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Buffeting Flows over Delta Wings

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Experimental evidence suggests that vortex breakdown is not the only source of buffeting of delta wings and fins. Other unsteady flow phenomena that contribute to buffeting at high angles of attack are fluctuations of vortex breakdown location and vortex shedding. Flow visualization and velocity measurements were carried out over a delta wing, over a wide range of angles of attack, to understand the transition between the helical mode instability and the vortex shedding. It was found that this transition is abrupt, as indicated by a jump in the frequency parameter, and that it occurs at the angle of attack at which breakdown reached the apex. The unsteady nature of vortex breakdown location was investigated by flow visualization for the interaction of vortex breakdown with a rigid flat plate. Although there are indications of a feedback effect on vortex breakdown, the amplitude of the fluctuations of breakdown location is smaller for impinging flows.

Nomenclature

a	= distance between trailing edge of wing and plate
c	= chord length
f	= frequency
H	= thickness of plate
k	= axial wave number
n	= azimuthal wave number
Re	= Reynolds number
S	= Power spectral density
s	= local semispan
t	= time
U_∞	= freestream velocity
u	= streamwise velocity
$\bar{u}$	= time-averaged streamwise velocity
u_{rms}	= rms value of streamwise velocity
x	= chordwise distance from wing apex
x_{bd}	= streamwise distance of breakdown location from the apex of the wing
$\bar{x}_{\mathrm{bd}}$	= time-averaged breakdown location
x'_{bd}	= fluctuations of breakdown location
$(x_{\mathrm{bd}})_{\mathrm{rms}}$	= rms value of breakdown location
y	= spanwise distance from wing root
z	= distance above wing surface
α	= angle of attack
Δt	= sampling time interval
ε	= offset distance between vortex and plate
Λ	= sweep angle
χ	= azimuthal angle
ω	= radial frequency

Introduction

BUFFETING is defined as the structural response of aircraft structures (such as wing, fin, tail, flap, and rudder) due to unsteady flow.[1] A typical fighter aircraft performs maneuvers at high angles of attack. Separated vortical flows originating from delta wings, leading-edge extensions, and forebodies interact with wings, fins, and tails. Several unsteady flow phenomena may excite different structural modes, depending on angle of attack and freestream velocity, and cause severe structural fatigue damage. Even though buffeting of secondary surfaces may not be a problem in the future (because aircraft such as X-36 will be tailless for better stealthy characteristics), wing buffeting will always remain an important consideration. Although the buffeting is unlikely to cause failure in wings, the ability of aircraft to aim missiles successfully will be affected by the degree of buffeting.[2] For this reason, both wing and fin buffeting will be considered in this paper. Several unsteady phenomena that contribute to buffeting at high angles of attack will be discussed.

Buffeting Phenomena and Objectives of Study

Helical Mode Instability

The measurements of buffeting on a slender delta wing model were reported by Mabey[2] (Fig. 1a). When the vortex breakdown location moved across the trailing edge (for $\alpha \cong 20$ deg), buffeting increased very rapidly, as seen in Fig. 1a. Also, sharply increased fluctuations in the normal force coefficient for delta wings were observed when the vortex breakdown moved over the wing.[3] Hence, the most important source of wing buffeting is the vortex breakdown phenomenon. It is also the source of fin buffeting in many cases. An example of rms pressure measured on a tail at the trailing edge of a delta wing is given by Washburn et al.[4] (Fig. 1b). Vortex breakdown appeared near the fin at $\alpha = 30$ deg, and the sharp increase in rms pressures at 32 deg was due to the vortex breakdown moving upstream of the fin.

Measurements of unsteady surface pressure, surface acceleration, and strain on wings and fins generally showed that spectra had a relatively sharp peak at high angle of attack due to the quasiperiodic nature of vortex breakdown flowfield. It is well known that the flow downstream of vortex breakdown exhibits a well-documented hydrodynamic instability. Periodic oscillations were observed in a variety of swirling flows after breakdown occurred. With regard to buffeting, unsteady pressure measurements over delta wings and fins revealed downstream convection of a wave pattern associated with the vortex breakdown.[2,5,6] Experimentally observed periodic velocity/pressure oscillations[6,7] correspond to the most unstable normal modes of the time-averaged velocity profiles of the vortex (downstream of breakdown) based on the linearized, inviscid stability analysis. The disturbances are represented as $\exp[i(kx + n\chi - \omega t)]$. By using two-point pressure measurements in the axial and spanwise directions,[6] it was demonstrated that these fluctuations are due to the first helical mode ($n = 1$). If one considers constant phase surfaces at a certain instant, the description for a helix is obtained, i.e., $kx + \chi = \mathrm{const}$, which shows that the sense of the helix is opposite to the direction of rotation in the vortex.[8] However, the whole structure rotates with a frequency ω in the same direction as the vortex. Experiments also indicate that the frequency decreases in the streamwise direction, which implies that the pitch of the helix increases in the streamwise direction. This was confirmed by the instantaneous azimuthal vorticity distribution in a plane that passes through the axis.[9] The vorticity concentrations are staggered like a von Kármán vortex street, and the spacing increases in the streamwise direction.

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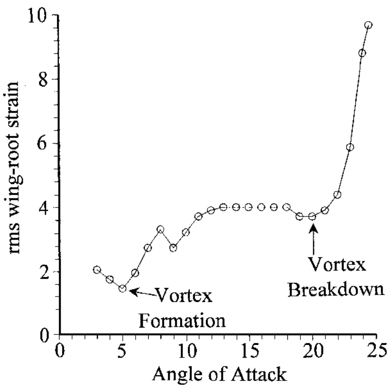


Fig. 1a Buffeting on a slender delta wing model.[2]

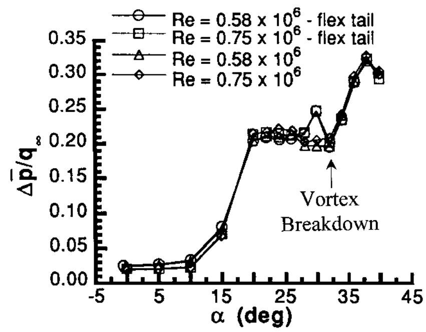


Fig. 1b RMS pressure on a tail.[4]

