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Transient Structure of Vortex Breakdown on a Delta Wing

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The transient relaxation process of the leading-edge vortex on a delta wing pitched to high angle of attack is quantitatively characterized using high-image density particle image velocimetry. Instantaneous distributions of azimuthal vorticity and patterns of sectional streamlines over an entire plane allow definition of a new, rapidly evolving mechanism at the onset of vortex breakdown; it marks the transition from a relatively high to low upstream propagation speed of the breakdown.

Nomenclature

C	= root chord, mm
c_v	= propagation speed of vortex breakdown along axis of vortex, mm/s
M	= magnification of camera lens
m	= dimensionless propagation speed of vortex breakdown, c_v/U
Re	= Reynolds number, UC/ν
t	= time, s
t_w	= thickness of delta wing, mm
t^*	= dimensionless time, tU/C
U	= freestream velocity, mm/s
X_b	= chordwise location of vortex breakdown, mm
Y_b	= distance of vortex breakdown from surface of wing, mm
$\dot{\alpha}$	= pitch rate, rad/s
α_f	= final angle of attack, deg
α_i	= initial angle of attack, deg
Λ	= sweep angle of delta wing, deg
ν	= kinematic viscosity, mm^2/s
Δt	= time increment, s

Introduction

A PRINCIPAL feature of the flow structure on delta wings undergoing maneuvers to high angle of attack is the onset and development of vortex breakdown within the leading-edge vortex. The complex features of this class of flows and the important issues deserving further research are reviewed by Rockwell.[1] An important consequence of vortex breakdown is the onset of large time, or phase, lags of the flow pattern relative to the motion of the wing. Reynolds and Abtahi[2] show that attainment of a steady-state location of breakdown requires at least 20–30 convective times C/U after completion of pitching motion of the wing. There have been a wide variety of related investigations, centered on tracking the onset of vortex breakdown, as reviewed by Ashley et al.[3] The adjustment process during or following pitching motion can exhibit a number of interesting characteristics, depending on the geometrical parameters of the wing and the dimensionless pitching parameters, as shown by Wolffelt,[4] Gilliam et al.,[5] LeMay et al.,[6] Hudson et al.,[7] Thompson et al.,[8] Magness et al.,[9] Atta and Rockwell,[10] and Jarrah.[11] These types of phase or time delays occur not only for pitching but also for rolling motion of the wing, as demonstrated by Hanff and Huang[12] and Ng et al.[13]

The structure of vortex breakdown has been investigated from a variety of theoretical and experimental perspectives, primarily focusing on the case of nominally steady flow. Insightful reviews are given by Hall,[14] Leibovich,[15,16] Escudier,[17] and Brown and Lopez.[18] Investigations assessed in these reviews, as well as the recent experimental studies of Brücker and Althaus[19] and Brücker,[20] have provided valuable insight into various features of the flow structure. Directly relevant to the present study is the investigation of Sarpkaya,[21] which describes the concept of a phase lag due to transient, forced flow in a tube.

An understanding of the phase, or time, delay of the unsteady development of vortex breakdown requires insight into the quantitative, instantaneous flow structure. In doing so, instantaneous distributions of vorticity, in relation to the topology of instantaneous streamline patterns, are called for. A first step in this direction is reported by Towfighi and Rockwell.[22] They showed that the onset of vortex breakdown is characterized by a switch in sign of azimuthal vorticity, in agreement with the concept put forth in the theoretical model of Brown and Lopez.[18] In a parallel numerical study, Visbal[23–25] shows that direct numerical simulation of this class of flows can provide detailed insight into the instantaneous, three-dimensional structure of the variation of vortex breakdown pattern.

The objective of the present work is to describe quantitatively the relaxation of the vortex following pitch up to high angle of attack. Emphasis is on a new mechanism of rapid adjustment of the flow structure in the vicinity of vortex breakdown. In turn, these detailed features of the flow structure will be related to the traditional representations of the onset of vortex breakdown.

Experimental System

Experiments were carried out at a flow velocity of 38 mm/s in a water channel having a cross section of 616 mm × 584 mm. The delta wing had a sweep angle $\Lambda = 75$ deg, a thickness to chord ratio $t_w/C = 0.053$, and a chord of 240 mm. The Reynolds number based on C was $Re = 9200$. The wing was pitched from an initial angle of attack $\alpha_i = 25$ deg to a final angle of attack $\alpha_f = 50$ deg at a dimensionless pitch rate $\dot{\alpha}C/2U = 0.15$. Images of the flow structure were acquired at dimensionless times $t^* = tU/C$, where $t^* = 0$ corresponds to cessation of the pitch-up motion.

