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Delta Wing Vortex-Burst Behavior Under a Dynamic Freestream

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A series of experiments was performed at Wichita State University's water tunnel on a 70-degree-sweep delta wing using a towing mount. A video camera captured dye-flow visualization images of the vortex burst that were subsequently analyzed using a computer-assisted image analysis software. The aim was to better understand the relationship between the freestream velocity and the time constants involved in the movement of the vortex-burst point. Experiments indicated that a change in the freestream velocity changed the forward progression of the vortex burst. Under pitch-up conditions, deceleration resulted in a momentary retardation in the forward progression of the burst, whereas acceleration resulted in a faster progression toward the apex.

Nomenclature

c	=	wing root chord
dU_∞/dt	=	deceleration rate
Re_c	=	chord Reynolds number, $U_\infty c/\nu$
s	=	coordinate along root chord
U_∞	=	freestream velocity
$U_{\infty,\max}$, $U_{\infty,\min}$	=	velocities before and after acceleration or deceleration
α	=	angle of attack
β	=	yaw angle
κ	=	nondimensional pitch rate, $(d\alpha/dt)c/(2U_\infty)$

Introduction

DELTA wings have evolved over the years and are now used primarily in the form of leading-edge extensions on many fighter aircraft. As these aircraft become more and more maneuverable, the understanding of the physics of time-dependent unsteady flows is becoming more important. In particular, if accurate computational models of these maneuvers are to be developed, it is necessary to understand the mechanisms involved in features such as vortex bursting and mixing on the delta wing. This is true of so-called hyperagile maneuvers.

It is well documented that delta wings at a fixed angle of attack generate lift by separating a shear layer of air (or fluid, such as water) at the leading edge, and this shear layer forms two strong counter-rotating vortices on either side of the wing [1–5]. These leading-edge (LE) vortices undergo small fluctuations in space [6], but remain relatively fixed over the suction side of the delta wing, and are critical to the generation of lift, as they produce a large suction peak on the surface. Two much smaller vortices, the secondary vortices, are also formed, as seen in Fig. 1. In other words, LE vortices are the result of a balance between vorticity being generated at the leading edge and the ability of the flowfield to convect said vorticity along the vortex core.

The LE vortices are not stable, and at some point, their coherent structure will undergo a dramatic change, expanding around the core, slowing down axially, and either forming a bubble or a spiral, with the spiral form being more predominant at Reynolds numbers of interest to delta wing designers. This change, called vortex burst or breakdown, is dependent on the aspect ratio of the wing, angle of attack, pressure gradients, yaw angle, and swirl angle of the vortex, among others [7,8]. The exact reason for this bursting is not known, but research has focused on two general areas:

1) The flows upstream and downstream of the vortex burst are two separate and very different flows, and the vortex burst is a necessary feature, similar to a hydraulic jump [7].

2) The core of the LE vortex serves as a mechanical waveguide for longitudinal waves; these waves either coalesce or become critical, thereby triggering the burst [9].

The effect of the vortex burst is to reduce the lift generated by the delta wing. If the delta wing is pitched to a given angle of attack α and then maintained at that angle until the transient flow features die down, it is said to be tested under static conditions. As this process is repeated at increasing values of α, the vortex-burst point will move forward toward the apex of the wing due to the increasing adverse pressure gradient. This progressively deprives a larger area of the delta from the benefits of the high suction peak.

In most flows, the strength of the vortex is dependent upon the Reynolds number. In delta wing flows, however, the LE vortex-burst behavior on delta wings appears to be less sensitive to Reynolds number when the burst is located over the delta wing. This is most likely due to the fact that the sharp leading edge serves as a fixed separation line. This peculiarity in the burst behavior allows a wide range of static testing of models in different media (air, water, etc.) to be directly compared.

Compare this with the dynamic situation in which the delta wing is continuously pitched, never allowing the flow features to become steady. Under dynamic conditions, in which the delta wing is pitched upward at a given rate, the location of the vortex burst is farther toward the trailing edge compared with the same angle of attack under static conditions (thus, it lags behind the static angle-of-attack location). This produces a phase lag in the burst location, allowing transient values of lift to exceed those obtained during static testing [10–14]. Similarly, pitching down the delta wing moves the vortex-burst location forward. This produces a phase lead (i.e., the vortex burst occurs at a position farther forward during the pitch-down than if it were static for a given angle of attack) and a reduction in lift, compared with the similar static angle of attack. This introduces the notion of a hysteresis effect, or time delay, in which there is a difference in the measured C_L values if the angle of attack is increasing or decreasing [15]. The magnitude of the phase lag/lead

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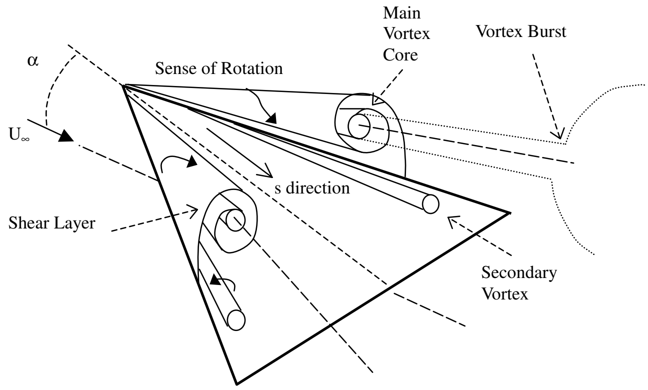

Fig. 1 Lift-producing mechanism of a delta wing [1].

increases as the pitch rate increases. The faster the pitch-up rate, the higher the angle of attack before the vortex burst appears over the surface of the delta wing.

Modern aircraft use either slender delta wings or similar devices (e.g., leading-edge extensions) that harness vorticity and take advantage of this hysteresis effect of the delta wing in an attempt to increase the performance envelope. In many cases, the increase in performance has led to aircraft with hyperagility, or the ability to maneuver at very fast rates. Take, for example, the case of the Su-27 aircraft undergoing a Cobra maneuver. In this situation, the aircraft enters a pitch-up at 190 kt indicated airspeed (KIAS) and, in the process of 2–5 s, reaches angles of attack up to 90 deg or more and an airspeed of 60 to 80 KIAS before coming nose-down and exiting at a much lower angle of attack and then accelerating [16,17].

The execution of this maneuver involves four general phases [18]. In the first phase, an increase in angle of attack and a reduction of the forward airspeed occur simultaneously. The burst location remains downstream due to the phase lag discussed earlier. As the angle of attack increases past about 50 deg and the pitch rate begins to slow down (phase 2), the forward velocity has reduced to the point at which it is possible for asymmetric shedding of vorticity from the forward part of the fuselage (the forebody) to occur [19].

Phase 3 involves the reversal of the process. The nose begins to come down toward the horizon. Pitch-down moves the burst location ahead toward the apex, forward of the static location. At this point, the flow is typical of a bluff-body separated condition. In phase 4, the aircraft now is pitching below the horizon and gaining flight velocity.

One question is how fast the vortex burst propagates forward toward the apex as the pitching delta wing slows down through phases 1 and 2 of the Cobra maneuver. It has been reported that rapid pitch-up in wind-tunnel models does not produce a migrating vortex-burst point, but rather a sudden and complete transition from a coherent vortex to one in which the burst is close to the apex [12]. Water-tunnel testing, however, has shown that the vortex-burst point moves forward at some velocity as the pitch-up maneuver progresses [13,14].

An example of this situation, but in reverse, is one in which a slow delta wing accelerates to a faster velocity. Lee and Ho [3] have stated that the time lag in the stabilization of the vortex-burst position while a delta wing accelerates is due to a favorable pressure gradient forming. This increases the vorticity flux at the leading edge, which then increases the vortex-core vorticity. The resulting change in swirl angle thus causes the burst to move upstream.

A second question regards the transmission of disturbances to the LE vortex core. Because the LE vortex can work as a mechanical waveguide for waves, there is an uneven time constant. A disturbance occurring at the apex is quickly entrained into the core, whereas the same disturbance occurring farther down the leading edge may take a longer amount of time to become part of the vortex structure. When the delta wing is pitching, the velocity observed at the leading edge is affected not only by the pitching rate, but also by the freestream velocity. Thus, the time constant involved in the vortex-burst time lags change with variation in freestream velocity.

A third question regards the swirl angle. This is given by the ratio of the velocity component in the LE vortex axial direction to the component in the azimuthal direction. Work by others in vortex tubes have shown that swirl angles in excess of approximately 55 deg cannot be sustained [8]. As the delta wing slows down, the angular momentum of the vortex should delay the deceleration of the azimuthal velocity component. If this is the case, the axial to azimuthal velocity ratio should change, and this in turn would change the swirl angle, bringing it closer to the limiting value.

