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Effect of Canards on Delta Wing Vortex Breakdown During Dynamic Pitching

Roy Y. Myose,* Shigeo Hayashibara,† Ping-Chian Yeong,‡ and L. Scott Miller§
Wichita State University, Wichita, Kansas 67260-0044

The effect of a canard on delta wing vortices was investigated in the 2 × 3 ft water tunnel at Wichita State University. It is well known that the leading-edge vortices generated by a delta-shaped wing greatly enhance a vehicle's performance at high angles of attack. In this experiment, different canards were placed in front of a 70-deg swept main delta wing. Dye flow visualization was used to observe the vortex breakdown location during dynamic pitch-up and pitch-down motion with varying pitch rates. Compared to the no-canard configuration, results showed that there was a delay in vortex breakdown because of the presence of the canard and the dynamic pitch motion. The most favorable delay was obtained when the canard was located closest to the main delta wing and the model was pitched up at a fast rate or pitched down at a slow rate. Complete vortex breakdown on the main delta wing (i.e., full stall) occurred at 53 deg for the static case without canard. In comparison, complete vortex breakdown occurred past 90 deg when a canard configured delta wing was pitched up at the fastest rate tested (i.e., k = 0.2).

Nomenclature

AR = wing aspect ratio, b^2/S
b = wing span
c_r = wing root chord
q = dynamic pressure, $\frac{1}{2}\rho U_\infty^2$
Re = Reynolds number, $U_\infty c_r/\nu$
S = wing area
U_∞ = freestream velocity
α = angle of attack
α' = pitch rate
κ = nondimensional pitch rate, $\alpha' c_r/2U_\infty$
Λ = sweepback angle
ν = freestream flow kinematic viscosity
ρ = freestream flow density

Introduction

HIGH-PERFORMANCE aircraft such as military fighters often require high-lift forces in a wide range of angles of attack to maintain their maneuverability. On two-dimensional airfoils, maximum lift is typically obtained at 10- to 15-deg angle of attack after which the airfoil stalls. Thus, high-performance aircraft require some form of lift enhancement under high-angle-of-attack conditions. One technique for obtaining enhanced lift at moderate angles of attack is the use of delta-shaped wings and strakes. As flow separates along the leading edges of a delta wing at nonzero angles of attack, vortical flow results. These delta wing vortices produce a very low-pressure region and can account for up to 30% of the total lift at moderate angles of attack.[1] A 70-deg swept delta wing, for example, continues to increase its lift until an angle of attack of about 40 deg is reached.[2] Unfortunately, there are limits to the benefits produced by the delta wing vortices. As the angle of attack is increased, there is a sudden breakdown in vortex structure. This phenomenon, also known as vortex bursting, results in a sudden stagnation in core axial flow and an expansion in radial size.[3] Once the vortex structure is broken down, lift is no longer enhanced aft of the breakdown point. Thus, it is desirable for the vortex burst to be delayed as far aft as possible to obtain enhanced lift from the vortex. Attempts to control the delta wing vortices (under static conditions) have included blowing,[4,5] suction,[6,7] and the use of leading-edge flaps.[8,9] The reader is referred to Lee and Ho[10] for a more complete review on delta wing vortices.

The aerodynamic response under unsteady flow conditions is quite different from those just discussed. According to McCroskey,[11] the maximum lift of an airfoil undergoing pitch oscillation (in steady freestream flow) can greatly exceed the static case. In oscillating freestream flow conditions (with stationary airfoil), Gursul et al.[12] reports a phenomenal ten-fold increase in the lift coefficient (compared to the static case) during some parts of the oscillating time period. By properly controlling their oscillation period, they were also able to increase the average lift value by a factor of 2. On delta wings, the unburst part of the leading-edge vortex becomes shorter as the angle of attack is increased. Under dynamic conditions, there is a hysteresis or phase lag in the vortex burst location. For example, the vortex burst location is further aft compared to the static case (at a given α) under pitch-up motion and further forward under pitch-down motion.[13] This phase lag is larger as the pitch rate is increased.[13,14] Thus, fast pitch-up and slow pitch-down is desired to delay vortex breakdown.

Past studies have investigated the effects of blowing,[13,15] variable sweep,[16] leading-edge flap,[16] and apex flap[17] on the delta wing vortices under dynamic conditions. The objective of the present series of experiments was to study the effect of canards on delta wing vortices under dynamic pitching conditions. A previous paper[18] discussed the results for the 70-deg swept canard placed at several locations in front of a 70-deg swept main delta wing model. This paper discusses the results when a 60-deg swept canard was placed at several locations and angles in front of a 70-deg swept main delta wing model. Vortex breakdown locations were observed in the water tunnel under static, pitch-up, and pitch-down conditions.

