Technical Notes

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Hysteresis of Vortex Development and Breakdown on an Oscillating Delta Wing

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Introduction

A CENTRAL feature of the vortex formation from a swept leading edge at finite incidence angle is the vortex core. At a sufficiently high angle of attack, this core breaks down, causing loss of local lift. For stationary wings, the location of vortex breakdown x_b, defined as the distance from the tip of the wing at which the vortex core diameter abruptly increases, attains its minimum value at maximum angle of attack, and conversely. For a full description of these and other features, as well as a synopsis of theoretical development pertaining to flows past wings and analogous internal tube flows, the reader is referred to the review of Wedemeyer.[1]

Characterization of the unsteady nature of vortex breakdown on a delta wing subjected to periodic excitation has remained unresolved. Basic features of the vortex development and breakdown on a wing oscillating in pitch are reported by Rockwell et al.[2] In general, it is expected that the location of vortex breakdown x_b will exhibit a hysteresis loop as angle of attack α is varied. This hypothesis is based upon analogous findings for a two-dimensional airfoil subjected to pitching motion,[3] as well as visualization of the overall flow structure on an oscillating delta wing.[4] In the latter, it was revealed that the gross behavior of the vortical flow structure was hysteretic with respect to the wing motion. This investigation focuses on the development and breakdown of the core of the vortex, defined by the vorticity fed into the vortex at and near the tip of the wing.

Experimental System

The delta wing had a sweep angle of 52 deg. Its maximum thickness was 4.7 mm and the leading edges were machined at an angle $\beta = 10$ deg to give an edge thickness of 0.5 mm. The Reynolds number based on chord was $Re = 5800$. In accord with previous findings, the location of vortex breakdown on the stationary wing was found to be insensitive to Reynolds number; values found in this investigation were in good agreement with those at higher Reynolds number summarized by Wedemeyer.[1]

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The wing was oscillated about its trailing edge over a range of reduced frequency $K = \pi fC/U$ and mean angle of attack $\bar{\alpha}$. Fluctuating angle of attack $\Delta\alpha$ was maintained at $\Delta\alpha = 10$ deg. Herein, we focus on the representative behavior of the core at $\bar{\alpha} = 10$ deg and $K = 0.76$.

The core of the vortex was visualized with a flying wire technique, described by Rockwell et al.[2] and Atta.[5] In essence, a 0.5 mm diam platinum (hydrogen bubble) wire was mounted a distance of 1 mm downstream of the tip of the wing; the angle between the axis of the wire and the tip of the wing was such that vorticity shed from the tip region was clearly marked. This wire was suspended between rigid supports, located well away from the wing; they were connected to the axis of the pitching mechanism such that they moved with the same angular velocity as the wing. Complementary experiments with dye injection from the tip region verified the accuracy of this method, which has additional advantages of allowing pulsing of the visualization marker and arbitrary location of the marker injection.

Core Development and Breakdown

Photo A in Fig. 1, taken at $\alpha = 19$ deg, shows the first appearance of the vortex core near the tip of the wing. In photo B, taken at maximum angle of attack $\alpha = 20$ deg, the core is well developed and its front has propagated substantially downstream of the tip. In photo C, taken at $\alpha = 17$ deg, the core has further developed and its front has moved to its maximum position from the tip of the wing. Onset of vortex breakdown is evident in photo D at $\alpha = 15$ deg and its subsequent development in photos E–G, taken at continuously decreasing angles of attack $\alpha = 12$, 8, and 5 deg.

There are several striking features of the vortex development and breakdown. First, the maximum extent of the laminar vortex core occurs near the maximum angle of attack (see photo C), rather than near the minimum angle of attack, which is in direct contradiction to what one would expect on the basis of quasisteady behavior. Likewise, occurrence of the greatest turbulence activity in the vortex core occurs near the minimum angle of attack (see photo G). These observations indicate a drastic phase shift of the vortex core development with respect to the wing motion. It is central to the occurrence of hysteresis in the overall flow structure and, undoubtedly, to the hysteresis of loading on the wing.

Second, regarding the development of the vortex core, it first occurs in the pure spiral (or sinuous) mode (see photo E), progresses to a double helix structure (photo F), and then to a turbulent state (photo G).