On the other hand, experimental results of delta wings at constant angles of attack when subjected to sinusoidal variations in freestream velocity indicated that the swirl angle was nearly constant, but that the vortex burst moves upstream during the acceleration of freestream [20]. This suggests that the external pressure gradient highly effects the burst location, whereas the swirl-angle effect may be of secondary importance. These questions are not only important to the design of hyperagile aircraft, but may be even more important to the design of smaller-scale vehicles, such as micro aerials vehicles (MAV) and unmanned combat aerial vehicles (UCAV). Other flow properties such as crossflow separation and secondary vortex behavior may or may not be sensitive to Reynolds number [21]. In particular, it has been reported that *nonslender* delta wings exhibit strong secondary vortices at $Re = 8000$ and 14,000. It would be expected that interactions between a strong secondary vortex and the LE vortex would be stronger and thus may affect the vortex-burst location [21]. This information would be important to MAV and UCAV designers and may shed some light into some of the nonlinear interactions observed at higher Reynolds numbers as well. With

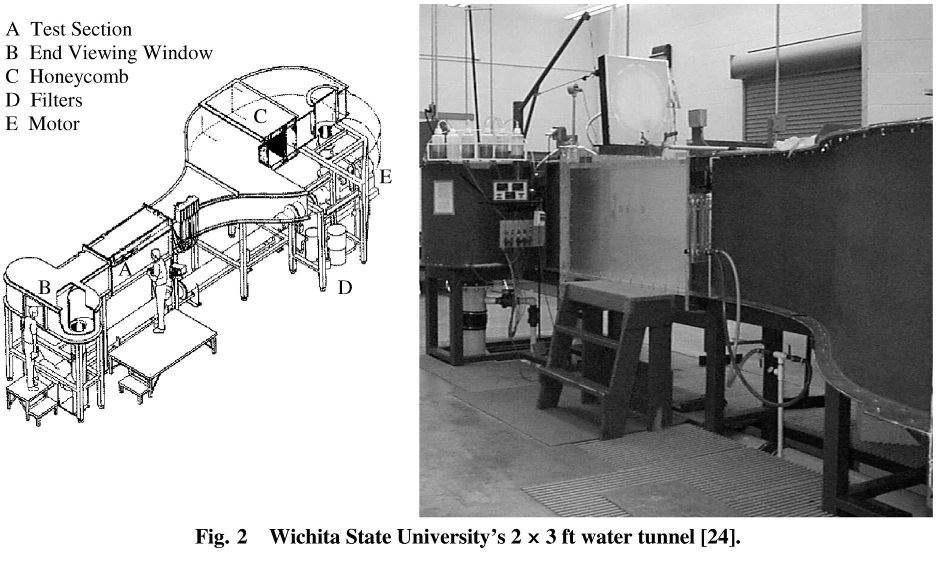

Fig. 2 Wichita State University's 2 × 3 ft water tunnel [24].

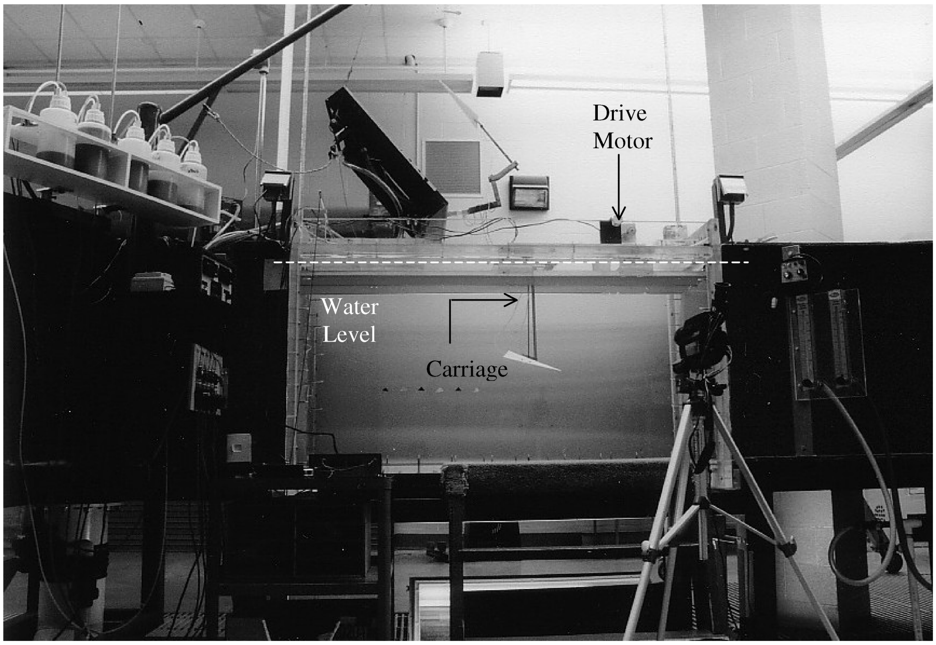

Fig. 3 Towing mount installed [23].

regard to this investigation, the Reynolds number attained is 33,000 at the baseline freestream velocity of 0.4 ft/s.

With these issues in mind, the goal of this investigation is to subject a known delta wing to a simultaneous pitch-up maneuver and a deceleration of the forward velocity. The vortex-burst position is then measured, thus quantifying the vortex-burst propagation rate. The present investigation is part of an ongoing project to investigate the effect of dynamic freestream. Past work has described the development of the towing system [22] and the preliminary work [23].

Experimental Setup

The water tunnel at Wichita State University's National Institute for Aviation Research is a 3500 gal facility with a 2 by 3 ft test section (Fig. 2). The test section of this tunnel is 6 ft long with Plexiglas® walls on three sides, allowing unrestricted viewing of the model [24].

Installed on this water tunnel is a dynamic pitching, unsteady freestream, delta wing mount, as shown in Fig. 3. When this mount is used, the water tunnel serves only as a water tank. It consists of an aluminum frame and track, on which a carriage is moved by a nylon line and dc motor arrangement. A strong spring is used to maintain tension on the towline. The model is mounted to the carriage upside down, such that pitch-up involves the apex of the delta wing moving down toward the tunnel floor. The lift generated then forces the carriage down on the tracks. Further details can be found in [23].

The delta wing model has a root chord c of 12 in., a sweepback angle of 70 deg, a thickness of $\frac{1}{8}$ in., and a sharp leading edge beveled at a 30 deg angle. It is equipped with dye ports near the apex. For this test, only the dye port closest to the camera is used for visualization of the LE vortex core. It is mounted such that it pivots about its half-chord location. This is the same model as used by Myose et al. [13] and Hayashibara et al. [14] in previous tests at this water-tunnel facility, but using a different, untowed, dynamic pitch mount.

To be able to compare with their results, the test conditions are set to match those of Myose et al. [13]. The model is towed at a constant speed of 0.4 ft/s with a stability of ±5%, yielding a chord Reynolds number of 33,000. It is then pitched-up from an angle of 15 deg, while simultaneously slowed down. This yields a nondimensional pitch rate κ different between the predeceleration and the postdeceleration regimes. This nondimensional pitch rate is defined as

$$\kappa = (d\alpha/dt)c/(2U_\infty)$$

where $d\alpha/dt$ is the pitch rate, c is the root chord, and U_∞ is the freestream velocity. In this case, the carriage velocity is also the freestream velocity. The nondimensional pitch rate κ changes as the freestream velocity U_∞ accelerates or decelerates. The actual dimensional pitch rate $d\alpha/dt$ does not change. For convenience, the *initial* freestream velocity is used to calculate the reported pitch rate κ throughout the text.

The images are obtained using the setup shown in Fig. 4. A Canon charge-coupled-device camcorder, used as a camera only, is placed looking through the side window perpendicular to the path of the delta wing. The image of the camera is mixed along with angle of

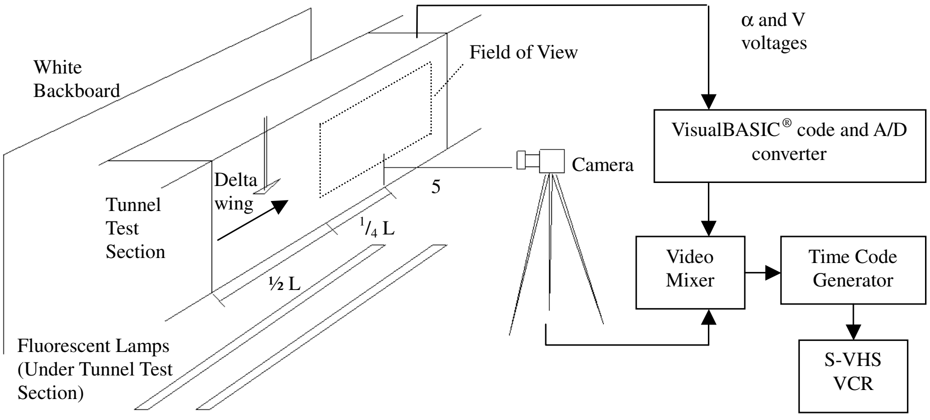

Fig. 4 Data-gathering setup.

attack α, velocity U_∞, and time-code information and recorded on S-VHS videotape for analysis. This provides an absolute time reference. Illumination was provided by fluorescent lamps located to evenly illuminate the field of view. To maximize contrast, the room lighting is turned off while videotaping.

To provide a relatively sudden deceleration (or acceleration) of the towed delta wing, a small dc gearhead motor was coupled to the potentiometer shaft of the power supply to the carriage drive system. The gearhead motor was then supplied with a pulse-width-modulated dc current. A square wave of fixed frequency and full voltage was applied to the gearhead, but the duty cycle of the square wave (i.e., the percentage of time that the motor is on in a given period) can be manipulated. This allowed the potentiometer's rotational velocity to be increased or decreased in very small increments without stalling or stopping. The advantage of this method is that both small and large values of dU_∞/dt can be dialed in. In the previous preliminary work [23], a bank of capacitors (19, 900 μF) was placed in parallel across the dc motor. The disadvantages of this method are that only a speed reduction can be achieved (as the capacitors discharge the voltage reduces) and that very large values of capacitance are needed.

The recordings are later analyzed using VisualBASIC® code written by the first author. The videotape is analyzed at each frame ($\frac{1}{30}$ s) and the code identifies the length of the root chord of the wing and the vortex-burst location of the leading-edge vortex. An uncertainty of $\pm 0.05c$ in the vortex-burst location is obtained with this system.

Experiment Limitations

There are a few limitations with this experimental setup that need to be acknowledged:

1) The location of the vortex burst is accomplished by identifying where the core flares out (bubble burst) or the location of the first sharp kink (spiral burst). As such, the identified location may or may not coincide with the actual core stagnation point. The assumption that the two are close, if not coincident, has been done in the past.