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*Assistant Professor, Department of Aerospace Engineering. Senior Member AIAA.

†Student, Department of Aerospace Engineering; currently at Department of Aerospace Engineering, University of Southern California, Los Angeles, CA 90089-1191.

‡Student, Department of Aerospace Engineering; currently at No. 6, P.P.M. Elopura, Batu Empat, Jalan Labuk, 90000 Sandakan, Sabah, Malaysia.

§Associate Professor, Department of Aerospace Engineering. Member AIAA.

Experimental Method

The experiment was conducted in the 2 × 3 ft water tunnel located at Wichita State University, National Institute for Aviation Research (NIAR). The facility is a closed-loop water tunnel containing a total of 3500 gal of water. The flow velocity is adjustable up to 1.0 ft/s using an impeller pump driven by a 5-hp variable-speed motor. The facility has excellent optical access providing two side views, a bottom view, and an end view.

Figure 1 shows a sketch of the test model and the five different test configurations. The 60-deg swept canard is placed in front of the main delta wing using a knife-edge-shaped support. The cross section of the support is made as thin as possible to minimize the flow disturbance. The canard and main delta wings are both made out of 0.125-in.-thick aluminum alloy. Both starboard and port sides are symmetrically beveled (11.3 deg) and sharp edged. The main delta wing model is painted white to enhance visual contrast. Black reference grid lines perpendicular to the wing centerline are marked in 5% chord intervals to determine the vortex breakdown locations. The test model specifications follow: 1) canard: $\Lambda = 60$ deg, $c_r = 2.5$ in., $b = 2.88$ in., $S = 3.60$ in.^{2}, AR = 2.30; and 2) main delta wing: $\Lambda = 70$ deg, $c_r = 12.0$ in., $b = 8.75$ in., $S = 52.5$ in.^{2}, and AR = 1.46.

A dynamic test mount consisting of a rotating turntable was used to obtain the dynamic pitch motion. The position and rotational speed of this belt-driven turntable are controlled by a variable-speed dc motor. The turntable is capable of 360 deg of rotation at rates up to 30 deg/s. The pitching motion produced by this dynamic test mount is a constant angular rate of change, i.e., a ramp-type pitching motion. Additional details about the dynamic test mount are presented by Miller and Gile.[13]

Dye flow visualization technique was used in this experiment. Two 0.06-in.-diam stainless-steel tubes were positioned slightly off center near the main delta wing apex. One tube was located on the port side and the other on the starboard side. However, only the starboard side vortex was visualized during the dynamic portion of the tests. The vortices from the canard were not visualized since the attachment of dye tubes would increase the width of the canard support sting mount. Food coloring (dye) was injected at a slow rate into the vortex, resulting in a clear view of its development and its ensuing breakdown. The visualized flow behavior was recorded by a charge-coupled device camera and S-VHS video system. A time code generator imprinted a time reference on the video every 1/30th of a second. The video tapes were carefully examined frame-by-frame, and the vortex breakdown locations and corresponding angles of attack were identified relative to the reference grid lines on the model and the time code recorded on the tapes. The vortex breakdown locations are expected to be accurate within 2–3% of the wing root chord using this method.[13]

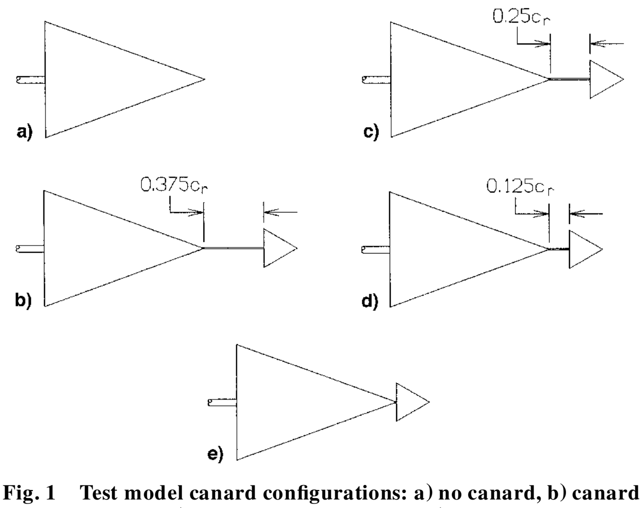

Fig. 1 Test model canard configurations: a) no canard, b) canard 0.375c_r forward, c) canard 0.25c_r forward, d) canard 0.125c_r forward, and e) canard 0.0c_r forward.

