High Angle of Attack Aerodynamics

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1 INTRODUCTION

In general, it is desired to avoid flow separation and maintain attached flow over wings. However, as the sweep angle is increased, it becomes more difficult to avoid flow separation. In this article, low-speed aerodynamics of highly swept wings will be discussed. Highly swept wings, known as *delta* wings due to their triangular planform, are used in a range of air vehicles. Some examples include fighter aircraft, unmanned combat air vehicles, supersonic civil transport aircraft, and space vehicles. Delta wings can fly at high angle of attack without stall. This quality is invaluable for military aircraft during a high angle of attack maneuver. On the other hand, supersonic civil transport aircraft cruises at supersonic speeds but flies at subsonic speeds and at higher angles of attack during take-off and landing. Various shapes of delta wings are used in wing designs: simple delta, notched delta, cropped delta, and double delta (Anderson, 1991). In addition, highly swept areas upstream of the main wing, called strakes and leading-edge extensions, are commonly used for fighter aircraft.

2 FLOW PATTERNS

At very low angles of attack, there might be attached flow depending on the thickness of the wing and leading-edge shape. However, with increasing angle of attack (beyond few degrees), flow is separated at the leading edge. The separated shear layer rolls up into the core of streamwise vortices over the suction surface of the wing as sketched in Figure 1a. At moderate and high angle of attack, the flow over a delta wing is dominated by two large, counter-rotating leading-edge vortices. The physical mechanism that generates these primary vortices is the flow separation, and the vorticity of these vortices originates from the boundary layer separation at the leading edge. Within the core of the vortices, the rotational fluid motion resembles a Rankine vortex as sketched by the swirl velocity profile in the left vortex in Figure 1a. An important feature of these leading-edge vortices is axial fluid motion in the vortex core (as sketched by the axial velocity profile in the right vortex in Figure 1a), which can reach up to five times the freestream velocity. The physical mechanism for high speeds in the core is related to the rotational

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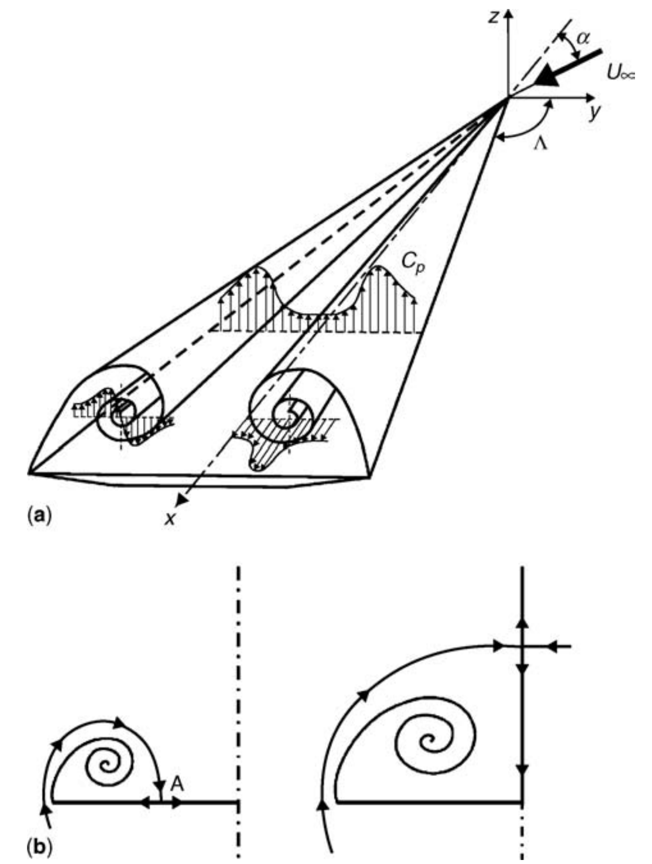

Figure 1. (a) Schematic of shear layer roll-up, axial, and swirl velocities in the vortex core and wing surface pressure distribution; (b) cross-flow streamline patterns with and without reattachment on wing surface.

motion within the vortex, which generates low pressure. The fluid around the core is drawn to this low-pressure region and is accelerated. The leading-edge vortices also generate low pressure (suction) on the wing surface as sketched at a streamwise station in Figure 1a. The suction peak on the wing surface and underneath the vortex axis is due to the leading-edge vortex. The pressure distribution is relatively flat away from the vortices. The vortical flows for delta wings with sharp leading edges become more complex for delta wings with rounded leading edges (Hummel, 2008).

Other features not shown in Figure 1a include reattachment lines and secondary vortices (Anderson, 1991). The secondary vortices are generated as a result of the boundary layer separation on the wing surface due to the primary vortices. For small angles of attack, the primary reattachment line is inboard of the leading-edge vortices as shown schematically in a cross-flow plane in Figure 1b (left sketch). The reattachment location on the wing surface (point A) moves inboard with increasing angle of attack and ultimately reaches the wing centerline. Beyond this angle of attack, a saddle point (Tobak and Peake, 1982) develops above the wing at the centerline as sketched in Figure 1b (right sketch). The latter pattern is typical for *slender* delta wings (defined as wing sweep angle $\Lambda \geq 65^\circ$) at high angle of attack.