2) Some of the features observed cannot be explored further using this system, and thus a certain amount of interpretation must be exercised. Nevertheless, the uncertainty is within $\pm 0.05c$.

3) The synchronization of the start of the slowdown process is accomplished manually. A switch is actuated when the angle of attack α corresponding to that particular test case is observed in the analog-to-digital conversion display. Through practice, it is possible to attain repeatability in α of $+1.5$ deg.

Results and Discussion

Fast Pitch-Up Results

Figures 5–9 show the results of decelerating the delta wing while pitching up. Figure 5 presents the situation for a large deceleration from 0.4 to 0.2 ft/s (minimum-to-maximum velocity ratio of 0.5, where velocity ratio $= U_{\infty,\max}/U_{\infty,\min}$) while pitching up at an initial rate of $\kappa = 0.2$ from 15 to 55 deg. The deceleration occurs between $30 < \alpha < 50$ deg. Four different experimental runs are overlaid and shown in the figure. A reduction in the vortex-burst propagation velocity is apparent at about 1.5 s after the freestream velocity begins to decelerate. This retardation delays the forward propagation of the vortex burst (toward the apex). The forward propagation of the burst location resumes about 5 s elapsed time and is initially more pronounced (i.e., the slope of the burst curve is more negative) than it is at the beginning of the experiment.

Figure 6 presents the burst behavior for a large deceleration while pitching up at an initial rate of $\kappa = 0.2$, but this time the deceleration occurs between $45 < \alpha < 50$ deg. A forward propagation of the burst location toward the apex occurs with very little change in its propagation velocity. This is probably due to the delta wing having

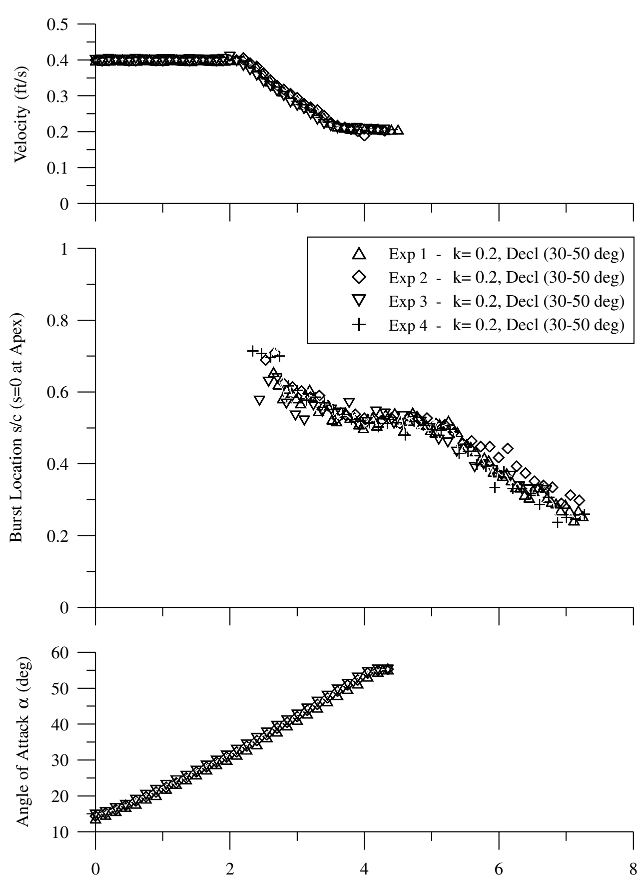

Fig. 5 Burst behavior, pitch-up at $\kappa = 0.2$, deceleration from 0.4 ft/s (30 deg) to 0.2 ft/s (50 deg).

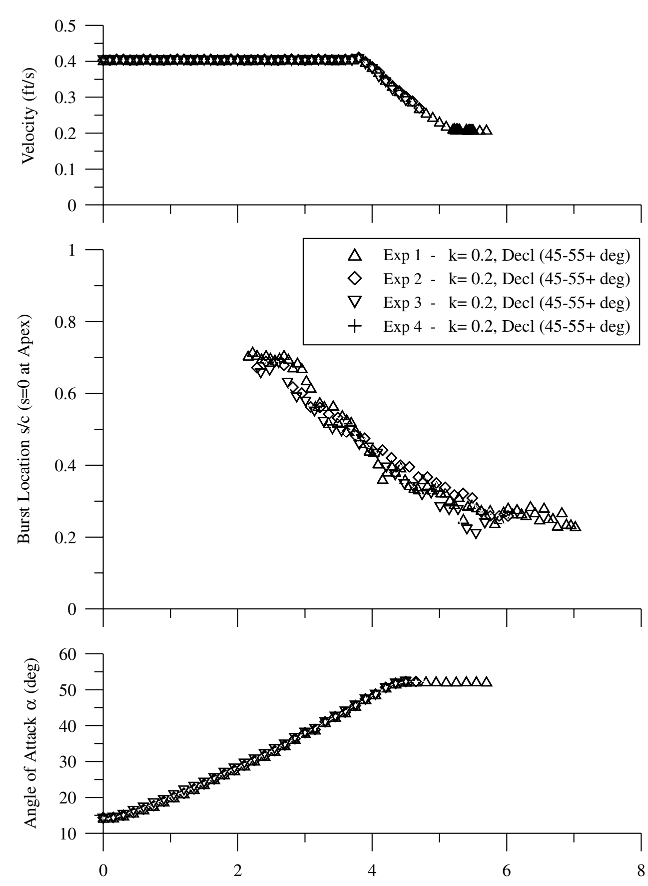

Fig. 6 Burst behavior, pitch-up at $\kappa = 0.2$, deceleration from 0.4 ft/s (45 deg) to 0.2 ft/s (beyond 55 deg).

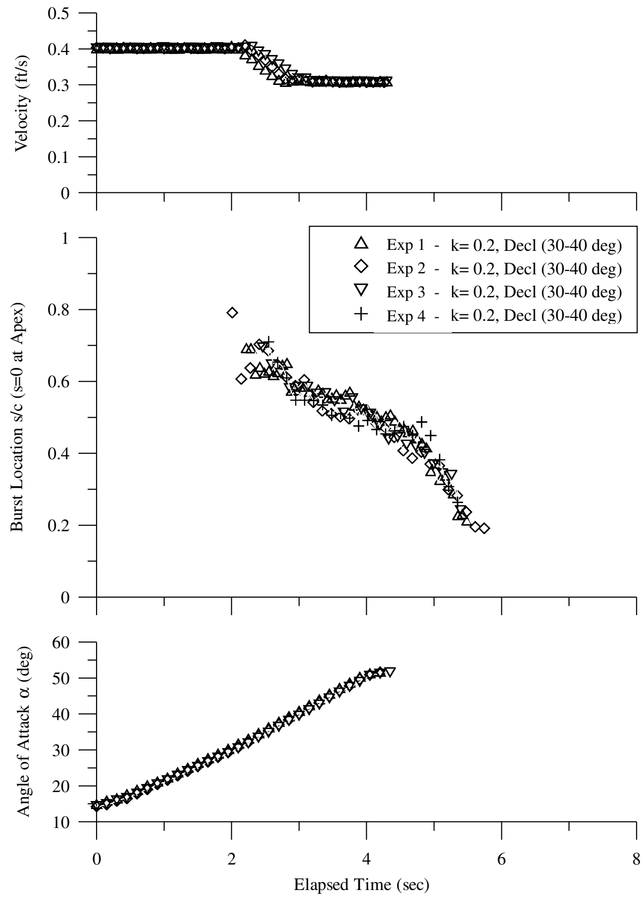

Fig. 7 Burst behavior, pitch-up at $\kappa = 0.2$, deceleration from 0.4 ft/s (30 deg) to 0.3 ft/s (40 deg).

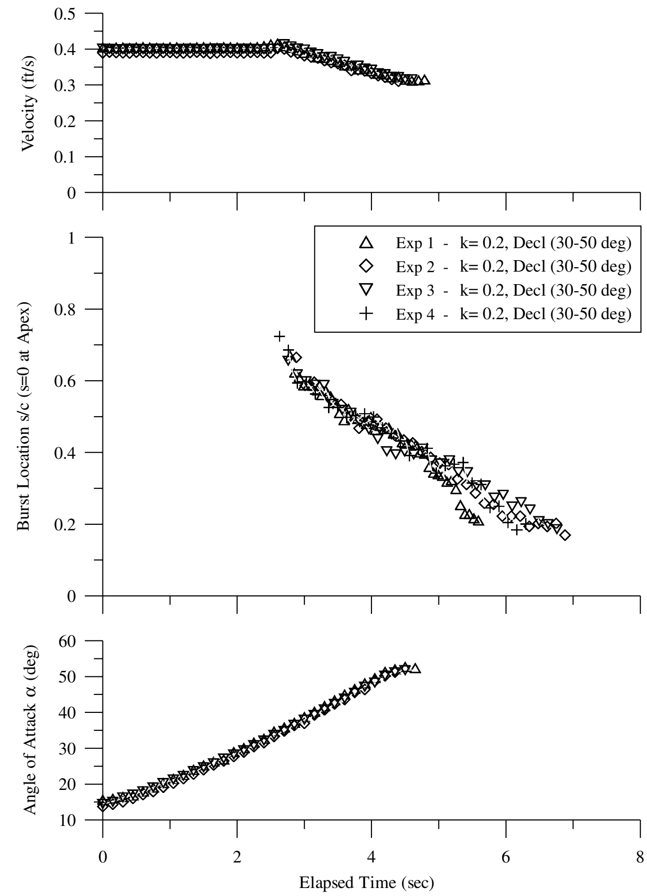

Fig. 8 Burst behavior, pitch-up at $\kappa = 0.2$, deceleration from 0.4 ft/s (30 deg) to 0.3 ft/s (50 deg).

reached its maximum angle of attack α and its new steady freestream velocity at about the same time that the burst location has stabilized at its new position near the apex (around $s/c = 0.2$).