For static and pitch-up runs, an observation problem often occurred for angles of attack less than 30 deg. At these angles, it was difficult to ascertain the exact vortex behavior. This same problem was also reported by Miller and Gile[13] and data for these angles were not taken.

A freestream velocity of $U_\infty = 0.4$ ft/s was used throughout the course of this experiment. This corresponds to a Reynolds number of $Re = 33 \times 10^4$, based on a main delta wing root chord ($c_r = 12$ in.). The five test configurations consisted of no canard (Fig. 1a) and canard located at 0.375, 0.25, 0.125, and 0.0c_r (i.e., 4.5, 3.0, 1.5, and 0 in.) in front of the main delta wing (Figs. 1b–1e). Vortex breakdown locations under static conditions were measured for angles of attack from 0 deg until full stall (i.e., breakdown of the entire main delta wing) in 5-deg increments. Dynamic vortex breakdown locations were measured for both pitch-up and pitch-down conditions with varying pitch rates. The model was pitched about the half-chord location of the main delta wing. Thus, κ based on α' (in rad/s) is given by[13]

$$\kappa = \alpha' c_r / 2U_\infty \tag{1}$$

Pitch-up and pitch-down tests were conducted for pitch rates of $\kappa = 0$ (i.e., static), 0.05, 0.10, 0.15, and 0.20. For dynamic pitch-up tests, measurements were started at $\alpha = 15$ deg and continued past $\alpha = 90$ deg. For dynamic pitch-down tests, measurements were started at $\alpha = 40$ deg and continued until $\alpha = 0$ deg.

Results and Discussion

Static Vortex Breakdown Locations

Figure 2 shows the vortex breakdown locations vs angle of attack under static ($\kappa = 0$) test condition. The breakdown locations are given in terms of percent chord measured from the main delta wing apex. Thus, a breakdown location of 0% corresponds to full stall where the delta wing vortex is completely bursted. The region below each curve corresponds to a condition where the vortex is not bursted. It is desirable for this region to be as large as possible since this is the area where enhanced lift from the vortical flow is still present. It is evident from Fig. 2 that the presence of the canard has a favorable effect in terms of delaying the vortex breakdown. This delay in breakdown was observed for all canard configurations up to an angle of attack of 50 deg. It is reasonable to assume that the wake flow from the canard is impinging upon the main delta wing and providing this beneficial effect of delaying the vortex breakdown. Some studies on somewhat different canard configurations have shown beneficial effects from a canard--

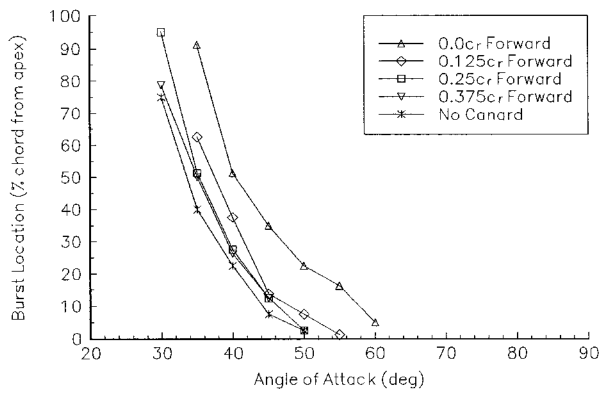

Fig. 2 Static vortex burst locations for 60-deg swept canard.

main delta wing interaction.[19,20] In the present experiment, however, this could not be verified since the canard wake flow was not visualized. Above 50-deg angle of attack, no delaying effect was observed with the canard configured $0.25c_r$ and $0.375c_r$ forward of the main delta wing. This may be because the canard wake flow is too far above the main delta wing vortices when the canard is configured so far forward. The most favorable effect in terms of delaying vortex breakdown was obtained with the canard located closest to the main delta wing ($0.0c_r$ forward). Full stall (i.e., where the delta wing vortex was completely broken down) occurred at 63-deg angle of attack. This compares to a full-stall angle of attack of 53 deg for the no-canard configuration. Thus, a 19% delay in full-stall angle of attack was obtained with the $0.0c_r$ forward canard configuration compared to the no-canard case.