Vortical flows over *nonslender* delta wings ($\Lambda \leq 55^\circ$) have some differences from those over slender delta wings. Primary vortices develop at very low angles of attack and form much closer to the wing surface. Hence, the interaction of the primary vortices and surface boundary layer is stronger. This may result in a dual primary vortex structure in which the primary vortex is split into two (Gursul, Gordnier and Visbal, 2005). The flow pattern in a cross-flow plane has the reattachment point on the wing surface (left sketch in Figure 1b) for angles of attack smaller than the stall angle.

3 VORTEX LIFT

It is clear from the discussion of the pressure distribution (Figure 1a) that leading-edge vortices increase the suction on the wing surface, which increases the total lift. The lift increment is called *vortex lift*. Polhamus (1971) calculated the total lift as the sum of the vortex lift and potential lift. The latter is predicted by assuming potential flow over the lifting surface and applying the Kutta condition at the trailing edge. The vortex lift was calculated by the leading-edge suction analogy (Polhamus, 1971), which assumes that the vortex lift is equal to the leading-edge suction force that would be required to maintain attached flow. Since the analogy requires that flow reattaches on the suction surface, the theory fails to predict the experimental data when the reattachment does not occur. The total lift can be expressed as

$$C_L = K_\mathrm{p} \sin\alpha \cos^2\alpha + K_\mathrm{v} \sin^2\alpha \cos\alpha \tag{1}$$

where the constants K_p and K_v are related to the potential lift and vortex lift, respectively. The constants can be estimated for delta wings with various planforms and mainly depend on the aspect ratio (AR). While the constant K_p increases with increasing aspect ratio (decreasing sweep angle), the constant K_v weakly depends on the aspect ratio. The general conclusion from this theory is that vortex lift contribution increases with wing sweep angle, hence it is more important for slender delta wings. It is also noted that the relative contributions of the potential lift and vortex lift depend on the angle of attack. The vortex lift contribution increases with increasing angle of attack. This is illustrated in Figure 2 for a sweep angle of $\Lambda = 76^\circ$. The total lift agrees well with the wind tunnel data. The vortex lift contribution (difference between the total lift and potential lift) becomes substantial with increasing angles of attack.

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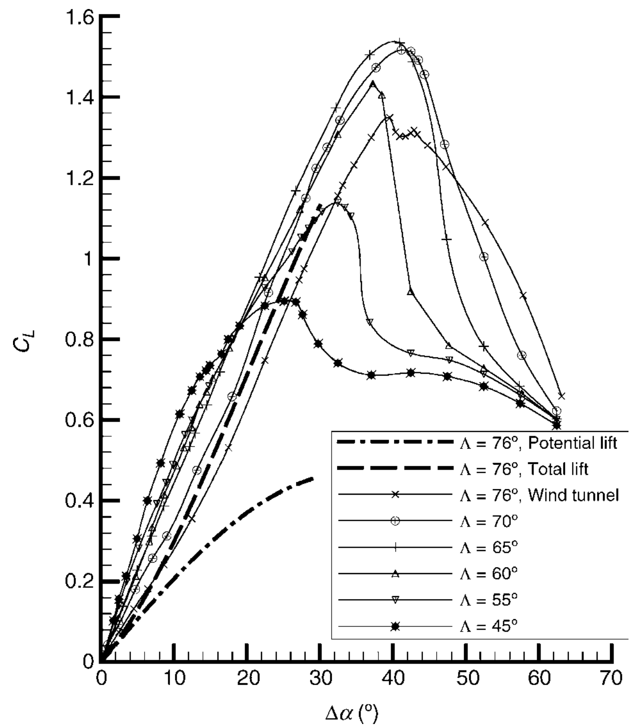

Figure 2. Variation of lift coefficient as a function of angle of attack from zero lift. The wind tunnel data (Earnshaw and Lawford, 1964) are shown for different sweep angles. In addition, the potential lift and total lift predictions are shown for sweep angle $\Lambda = 76°$.

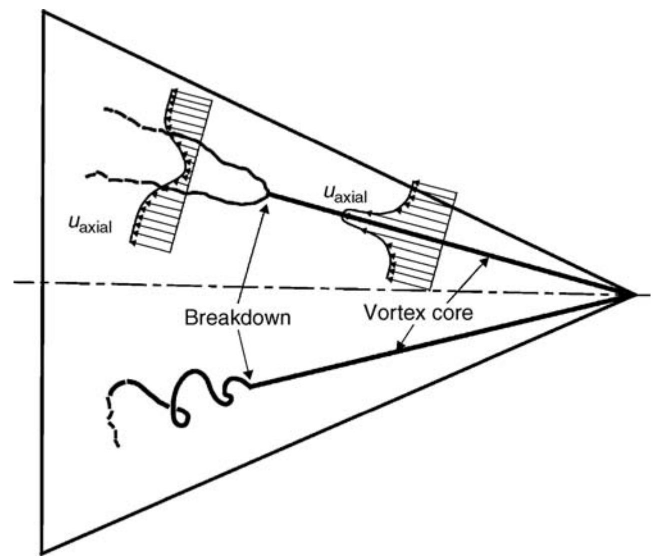

Figure 3. Schematic of bubble-type and spiral-type breakdowns and axial velocity profiles upstream and downstream of breakdown.