This description of the helical mode instability is consistent with well-known observations of the spiral breakdown over delta wings.[10] It is known that this is the dominant mode observed over delta wings.[10–12] It was also observed in the flight[13] of an F-18, which indicates that it is not limited to low Reynolds numbers. Jumper et al.[14] indicated that even in the cases where breakdown looked like a bubble type, a spiral form was identified in instantaneous pictures with short exposure time. For spiral breakdown, the sense of the helix is opposite to the direction of rotation in the main vortex as observed over delta wings.[14] However, in some vortex-tube experiments (with guide-vane-type swirl generators[15,16]), it was reported that the sense of helix is the same as the direction of swirl, whereas in some others (with tangential inlets) the opposite was found.[17] Leibovich[18] attributed this inconsistency to the differences in the ways the swirl was generated. However, in recent experiments in which the swirl was also generated by guide vanes,[19] the sense of helix was found to be opposite to the direction of the swirl in all swirling flows with two exceptions,[15,16] and the reason behind this difference remains unknown. The opposite sense is consistent with the unsteady flow in the breakdown wake. Also, Jumper et al.[14] pointed out in a simple model of breakdown that the sense of helix should be opposite to the direction of swirl to have axial velocities (due to the Biot–Savart induction) opposite to the freestream flow to generate stagnant flow behind the vortex breakdown.

Flow visualization at low Reynolds numbers indicates that the helical vortex filament persists for several turns before breaking up into large-scale turbulence. However, coherent pressure fluctuations were detected at downstream locations that are very far away from the breakdown location. In addition, these coherent fluctuations were detected at high Reynolds numbers[20] (on the order of 10^6), as well as on full-scale aircraft. Wolfe et al.[21] show that dominant frequencies of surface pressure fluctuations on fins agree very well with those on the surface of delta wings without a fin.[6] The dominant frequencies for aircraft models also agree with the frequency of the helical mode instability.[22]

Fluctuations of Breakdown Location

An important feature of the spectra of buffeting is the existence of a low-frequency peak. For several vortex–fin interactions, a low-frequency peak was observed in the spectra of fin surface pressure, tip acceleration, strain, and velocity fluctuations around the fin.[23–25] It was suggested by Wolfe et al.[24] that this low-frequency peak is due to the fluctuations of breakdown location in the streamwise direction. Also, a low frequency in the pressure/velocity spectra was observed in the wake of breakdown in several investigations[20,22,26,27] in the absence of a fin.

Motivated by the observations of low-frequency components in the spectra of pressure/velocity, Gursul and Yang[27] studied the time-dependent location of vortex breakdown by flow visualization. It was shown that the breakdown location may exhibit large fluctuations along the axis of the vortices, depending on the angle of attack and sweep angle. The fluctuations consist of large-amplitude quasiperiodic oscillations and high-frequency small-amplitude displacements. The quasiperiodic oscillations are due to an interaction between the vortices, which causes the antisymmetric motion of breakdown locations for left and right vortices.[28] Other researchers[29,30] also made qualitative observations of similar oscillations of breakdown location.

Vortex Shedding

Bean et al.[31] demonstrated that buffeting of fins is possible at very large angles of attack, where leading-edge vortex no longer exists. Figure 2a shows the rms pressure fluctuations on the fin, as well as the buffeting response as a function of angle of attack. Their[31] delta wing had a sweep angle of $\Lambda = 60$ deg. By using reported breakdown locations from the literature,[32] as shown in Fig. 2b, one expects the breakdown location to reach the apex of the wing around $\alpha \approx 34$ deg. Bean et al.[31] showed that, for both rigid and flexible fins, the unsteady loading starts to increase around $\alpha = 34$ deg and reaches a sharp peak at $\alpha = 43$ deg. It was shown that unsteady

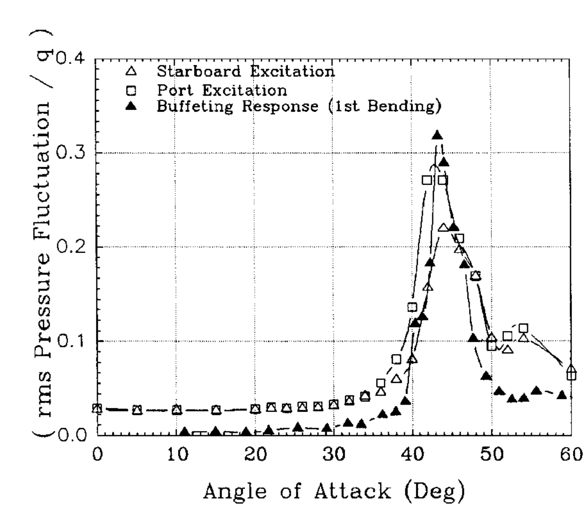


Fig. 2a RMS pressure on a fin.[31]

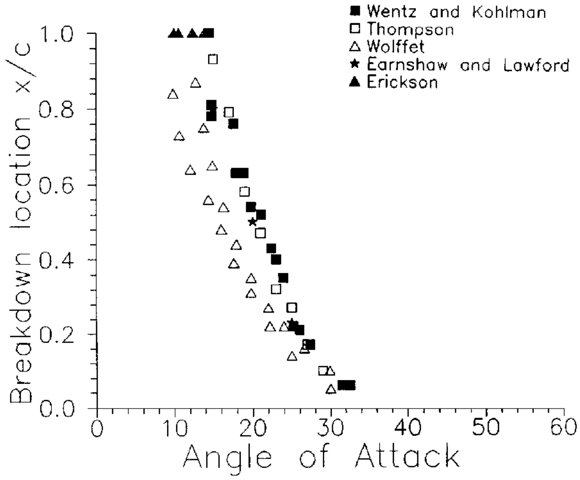


Fig. 2b Breakdown location for $\Lambda = 60$ deg.[32]

pressure on the fin surface exhibited quasiperiodic behavior. It is interesting that the buffeting was small for $\alpha < 34$ deg, i.e., vortex breakdown did not excite the fin because the fin was located at the wing centerline near the trailing edge and, therefore, was away from the vortex axis. Instead, buffeting occurred in the poststall region, where the vortex shedding from the wing takes place.[33]

Based on velocity measurements in the wake of a delta wing, Rediniotis et al.[33,34] showed that vortex shedding occurs at large angles of attack. It was suggested that both symmetric and antisymmetric modes of shedding existed. They conducted experiments on several delta wings with $\Lambda = 76$ deg. They suggest that up to $\alpha = 70$ deg, only the symmetric mode of vortex shedding occurs. At angles of attack larger than 70 deg, both shedding modes exist simultaneously, although the symmetric mode is more dominant. Because the vortex shedding involves an interaction between the shear layers, the wing span was used as a characteristic length in the definition of the dimensionless frequency.