Effect of Dynamic Pitch-Up

Figure 3 shows the vortex breakdown locations (in percent chord measured from the main delta wing apex) vs angle of attack under dynamic pitch-up conditions. The figure is sequenced according to canard configuration as per Fig. 1. At a given angle of attack and canard configuration, Fig. 3 shows that the most favorable delaying effect is obtained at the fastest pitch rate (i.e., $\kappa = 0.20$). This is consistent with previous results on delta wings under dynamic pitch conditions.[13,14] For the $0.0c_r$ forward configuration shown in Fig. 3e, full stall occurs at 63-deg angle of attack under static condition. This is delayed until 94-deg angle of attack when pitched-up at the fastest rate ($\kappa = 0.20$). Thus, a 49% delay in full-stall angle of attack is obtained when the canard-configured delta wing is pitched up at a fast rate compared to the static case. Figure 4 compares the vortex breakdown locations at the fastest pitch rate ($\kappa = 0.20$) for all five configurations. The figure shows that the breakdown of the delta wing vortex is delayed by the presence of the canard. This delaying effect is improved as the canard is moved closer to the main delta wing. The most favorable delaying effect is obtained when the canard is located closest to the main delta wing (i.e., $0.0c_r$ forward). Full stall occurs at 77-deg angle of attack for the no-canard configuration and 94-deg angle of attack for the $0.0c_r$ configuration. Thus, a 22% delay in full-stall angle of attack is obtained with the $0.0c_r$ forward configuration compared to the no-canard case.