Figure 2 shows the variation of lift coefficient for delta wings with various sweep angles in the range of $\Lambda = 45°$–$76°$, adapted from the data of Earnshaw and Lawford (1964). The lift slope is small compared to that of large aspect ratio wings, but the stall angle is large. Hence, aircraft with delta wings need to fly at high angle of attack for low-speed flight in order to generate high values of lift coefficient. The data show that the slope of the lift coefficient increases with decreasing sweep angle (increasing aspect ratio). However, for low-sweep angle wings, the maximum lift coefficient and the stall angle decrease with decreasing sweep angle.

4 VORTEX BREAKDOWN

As the angle of attack is increased, the leading-edge vortices undergo a sudden transition known as *vortex breakdown* or *bursting*, which was first observed by Werle (1954) in a water tunnel. Vortex breakdown is essentially a sudden expansion of the vortex core, which results in the stagnation of the axial flow. This phenomenon is illustrated in Figure 3, which is adapted from the flow visualization picture obtained in a water tunnel by Lambourne and Bryer (1961). It is seen that two different types, so-called bubble-type and spiral-type, of breakdown are captured in this picture. The spiral type of breakdown is more common over delta wings. Some researchers believe that the spiral form is a consequence of the instability of the bubble form. Note that the sense of helix is opposite to the direction of rotation in the leading-edge vortex.

In Figure 3, axial velocity upstream and downstream of the vortex breakdown is shown schematically. While the axial velocity is jet-like upstream, it becomes wake-like downstream due to the stagnation of the flow at the breakdown location. The vortex core becomes much larger while the maximum swirling velocity decreases (not shown in Figure 3). Since the swirl velocity decreases with vortex breakdown, suction induced by the vortex decreases as well. This leads to a loss in vortex lift for slender delta wings.

Different explanations of the vortex breakdown phenomenon based on the hydrodynamic instability, wave propagation, and flow stagnation are summarized in several review articles (Hall, 1972; Leibovich, 1984; Delery, 1994). It is generally agreed that this phenomenon is a wave propagation phenomenon, and there is a strong analogy to shocks in gas dynamics. Experiments and theoretical explanations agree that there are two important parameters affecting the occurrence and movement of vortex breakdown: *swirl level* and *external pressure gradient* outside the vortex core. Vortex breakdown moves upstream over delta wings when the magnitude of either parameter is increased.

When the angle of attack is increased, vortex breakdown moves upstream. Figure 4 shows the angle of attack at which vortex breakdown crosses the trailing edge for simple delta

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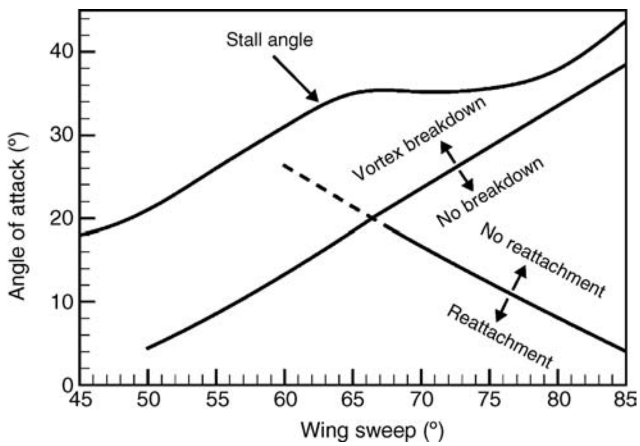

Figure 4. Variation of stall angles and boundaries of vortex breakdown and flow reattachment on the wing surface as a function of sweep angle. Reproduced from Gursul, Wang and Vardaki (2007) © Elsevier.

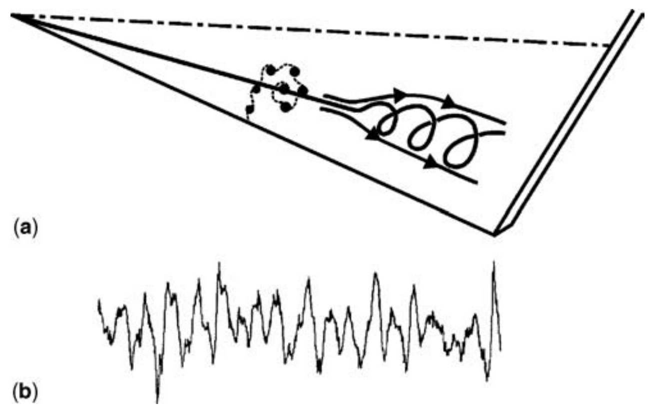

Figure 5. (a) Schematic of vortex breakdown, helical mode instability, and shear layer instabilities; (b) time history of wing surface pressure fluctuations at a location downstream of breakdown (length of the time record is approximately $10c/U_\infty$). Reproduced with permission from Gursul (2005) © AIAA.