The dominant frequencies reported by Rediniotis et al.[33] were used to calculate the conventional definition of dimensionless frequency (fc/U_∞) to compare with frequencies of other unsteady phenomena (Fig. 3a). In Fig. 3b, the variation of breakdown location over delta wings with $\Lambda = 75$ deg, is shown, using reported values from the literature,[35] as well as the results from the present study. The angle of attack at which breakdown location reaches the apex was estimated as $\alpha \approx 58$ deg by extrapolation of data, although the present study suggests a value around 60 deg. Figure 3a suggests that the dominant frequencies of the helical mode instability and those of vortex shedding form a continuous curve. This rather interesting result suggests a smooth transition from one phenomenon to the other one.

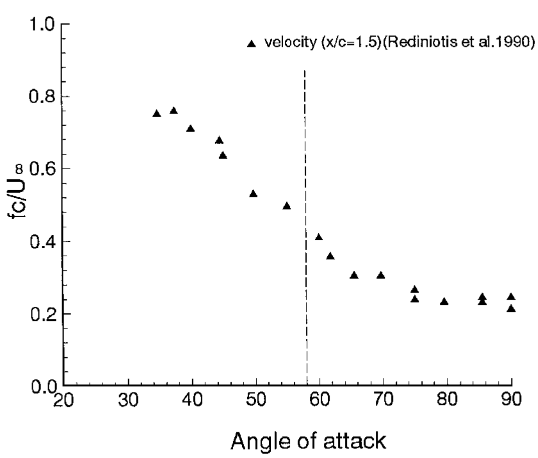


Fig. 3a Dominant frequencies in the wake for $\Lambda = 76$ deg.

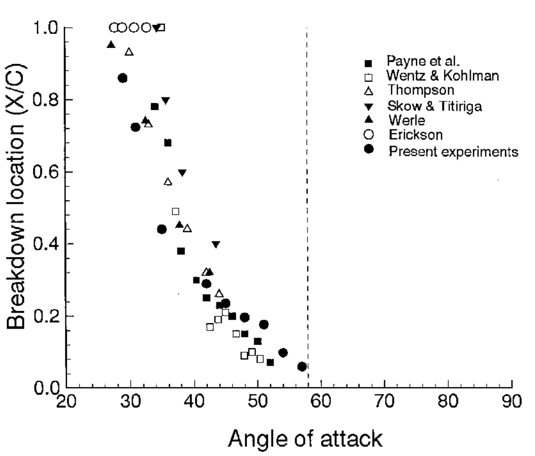


Fig. 3b Breakdown location over delta wings for $\Lambda = 75$ deg.

Objectives

The preceding sections clearly showed that buffeting occurs over a wide range of angles of attack and is due to a variety of unsteady flow phenomena. Therefore, it is important to understand the flow structure not only at moderate angles of attack, where vortex breakdown and helical mode instability are dominant, but also at larger angles of attack, where vortex shedding is expected to be the source of buffeting. The first objective of this study is to investigate the characteristics of the unsteady flow at large angles of attack and, in particular, the transition between the helical mode instability and vortex shedding. For this purpose, velocity measurements were carried out for a wide range of angles of attack over a delta wing in the first set of experiments. Spatial as well as spectral characteristics of the unsteady flow were investigated.

The second objective is to study the interaction of vortex breakdown with the fins. This interaction affects the time-averaged breakdown location (which, in turn, causes quasiperiodic oscillations with a certain dominant frequency), as well as the unsteady nature of breakdown location (which is suspected to be the source of the low-frequency oscillations, as proposed by Wolfe et al.[24]). Patel and Hancock[36] also suggested a possible coupling between the flow separation over the surface and the vortex breakdown. Therefore, it was decided to investigate this possibility by studying the unsteady nature of breakdown location. For this purpose, the interaction of leading-edge vortices with a flat plate was studied by flow visualization in the second set of experiments.

Experimental Setup

Flow visualization and laser Doppler velocimetry (LDV) measurements were carried out over a delta wing. The experiments were performed in a water channel with a cross-sectional area of 61×61 cm. The turbulence level in the channel was 0.6%. The freestream velocity spectrum was free from any peaks. The delta wing model had a sweep angle of $\Lambda = 75$ deg and a chord length of $c = 203$ mm. The lee surface was flat, whereas the leading edges were beveled at 45 deg on the windward side. The maximum blockage ratio was 3.5% at the highest angle of attack. The Reynolds number based on the chord length was around $Re = 4.1 \times 10^4$.

The velocity was measured with a single-component LDV system operating in the back-scattering mode. It consisted of a 10-mW-HeNe laser, a Bragg cell for frequency shift, an integrated laser optics package, and a fiber optic cable. A correlation signal processor was used to analyze the data. The measurement volume size was about 0.08 mm in diameter and 0.65 mm in length. The measurement uncertainty for the mean velocity was estimated as 1%. The component of flow velocity in the freestream direction was measured at points in a plane perpendicular to the freestream direction. For most of the experiments, the measurement plane was located at the trailing edge. Because tails and fins are located around trailing edges of wings, the unsteady features of the flow in this plane have particular importance. Measurements in other parallel planes were also conducted.

Flow visualization of vortex breakdown was performed by injecting fluid with food coloring dye near the apex of the model. The motion of vortex breakdown location was recorded by a video system, which consisted of a video cassette recorder (at 30 frames/s resolution), a frame counter/window inserter, and a charge-coupled device camera with a zoom lens. The videotape recording of the motion was analyzed frame by frame, and the chordwise distance of the breakdown location from the apex was measured. The breakdown was spiral type most of the time, as generally observed over delta wings. The location of breakdown was taken as the location where the streakline marking the core makes an abrupt kink to form a spiral. Defined as the point of the kink, the spiral-type breakdown was easy to determine. The uncertainty in breakdown location depends on the uncertainty in locating the breakdown, the reading uncertainty of scale on video images, and the magnification of the lens. The overall uncertainty in breakdown location was estimated to be $0.004c$. Although the uncertainty seems large compared to the smallest rms value of the fluctuations reported here (about $0.01c$), the peak-to-peak variation in breakdown location was around $0.04c$, which is 10 times larger than the breakdown uncertainty in the worst

