequency, and blowing coefficients.

Acknowledgments

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