Figure 7 presents the situation for a small deceleration from 0.4 to 0.3 ft/s (minimum-to-maximum velocity ratio of 0.75) and starting pitch-up with a rate of $\kappa = 0.2$ between 15 and 55 deg. The deceleration occurs between $30 < \alpha < 40$ deg. In this instance, a reduction in the vortex-burst propagation velocity is apparent at 3 s elapsed time (approximately 1 s after the freestream velocity begins to change). This retardation delays the forward propagation of the vortex burst (toward the apex). The forward propagation of the burst location resumes about 4.5 s elapsed time and appears to be at the same propagation rate (i.e., the slope of the burst) as it is at the beginning of the experiment. Although the length of time that the vortex-burst location remains fixed (during the arresting of the forward motion) and the time (or phase lag) between the initiation of the change of speed and the change in the behavior of the vortex is different between Fig. 7 and previous decelerations, a pattern is beginning to emerge at this point. At $\kappa = 0.2$ for large ranges of angle of attack α, deceleration of the freestream velocity appears to arrest the motion of the burst location anywhere between 1.5 and 2.5 s after the deceleration begins to take place. For smaller ranges of α, it appears that the stop in burst location occurs slightly more quickly.

Figures 8 and 9 also present the burst behavior for a small deceleration while pitching up at an initial rate of $\kappa = 0.2$, but this time the deceleration occurs between $30 < \alpha < 50$ deg and $45 < \alpha <$ beyond 55 deg, respectively. Very little change in the forward propagation of the burst location toward the apex occurs. This is probably due to the delta wing having reached its maximum angle of attack α and its new steady freestream velocity at about the same time.

Figure 10 shows a comparison of the results for four experimental runs under acceleration ($\kappa = 0.2$, velocity ratio 0.5, $dU_\infty/dt = 0.092$ ft/s^2, and $30 < \alpha < 50$ deg) and four experimental runs under deceleration. For convenience, a positive outcome is one in which the propagation of the vortex burst is delayed or arrested, whereas a negative outcome is one in which the burst moves forward faster (or jumps) than normal for a steady-velocity pitch-up. The figure shows that deceleration has a positive effect of retarding the forward progression of the vortex burst, this being in evidence by the level-off in the scatter plot at about $s/c = 0.5$ (4 s elapsed time). The acceleration, on the other hand, shows a negative effect with a definite forward jump in the scatter plot. Comparing with the constant-velocity case and extrapolating linearly shows that at least 1 to 1.5 s can be gained before the burst has progressed to a spatial location (for example, $s = 0.4c$) when subjected to a deceleration.

Figure 11 ($\kappa = 0.2$, velocity ratio 0.75, $dU_\infty/dt = 0.046$ ft/s^2, and $30 < \alpha < 50$ deg) indicates that slower accelerations still have a negative effect on the burst location, as a forward jump in the scatter is visible starting at about 5 s. The slow deceleration in this case, however, does not contribute greatly to the delay in the forward propagation of the burst location, as the scatter plot lies almost parallel to the linear extrapolation for a constant speed pitch-up.

Figure 12 ($\kappa = 0.2$, velocity ratio 0.5, $dU_\infty/dt = 0.092$ ft/s^2, and $45 < \alpha <$ beyond 55 deg)indicates that acceleration has a negative effect, deceleration has a mild positive effect, and the angle of attack at which the change in the slope of the scatter plot (i.e., the change in propagation velocity) also has an effect. If the reader equates elapsed time with angle of attack α, and compares Fig. 10 with the current figure, the point in time at which the burst location experiences a change in slope is the same for acceleration and deceleration in Fig. 10, but different in Fig. 12: the acceleration precipitates a forward jump sooner than the deceleration arrests the burst progression.

Figure 13 ($\kappa = 0.2$, velocity ratio 0.75, $dU_\infty/dt = 0.046$ ft/s^2, and $45 < \alpha <$ beyond 55 deg) indicates that at the higher angle extremes, changes in velocity have little impact on the burst position.

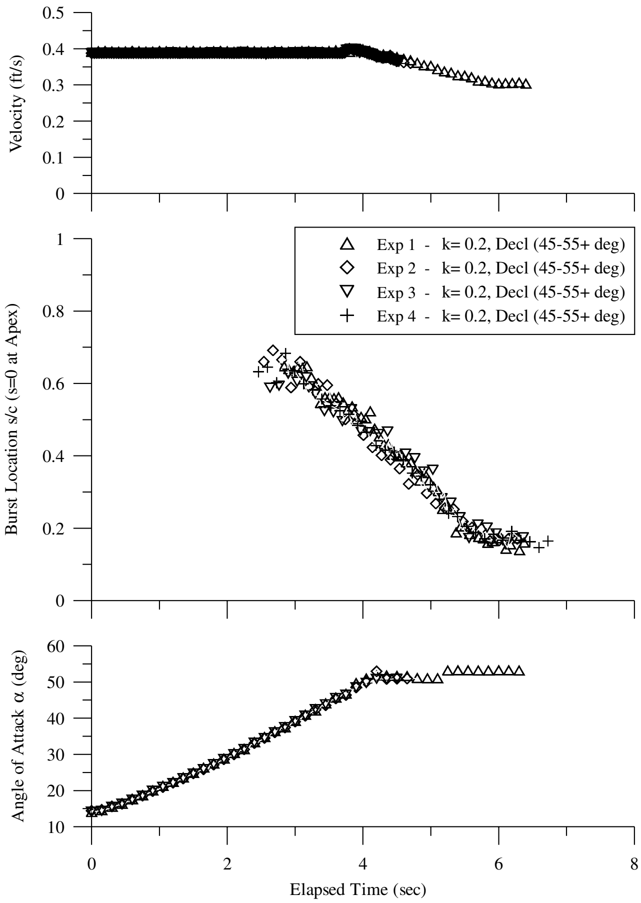

Fig. 9 Burst behavior, pitch-up at $\kappa = 0.2$, deceleration from 0.4 ft/s (45 deg) to 0.3 ft/s (beyond 55 deg).

There is a slight change in the slope at approximately 5 s elapsed time. This discontinuity appears in both accelerating and decelerating experiments.

In Fig. 14 ($\kappa = 0.2$, velocity ratio 0.75, $dU_\infty/dt = 0.092$ ft/s^2, and $30 < \alpha < 40$ deg), the deceleration appears to have a mild positive effect. So mild, in fact, that it is difficult to say whether the downward inflection is the result of the acceleration or just the normal change in slope that occurs when κ changes value. (Recall that κ changes value in proportion to the freestream velocity.) The acceleration does not appear to have any changes, as the slope remained quasi-linear throughout the maneuver.

To summarize, pitching up at $\kappa = 0.2$ at different angle-of-attack ranges and velocity ratios produces a mild-to-strong negative effect on the burst location when accelerating. This negative effect is almost independent of the actual acceleration or range of α over which it occurs. The positive delay in the burst movement, on the other hand, appears to be strongest when the delta wing experiences a strong deceleration ($dU_\infty/dt = 0.092$ ft/s^2) over a large range of α values (30 to 50 deg). This effect becomes much smaller at slower decelerations and/or limited values in the α range. This implies that, perhaps, instabilities (whether inherent or external to the vortex core) could help precipitate the forward jump (as in Fig. 12), making it easier to lose lift than to keep lift.

From the results obtained, it is clear that the deceleration has some retardation effect on the progression of the burst to the apex, hence delaying the loss of lift that accompanies the forward motion of the burst. A possible scenario is laid out as follows. Considering the different velocity components shown in Fig. 15, the velocity component that is directly responsible for vorticity production at the leading edge is given by

$$V_{\perp_s} = U_\infty \sin\alpha \cos\beta \tag{1}$$

It can be seen that $\cos\beta$ is constant for a given installation (i.e., no sideslip component, $\beta = 0$, and $\cos\beta = 1$). Taking the time differential,

$$dV_{\perp_s}/dt = [(dU_\infty/dt)\sin\alpha + U_\infty(d\alpha/dt)\cos\alpha]\cos\beta \tag{2}$$

Both dU_∞/dt and $d\alpha/dt$ are, for the purposes of these experiments, quasi-constant numbers. The relative magnitudes of both numbers set a balance. The change in the leading-edge perpendicular velocity is therefore given by the two terms in the brackets.

In Fig. 16, a constant pitch-up at $\kappa = 0.2$ is modeled numerically in time using Eqs. (1) and (2). It produces an apparent increase in the leading-edge velocity component perpendicular to the plane of the delta wing. This is due to the change in angle of attack and the pitch rate (the second term, $U_\infty d\alpha/dt\cos(\alpha)$, being directly responsible). Thus, even though the freestream is constant, the leading edge experiences an increasing velocity across its sharp radius.

Figure 17 shows the effect of various terms for the deceleration case presented in Fig. 10 ($dU_\infty/dt = -0.092$ ft/s^2 and $d\alpha/dt = 9.16$ deg/s $= 0.16$ rad/s at $\kappa = 0.2$). When the deceleration begins in this case, a large change in the character of the curves occurs. The increase in velocity perpendicular to the leading edge is initially driven by the $U_\infty d\alpha/dt\cos\alpha$ term. However, the velocity perpendicular to the leading edge is reduced when deceleration is introduced (i.e., with the inclusion of the $dU_\infty/dt\sin\alpha$ term). This in turn would reduce the formation of vorticity at its source.

