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Effects of Canard Sweep and Canard-Spanwise Blowing Magnitude on Lift Increment

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The effects of different canard's swept angles and jet momentum coefficients on the lift increment of simple close-coupled canard configurations with a 40-deg swept delta wing were investigated in a low-speed wind tunnel by force measurement. The experimental results show that at a certain range of attack angles (16–50 deg), on the condition of no blowing, with the increasing of the canard's swept angles, the lift increment and critical stall angles increase, which shows that the canard can be used as a controlling element for aerodynamic forces. On the condition of blowing, when the jet momentum coefficient exceeds a certain value, the more the jet momentum coefficient is, the more the lift increment is, which suggests that indirectly controlling the wing vortex is possible by canard-spanwise blowing for close-coupled canard configurations.

Nomenclature

C_L = Lift coefficient
C_μ = Jet momentum coefficient, ($C_\mu = \dot{m}V_j/q_\infty S_c$)
$\dot{m}$ = Nozzle air mass flow rate
q_∞ = Free-stream dynamic pressure, Pa
S_c = Canard reference area
V_j = Jet velocity, m/s

Introduction

PREVIOUS researchers such as Behrbohm [1], Gloss [2–5], Er-El [6,7], and others [8–12] have done a series of experiments on close-coupled canard configurations. The results show that by use of the favorable mutual interaction between the vortex systems of the wing and the canard, a close-coupled canard configuration could delay flow separation on the wing, increase the lift and decrease the drag force at high angles of attack (AOA), improve the lift-drag ratio of the supersonic cruise, and enlarge the critical value of the stall angle, all of which are beneficial to the high maneuverability fighter. Because of the favorable mutual interaction between the vortex systems, the canard vortex has an evident effect on others' aerodynamic elements of aircraft. For example, at high angles of attack, the downwash of the canard vortex decreases the effective AOA of the wing, which makes the wing's vortex breakdown (VBD) delay, the lift increase, and the aerodynamic efficiency improve. To use this favorable mutual interaction, controlling the canard vortex is a reasonable consideration.

The wing-spanwise blowing has been studied extensively [13–18]. It has been thought of as a hopeful technique for controlling vortex in the future, but has not been used in practice due to demanding a mass of blowing. Erickson and Campbell [16] found that canard-spanwise blowing has 2.5 times aerodynamic efficiency than wing-spanwise blowing on a close-coupled canard configuration with the same jet momentum coefficients. So the studies on the vortex control technique of canard-spanwise blowing are very necessary and important. The concept of the vortex control technique of canard-spanwise blowing is defined as introducing a high jet on the canard's upper surface in a direction essentially parallel to the leading edge to control flow on the wing indirectly. This high jet may have some advantages: strengthening or reformation of the canard's leading edge vortex, increasing the axial velocity of the vortex, and delaying its breakdown; moreover the delayed or improved canard vortex can affect and improve the flow on the wing, delay the wing's VBD, and enhance the wing's lift. In the present paper, a detailed experimental study will be made on the lift increment of close-coupled canard configurations with the vortex control technique of canard-spanwise blowing.

Experiment Setup

The aerodynamic forces were measured in the D4 wind tunnel of Beijing University of Aeronautics and Astronautics, which has a 1.5×1.5 m square-shaped test section with 2.5 m length. The maximal wind speed is 60 m/s and the turbulence intensity of the incoming flow is less than 0.08%. In this experiment the free-stream velocity is 20 m/s and the Reynolds number based on the delta-wing root chord (217 mm) is 3.0×10^5.

Four different experiment models of canard configurations with a 40-deg swept delta wing and 40-deg, 50-deg, 60-deg, and 70-deg swept delta canards are adopted. Figure 1 shows the canard configuration with a 40-deg swept wing and a 40-deg swept canard. The wing and canard are coplanar, and longitudinal distance between them is zero. They are made of duralumin with 4 mm thickness and the leading edges are beveled windward at 45 deg. The wing area is 0.05625 m^2 and all canards have the same area of 0.0068 m^2.