A laser scanning version high-image density particle image velocimetry (PIV) was employed to determine the instantaneous flow structure over an entire plane. This technique is described by Rockwell et al.[26,27] and Rockwell and Lin.[28] In essence, the scanning laser sheet originating from a continuous wavelength argon-ion laser (3 W) is aligned with the axis of the leading-edge vortex. Images are acquired using a Nikon F-4 camera having a 105-mm lens with a magnification $M = 0.2$. The patterns of particle images on the 35-mm high-resolution Tmax Kodak film (400 ASA) were interrogated with a high-resolution Nikon digitizer system at 125 pixels/mm. By application of two successive Fourier transform

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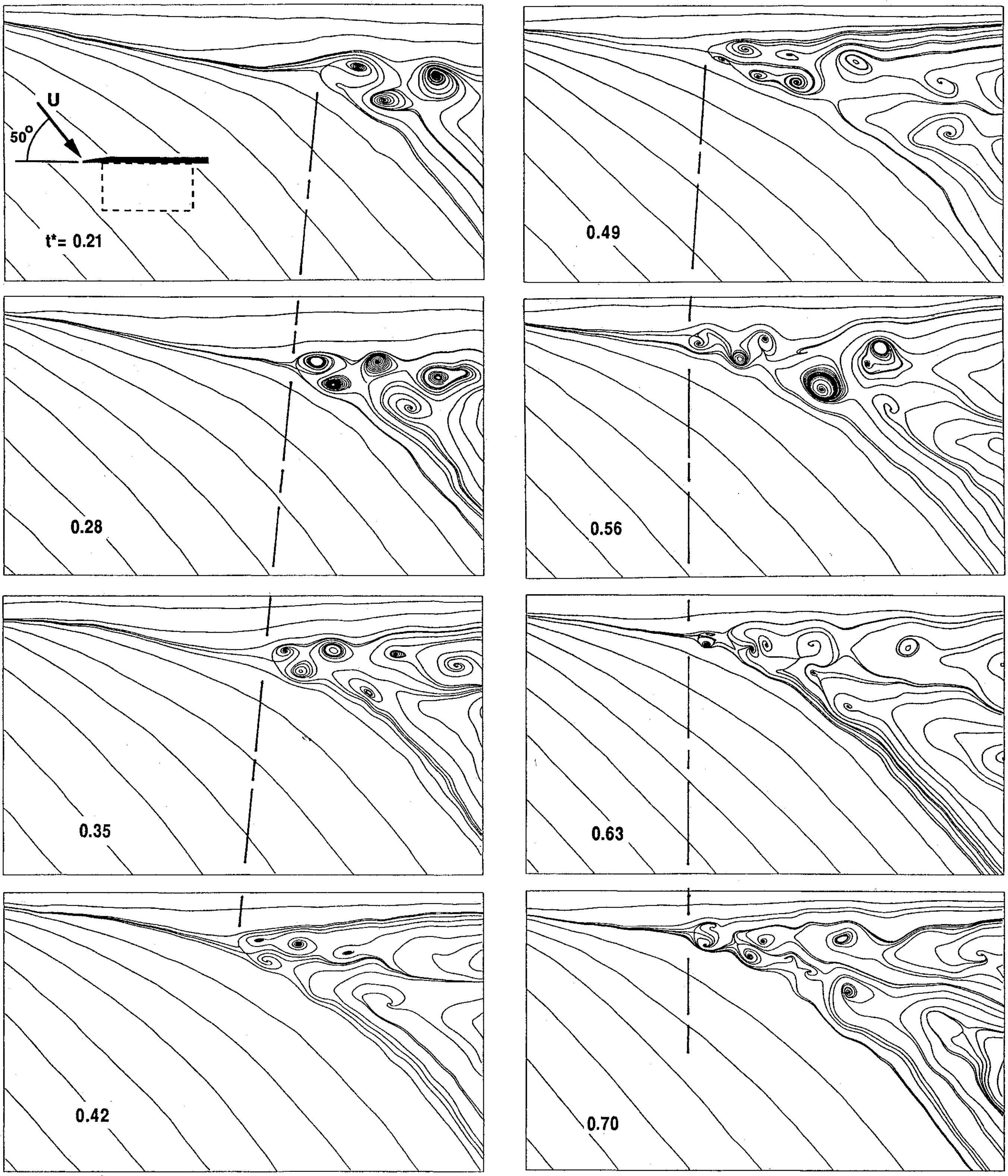


