Technical Notes

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Transient Response of Leading-Edge Vortices to Localized Suction

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Introduction

THIS investigation addresses the restabilization of a leading-edge vortex on a delta wing by transient suction. The suction is applied through a probe located well downstream of the onset of vortex breakdown. Of particular interest are hysteresis of the vortex response and the overall time required for stabilization of the vortex.

Control of the location of breakdown of leading-edge vortices has been attempted using a variety of techniques. Most relevant for the present study is the application of blowing in the form of a jet along the leading edge of a wing. Recent investigations of Shi et al.[1] and Visser et al.,[2] as well as the range of references cited therein, demonstrate that the length of the vortex core prior to occurrence of breakdown can be extended through proper application of blowing. The magnitude of the dimensionless jet momentum coefficient $C\mu$ that is required to effect a substantial change in the location of vortex breakdown, lift, or moment varies widely with location and orientation of the fit. Maximum values of $C\mu$ employed include the values $C\mu=0.17$,[3] $C\mu=0.09$,[4] $C\mu=0.32$,[2] and $C\mu>10.0$.[1] In most of these studies, detectable response to the jet blowing has been discernible at substantially lower values of $C\mu$ as, for example, in the optimization study of Visser et al.,[2] who employed values as low as $C\mu=0.0023$. The response of the breakdown location to transient, as opposed to steady, blowing has not yet been addressed.

In contrast to the extensive employment of blowing as described in the foregoing, the effectiveness of localized suction applied well downstream of the location of vortex breakdown has received very little attention. Werle[5] presents a visualization photo showing stabilization of the vortex core by steady suction through a probe; no quantitative information is provided.

The objective of this investigation is to determine the response of the leading-edge vortex to the abrupt onset and cessation of suction. The following aspects are addressed: visualization of the unsteady evolution of the vortex core, the nature of hysteresis of the core development, and the overall response time from the onset of suction to the stabilization of the core as a function of suction amplitude and suction probe location.

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Experimental Techniques and Findings

A delta wing having a sweep angle $\lambda=75$ deg at an angle of attack 35 deg was mounted in a water channel having interior dimensions of 604×914 mm. The root chord C of the wing was $C=242$ mm, and the Reynolds number Re based on C and freestream velocity U was $Re=3.1\times10^4$. The diameter d_p of the suction probe was $d_p=6.35$ mm. The suction probe was located a distance x_p from the apex of the wing, where x_p is measured along the wing centerplane. The coordinates y_p and z_p, measured from the centerplane and surface of the wing, respectively, had values corresponding to maximum effectiveness of the suction.

Dye visualization allowed observation of the unsteady breakdown process and the time-dependent variations of the location x_b of onset of vortex breakdown, measured from the apex of the wing. Dye was injected into the core of the vortex near the apex. It originated through the support sting of the wing, passed through the main body of the wing, then out through a port having a diameter of 1 mm and located a distance of 18 mm from the apex of the wing and 4 mm from the leading edge of the wing. The suction flow was generated by a pump located outside the test section. The dimensionless suction coefficient is defined as $C\mu=[V_p/U]^2(A_p/A_w)$, in which $U=$ freestream velocity, $V_p=$ velocity at the suction probe inlet, $A_p=$ area of the probe inlet, and $A_w=$ surface area of the wing.

The flow visualization of Fig. 1 represents the response of the vortex with time t^*, where $t^*=tU/C$ varies from $t^*=0.10$, shortly after the onset of suction, to $t^*=2.76$, marking complete stabilization of the core flow. For this experiment, the suction was continued after stabilization of the core flow was achieved. The visualization shows that there are four identifiable stages leading to stabilization: 1) downstream movement of the breakdown and insignificant change of the radius of the breakdown spiral (compare $t^*=0.10$ with $t^*=1.55$); 2) continued downstream movement of the spiral pattern, accompanied by a decrease in radius of the spiral (compare $t^*=1.55$ with $t^*=1.95$); 3) rapid decrease in radius of the spiral, eventually becoming indiscernible and leaving a breakdown bubble upstream of a turbulent wake (compare $t^*=1.95$ with 2.29); and 4) stabilization of the turbulent breakdown region as it is drawn into the probe (compare $t^*=2.29$ with 2.56).