Two stainless steel nozzles with an inner diameter of 2 mm and an outer diameter of 2.5 mm are fixed on 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 nozzles vertical

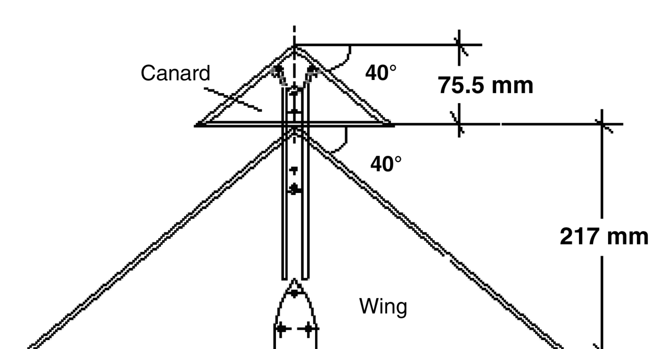

Fig. 1 The canard configuration with a 40-deg swept wing and a 40-deg swept canard.

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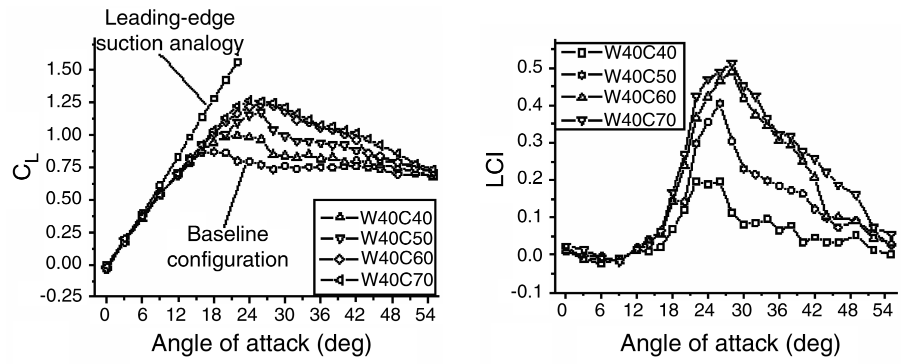
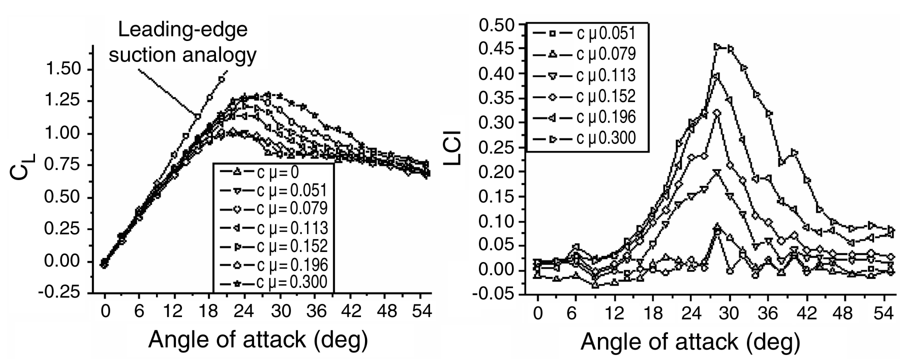


a) b)

Fig. 2 The lift coefficient and LCI curves with no blowing.



a) b)

Fig. 3 The lift coefficient and LCI curves with blowing.

Table 1 The corresponding values of C_μ, V_j, and V_j/V_∞

The jet momentum coefficient	0.051	0.079	0.113	0.152	0.196	0.3
The jet velocity, m/s	50.1	62.6	75.1	87.6	100.1	125.2
The ratio of jet velocity and free-stream velocity	2.5	3.1	3.8	4.4	5.0	6.3

height is 2.5 mm, and the length is 3 mm on the canard surface. The orientation is parallel to the leading edge of the canard. The total pressure of high-speed air entered into these nozzles is about 8 times atmospheric pressures and the value keeps constant in the whole experiment process.

Forces and moments are recorded by a six-component strain-gage balance. The range of AOA is 0–50 deg at intervals of 2–3 deg. The mean-square-root error of seven repeated experiments with a canard configuration with a 40-deg swept wing and a 40-deg swept canard is 0.0084 for the lift coefficient.

Results and Discussion

The lift coefficient of the delta wing (baseline configuration) adopts the wing area as a reference area, but the reference area of the canard configurations is the sum of the wing area and the canard area.

1) The effect of the canard's swept angle with no spanwise blowing on C_L and the lift-coefficient increment (LCI).

Previous studies by Gloss [2–5] and Ma et al. [12] revealed that in the low speed flow, if the Reynolds number, wing's swept angle, and the canard's reference area and the wing's reference area are given, the lift coefficient of the canard configuration is a function of AOA and the canard's swept angle. Four different canard configurations with a 40-deg swept wing and 40-deg, 50-deg, 60-deg, and 70-deg swept canards are adopted to investigate the effect of the canard's swept angle on the lift increment. The LCI is the difference of C_L between the canard configuration and the corresponding baseline configuration.