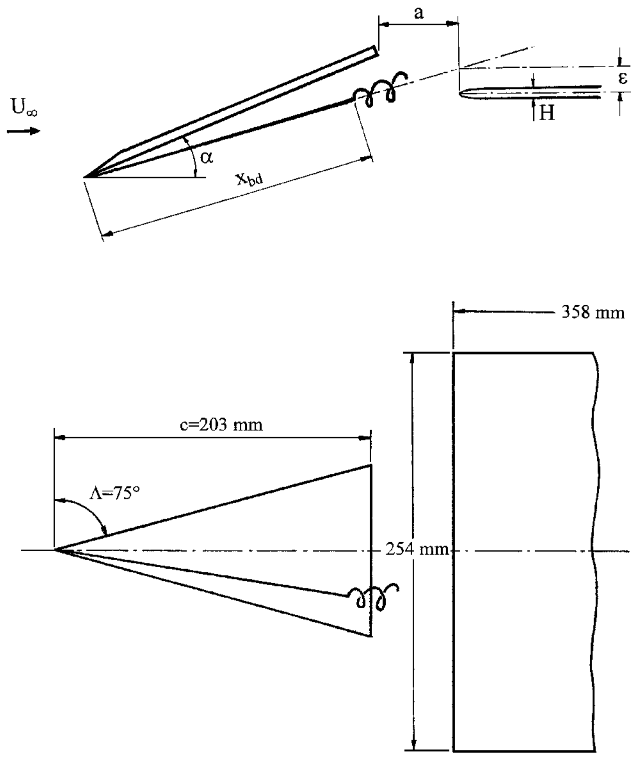


Fig. 4 Schematic of experimental arrangement of plate and delta wing.

case. The time history of breakdown location was obtained for a total length of time record of approximately $100c/U_\infty$ and with a sampling frequency of 3 frames/s (corresponding to a time resolution of $\Delta t = 0.333c/U_\infty$).

To study the interaction of vortex breakdown with a surface, a flat plate (parallel to the freestream) was placed around the trailing edge of the delta wing, as shown in Fig. 4. The plate was 358 mm long, 254 mm wide, and 6 mm thick. Its leading edge was elliptical with a ratio of major to minor axes of 2:1. The symmetry planes of the delta wing and the plate coincided, and the interaction of only one vortex with the plate was studied.

Unsteady Flow Phenomena at High Angle of Attack

The variation of breakdown location as a function of angle of attack is shown in Fig. 3b. The results from the present experiments are within the scatter of data reported by others. As demonstrated by several investigators, and also recently by Lowson and Riley,[37] Reynolds number was found to have little effect on the scatter, whereas the detailed geometry of the wings played an important role. The data from the present experiments suggest that the angle of attack at which breakdown location reaches the apex is around $\alpha \approx 60$ deg.

Velocity Measurements

Detailed velocity measurements were carried out at $x/c = 1.0$ for angles of attack for which breakdown occurs over the wing ($\alpha = 31, 42, 48, 54,$ and 57 deg) and for larger angles of attack ($\alpha = 62$ and 70 deg), to understand the transition between different flow regimes. Constant contours of the normalized time-averaged streamwise velocity are shown in Fig. 5. The notation apex in Fig. 5 refers to the projection of the apex onto the measurement plane. For $\alpha = 31$ deg, the approximately round region of low velocity in the breakdown flowfield is an indication of the swirling nature of the flow around the vortex axis. Very low and even reversed velocities are characteristic of breakdown flowfields. This swirling flow regime continues to exist as the angle of attack is increased. For $\alpha = 42$ and 48 deg, the region of closed contour lines moves away from the wing surface as the breakdown location gets closer to the apex. For $\alpha = 54$ deg, the closed contours become more elongated in the normal direction as the separated flow region becomes larger. Note that the time-averaged breakdown location is $\bar{x}_{bd}/c \cong 0.10$. For

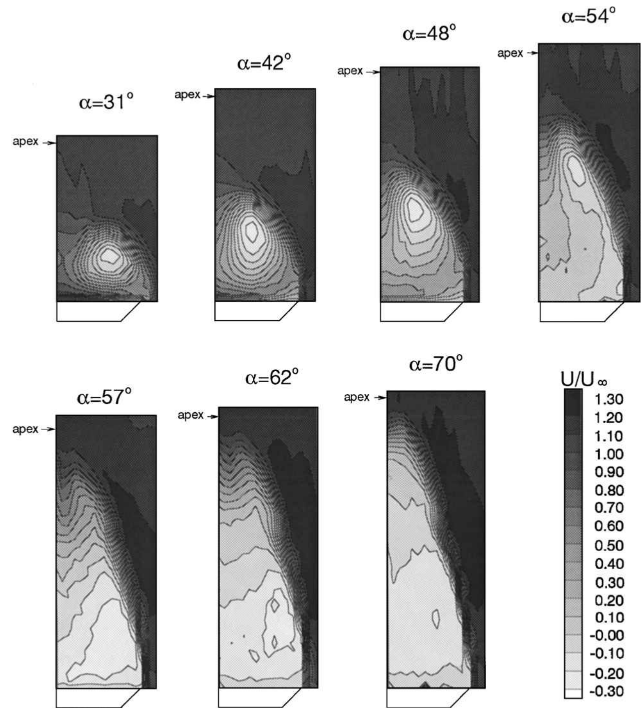


Fig. 5 Constant contours of normalized time-averaged streamwise velocity for several values of angle of attack ($x/c = 1.0$).