Fig. 1a Evolution of instantaneous streamline patterns with time $t^* = tU/C$ following cessation of pitch-up maneuver.

techniques, the field of 99 × 58 velocity vectors was determined; therefore, the total number of vectors was 5742. This instantaneous velocity distribution over the entire plane led to contours of constant azimuthal vorticity and sectional streamline patterns.

All experimental data were acquired in a plane passing through the centerline of the leading-edge vortex. The entire camera-image shifting system was rotated to the angle of attack of the wing. Therefore, in all images, the top boundary corresponds approximately to the surface of the wing. The field of view in relation to the leeward surface of the wing is shown in the insert of Figs. 1a and 1b.

Experimental Results

Overview of Transient Evolution of the Leading-Edge Vortex

The development of the leading-edge vortex in terms of instantaneous sectional streamlines and contours of azimuthal vorticity is illustrated in Figs. 1a and 1b, respectively. Considering first the streamline plots of Fig. 1a, a reference line connects the approximate locations of the apparent onset of vortex breakdown for successive values of time $t^* = tU/C$. Regarding the detailed structure of the breakdown regime, a saddle point is identifiable on the upstream surface of the breakdown bubble at all values of t^*. This saddle

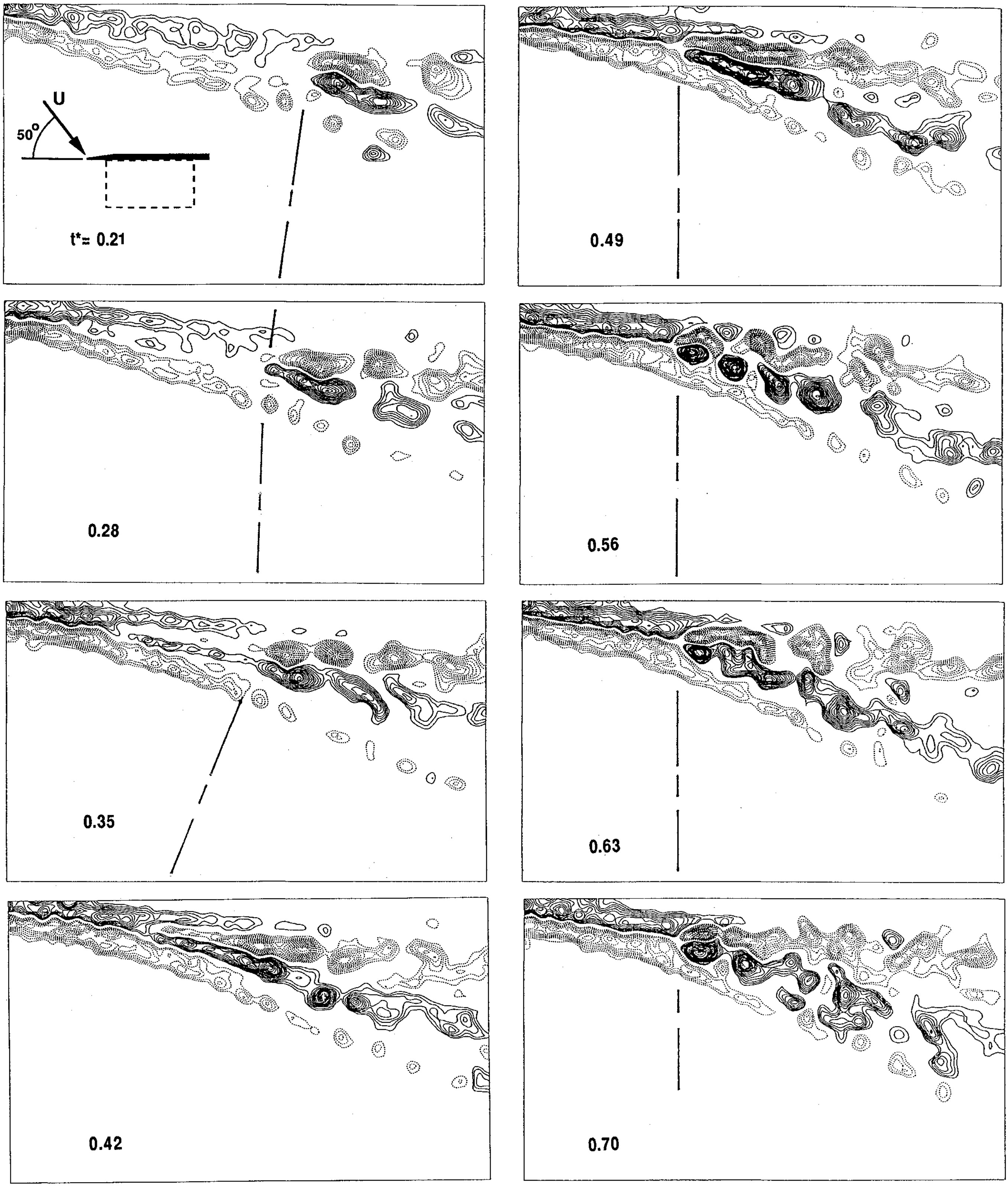
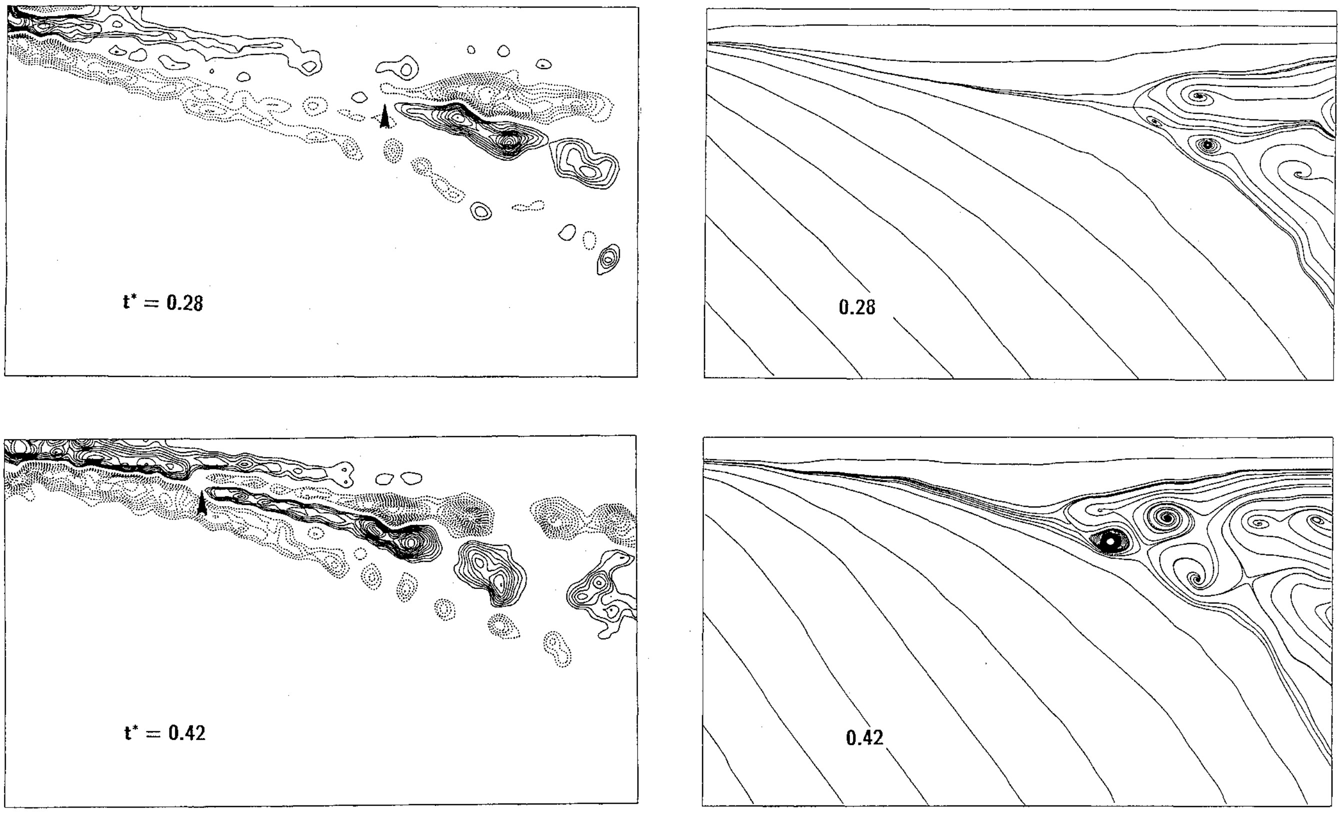