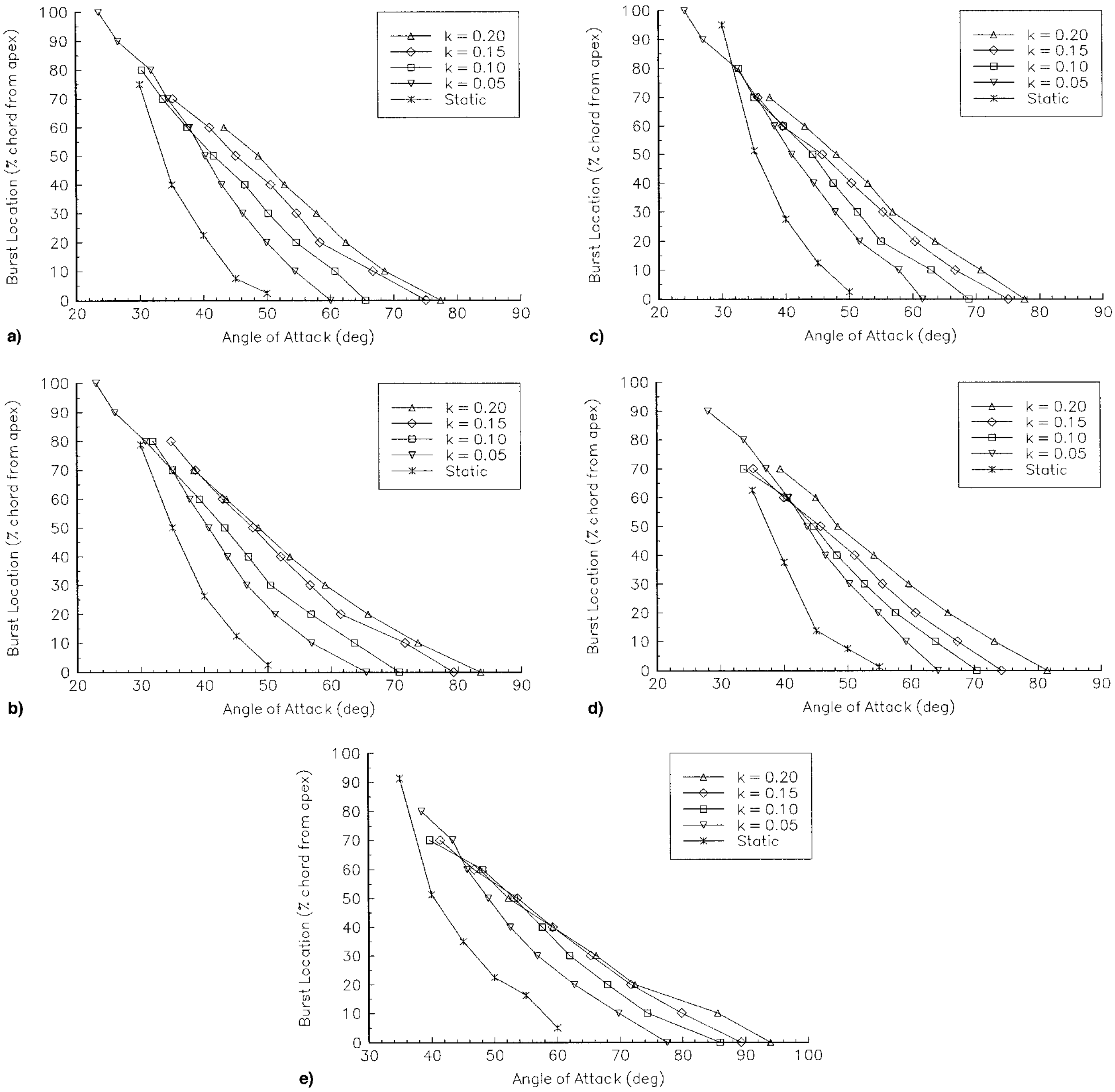

Fig. 3 Pitch-up vortex burst locations: a) no canard, b) 60-deg swept canard $0.375c_r$ forward, c) 60-deg swept canard $0.25c_r$ forward, d) 60-deg swept canard $0.125c_r$ forward, and e) 60-deg swept canard $0.0c_r$ forward.

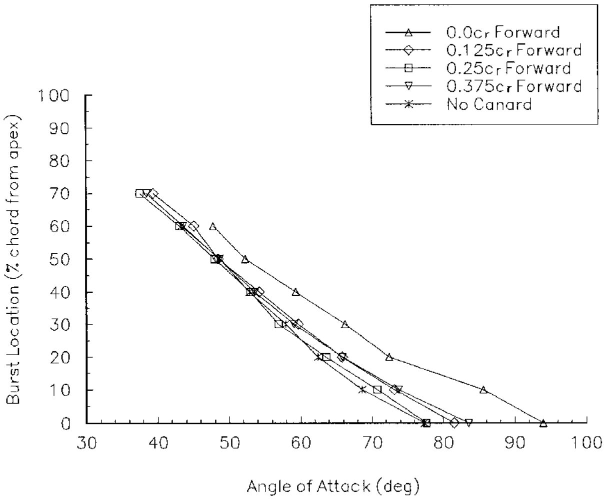

Fig. 4 Pitch-up vortex burst locations for 60-deg swept canard at $k = 0.2$.

Effect of Dynamic Pitch-Down

Figure 5 shows the vortex breakdown locations (in percent chord measured from the main delta wing apex) vs angle of attack under dynamic pitch-down conditions. Again, the figure is sequenced according to canard configuration as per Fig. 1. At a given angle of attack and canard configuration, a smaller percentage of the delta wing vortex is bursted with the static case compared to the pitch-down cases. Thus, dynamic pitch-down motion has a negative (i.e., undesirable) effect in terms of vortex breakdown location. The best pitch-down result is obtained with the slowest pitch rate ($\kappa = 0.05$). Miller and Gile[13] found similar results under pitch-down conditions. Figure 6 compares the vortex breakdown locations at the slowest pitch rate ($\kappa = 0.05$) for all five configurations. It is evident from the figure that a smaller percentage of the delta wing vortex is bursted when a canard is located close to the main delta wing compared to the no-canard case. A fighter aircraft that pitches up under maneuver will eventually have to pitch down. It is clear that the pitch down should be accomplished at a slow rate. The results show that at a given pitch-down rate, the breakdown of the delta wing vortex is delayed by the