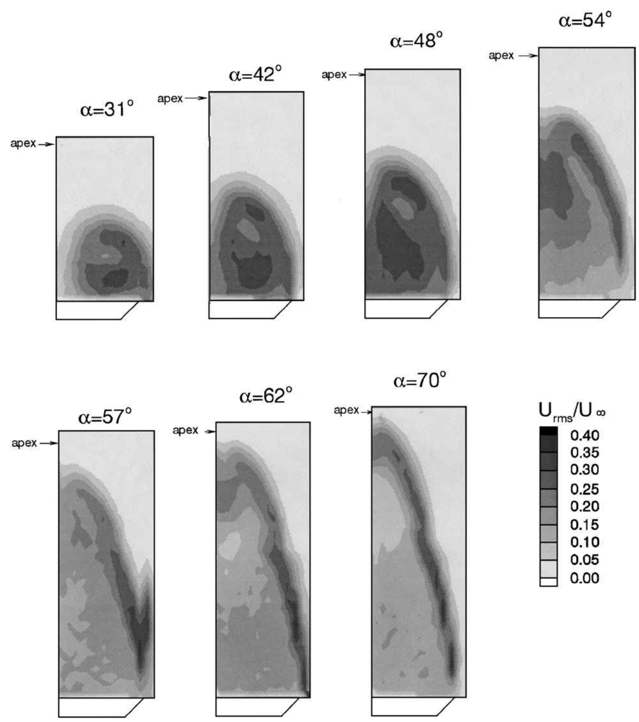
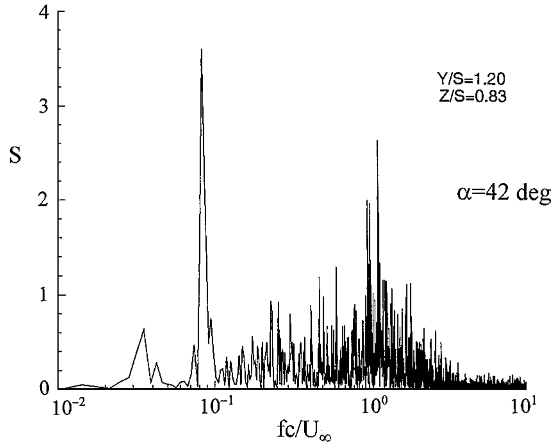
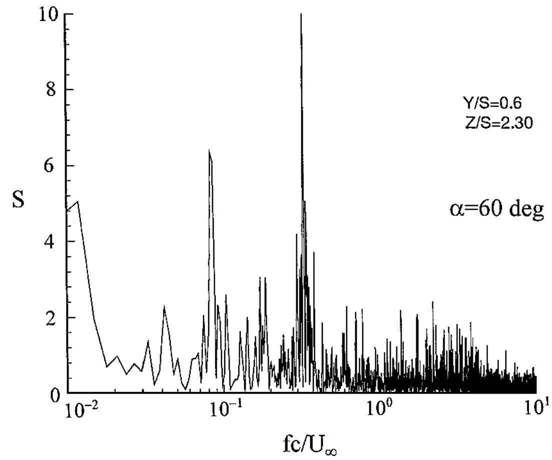


Fig. 6 Constant contours of normalized rms streamwise velocity for several values of angle of attack ($x/c = 1.0$).

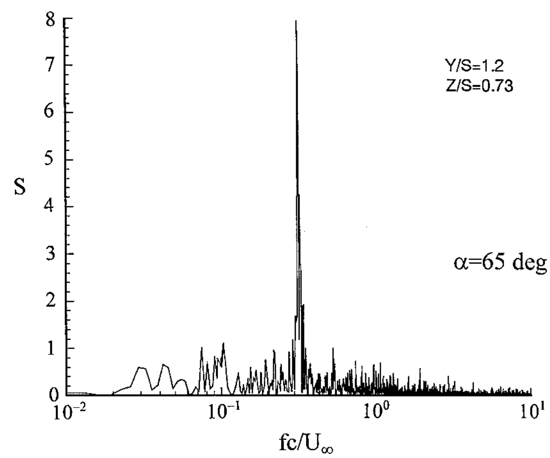
$\alpha = 57$ deg, the swirling flow as identified by the closed contours disappears. However, Fig. 3b shows that the vortex breakdown occurs over the wing and that the time-averaged breakdown location is around $\bar{x}_{bd}/c \cong 0.06$. Although the time-averaged flow does not reveal closed contours for $x/c = 1.0$, the measurements upstream (at $x/c = 0.75$, not shown here) show the existence of a swirling flow regime. As shown later, the spectra reveal the existence of swirling flow instabilities even at $x/c = 1.0$. For angles of attack larger than 60 deg (at which breakdown location reaches the apex), no indications of swirling flow were found (see contour lines for $\alpha = 62$ and 70 deg). Instead, separated shear layer is evident, which leads to vortex shedding. This regime was called the vortex shedding regime, as suggested by Redinotis et al.[33]



a) $\alpha = 42$ deg



b) $\alpha = 60$ deg



c) $\alpha = 65$ deg

Fig. 7 Spectrum of streamwise velocity fluctuations.

Constant contours of the normalized rms streamwise velocity are shown in Fig. 6 for the same values of angles of attack as in Fig. 5. For $\alpha = 31$ deg, the velocity fluctuations are confined to the breakdown region. Note that the fluctuations are large at the vortex axis, but the local maximum is observed between the vortex axis and the wing surface. For $\alpha = 42$ and 48 deg, there is a second local maximum above the vortex axis. For $\alpha = 54$ deg, one of the local maximums becomes very elongated. As the angle of attack is increased, first indications of the shear layer formation from the region downstream of breakdown are observed for $\alpha = 54$ and 57 deg. In the vortex shedding regime ($\alpha = 62$ and 70 deg), the shear layer extends from the leading edge of the wing to very near the projection of the apex onto the measurement plane.

Spectral Analysis

The spectra of streamwise velocity fluctuations were analyzed in most of the measurement locations for the same values of angles of attack as in Fig. 5, as well as for additional angles of attack. In Fig. 7a, an example is shown for $\alpha = 42$ deg. Two dominant frequencies are identified. These two peaks appear in almost all locations in the measurement plane, although their relative magnitudes differ depending on the location of measurement with respect to the vortex. The ensemble average of the measurements at different locations provide $fc/U_\infty = 0.079$ for the smaller peak in the spectra. Similar measurements at upstream planes (not shown here) showed a slight variation of this frequency: $fc/U_\infty = 0.075$ for $x/c = 0.75$ and $fc/U_\infty = 0.066$ for $x/c = 0.5$. Note that the time-averaged breakdown location is $\bar{x}_{bd}/c \cong 0.30$. It is known that the dominant frequency of the quasiperiodic oscillations of breakdown location for $\alpha = 42$ deg is around $fc/U_\infty \cong 0.06$ (with a bandwidth resolution of 0.01).[28] Therefore, the lower dominant frequency in the spectrum in Fig. 7a is believed to be due to this vortex interaction mechanism.

The larger dominant frequency in the spectrum in Fig. 7a is due to the helical mode instability. This frequency agrees well with the reported values from the surface pressure measurements near the trailing edge,[6] as shown in Fig. 8. In general, this instability appears as a broader peak in the spectra of velocity fluctuations. For larger angles of attack, while $\alpha < 60$ deg, the spectra are very similar to that of $\alpha = 42$ deg. As mentioned earlier, the relative magnitudes of these two peaks vary with the measurement location. In general, the peak due to the vortex interaction becomes larger as one gets closer to the apex region in the measurement plane.