wings (the line represents the average of the data collected from various sources). It is seen that this angle of attack increases with increasing wing sweep angle. In addition, the stall angle from various sources is shown in the same figure. It is seen that, for slender delta wings for which the vortex lift contribution is larger, the wing stalls quickly after the vortex breakdown appears on the wing. On the other hand, for nonslender delta wings, vortex lift contribution is smaller and vortex breakdown does not affect the lift drastically. There is no obvious correlation between the onset of vortex breakdown and the variation of the lift coefficient. It is seen from Figure 4 that the stall angle for nonslender delta wings is much larger than the angle of attack at which vortex breakdown appears on the wing. Another feature shown in Figure 4 is the angle of attack at which the reattachment of flow on the wing surface fails to occur. This boundary determines what type of cross-flow pattern (see Figure 1b) is expected for a given angle of attack and sweep angle.

5 VORTEX INSTABILITIES

Vortex flows over delta wings are highly unsteady and complex. Readers can find advanced discussions of the unsteady aspects in reviews by Rockwell (1993) and Visbal (1995). There are various sources of unsteadiness (Gursul, 2005) of the flow over delta wings: the shear layer instabilities (as sketched in Figure 5a), vortex wandering, helical mode instability of vortex breakdown (also sketched in Figure 5a), oscillations of breakdown location, vortex interactions, and vortex shedding. Separated shear layers roll up periodically into discrete vortical substructures (Gad-el-Hak and Blackwelder, 1985; see also the flow visualization picture in Flow Visualization by Direct Injection Technique) because of the *Kelvin–Helmholtz instability* (Flow Instabilities and Transition). The frequency of the instability was found to agree with the predictions from the linear stability analysis of the cross-flow shear layer (Gordnier and Visbal, 1994). In addition to this unsteady instability, several researchers revealed the existence of stationary, small-scale vortices around the primary vortex. The origin of these steady structures is not well understood and has been the subject of various hypotheses (Gursul, 2005). *Vortex wandering* is defined as the random displacements of the vortex core and is also observed in tip vortices. This phenomenon causes large-amplitude velocity fluctuations in the core of the vortices, even upstream of breakdown or in the absence of breakdown.

The main instability associated with vortex breakdown is the *helical mode instability*. An example of the time history of wing surface pressure is shown in Figure 5b, which reveals the quasi-periodic nature of the pressure fluctuations. The periodic velocity or pressure fluctuations correspond to the most unstable modes of the time-averaged velocity profiles of the vortex (downstream of breakdown). The disturbances are represented as $\exp\{\mathrm{i}(kx + n\phi - \omega t)\}$, where ω is the radial frequency, k is the wave number in the axial direction, and n the wave number in the angular direction. It has been shown that these fluctuations are in the form of the first helical mode (the wave number in the angular direction is $n = 1$). It has been suggested by several researchers that the spiral form of breakdown is a consequence of this instability of the breakdown wake (Gursul, 2005). This explains why the sense of the helix is opposite to the direction of rotation

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in the vortex. Readers can find extensive discussions of this topic in the reference by Gursul (2005). The experiments indicate that the frequency decreases while the pitch of the helix increases in the streamwise direction for the nearly conical flow over a slender delta wing. While this instability causes large-amplitude pressure or velocity fluctuations, oscillations of the breakdown location introduces further complications. The location of breakdown is not steady and exhibits fluctuations along the axis of the vortices. These oscillations are largely due to the interaction between the vortices over slender wings and usually have very low frequency compared to that of other instabilities.

At very high angles of attack after the vortex breakdown reaches the apex, there is no more coherent streamwise vortex flow. Instead, *vortex shedding* occurs, which may be in the symmetric or anti-symmetric form (Rediniotis, Stapountzis and Telionis, 1990). The spectrum of unsteady flow phenomena that has quasi-periodic nature is shown in Figure 6. The frequency spectrum of the unsteady flow phenomena over stationary slender delta wings is very wide. In other words, the characteristic time scales of these phenomena differ by several orders of magnitude, which is one of the challenges in numerical simulations of these flows. When compared to the frequency of other phenomena, the frequency range of the oscillations of breakdown location for a stationary delta wing is much closer to that of typical aerodynamic maneuvers (up to $fc/U_\infty \cong 0.03$ for fighter aircraft).

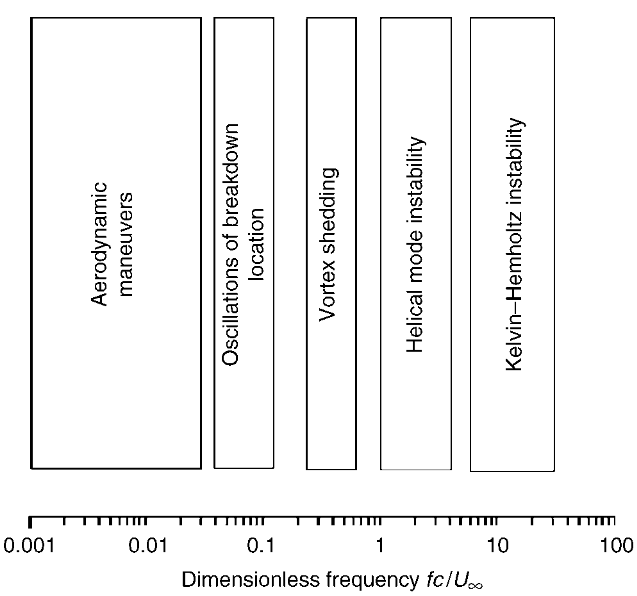

Figure 6. Spectrum of unsteady flow phenomena over slender delta wings as a function of dimensionless frequency. Reproduced with permission from Gursul (2005) © AIAA.