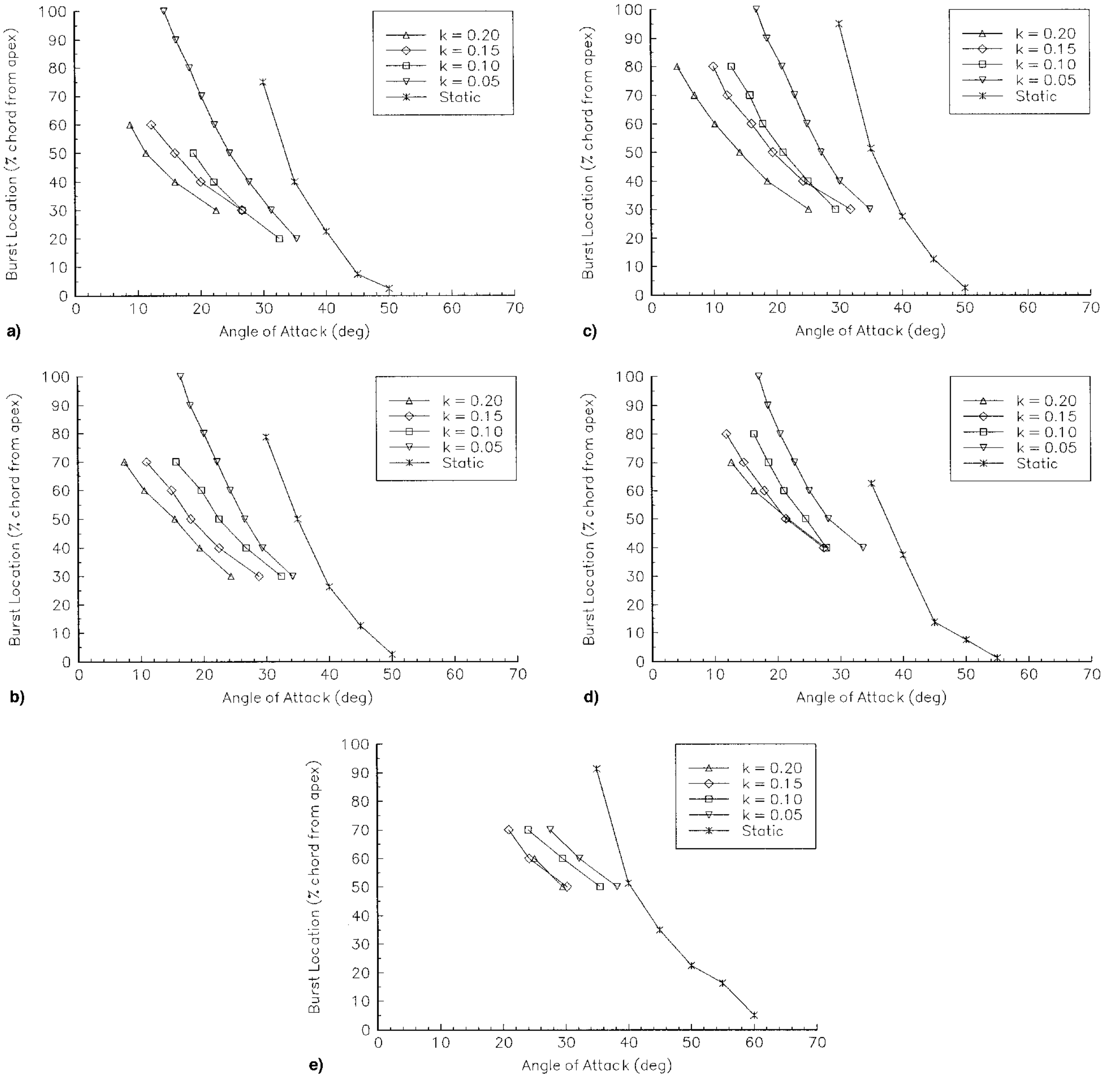

Fig. 5 Pitch-down vortex burst locations: a) no canard, b) 60-deg swept canard $0.375c_r$ forward, c) 60-deg swept canard $0.25c_r$ forward, d) 60-deg swept canard $0.125c_r$ forward, and e) 60-deg swept canard $0.0c_r$ forward.

presence of the canard. This delaying effect is improved as the canard is moved closer to the main delta wing. Again, the most favorable delaying effect is obtained when the canard is located closest to the main delta wing (i.e., $0.0c_r$ forward).

Effect of Canard Sweep-Back Angle or Area

The investigation described previously was repeated using canards with sweep-back angles of 70 and 45 deg. The specifications for these two canards are as follows: 1) 70-deg swept canard: $\Lambda = 70$ deg, $c_r = 2.5$ in., $b = 1.82$ in., $S = 2.28$ in.^{2}, AR = 1.46; and 2) 45-deg swept canard: $\Lambda = 45$ deg, $c_r = 2.5$ in., $b = 5.0$ in., $S = 6.25$ in.^{2}, AR = 4.0. A previous paper[18] discussed the results for the 70-deg swept canard in full detail. The results for all configurations are summarized in Figs. 7 and 8.

Figure 7 shows the results for the different canards when located $0.0c_r$ forward of the main delta wing and pitched at the fastest pitch-up rate. The figure shows that the presence of a canard close to the main delta wing has a beneficial effect on vortex breakdown delay. Full stall occurred at an angle of attack of 77 deg for the no-canard configuration. This compares to full-stall angles of attack of 90, 94, and 96 deg using canards with sweep-back angles of 70, 60, and 45 deg, respectively. This corresponds to improvements in the full-stall angles of attack by 17, 22, and 25% using the respective sweep-back canards as compared to the no-canard configuration. Figure 8 shows the pitch-down results with different sweep-back canards. Just like the pitch-up case, the 45-deg swept canard has the largest beneficial effect. It is difficult to conclude, however, that sweep-back angle is the controlling parameter since the area and span of the three canards also changed.