For $\alpha \geq 60$ deg, the spectra show a change in the dominant frequency. Figure 7b shows an example of the spectra for $\alpha = 60$ deg for which the breakdown location reaches the apex. From the two dominant peaks, the smaller frequency is around the frequency of the vortex interaction instability as for $\alpha < 60$ deg. However, the larger frequency is much smaller than the corresponding frequencies for $\alpha < 60$ deg. As shown in Fig. 8, this frequency is due to the vortex shedding of the separated shear layers and is in close agreement with the results of measurements in the wake.[33] Note that the amplitude due to the vortex interaction is smaller even though the measurement location is very close to the apex region. For larger angles of attack, the vortex interaction instability disappears, and only one dominant peak corresponding to vortex shedding is observed. An example is shown for $\alpha = 65$ deg in Fig. 7c.

The dimensionless frequencies of these unsteady flow phenomena are shown in Fig. 8 as a function of angle of attack. The helical mode instability of the swirling flow disappears around $\alpha = 60$ deg, for which the breakdown location reaches the apex (this is shown by the vertical dashed line). We conclude that the transition from the helical mode instability to the vortex shedding is abrupt, as

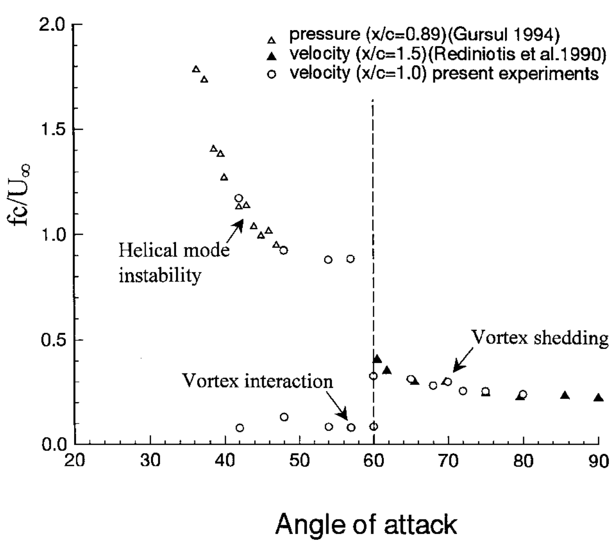


Fig. 8 Variation of dimensionless frequency for unsteady phenomena as a function of angle of attack.

indicated by the jump in the frequency parameter. It is known that the wavelength of the helical mode instability increases substantially over the delta wing after the onset of breakdown, which results in significant decrease of the dominant frequency in the streamwise direction.[6,9] The present results imply that the frequency of the helical mode instability continues to decrease in the streamwise direction in the near wake. Because of this effect, the measurements of the dominant frequency in the wake[33] give smaller values than the present results obtained at the trailing edge. The dominant frequency of the vortex shedding appears first at $\alpha = 60$ deg. It is seen in Fig. 8 that the dominant frequency is in very good agreement with the results of measurements in the wake ($x/c = 1.5$). This also implies that the frequency of the vortex shedding is nearly constant in the near wake.

Interaction of Vortex Breakdown with a Plate

The time-averaged breakdown location strongly depends on the angle of attack α (which also determines the strength of the vortex) and normalized offset distance ε/H, for a given distance a between the trailing edge of the wing and the leading edge of the plate. Note that the offset distance ε is measured relative to the vortex axis for each angle of attack (Fig. 4). Although experiments were conducted for $a/c = 0$, 0.07, 0.17, and 0.25, only the results for $a/c = 0.25$ will be reported here because the effect of this parameter on the unsteady nature of interaction is very small.[38] Figure 9 shows the time-averaged breakdown location for $\varepsilon/H = 0$ as a function of angle of attack. Also shown with open symbols are the breakdown locations for nonimpinging vortices (in the absence of the flat plate). Whereas for small angles of attack (15 and 20 deg) the breakdown location is not observed in the absence of the plate, breakdown is induced near the leading edge of the plate for impinging vortices. At larger angles of attack (25 and 30 deg), the breakdown location moves farther upstream when the plate is placed downstream of the breakdown location. At the largest angle of attack (35 deg), the difference between the breakdown locations for impinging and nonimpinging vortices is small. It is clear that the presence of the plate is most important at low angles of attack, where breakdown is not normally observed but is induced because of the adverse pressure gradient set by the plate. The practical implication of the earlier vortex breakdown is that the dominant frequencies of the helical mode instability may be different than those at high angle of attack, and further studies are needed.

The rms value of fluctuations of breakdown location is shown in Fig. 10 together with the results for nonimpinging breakdown.[28] It is seen that the amplitude of the fluctuations initially increases with angle of attack and then reaches a plateau. It is interesting that the rms value of fluctuations is smaller for impinging breakdowns. The spectrum of breakdown location is compared in Fig. 11 for impinging and nonimpinging breakdowns for $\alpha = 35$ deg. The nature of the dominant peak in the spectrum for nonimpinging breakdown was studied in detail by Menke et al.[28] and by Menke and Gursul.[39] It was shown that the quasiperiodic oscillations are in the form of an antisymmetric motion of left and right breakdown locations and are caused by an interaction between the breakdowns. We conclude from Fig. 11 that these quasiperiodic oscillations are smaller for impinging vortex breakdown. Also, a very low-frequency component seen in the absence of the plate (which corresponds to a slow drift of breakdown location) is not observed for impinging breakdown. Instead, small-amplitude, higher frequency components are seen.

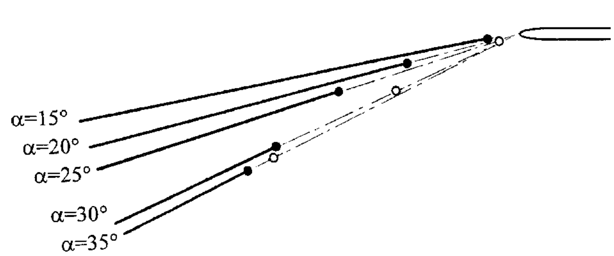


Fig. 9 Time-averaged breakdown location for $\varepsilon/H = 0$ as a function of angle of attack.