6 WING AND FIN BUFFETING

Buffeting is defined as the structural response of aircraft structures (such as wing, fin, tail, and flap) due to unsteady flow (Mabey, 1989). Highly unsteady vortical flows can lead to buffeting of flexible delta wings due to the fluctuating loads on the surface of the wing. Vortex breakdown, vortex interactions, and vortex shedding, either alone or in combination, play an important role. Wing buffeting occurs when the frequency of the quasi-periodic flow oscillations is close to the natural frequencies of the structural modes of the wing. The most important source of wing buffeting over slender delta wings is the vortex breakdown. Figure 7 shows the variation of wing tip acceleration for a slightly flexible delta wing (sweep angle of $\Lambda = 60^\circ$) as a function of angle of attack (Gursul, Gordnier and Visbal, 2005). Different vortex flow regimes are also shown on the same graph. When there is no vortex breakdown over the wing, the buffeting is small. It increases substantially when the vortex breakdown moves over the wing and reaches a maximum when the breakdown is close to the apex of the wing. Buffeting decreases very rapidly in the vortex shedding regime at higher angles of attack.

Buffeting of wings with low sweep angle is qualitatively similar, however, the highly unsteady nature of the flow reattachment zone rather than the vortex breakdown may become the main source of buffeting. For very flexible nonslender delta wings, the wing flexibility may couple with the vortical flow. At post-stall angles of attack, self-excited vibrations of the wing excite the separated shear layer and promote the flow reattachment (Taylor *et al*., 2007). This results in substantial lift enhancement. This phenomenon appears to be a feature of nonslender wings only and is observed when the natural frequency of the wing vibrations is in the same range as the natural frequencies of the shear layer instabilities.

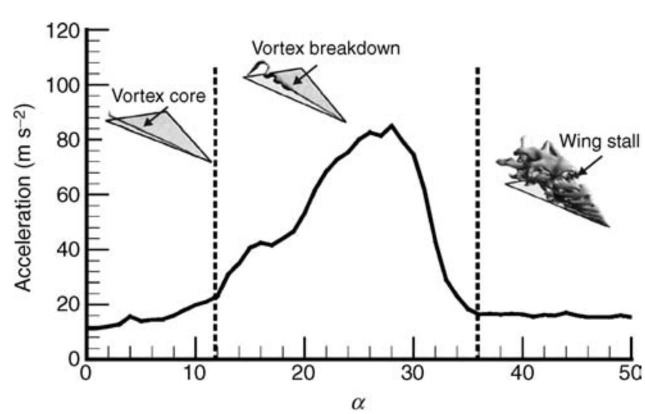

Figure 7. Variation of wing tip rms acceleration as a function of the angle of attack for a $\Lambda = 60^\circ$ sweep half delta wing model. Reproduced from Gursul, Gordnier and Visbal (2005) © Elsevier.

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Unsteady vortex flows may cause large structural vibrations and severe fatigue damage of fins (also called tails). The best-known example of fin buffeting is F/A-18 aircraft, which has twin tails. Single-tail fighter aircraft may also suffer from buffeting. Vortex breakdown is the main source of fin buffeting, although other unsteady flow phenomena may also contribute. In most cases, it occurs when the frequency of the helical mode instability of vortex breakdown is close to the natural frequency of the structural modes (usually, the first mode) of the fin. The dimensionless frequency of the flow oscillations, fc/U_∞, is on the order of unity and depends on the location of vortex breakdown, angle of attack, and wing sweep. Mabey (1997) proposed an empirical relationship for the frequency of the helical mode instability:

$$\frac{fc}{U_\infty} \cot \Lambda \sin \alpha = 0.27 \qquad (2)$$

for the frequency at the trailing edge, which is a useful design rule for delta wings. These data are valid for vortex breakdown naturally occurring over stationary slender delta wings. Effects of dynamic maneuver of the wing, which may result in substantial changes in the location of breakdown, and premature breakdown such as induced by the presence of the fin itself are not accounted. Other aspects of fin buffeting, including the effects of other unsteady flow phenomena and aeroelastic effects (fin surface deflections), are discussed by Gursul (2005).

7 LEADING-EDGE VORTICES IN UNSTEADY FLOWS

The behavior of vortices over a maneuvering aircraft or in an unsteady freestream is important for aircraft stability and control. In particular, development of highly maneuverable fighter aircraft and unmanned combat aircraft is highly dependent on the unsteady aerodynamics of leading-edge vortices. Early experiments summarized by Gursul (2005) indicated that there is a time delay in the variation of the vortex core in response to the heaving or pitching motion of the wing. Hence, even in the absence of vortex breakdown, a time lag in the development of the cross-flow pattern indicates the importance of unsteady effects on the vortices.