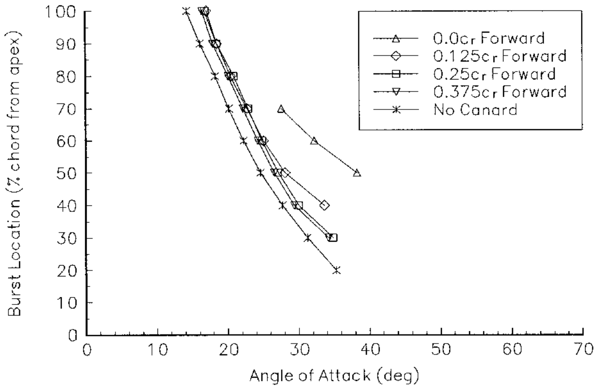

Fig. 6 Pitch-down vortex burst locations for 60-deg swept canard at $k = 0.05$.

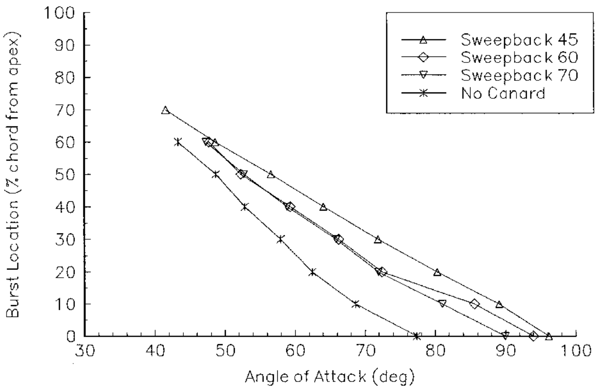

Fig. 7 Pitch-up vortex burst locations for different canards, $0.0c_r$ forward and $k = 0.2$.

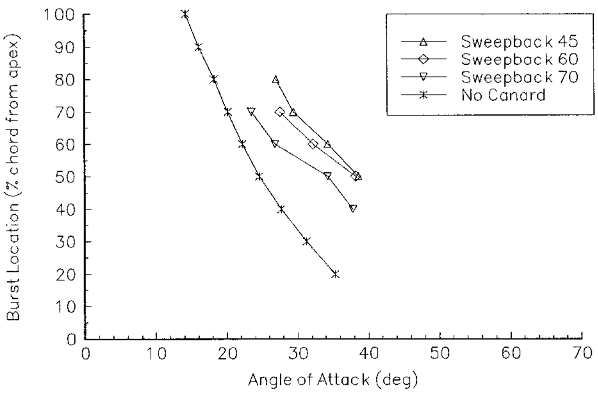

Fig. 8 Pitch-down vortex burst locations for different canards, $0.0c_r$ forward and $k = 0.05$.

Effect of Canard Incidence

The canard support sting mount was modified to investigate the effect of canard incidence. Because of physical limitations, it was not possible to pivot the canard in the positive rotation direction. As shown in Fig. 9, incidence angles of −15 and −30 deg were investigated with the 60-deg swept canard located $0.125c_r$ and $0.25c_r$ forward of the main delta wing.

Figure 10 shows the vortex burst locations under static conditions for different canard incidence angles. At low angles of attack, the canard at negative incidence is ineffective in terms

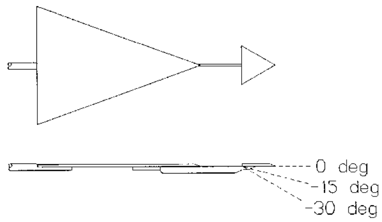

Fig. 9 Canard incidence angles.

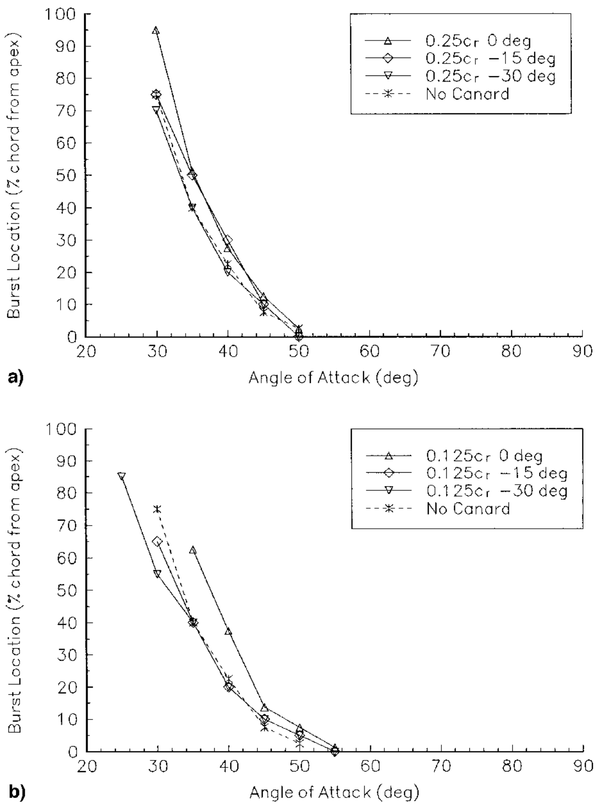

Fig. 10 Static vortex burst locations as a function of canard incidence angle: a) 60-deg swept canard $0.25c_r$ forward and b) 60-deg swept canard $0.125c_r$ forward.