The location x_b/C of vortex breakdown as a function of dimensionless time $t^*=tU/C$ is shown in Fig. 2 for representative values of suction coefficient $C\mu$. To permit a direct comparison of the curves of x_b/C vs t^*, plots corresponding to the abrupt onset and abrupt cessation of suction are shown on the same set of axes. This means that $t^*=0$ corresponds to the onset of suction at the beginning of a cycle and to return of the vortex breakdown to its equilibrium position at the end of the cycle. At the lower value of $C\mu$ in Fig. 2a, there is substantial hysteresis. For increasing values of t^*, a number of small plateaus of x_b vs t occur such that x_b is constant over correspond-

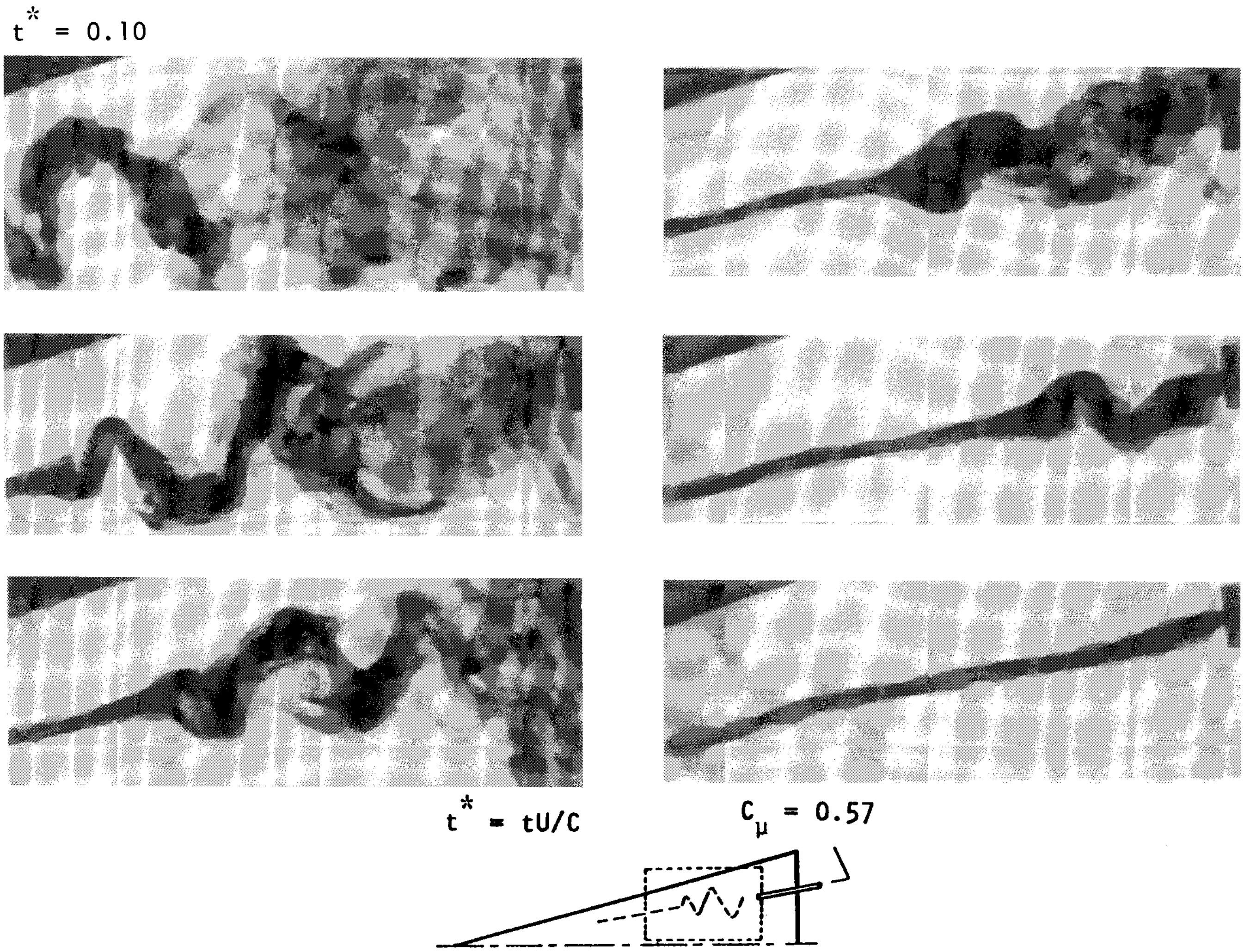

Fig. 1 Visualization of process of stabilization of vortex core after abrupt onset of localized suction at $t^*=0$. Left boundary of photo is at $x/C=0.55$; vortex breakdown in the absence of suction occurs at $x_b/C=0.45$; amplitude of suction coefficient $C\mu=0.57$; suction probe located at $x_p/C=0.95$ $Re=3.1\times10^4$.

ing intervals of t^*. Moreover, when the plot of Fig. 2a is viewed as a whole, a plateau occurs extending over a large time scale, at a nominal value of $x_b/C=0.9$, before the core attains its completely stabilized condition at $x_b/C=1.0$. The apparent scatter of the data is not due to experimental uncertainty; location x_b/C is resolvable to $\simeq 0.01C$. Occurrence of plateaus of x_b/C vs t^* indicates the competition between the inherently unstable vortex and the applied suction. In other words, the relatively low value of suction rate produces a marginally stable approach of the vortex core to a state of complete stabilization. When there is abrupt cessation of the suction flow, the vortex breakdown position returns to its equilibrium position along the path indicated by the arrows pointing down and to the left. The time required for the vortex to return to its no-suction equilibrium position is less than half the time of its travel to the tip of the suction probe after abrupt onset of suction, a trend characteristic of low values of momentum coefficient $C\mu$. Figure 2a, viewed as a whole, exhibits hysteresis analogous to that occurring for low-frequency variations of angle of attack of a delta wing in the absence of applied suction.[6]