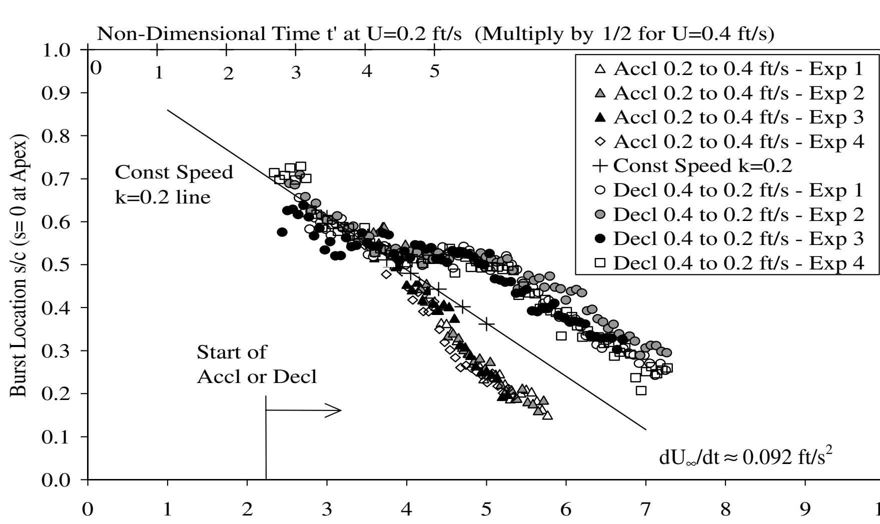

Fig. 10 Burst comparison, pitch-up at $\kappa = 0.2$, velocity ratio of 0.5 acceleration/deceleration from initial speed (30 deg) to final speed (50 deg).

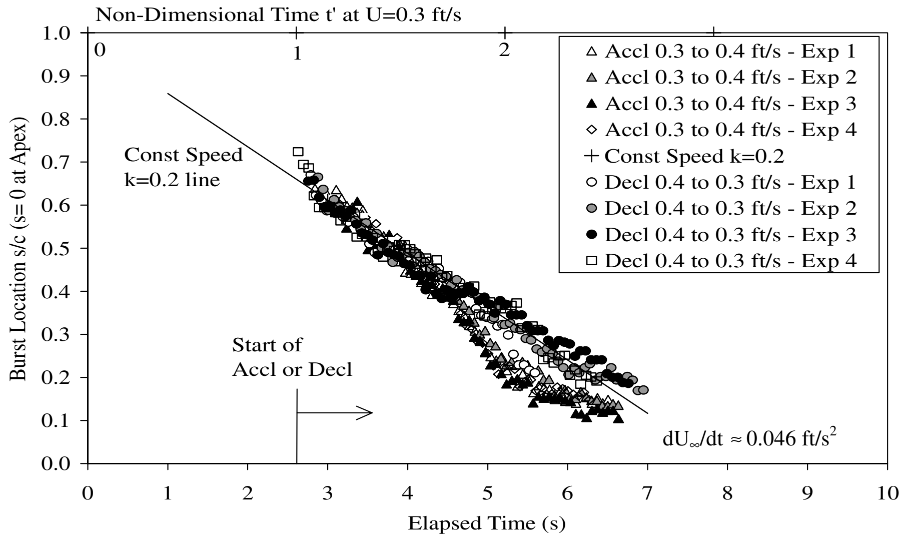

Fig. 11 Burst comparison, pitch-up at $\kappa = 0.2$, velocity ratio of 0.75 acceleration/deceleration from initial speed (30 deg) to final speed (50 deg).

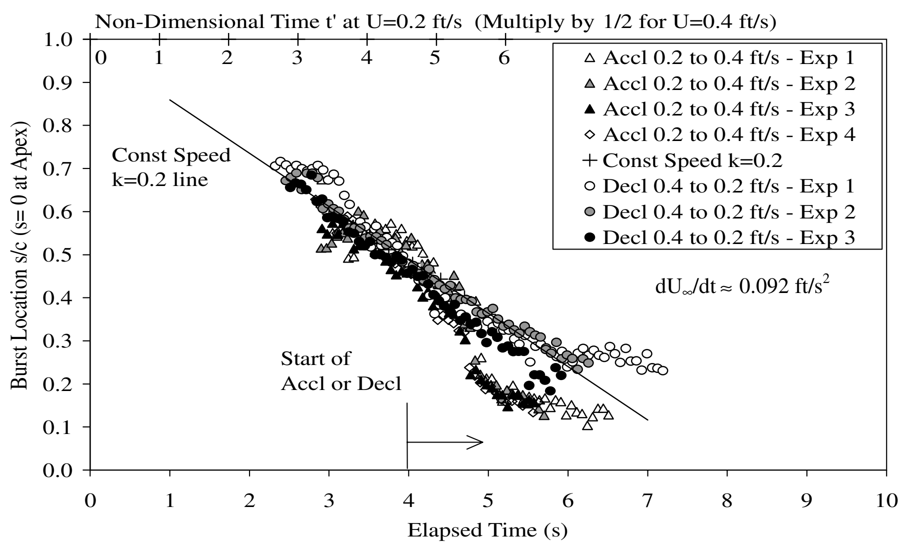

Fig. 12 Burst comparison, pitch-up at $\kappa = 0.2$, velocity ratio of 0.5 acceleration/deceleration from initial speed (45 deg) to final speed (beyond 55 deg).

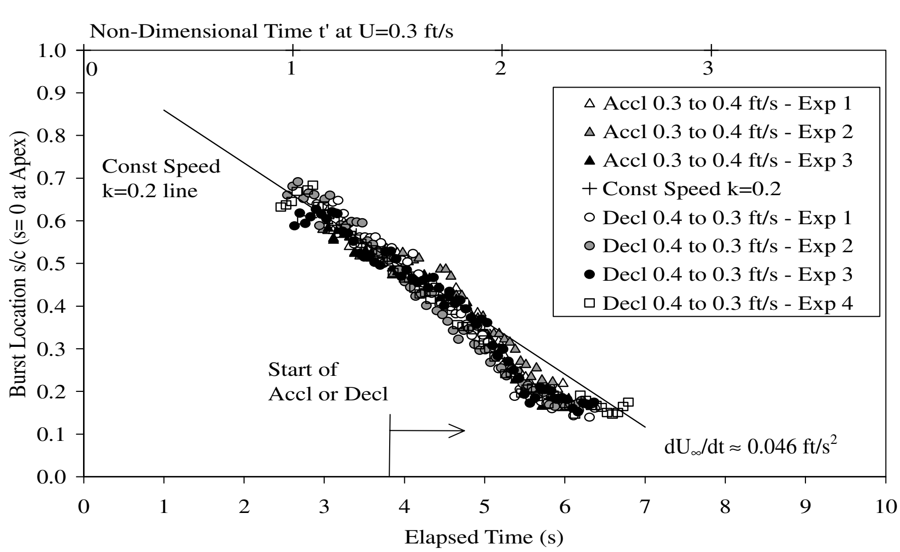

Fig. 13 Burst comparison, pitch-up at $\kappa = 0.2$, velocity ratio of 0.75 acceleration/deceleration from initial speed (45 deg) to final speed (beyond 55 deg).

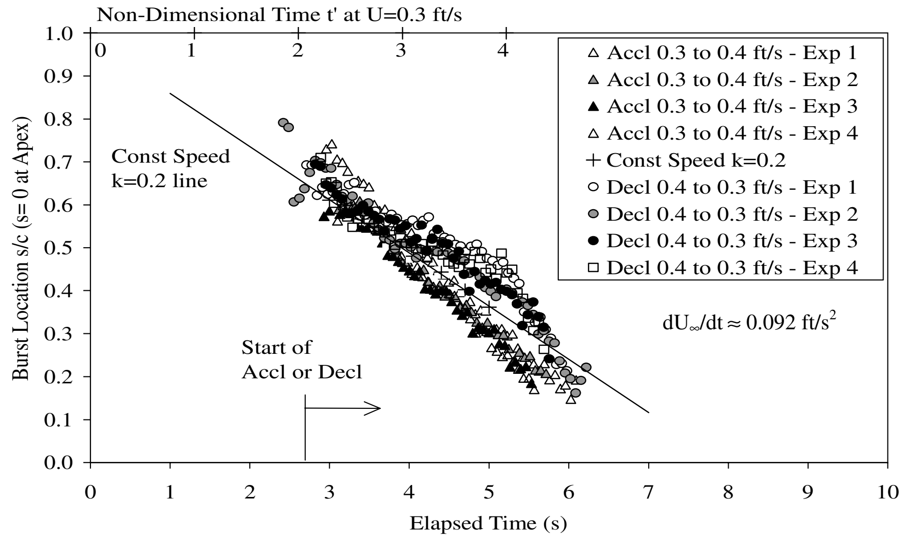

Fig. 14 Burst comparison, pitch-up at $\kappa = 0.2$, velocity ratio of 0.75 acceleration/deceleration from initial speed (30 deg) to final speed (40 deg).

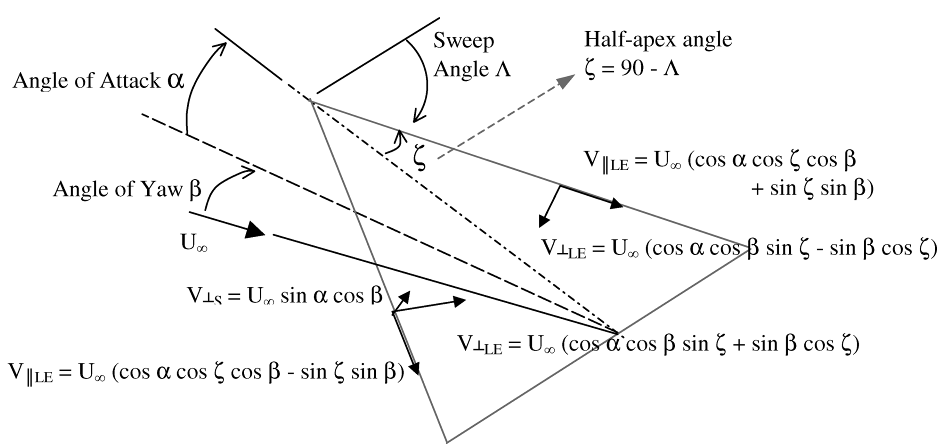

Fig. 15 Velocity components on the leading edge of a delta wing.