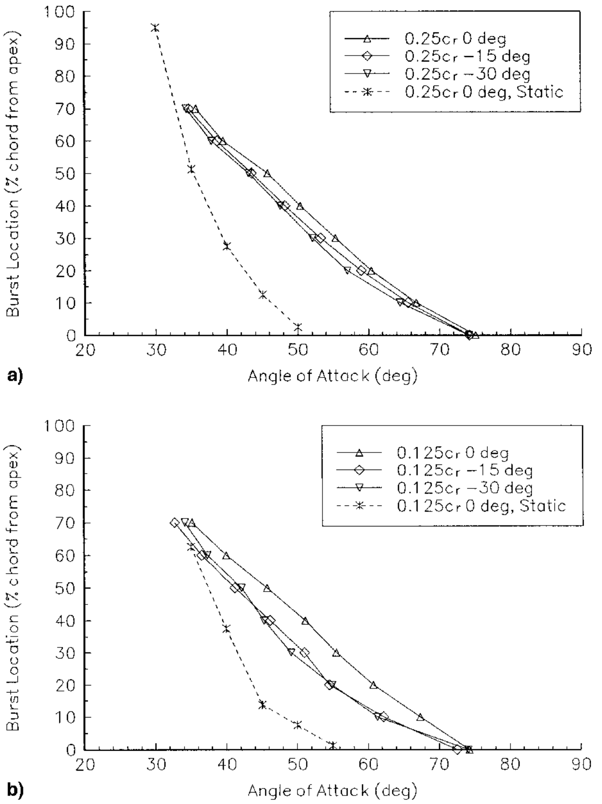

Fig. 11 Pitch-up vortex burst locations as a function of canard incidence angle: a) 60-deg swept canard 0.25c_r forward and b) 60-deg swept canard 0.125c_r forward.

of delaying the vortex breakdown. The canard at zero incidence is most effective, whereas −30-deg incidence is similar to or less effective than the no-canard configuration. At high angles of attack, the curves for the three different canard incidence angles begin to merge together.

Figure 11 shows the pitch-up results. Again, the canard at zero incidence was most effective in terms of delaying the vortex breakdown, and the canard at −30-deg incidence was least effective. Although measurements were taken for pitch-down at negative canard incidence, the results are not presented here. At pitch-down negative incidence conditions, the scatter in burst location was much more than the 2–3% of wing root chord accuracy achieved in all other measurements.

Conclusions

A water-tunnel flow visualization experiment was undertaken to investigate the effects of canards on delta wing vortices during dynamic pitch-up and pitch-down motion. Based on the results, the following conclusions can be made:

1) The presence of a canard produced a delay in static vortex breakdown location. The effect was greatest when the canard was located close to the main delta wing (0.0c_r forward), and resulted in a 19% delay in full-stall angle of attack.

2) As previously reported by other investigators,[13,14] dynamic pitch-up motion produced a delay in vortex breakdown location. The effect was greatest at the fastest pitch-up rate tested (κ = 0.20). With a 60-deg canard located close to the main delta wing, the full-stall angle of attack at the fastest pitch rate was delayed by 49% compared to the static case.

3) Dynamic pitch-down motion had an undesirable effect on the vortex breakdown. The worst effect was observed at the fastest pitch rate. Thus, a slow pitch rate is recommended for pitch-down motion. The results also showed that the presence of a canard located close to the main delta wing helped ease the undesirable vortex breakdown effect.

4) Increasing the canard sweep-back angle, area, or span had a beneficial effect on vortex breakdown. Whether this effect was caused by sweep-back angle, area, or spanwise width could not be determined at this time.

5) The canard at a negative incidence angle reduced the effectiveness of the canard in terms of delaying the vortex breakdown.

In summary, it is possible to maintain dynamic lift forces beyond 90-deg angle of attack by combining a fast pitch-up and slow pitch-down maneuver.

Acknowledgments

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