At a relatively high value of suction coefficient $C\mu$, shown in Fig. 2b, the nature of the hysteresis is drastically altered. In contrast to that of Fig. 2a, it is in the counterclockwise direction. At the onset of suction, the time delay until initiation of movement of the breakdown position x_b/C is a substantial fraction of the total time of travel of the vortex to the tip of the probe. This feature is representative of higher values of momentum coefficient $C\mu$.

Hysteresis loops of the type shown in Figs. 2a and 2b are functions of the location x_p/C of the probe and the magnitude of the suction coefficient $C\mu$. Defining t_p^* as the total time elapsed from the onset of suction to attainment of stabilization of the vortex core up to the tip of the probe, the values of t_p^* in relation to probe locations x_p/C are given in Fig. 3. Several trends are evident.

1) For a given value of x_p/C, when $C\mu$ is sufficiently large, further increases in $C\mu$ do not significantly alter t_p^*. This threshold value of momentum coefficient is about $C\mu \simeq 0.35$ (except for the probe location furthest downstream, $x_p/C=1.2$). Decreases in $C\mu$ below this threshold value produce relatively large increases in t_p^*.

2) At the lowest value of $C\mu$, $C\mu=0.035$ (limited by the pumping system), stabilization of the vortex is attainable for probe locations upstream of, and at, the trailing edge of the wing ($x_p/C\leq 1.0$), whereas it is not for locations downstream of the wing ($x_p/C>1.0$).

3) For lower values of $C\mu$, location of the probe downstream of the trailing end of the wing substantially increases the value of t_p^*; for example, at $C\mu \simeq 0.2$, movement of the probe from $x_p/C=1.0$ to 1.2 produces nearly a threefold increase in t_p^*.