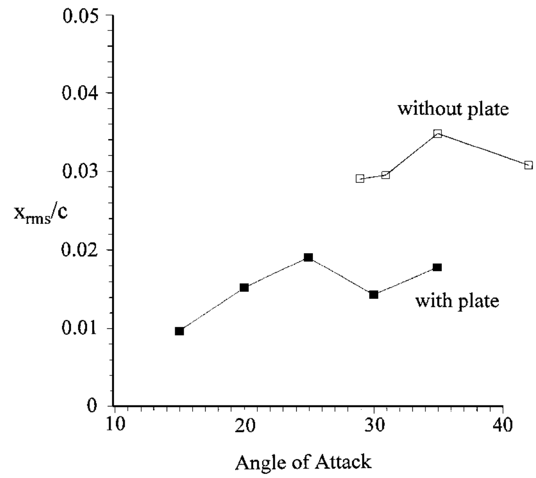


Fig. 10 RMS value of breakdown location for $\varepsilon/H = 0$ as a function of angle of attack.

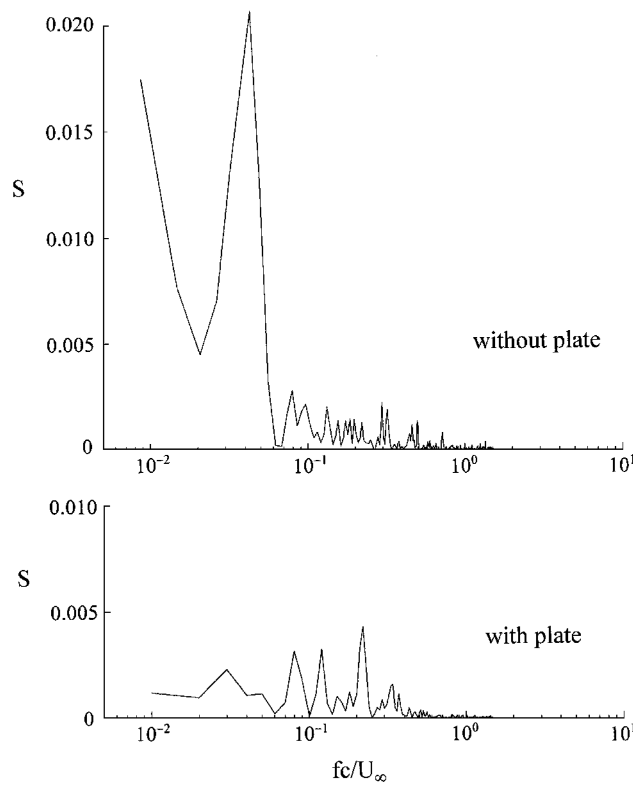


Fig. 11 Spectra of fluctuations of breakdown location for $\varepsilon/H = 0$ and $\alpha = 35$ deg.

The effect of the offset distance ε was studied for $\alpha = 15$, 20, and 30 deg. The time-averaged breakdown locations for different values of ε/H are shown in Fig. 12. For $\alpha = 15$ and 20 deg, the time-averaged breakdown location exhibits a sudden jump as the offset distance increases and the breakdown location moves downstream. Again, the open symbols show the breakdown location for nonimpinging vortex breakdown. For $\alpha = 30$ deg, this sudden jump is not observed. The rms value of fluctuations of breakdown location is shown in Fig. 13 for $\alpha = 15$ and 30 deg. There is a corresponding increase in the rms level when the sudden jump in the time-averaged breakdown location takes place for $\alpha = 15$ deg. However, for the largest value of offset distance, the rms level somewhat decreases. For $\alpha = 30$ deg, the rms level is roughly constant, with a slight trend of increase as the offset distance increases.

The spectra of breakdown location for selected values of ε/H are shown in Fig. 14 for $\alpha = 15$ deg. For zero and small values of ε/H, the amplitude of the fluctuations is small with no dominant features. When the time-averaged breakdown location jumps to downstream of the leading edge of the plate, a dominant peak

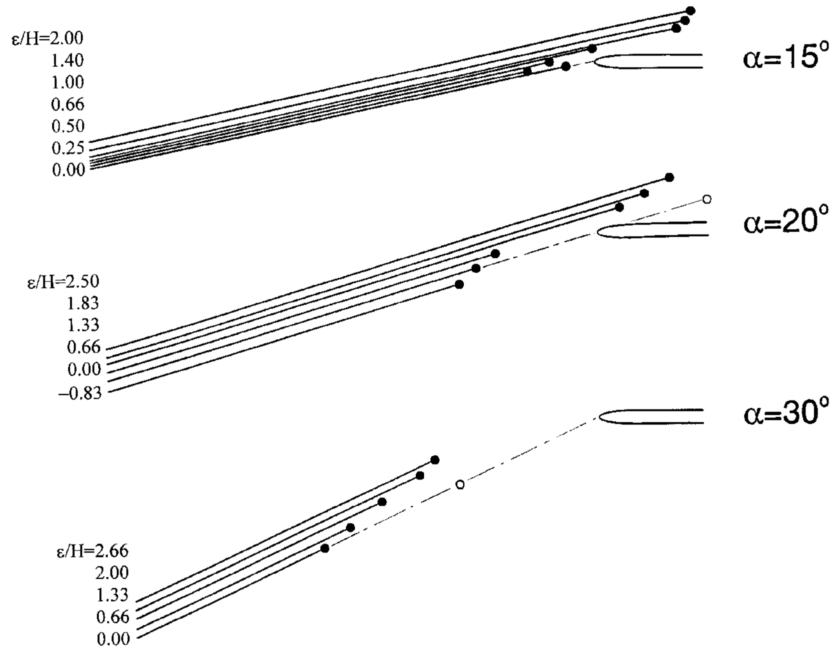


Fig. 12 Time-averaged breakdown location for different values of ε/H.

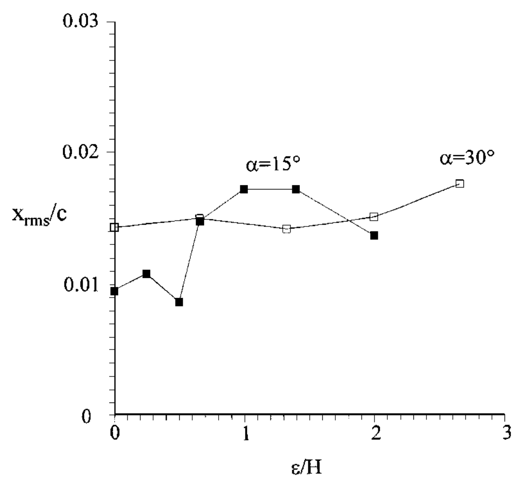


Fig. 13 RMS value of breakdown location as a function of ε/H.