Figure 18 shows the effect of various terms for the acceleration case corresponding to the situation of Fig. 10 ($dU_\infty/dt = 0.092$ ft/s^2 and $d\alpha/dt = 9.16$ deg/s $= 0.16$ rad/s at $\kappa = 0.2$). When acceleration begins in this case, a large change in the character of the curve occurs once again. This time, however, the velocity perpendicular to the leading edge is increased when acceleration is introduced (i.e., with the inclusion of the $dU_\infty/dt \sin\alpha$ term). This would lead to an increase in the production of vorticity at its source. This in turn is likely to lead to the negative result of early vortex burst (i.e., movement of the burst closer to the apex) seen in Fig. 10.

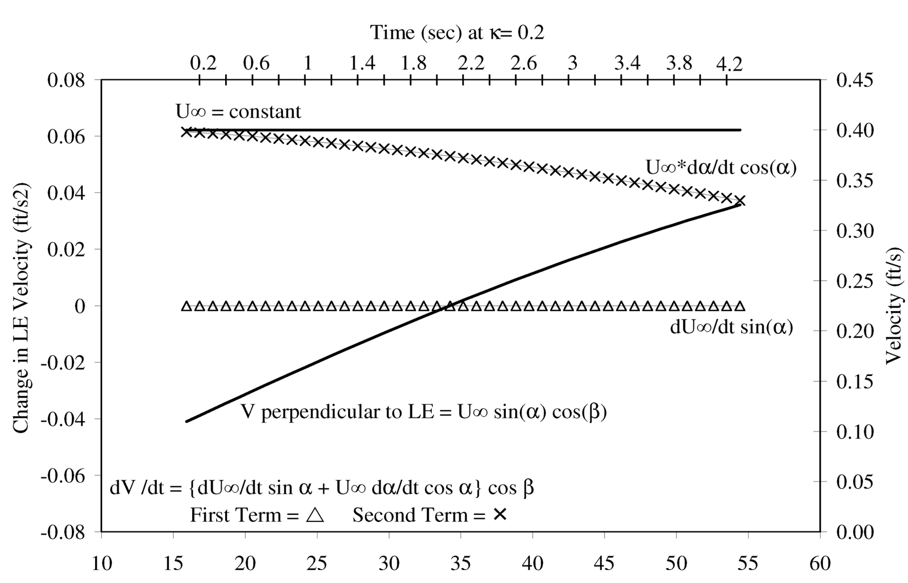

Fig. 16 Example of perpendicular velocity at the leading edge [Eq. (2)], constant pitch-up rate, $dU_\infty/dt = 0$ (ideal representation of Myose et al. [14]).

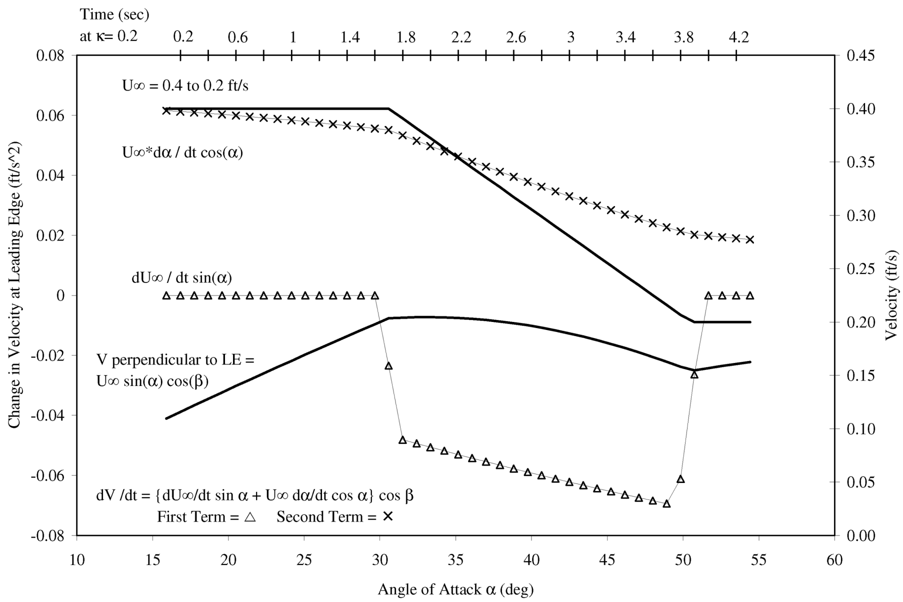

Fig. 17 Example of perpendicular velocity at the leading edge, constant pitch-up rate and deceleration (ideal representation of Fig. 10's deceleration case).

The figures do not include the effect of time delay it takes to convect the vorticity from the leading edge into the vortex core. This time delay will be nonexistent at the apex and increases linearly with chord location toward the trailing edge. Thus, the velocity calculated in Figs. 17 and 18 are first experienced at the apex, then further down the length of the vortex core, and at the trailing edge last. This should set up a distribution along the chord direction. In the case of a constant U_∞, the distribution is linear along the chord direction. In the case of a deceleration, the distribution will start linear, then as the slower velocities are convected into the core, this distribution will be altered (Fig. 19).

Results for Pitch-Up at a Moderate Rate

Pitching up at half the pitch rate ($\kappa = 0.1$), such as is the case in Fig. 20 ($\kappa = 0.1$, velocity ratio 0.5, $dU_\infty/dt = 0.046$ ft/s^2, and $30 < \alpha < 50$ deg), produces results in which the deceleration has a clear, positive effect on the burst location. The scatter is also increased. Note that the deceleration produces a slope (at 7 s elapsed time) close to that of a constant speed pitch-up at $\kappa = 0.2$, which is intuitively correct when one considers that, because U_∞ occurs in the denominator, reducing it to one-half of the initial magnitude should double the value of κ.

In Fig. 21, the acceleration does not appear to change the slope of the propagation curves. On the other hand, the deceleration produces a mild retardation in the burst propagation. In one run (experiment 3, with black circular symbols), a clearly visible change in slope occurred at 5 s. The other two runs produced a barely discernible change in slope at approximately 4.5 s. Note that both Figs. 20 and 21 present the results of experiments at the higher dU_∞/dt value (0.046 ft/s^2), but the range of α values tested for Fig. 21 starts at a very high value of α; thus, the deceleration appears to have a smaller effect when started at a higher angle of attack.

Figures 22 and 23 are similar in that the experiments occurred at the lower value of dU_∞/dt tested (0.023 ft/s^2). In both cases, it is hard to observe any clear effect of the change in velocity, as there is no discernible change in slope, particularly during the deceleration portion. The acceleration of the experiments in Fig. 22 did change the

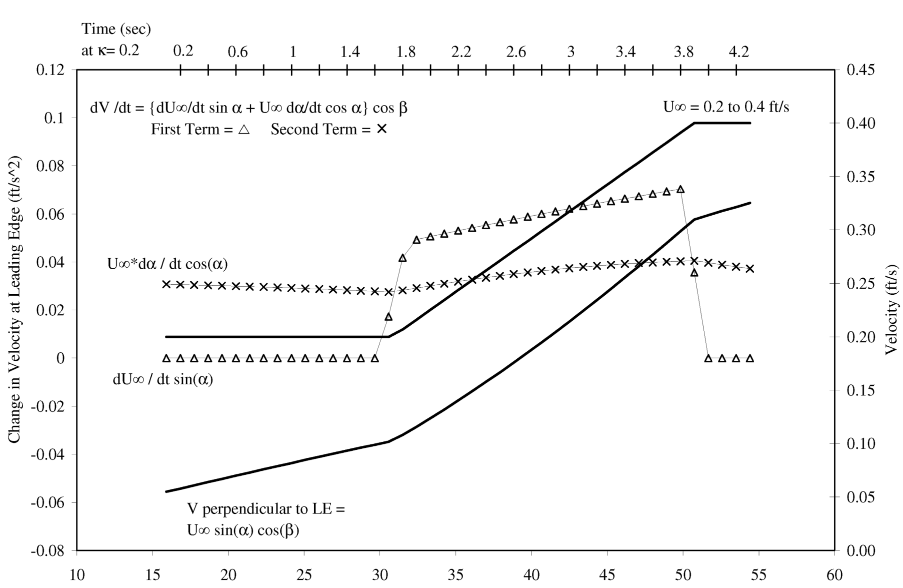

Fig. 18 Example of perpendicular velocity at the leading edge, constant pitch-up rate and acceleration (ideal representation of Fig. 2's acceleration case).