The lift coefficient and LCI curves varying with the canard's swept angles are shown in Fig. 2 with no blowing. It can be seen that the lift coefficients and the stall angles of canard configurations are larger than the baseline configuration. Moreover, with the increasing of the canard's swept angles, the lift coefficients and the stall angles also increase. The maximal value for LCI is 0.5 (about 60% of the baseline configuration) and the maximal stall angle is delayed by 6 deg (Fig. 2a).

There are three segments in the LCI curves (Fig. 2b) for any different canard configurations. In the range of 0–16 deg (the low AOA), the LCI is almost zero. The vortex of the canard and wing is weak and the effect between vortex systems is dominated by "washing." The downwash of the canard flow decreases the effective AOA of the wing, so the lift increments offered by the canard and the lift decrements induced by the smaller effective AOA offset each other and the total lift has no change. In the range of 16–30 deg (the middle AOA), the bigger AOA is, and the more LCI is. The vortex of the canard and wing become more and more strong and the effect between vortex systems is predominated by "favorable interaction." This favorable interaction improves the wing flow, delays its VBD, and increases vortex lift, so the total lift also increases (The total lift includes the canard's lift and the wing's lift). When AOA is more than 30 deg, the LCI decreases with the increasing of AOA. The location of the wing's VBD develops upward inch by inch, and the flow is separated completely until 50 deg and the LCI is almost zero.

With the varying of the canard's swept angle the LCI is different, but the trend is that the higher the canard's swept angle is, the more LCI is. The reason is that the vortex on the canard becomes stronger and steadier and it is difficult to break down with the increasing of the canard's swept angle.

2) The effect of C_μ on C_L and LCI.

When blowing, if the wing's swept angle is given, the lift coefficient of the canard configuration is a function of AOA and C_μ. In this section, the canard configuration with a 40-deg swept wing and a 40-deg swept canard is adopted to investigate the effect on the lift increment. As a control parameter of spanwise blowing, six jet momentum coefficients C_μ are adopted. Table 1 gives the corresponding values of jet velocity and the ratio of jet velocity and free-stream velocity. The LCI is the difference of C_L between with and without blowing.

The lift coefficient and LCI curves varying with different C_μ are shown in Fig. 3. There is little LCI when $C_\mu = 0.051$ and $C_\mu = 0.079$ due to the jet velocity being low. The axial velocity of steady vortices is above 2.4–3.0 times the free-stream velocity [19], so the jet velocity is not less than $(2.4\text{–}3.0)V_\infty$. Except these two curves, the more C_μ is, the more LCI is. The maximal LCI is about 0.45 and the critical stall angle is delayed 8 deg when $C_\mu = 0.3$ (Fig. 3a).

There are also three segments in LCI curves (Fig. 3b) varying with AOA. In the range of 0–16 deg, the LCI is almost zero, which implies that blowing has no effect on the wing flow and cannot control aircraft in these AOA (because the flow is dominated by washing). In the range of 16–30 deg, the LCI increases with the increasing of AOA. Canard-spanwise blowing can delay canard's VBD and improve canard flow. Because the flow is predominated by "favorable interaction" in this range of AOA, the delayed or improved canard vortex can affect and improve the wing flow, delay the wing's VBD, and enhance the wing's lift. So the total lift increases. When AOA is more than 30 deg, the LCI decreases with the increasing of AOA, which indicates that the canard spanwise cannot control the wing's VBD entirely; moreover the location of VBD develops upward gradually. When AOA reaches 50 deg, the flow separates completely and the LCI is almost zero.

The controlling range is 16–50 deg by canard-spanwise blowing for the simple canard configuration with a 40-deg sweep delta wing and a 40-deg sweep delta canard.

Conclusions

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

1) On the condition of no blowing, with increasing of the canard's swept angles, the LCI and critical stall angles increase. The lift increment range of AOA is 16–50 deg, which shows that the canard can be used as a controlling element for aerodynamic forces.

2) On the condition of canard-spanwise blowing, the LCI are different with varying C_μ. When C_μ exceed a certain value ($V_j/V_\infty > 2.4\text{–}3.0$), the more C_μ is, and the more LCI is. The controlling parameter C_μ and the LCI have relevant relations. At any C_μ in this experiment, the AOA range of lift increment is from 16–50 deg and the LCI are different with the AOA, which suggests the indirect controlling of the wing's vortex, the delay of its breakdown, and the increase of the lift with the technique of canard-spanwise blowing for the close-coupled canard configuration are possible.

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