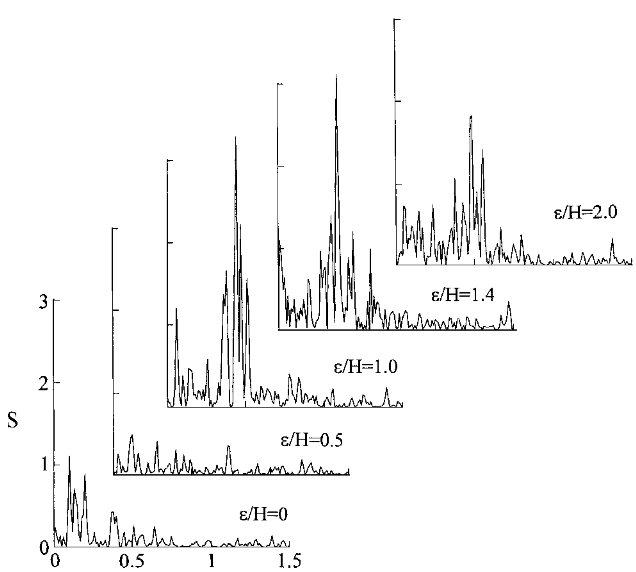


Fig. 14 Spectra of fluctuations of breakdown location for different values of ε/H for $\alpha = 15$ deg.

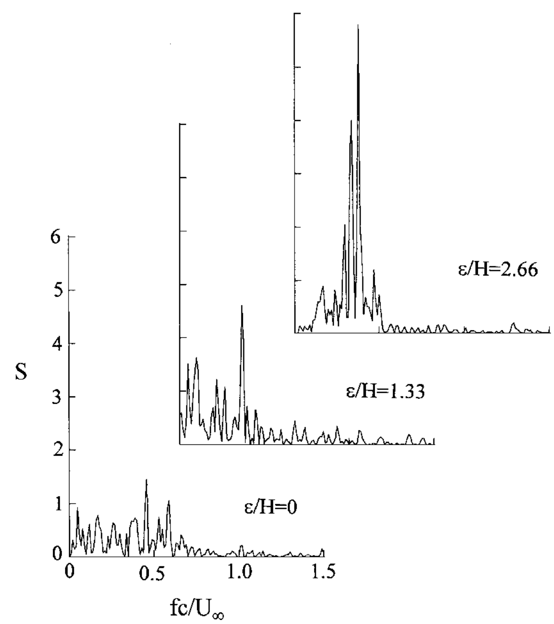


Fig. 15 Spectra of fluctuations of breakdown location for different values of ε/H for $\alpha = 30$ deg.

is observed in the spectra. This dominant frequency varies in the range of $fc/U_\infty = 0.38$–0.48 as ε/H is varied. Figure 15 shows the spectra for several values of ε/H for $\alpha = 30$ deg. Whereas there is no dominant peak for $\varepsilon/H = 0$, a dominant peak with increasing amplitude is observed at larger values of ε/H, as the time-averaged breakdown location moves closer to the leading edge of the plate. The dominant frequency varies in the range of $fc/U_\infty = 0.35$–0.38. In both experimental[24] and computational[40] studies of a similar interaction, low-frequency peaks ($fc/U_\infty = 0.48$ for experiments and $fc/U_\infty = 0.40$ for computations), in addition to those corresponding to the helical mode instability, were observed in the spectra of pressure fluctuations at the leading edge of the plate. Hence, this evidence suggests that the quasiperiodic oscillations of breakdown location may play an important role in the buffeting of fins. Also, because these (higher frequency) dominant peaks are not observed in nonimpinging flows, they may be an indication of a feedback effect on vortex breakdown. Gordnier and Visbal[40] showed that a very complicated, unsteady separation takes place at the leading edge of the plate. The unsteady flow separation from the leading edge of the plate may be the source of these oscillations of breakdown location. Note that the disturbances generated at the leading edge of the plate may propagate upstream in the subcritical flow downstream of vortex breakdown.[18] The subcritical flow refers to the wave propagation characteristics of the vortex flow. If the waves can propagate upstream through the vortex core, the flow is called subcritical. This definition is based on the time-averaged flow in columnar vortices. According to Leibovich,[18] the measured flows downstream of breakdown are subcritical. Also, in real scenarios, disturbances due to aeroelastic effects (surface deflections) may propagate upstream, resulting in large oscillations of breakdown location. These aspects require further studies.

Conclusions

Experimental evidence suggests that vortex breakdown is not the only source of buffeting of wings and fins. Other unsteady flow phenomena that contribute to buffeting at high angles of attack are fluctuations of breakdown location and vortex shedding. Flow visualization and velocity measurements were carried out over a delta wing over a wide range of angle of attack to understand the transition between the helical mode instability and vortex shedding. Swirling flow regime at moderate angles of attack when vortex breakdown is over the wing and vortex shedding regime at large angles of attack after breakdown reaches the apex were identified from the detailed measurements of the time-averaged and rms streamwise velocity at the trailing edge. Spectral analysis revealed the dominant frequency of the helical mode instability in the swirling flow regime, as well as the dominant frequency of the quasiperiodic oscillations of breakdown location caused by the interaction of the vortices. After vortex breakdown reaches the apex, the helical mode instability of the swirling flow disappears, and the dominant frequency of the vortex shedding appears in the spectra. The transition from the helical mode instability to the vortex shedding was found to be abrupt, as indicated by a jump in the frequency parameter, and occurred at the angle of attack at which breakdown reached the apex. This conclusion seems to be in disagreement with previous results obtained in the wake. This discrepancy was explained by the significant changes in the wavelength of the helical mode instability in the streamwise direction in the near wake.

The interaction of leading-edge vortex breakdown and a rigid flat plate was studied by flow visualization. The unsteady nature of this interaction was investigated. For a rigid plate, the amplitude of the fluctuations of breakdown location is smaller for impinging breakdown compared to nonimpinging breakdown. The spectra revealed that the quasiperiodic oscillations that originate from the vortex interaction are smaller. Although smaller in amplitude, dominant peaks in the range of $fc/U_\infty = 0.35-0.48$ were observed in the spectra, depending on the angle of attack and offset distance. There are indications that the unsteady flow separation from the leading edge of the plate may provide a feedback effect on the vortex breakdown.

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