This unsteady response becomes further complicated when there is vortex breakdown over the wing. Figure 8 shows the variation of the chordwise location of vortex breakdown for a periodically pitching delta wing (LeMay, Batill and Nelson, 1990). During the upstroke, the location of vortex breakdown is downstream of that for stationary wing at the same angle of attack. During the downstroke, the location of vortex breakdown is upstream of that for stationary wing at the same angle of attack. In other words, there is a time lag of vortex breakdown location with respect to its variation in the quasi-steady case. This time lag results in the hysteresis loop shown in Figure 8. The loops become wider with increasing frequency. This time lag, which is important for the stability and control of aircraft, has also been observed for other types of wing motion. In fact, when vortex breakdown is subjected to an external harmonic forcing (such as wing oscillations or oscillating control surfaces), its response has been found to be similar to that of a first-order dynamic system, with a normalized time constant $\tau U_\infty/c$ order of unity. The amplitude attenuation with increasing frequency is similar to that of a low-pass filter. For frequencies higher than the cutoff frequency, vortex breakdown does not respond to the external forcing. This can be interpreted as the inability of disturbances to propagate upstream at high frequencies (Gursul, 2005). The normalized time constant has been found to be

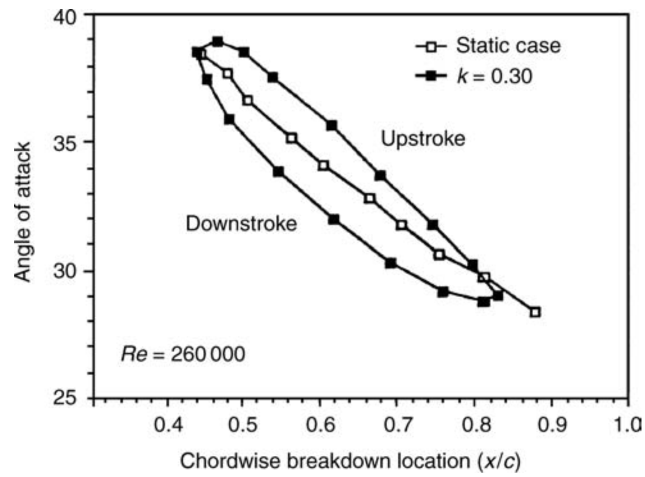

Figure 8. Chordwise location of vortex breakdown for a pitching delta wing (LeMay, Batill and Nelson, 1990). Reproduced with permission from Professor Robert Nelson, University of Notre Dame.

$$\frac{\tau U_\infty}{c} = 1 \quad \text{to} \quad 2 \qquad (3)$$

for slender wings. For nonslender delta wings, the time constant is somewhat larger. It is noted that the time lag of vortex development (in the absence of breakdown) is very small compared to the large time lag of breakdown location. Various suggestions as to the origin of the time lag of location of vortex breakdown are summarized by Gursul (2005).

The response of breakdown location was also studied for transient motions such as a finite ramp pitching motion or plunging motion. Similar observations of time lag were made for a variety of wing shapes, including diamond,

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cropped, delta, and double delta wings. Other types of unsteady flows investigated include delta wings in unsteady freestream, where the magnitude, but not the direction, of the freestream velocity varies periodically (Lee and Ho, 1990; Gursul, 2005). Even though the effective angle of attack does not vary in this case, the freestream unsteadiness may cause large variations in the location of vortex breakdown.

8 WING ROCK

Wing rock is a self-induced limit-cycle roll oscillation that has been observed for slender delta wings as well as aircraft configurations (Katz, 1999). These roll oscillations are observed at a high angle of attack, when the leading-edge vortices are the dominant feature of the flow. An example of the time history of the roll angle for a slender wing (sweep angle $\Lambda = 80^\circ$) is shown in Figure 9a (Arena and Nelson, 1994). Gradual buildup of the roll oscillations is seen at an angle of attack of 30°. Note that the mean roll angle is zero, which is different from the behavior of free-to-roll nonslender delta wings. Wing rocks of slender delta wings were observed