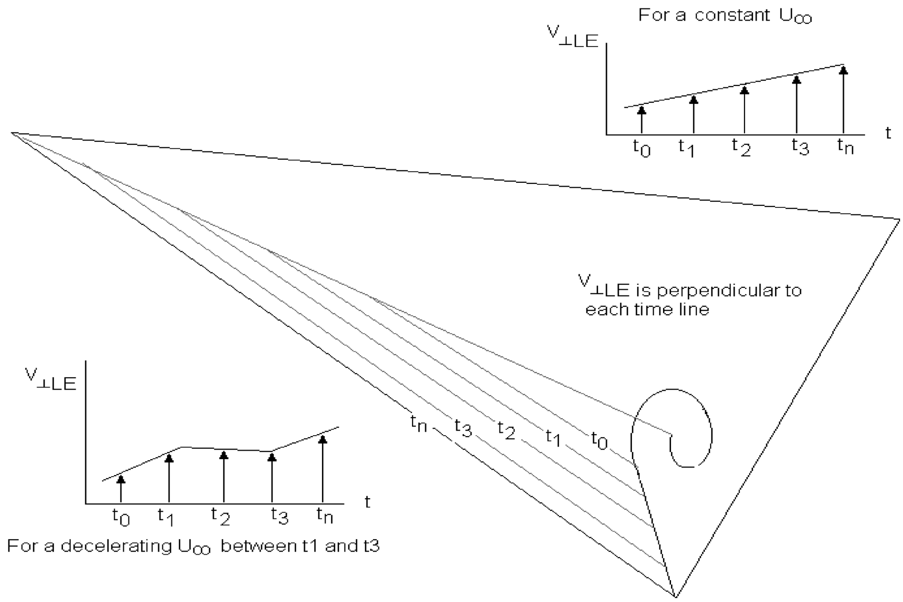

Fig. 19 Time progression of perpendicular velocity at the leading edge into the vortex core.

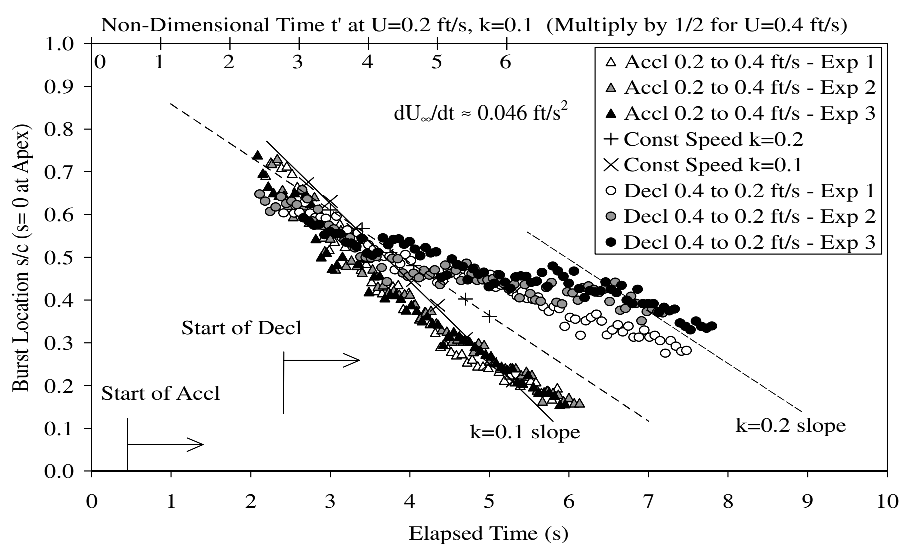

Fig. 20 Burst comparison, pitch-up at $\kappa = 0.1$, velocity ratio of 0.5 acceleration/deceleration from initial speed (30 deg) to final speed (50 deg).

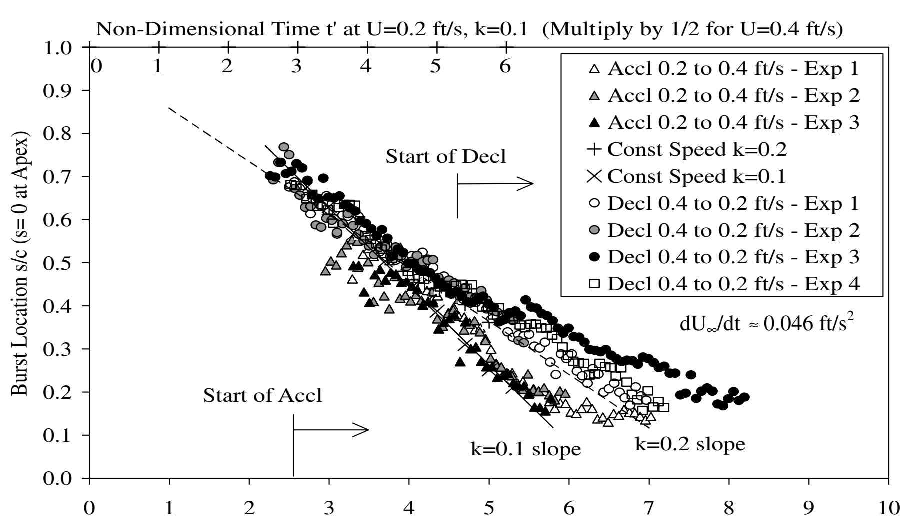

Fig. 21 Burst comparison, pitch-up at $\kappa = 0.1$, velocity ratio of 0.5 acceleration/deceleration from initial speed (45 deg) to final speed (beyond 55 deg).

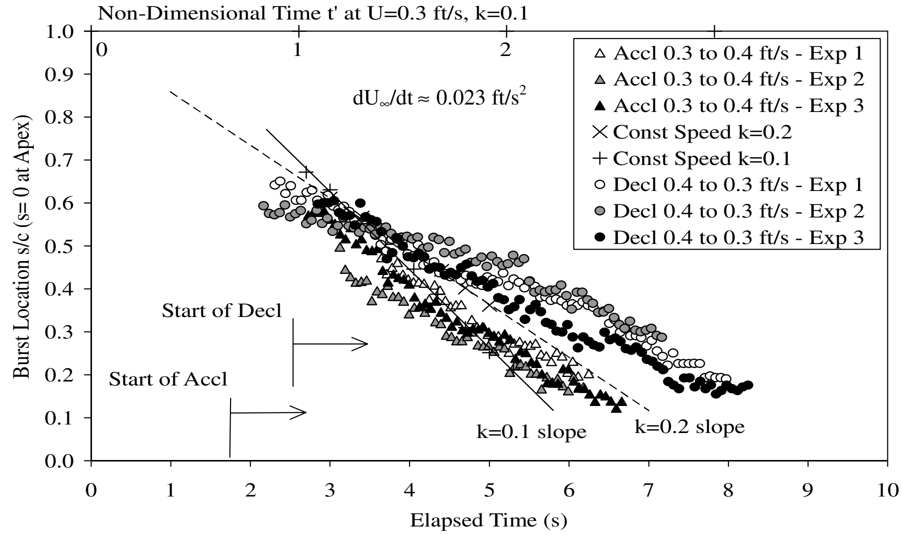

Fig. 22 Burst comparison, pitch-up at $\kappa = 0.1$, velocity ratio of 0.75 acceleration/deceleration from initial speed (30 deg) to final speed (50 deg).

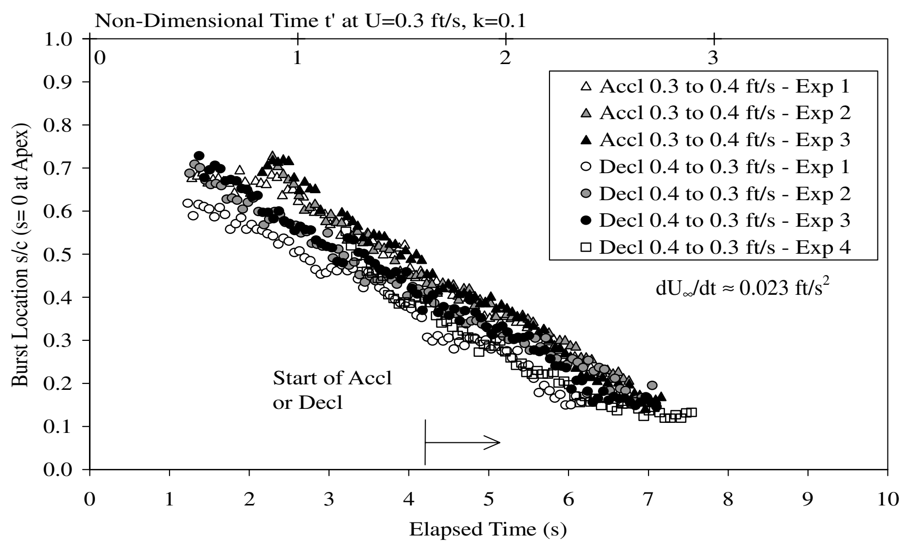

Fig. 23 Burst comparison, pitch-up at $\kappa = 0.1$, velocity ratio of 0.75 acceleration/deceleration from initial speed (45 deg) to final speed (beyond 55 deg).

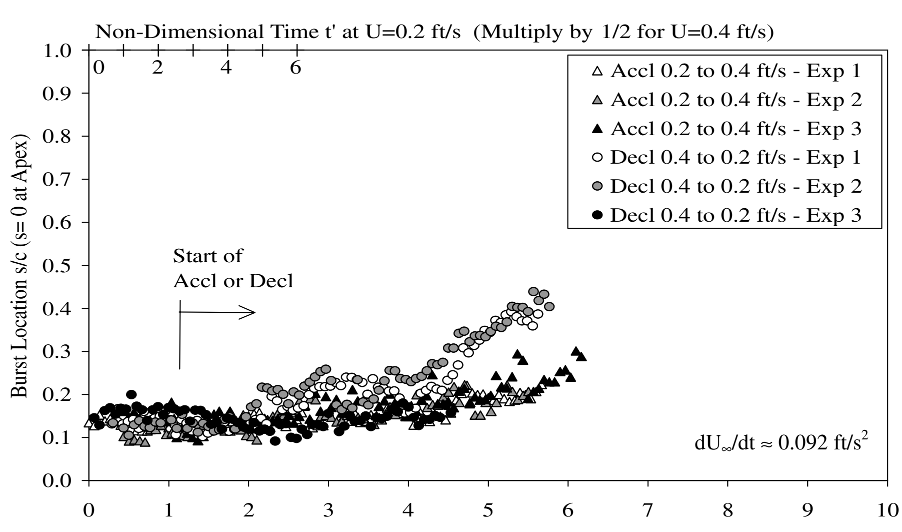

Fig. 24 Burst comparison, pitch-down at $\kappa = 0.1$, velocity ratio of 0.5 acceleration/deceleration from initial speed (50 deg) to final speed (40 deg).