Fig. 1b Evolution of contours of constant azimuthal vorticity with time $t^* = tU/C$ following cessation of pitch-up maneuver.

point, corresponding to the intersection of streamlines, does not, however, form at the leading edge of the breakdown bubble. Rather, it tends to appear above it at $t^* = 0.21$, or below it at $t^* = 0.42$. In fact, the layout of Fig. 1a shows that the evolution with time of the instantaneous pattern of streamlines in the initial region of breakdown exhibits a continuously changing form; there appears to be no universal form of the breakdown bubble. For later times t^* in Fig. 1a, starting with $t^* = 0.49$, there is a basic change in the form of the streamline pattern in the initial region of breakdown; it gradually tends toward a breakdown bubble whose outer streamlines are suggestive of a typical bubble form, but whose inner streamlines show different patterns in the upper and lower regions of the bubble. This bubble form is first detectable at $t^* = 0.63$, and becomes larger at $t^* = 0.70$. Moreover, this initially formed bubble tends to move away from the downstream portion of the breakdown region, i.e., it tends to a detached bubble of the type observed in the simpler, confined axisymmetric flow of Brown and Lopez.[18]



a) b)

Fig. 2 Closeups of contours of constant azimuthal vorticity and corresponding patterns of streamlines showing abrupt transformation of structure of leading edge vortex.

Corresponding contours of azimuthal vorticity are shown in Fig. 1b. A reference line extending between successive images indicates the location where pronounced concentrations of azimuthal vorticity first appear along the centerline of the vortex. At this location, the relative positions of the positive and negative vorticity contours switch; upstream of the switch, positive contours are closest to the wing, and downstream of it, negative contours are adjacent to the surface of the wing. The onset of this vorticity switch, in a very approximate sense, corresponds to the location of the stagnation (saddle) point at $t^* = 0.21$ in Fig. 1a. This general observation is in accord with the theoretical model of Brown and Lopez.[18] At a later time $t^* = 0.28$, the leading edge of the switched vorticity contours has moved upstream. At $t^* = 0.35$, however, no further upstream movement has occurred. At $t^* = 0.42$, there is a rapid and abrupt upstream extension of the switched vorticity contours within the central portion of the leading-edge vortex. At $t^* = 0.49$, the leading edge of these switched contours has actually retreated in the downstream direction. For subsequent times, there is little movement of the leading edges of the switched vorticity contours. There is, however, very rapid development of pronounced concentrations of vorticity at the interior of the leading-edge vortex. At $t^* = 0.56$, the initially formed concentrations are highly organized, suggesting a well-defined helical mode instability, but at successive times $t^* = 0.63$ and 0.70, they transform to less organized states.

Region of Rapid Transformation of Vortex Breakdown

Representative closeups of the contours of constant azimuthal vorticity and streamline patterns are shown in Figs. 2a and 2b, respectively. To emphasize the general repeatability of the flow patterns, the images in Fig. 2 were taken from a different pitch-up maneuver than those of Fig. 1. It is evident that the overall form of the vorticity contours at $t^* = 0.28$ and at 0.42 in Fig. 2a is the same as that shown in the corresponding images of Fig. 1b. However, details of the small-scale vorticity contours should not be the same from one run to the next. The instability occurring at the onset of vortex breakdown has a much smaller time scale than the time scale of the pitching motion and, therefore, cannot phase-lock to the motion of the wing.

The sudden extension of the switched vorticity contours (indicated by the arrows in Fig. 2a) in the upstream direction through the core of the vortex occurs over a remarkably short time $\Delta t \cong 0.14C/U = (0.42 - 0.28)C/U$. Comparing the vorticity contours of Fig. 2a with the streamlines of Fig. 2b, it is evident that the apparent stagnation point of the streamline pattern does not abruptly move upstream with the leading edge of the switched vorticity contours. This observation underscores the importance of interpreting sectional streamline patterns with caution, especially in rapidly evolving vorticity fields of the sort shown here. As will be demonstrated subsequently, this abrupt change in structure of the vortex is particularly important because it represents the transformation from a fast to a slow upstream propagation speed of the region of vortex breakdown.