The high sensitivity of t_p^* to small changes in probe location x_p/C may be explained by viewing the probe inlet as a

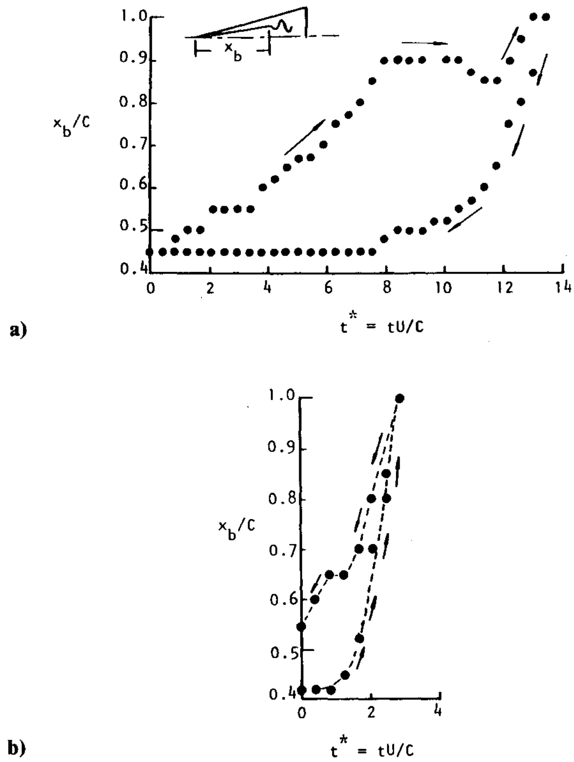

Fig. 2 Time-dependent variation of vortex breakdown location for a) low-amplitude suction coefficient $C\mu = 0.09$, suction probe at $x_p/C = 1.06$; and b) large-amplitude suction coefficient $C\mu = 0.76$, suction probe located at $x_p/C = 1.0$, $Re = 3.1 \times 10^4$.

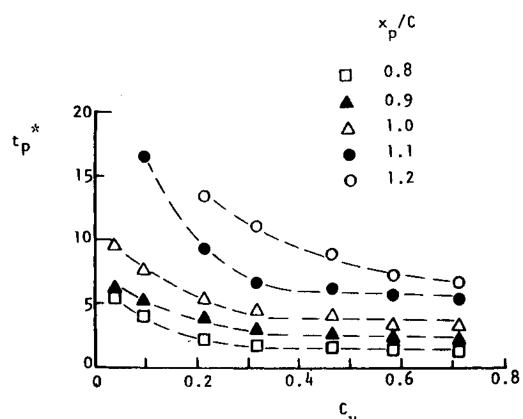

Fig. 3 Response time t_p^* for stabilization of vortex after onset of suction as a function of momentum coefficient $C\mu$ at various chordwise locations x_p/C of the suction probe.

point sink, since the probe tends to draw fluid from essentially all directions when located within the low-velocity recirculation zone of the vortex breakdown region. When the probe is located upstream of the trailing end of the wing ($x_p/C < 1$), the impermeable surface of the wing causes a different sink flow pattern than that resulting from the probe located downstream ($x_p > 1$) of the wing. The former pattern is apparently more efficient than the latter in removing the low-velocity fluid in the breakdown region, associated with movement of the vortex breakdown in the downstream direction.

Regarding the minimum value of suction coefficient $C\mu$ that produces stabilization of the core, it is obviously a strong function of the probe location relative to the position of vortex breakdown in the absence of suction. For breakdown at $x_p/C = 0.45$ in the absence of suction and a probe location at $x_p/C = 1.0$, values of suction coefficient as low as $C\mu = 0.035$ allowed restabilization of the flow. Considerably lower values of $C\mu$ are expected to be effective when the tip of the probe is located further upstream, closer to the onset of vortex breakdown.

Acknowledgment

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Effect of Surface Grooves on Base Pressure for a Blunt Trailing-Edge Airfoil

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Nomenclature

A	= model base area
C_{pb}	= local base pressure coefficient, $(p - p_{ref})/q_\infty$
$\overline{C_{pb}}$	= average base pressure coefficient
D	= groove depth
d	= diameter
q_∞	= freestream dynamic pressure, $0.5\,\rho_\infty V_\infty^2$
Re_L	= Reynolds number based on chord length
s	= model span
V_∞	= freestream flow speed
z	= spanwise coordinate measured from the left end of model as viewed from downstream
α	= groove half angle
$\Delta\overline{C_{pb}}$	$= [\overline{C_{pb}} - (\overline{C_{pb}})_{\text{baseline}}]/(\overline{C_{pb}})_{\text{baseline}}$
δ	= boundary-layer thickness (based on ratio of local velocity to freestream velocity equal to 0.99)

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