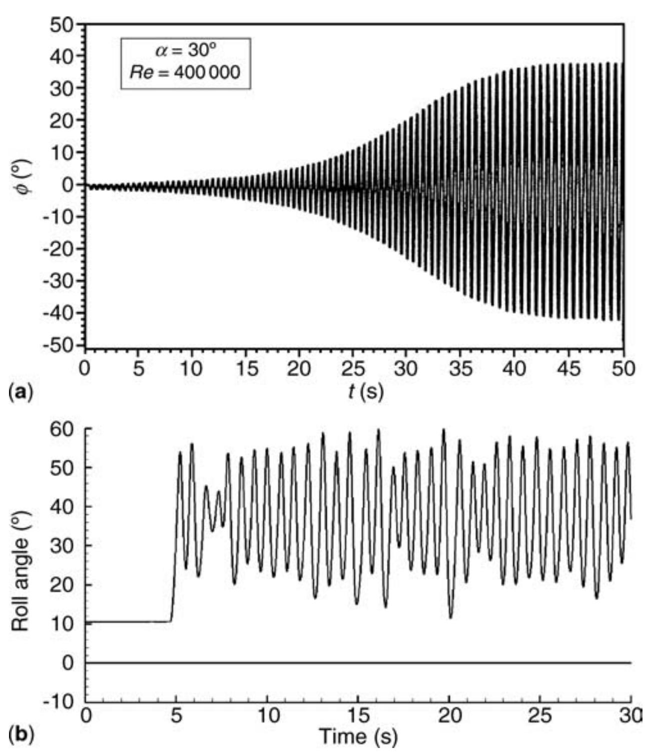

Figure 9. (a) Wing rock time history for $\alpha = 30^\circ$ and $\Lambda = 80^\circ$ (Arena and Nelson, 1994). Reproduced with permission from Professor Robert Nelson, University of Notre Dame. (b) Time history of roll angle for $\alpha = 27.5^\circ$ and $\Lambda = 50^\circ$. Reproduced from Gursul, Gordnier and Visbal (2005) © Elsevier.

for highly swept wings ($\Lambda \geq 75^\circ$, AR ≤ 0.54). Similar roll oscillations were observed for very-low-aspect-ratio rectangular wings (AR ≤ 0.5), as the tip (or side-edge) vortices also drive the motion. These observations have suggested that the proximity of the leading-edge vortices to each other may be important. Vortex interactions are expected to be stronger on very-low-aspect-ratio wings.

As the angle of attack is increased, the wing rock motion first appears at a specific incidence, known as the onset angle of attack. Typically, the amplitude of the roll oscillations reaches a peak with increasing angle of attack and then drops to zero at a very high angle of attack. The onset angle of attack, at which wing rock starts, decreases as the wing planform becomes more slender. While vortex interactions due to the proximity of the vortices may be a possible mechanism that starts wing rock, it is believed that vortex breakdown is not a necessary condition for wing rock. For slender wings, no breakdown is seen on the wing during the oscillations at the onset of the motion. Once the wing rock is initiated, it may be sustained with a different mechanism. Arena and Nelson (1994) suggested that a possible mechanism to sustain the wing rock motion is the time lag in the position of the vortices normal to the wing surface. Forebody vortices originating from the fuselage or strake vortices may interact with the main wings and may also cause wing rock motion of generic fighter aircraft (Katz, 1999). Various control methods to suppress the wing rock roll oscillations are reviewed by Katz (1999).

Somewhat different type of roll oscillations is observed for nonslender delta wings. An example is shown in Figure 9b for a delta wing with sweep angle $\Lambda = 50^\circ$ at $\alpha = 27.5^\circ$ (Gursul, Gordnier and Visbal, 2005). The self-induced roll oscillations have a nonzero mean roll angle and are observed when the angle of attack is in a small range near the stall angle. The asymmetric flow reattachment is believed to be behind these observations. These roll oscillations about a nonzero mean roll angle were observed for delta wings with sweep angles of $50^\circ \leq \Lambda \leq 60^\circ$ and sharp leading edges (Gresham, Wang and Gursul, 2008). If the leading edge is rounded (hence the separation line is not fixed), unsteady separation at the leading edge might also contribute to the roll oscillations. The Strouhal number of the roll oscillations is on the order of 10^{-2}.

Even when there are no roll oscillations, free-to-roll nonslender delta wings may have trim positions at nonzero roll angles. In other words, zero roll angle is not stable to roll disturbances. Experiments for low-sweep delta wings (as low as 40°) revealed that the nonzero trim angles are related to asymmetric reattachment of the separated flows. It is recalled that reattachment on the wing surface is typical for nonslender wings. The magnitude of the roll trim angle decreases with

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increasing sweep angle and reaches zero at $\Lambda = 70°$. This can be attributed to the reattachment point moving away from the wing surface with increasing sweep angle.

9 MULTIPLE VORTICES

For generic aircraft configurations, there are multiple vortex pairs. These include forebody vortices that originate from the fuselage, leading-edge vortices from the highly swept areas known as strakes or leading-edge extensions, and the main wing vortices as shown schematically in Figure 10. The double delta wing shown in this figure is a generic planform that generates multiple vortices.

Upstream vortices originating from forebodies, strakes, and canards interact with the vortical flow on the main wing, energize the flow, and delay the stall. The strake vortices generate additional lift, persist over the wing, and produce favorable conditions for the main wing vortex. At low angles of attack, the vortices may remain separate as sketched with solid lines in Figure 10. With increasing angle of attack, the breakdown of the strake vortex may be triggered by the breakdown of the main vortex (Verhaagen, 1995).

At higher angles of attack, the vortices may interact, coil up, and merge as sketched with dashed lines, especially if the aircraft has a sideslip angle (see also the flow visualization picture in Flow Visualization by Direct Injection Technique). The process of coiling up and merging is sensitive to Reynolds number (Hebbar, Platzer and Fritzelas, 2000). Strake and wing vortices are coiled up at low Reynolds numbers, whereas they become separated at high Reynolds numbers. Vortex interactions over generic double delta wings may become more complex for maneuvering aircraft (Grismer and Nelson, 1995).