Forms of Initial Region of Vortex Breakdown

As already suggested in the overview of Fig. 1a, the initial region of vortex breakdown exhibits a number of possible streamline patterns as the region of vortex breakdown evolves toward the apex of the wing. It is possible, however, to define basic forms of these patterns. Figures 3a and 3b show two basic patterns, represented by instantaneous streamlines and their superposition on contours of constant vorticity. These images were selected as typical of basic patterns after examining the evolution of the flow structure during three different pitch-up maneuvers. In Fig. 3a, the antisymmetrical streamline pattern suggests a helical mode of vortex breakdown, even though initial concentrations of vorticity within the bubble are approximately symmetrical. The different degree of concentration of vorticity and circulation of these initial positive (solid line) and negative (dashed line) vorticity concentrations, along with an additional concentration of negative vorticity on the upper side of the breakdown region, are associated with this antisymmetrical streamline pattern. Moreover, at $t^* = 0.42$, the first negative (dashed line) concentration of vorticity corresponds to an unstable focus, that is,

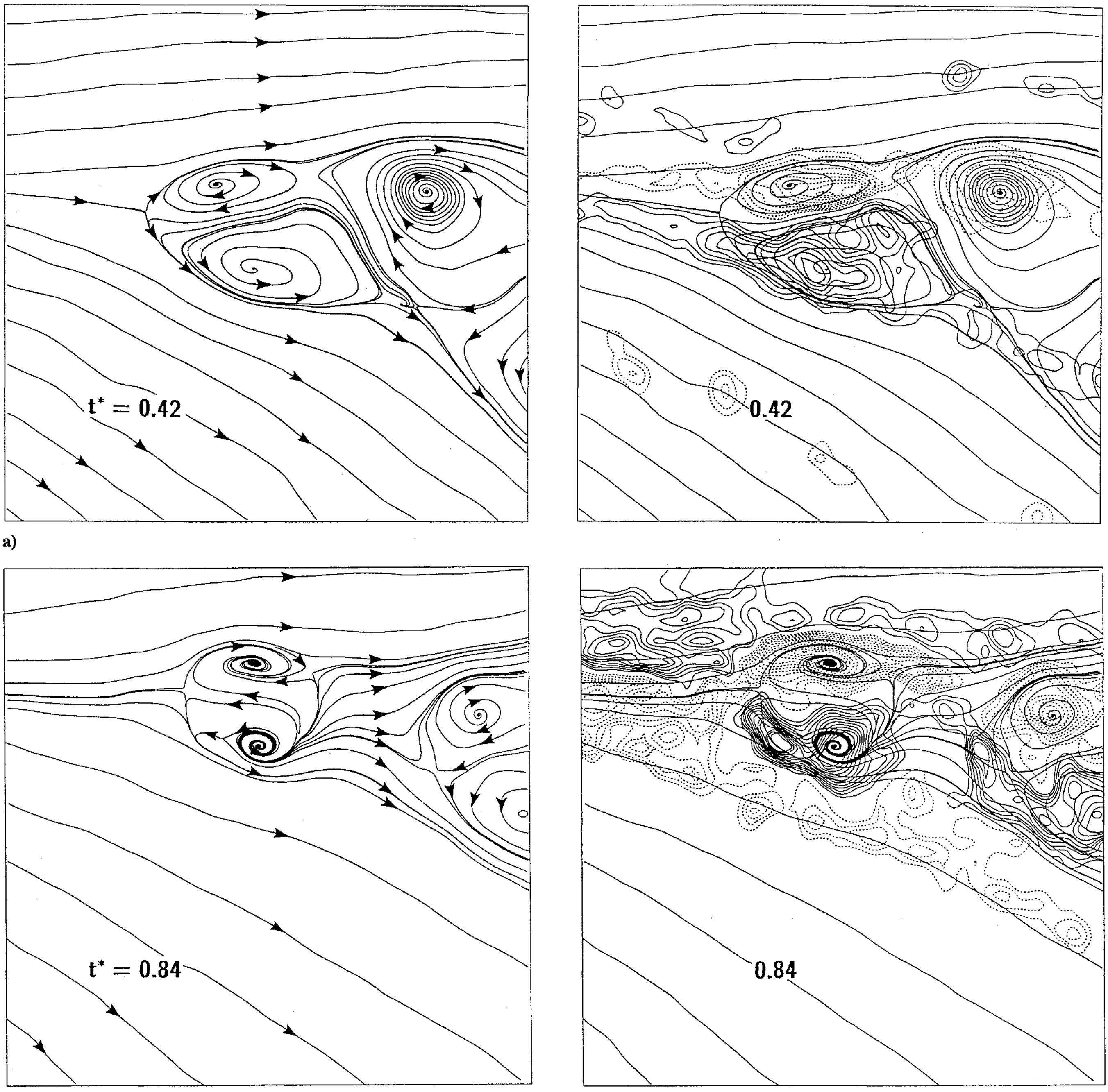


Fig. 3 Basic forms of vortex breakdown before (t^* = 0.42) and well after (t^* = 0.84) abrupt transformation of structure of leading edge vortex.

an outward spiraling streamline pattern, whereas that of the lower positive (solid line) concentration of vorticity corresponds to a stable, i.e., inward-spiraling, focus. At $t^* = 0.84$, well after the abrupt transformation of the structure of vortex breakdown addressed in Figs. 1 and 2, the onset of vortex breakdown exhibits a bubble that is nearly detached from the downstream region of the breakdown. The sectional streamlines in the upper and lower portions of the initially formed bubble