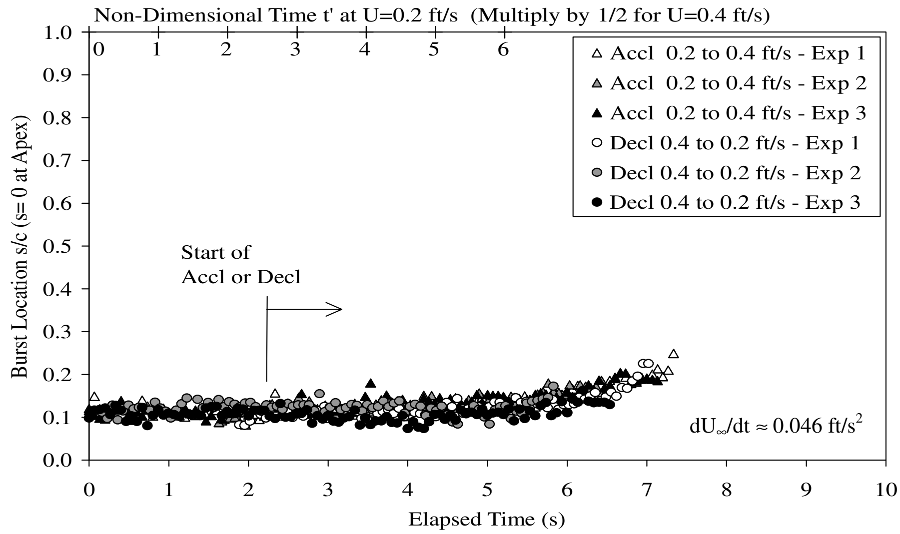

Fig. 25 Burst comparison, pitch-down at $\kappa = 0.1$, velocity ratio of 0.5 acceleration/deceleration from initial speed (50 deg) to final speed (30 deg).

slope toward the end (at approximately 5 s elapsed time), but the change was to flatten (delay) the forward motion of the burst location. This change in slope was probably due to the fact that the pitch-up was close to the end point.

To summarize, pitching up at $\kappa = 0.1$ at different ranges and velocity ratios produced mild to unobservable negative and positive effects. Both effects appeared to occur when the delta wing experienced a strong deceleration ($dU_\infty/dt = 0.046$ ft/s^2) over a large range of α values (30 to 50 deg). At slower decelerations and/or limited values in the α range, the effects became almost unobservable in the scatter plots, due in part to the increased scatter. Instabilities (whether inherent or external to the vortex core) or other mechanisms (i.e., laminarity in the viscous regions) could play a more dominant effect at the low Reynolds numbers experienced under these conditions by the delta wing.

Pitch-Down Results

Figures 24–26 present the results of a pitch-down at $\kappa = 0.1$ under different values of dU_∞/dt and α ranges. The deceleration does appear to move the burst back toward the trailing edge (a positive effect) faster in the case in which dU_∞/dt is high (0.092 ft/s^2). In the other two cases, in which dU_∞/dt has intermediate and low values, there is no appreciable difference between accelerating and decelerating. Scatter is well controlled in all three figures. Thus, the benefits of decelerating the delta wing to delay the forward progression of the burst appear to be confined to the pitch-up regime of flight.

Discussion

Decelerating from 0.4 to 0.2 ft/s (i.e., a velocity ratio of 0.5), a reduction in the vortex-burst propagation velocity is apparent at about 1.5 s after the freestream velocity begins to decelerate. One possible means to nondimensionalize the time axis and to thus be able to generalize the results to other experiments of this type, is to use a nondimensional time frame:

$$t' = (t \cdot a)/(\omega \cdot c) \tag{3}$$

where t is the elapsed time, a is acceleration (dU_∞/dt), ω is the pitch rate ($d\alpha/dt$) in radians per second, and c is the chord. Using this definition, the reduction in forward propagation of the vortex-burst location occurs at $t = 1.5$ s, which corresponds to $t' = 0.863$ when the delta wing is decelerated with a velocity ratio of 0.5 during pitch-up between 15 to 55 deg at a rate of $\kappa = 0.2$. Accelerating from 0.2 to 0.4 ft/s (i.e., a minimum-to-maximum velocity ratio of 0.5) and pitching up at $\kappa = 0.2$ between 15 to 55 deg, there was a slight downward inflection in the burst location curves at approximately 1.75 and 2 s ($t' = 1.01$ to 1.15, respectively) after the beginning of the velocity ramp-up (acceleration from 0.2 ft/s).

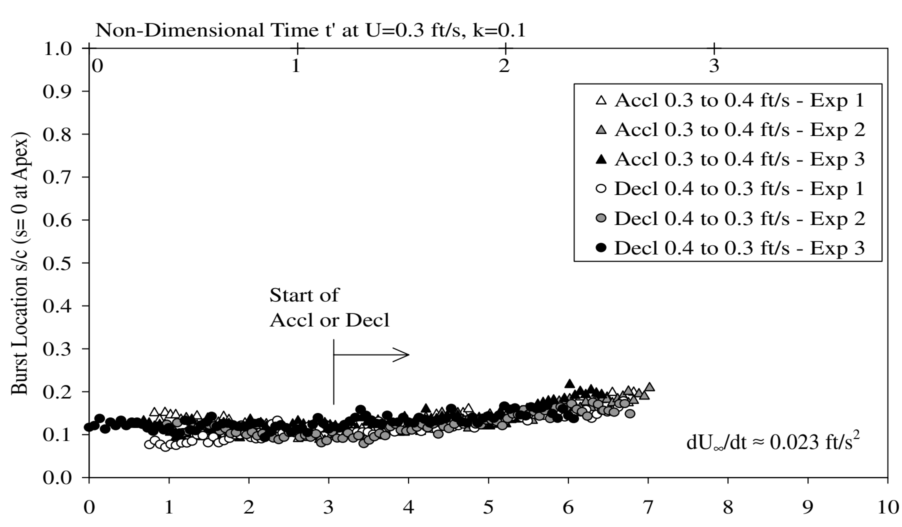

Fig. 26 Burst comparison, pitch-down at $\kappa = 0.1$, velocity ratio of 0.75 acceleration/deceleration from initial speed (50 deg) to final speed (30 deg).

During a small deceleration from 0.4 to 0.3 ft/s (i.e., a velocity ratio of 0.75) and pitching up at a rate $\kappa = 0.2$ between 15 to 55 deg, a reduction in the vortex-burst propagation velocity was apparent at approximately 1 s after the freestream velocity began to change ($t' = 0.288$). This retardation delays the forward propagation of the vortex burst (toward the apex). The forward propagation of the burst location resumes at about 4.5 s elapsed time ($t' = 1.294$), and this appeared to be at the same propagation rate (i.e., the slope of the burst) compared with the beginning of the experiment.

It appears that at $\kappa = 0.2$ for large ranges of angle of attack α, deceleration of the freestream velocity appeared to arrest the motion of the burst location anywhere between 1.5 and 2.5 s after the deceleration began to take place (i.e., $0.863 < t' < 1.438$). The positive delay in the burst movement appeared to be strongest when the delta wing experienced a strong deceleration ($dU_\infty/dt = 0.092$ ft/s^2) over a large range of α values (30 to 50 deg). This effect became much smaller at slower decelerations and/or limited values in the α range. This implies that, perhaps, instabilities (whether inherent or external to the vortex core) could help precipitate the forward jump, making it easier to lose lift than to keep lift.

It appears that acceleration had the effect of increasing the forward propagation of the vortex burst along the leading-edge vortex core. At different α ranges and velocity ratios, accelerating produced a mild-to-strong negative effect on the burst location when accelerating. This negative effect was almost independent of the actual acceleration or range of α over which it occurred.

The results obtained during pitch-up at the slower rate of $\kappa = 0.1$ for different combinations of acceleration and deceleration exhibited the same general features as those observed during the faster pitch-ups: deceleration in the freestream velocity appeared to have a beneficial effect; that is, it arrested the forward motion of the burst location (thereby delaying the propagation of the vortex burst toward the apex). Acceleration in the freestream velocity appeared to have the opposite effect, that of pushing the burst location forward.

A second trait observed during the slower pitch-up tests was that the degree of scatter in the data increased. In some cases, there were large fluctuations along the time axis on which the forward propagation accelerated. In other cases, slightly different curves (one for each experiment performed) were traced, each having identical slope but separated from its neighbor by a few fractions of a second. This indicated that at the slower pitching rate, the experiment was more sensitive to either external noise (such as unavoidable vibrations in the carriage being transmitted to the delta wing) or to something intrinsic within the flow phenomenon. The experiment as it was performed could not isolate the cause of this variability.

Conclusions

A series of experiments was conducted on a 70-deg-sweepback delta wing to study the effect of simultaneous dynamic pitch and unsteady freestream on the delta wing's vortex-burst behavior. It was found that acceleration had the undesirable negative effect of increasing the forward propagation of the vortex burst along the leading-edge vortex core. This negative effect was almost independent of the actual acceleration or range of α over which it occurred. Deceleration, on the other hand, was found to delay the forward movement of the burst along the vortex core. This was consistent for the pitch rates of $\kappa = 0.1$ and 0.2 and in all cases resulted in a momentary reduction of the forward propagation of the burst location. In the more extreme case in which the velocity ratio was large (e.g., deceleration with a velocity ratio of 0.5), a complete stop in the forward movement of the burst was possible for a short length of time. The reason for this reduction in forward propagation rate is hypothesized to be caused by a reduction in the leading edge's velocity due to the deceleration. The reduction in the leading edge's velocity, in turn, reduces the formation of vorticity at its source.

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