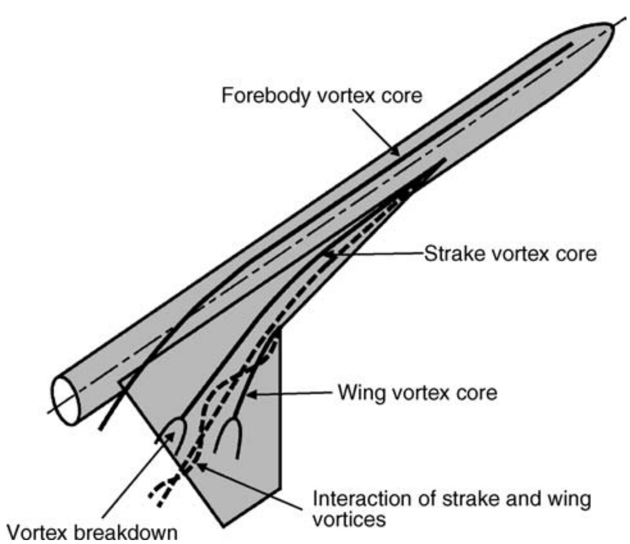

Figure 10. Schematic of a generic aircraft configuration with forebody, strake, and wing vortices. Interaction of strake and wing vortices is shown with dashed lines.

10 VORTEX CONTROL TECHNIQUES

Controlling vortical flows over delta wings may have various benefits such as enhancement of lift force and delay of stall, generation of forces and moments for flight control, and attenuation of wing and fin buffeting. These objectives require modifications to the vortex location, strength and structure, and can be met with active and passive flow control methods (see Aerodynamic Flow Control). For slender delta wings, delay of the vortex breakdown (Mitchell and Delery, 2001) is the primary goal of flow control methods, which is possible with the modifications to the swirl level and external pressure gradient. For nonslender delta wings, control of flow reattachment becomes a more important goal.

The use of control surfaces such as leading-edge flaps makes it possible to control the location and strength of the leading-edge vortices (Rao and Campbell, 1987). Since the entire vorticity of the leading-edge vortices originates from the separation point along the leading-edge, leading-edge flaps are particularly effective. Upward or downward deflection of flaps can be used for improving performance, landing, or aerodynamic maneuvers. Because most of the vorticity with the vortex core originates from a small region near the apex of the wing, an apex flap can also be an effective control surface. Blowing and suction at the leading-edge, trailing-edge (which has applications in thrust vectoring of aircraft), or along the core have differences in terms of their effects on swirl level and pressure gradient affecting the vortex core (Gursul, Wang and Vardaki, 2007). Along-the-core blowing is the most effective method for delaying vortex breakdown. Plasma-based actuators are promising as they do not introduce mechanical control surfaces or plumbing for blowing techniques.

Active flow control using high frequency (Strouhal number based on the chord length on the order of unity) has small effect on vortex breakdown (as we would expect from the discussion on the frequency response of vortex breakdown) but can excite the Kelvin–Helmholtz instability of the separated shear layer and promote reattachment for nonslender delta wings. The resulting lift enhancement at the post-stall incidences is orders of magnitude more effective than steady blowing. Here, the effectiveness is defined as the ratio of the force coefficient increment to momentum coefficient, $\Delta C_N / C_\mu$.

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11 SUMMARY

Leading-edge vortices develop on highly swept wings as a result of flow separation and increase the lift force. The vortex lift increases with increasing sweep angle and can be predicted well with the leading-edge suction analogy. At a high angle of attack, the leading-edge vortices break down or burst, resulting in nearly stagnant axial flow downstream. This phenomenon causes the wing stall for slender delta wings.

Vortex flows over delta wings are highly unsteady. Vortex breakdown is the main phenomenon that causes unsteadiness, although others such as shear layer instabilities, vortex interactions, and vortex shedding may also be important. Wing and fin buffeting are observed when the frequencies of the vortex instabilities are close to the natural frequencies of the structural modes. Leading-edge vortices in unsteady flows exhibit substantial time lag and hysteresis effects. Self-induced roll oscillations of slender delta wings and fighter aircraft, known as wing rock, are driven by the leading-edge vortices.

Multiple vortices that form over aircraft may interact with each other during a maneuver. In certain flight regimes or maneuvers, it may be necessary to control the location and strength of the leading-edge vortices by means of active and passive flow control techniques.

LIST OF SYMBOLS

AR	=	aspect ratio
c	=	chord length
C_L	=	lift force coefficient
C_N	=	normal force coefficient
C_P	=	pressure coefficient
C_μ	=	momentum coefficient
f	=	frequency
Re	=	Reynolds number
u	=	velocity
U_∞	=	freestream velocity
x	=	chordwise distance
y	=	spanwise distance
z	=	normal (to the wing surface) distance
α	=	angle of attack
ω	=	radial frequency
ϕ	=	roll angle
τ	=	time constant
Λ	=	leading-edge sweep angle

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