exhibit opposite foci. In the upper portion, the streamlines spiral inward, whereas in the lower portion, they spiral outward. This topology is in close agreement with that obtained in the direct numerical simulation of Visbal[25]; it appears to be inherent to the later stages of relaxation of the breakdown process.

Variation of Location of Onset of Vortex Breakdown with Time

As indicated in the Introduction, the traditional approach to characterizing the relaxation of the flow during or following a maneuver is to track the onset of vortex breakdown with time. Figure 4a shows such a plot over a wide range of $t^* = tU/C$ using two criteria to represent the onset of vortex breakdown: the location of the leading edges of the switched vorticity contours; and the stagnation point of the streamline pattern. At small values of t^*, the onset of vortex breakdown moves upstream toward the apex at a relatively high, essentially constant speed; the slope m corresponds to an upstream propagation speed $m = c_v/U = -0.72$. This region of constant speed is followed by one of abrupt acceleration having a slope $m = -1.12$; it corresponds to the sudden transformation of the vortex structure shown in Fig. 2. In turn, this region is followed by one of deceleration to an eventually constant speed corresponding to a slope $m = c_v/U = -0.04$. We conclude that the abrupt transformation of the vortex breakdown structure described in Figs. 1 and 2 corresponds to a transformation from a relatively fast to slow speed of the upstream movement of the onset of vortex breakdown, i.e., from $c_v/U = -0.72$ to -0.04. This decrease of nearly a factor of 20 in the upstream propagation speed has obvious consequences for

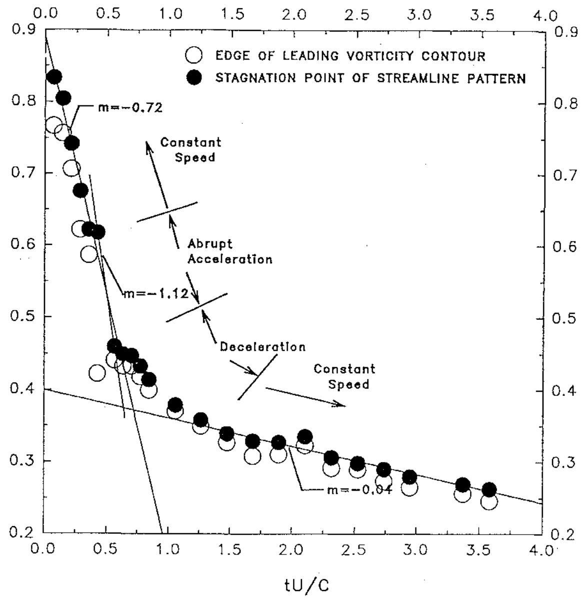


Fig. 4a Location of onset of vortex breakdown X_b/C as a function of time $t^* = tU/C$ in relation to propagation speed of breakdown c_v normalized by freestream velocity U, i.e., $m = c_v/U$.

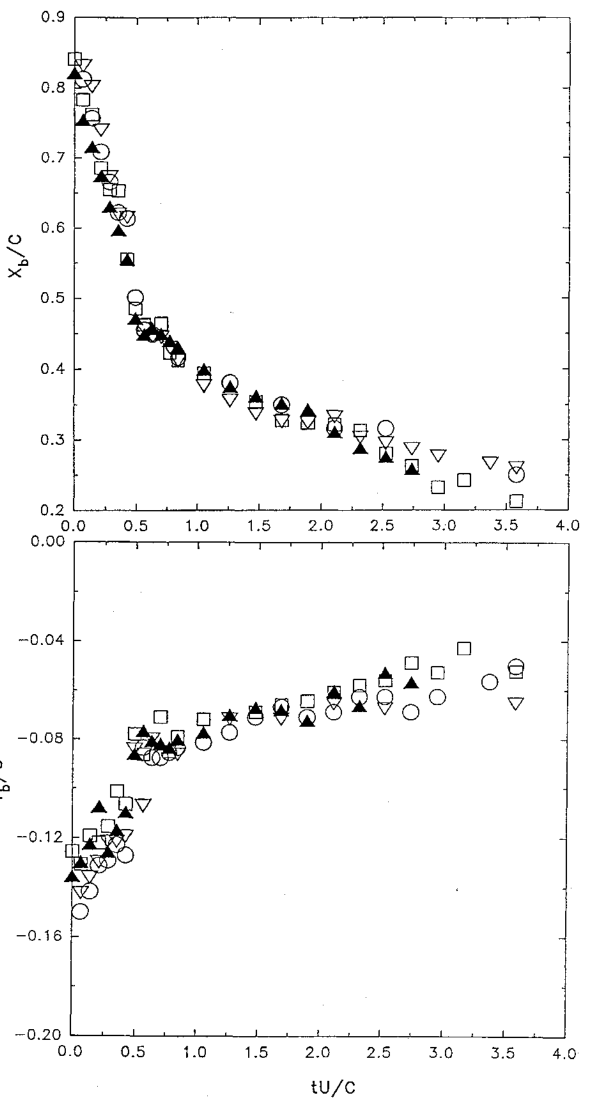


Fig. 4b Plots of location of onset of vortex breakdown, in terms of chordwise distance X_b/C from apex and distance from surface of wing Y_b/C, as a function of time $t^* = tU/C$.

the phase or time lags during a maneuver. If a means can be found to control or delay the abrupt transformation of the vortex structure, then the upstream propagation speed can be kept high, thereby minimizing the time or phase delays. On the other hand, if it is desired to maximize the time delay, in order to generate lift overshoot relative to the static lift characteristic, then it may be desirable to hasten abrupt transformation of the vortex structure.

The chordwise location X_b of the onset of vortex breakdown and the distance Y_b of the breakdown from the surface of the wing are plotted as a function of dimensionless time $t^* = tU/C$ in Fig. 4b. To emphasize the general repeatability of X_b and Y_b, data from four pitch-up maneuvers are superposed. An interesting observation is that the abrupt transformation evident in the plot of X_b/C vs tU/C corresponds to an abrupt movement of the vertical position of the breakdown toward the surface of the wing, i.e., a decrease in the value of Y_b/C in Fig. 4b.

Concluding Remarks

At high angle of attack, the process of vortex breakdown does not evolve through a series of quasisteady states after cessation of a pitching maneuver. Rather, it undergoes a series of abrupt transformations, the most important of which involves a sudden penetration of the leading edges of the switched vorticity contours to a location well upstream and within the leading edge vortex. Prior to this abrupt transformation, the upstream propagation speed of the breakdown regime is relatively fast; after the transformation, it decreases by nearly a factor of 20.

Immediately following this abrupt transformation, the relatively distributed, switched vorticity contours within the leading edge vortex undergo rapid development to pronounced concentrations of azimuthal vorticity, suggesting abrupt onset of a helical mode instability within the core of the vortex. Finally, at larger times, the degree of organization, or coherence, of the concentrations of vorticity degrades to a more random form.

The general form of the breakdown bubble is different before and after the abrupt transformation of the vortex structure. Prior to it, the vorticity concentrations within the bubble are associated with an antisymmetrical streamline pattern suggesting a helical instability. On the other hand, well after the transformation, an additional bubble appears upstream of, and nearly detached from, the primary region of vortex breakdown. Within this bubble, the adjacent, spiraling streamlines patterns exhibit opposite forms: one spirals inward (stable focus) and the other spirals inward (unstable focus).

Acknowledgments

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