Third, we note that, over a portion of the oscillation cycle, there occurs no vortex core, i.e., examination of the video sequence for angles not shown in Fig. 1 shows no core to be present for angles of attack $2 \leq \alpha \leq 17$ deg. Again, this is in striking contrast to what one would expect on the basis of quasisteady considerations. For a wing of the sweep angle employed here, static experiments show a core to be present for $5 \leq \alpha \leq 20$ deg.

The top plot of Fig. 2 shows the position x_c of the leading-edge of the vortex core during the initial "shooting" stage of

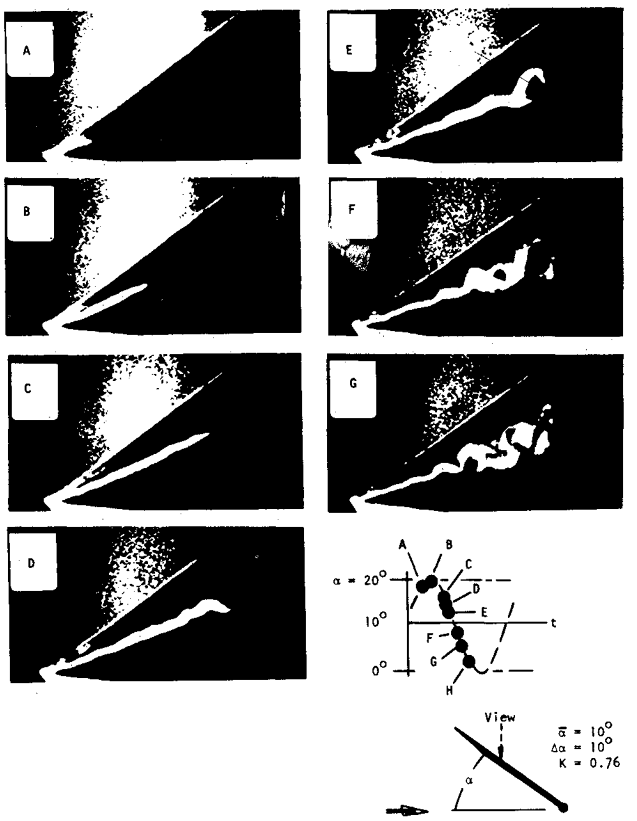

Fig. 1 Visualization of vortex breakdown on an oscillating swept wing.

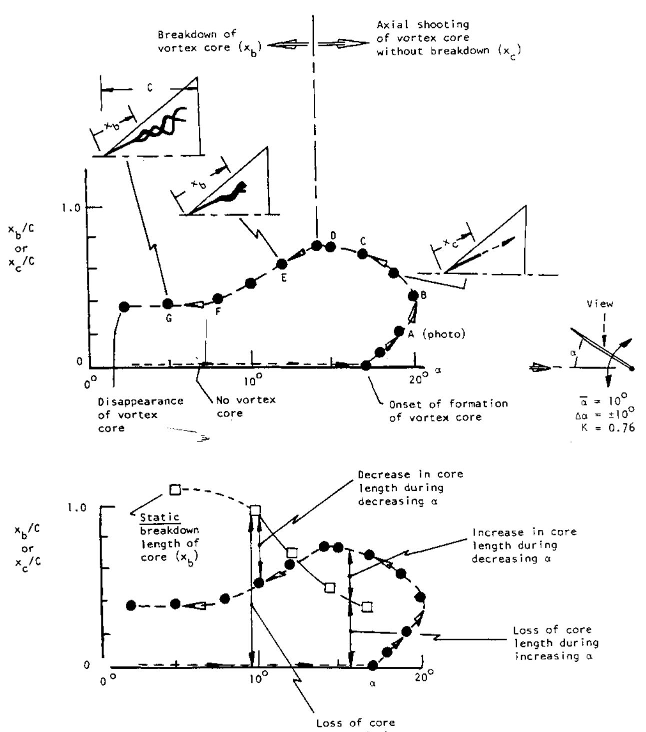

Fig. 2 Hysteresis loop corresponding to vortex breakdown on an oscillating swept wing.

core formation, as well as the location x_b of vortex core breakdown after the core has formed. The designations A, B, ... along the curve refer to the corresponding photos of Fig. 1; likewise, the schematics refer to the same series of photos. The bottom plot of Fig. 2 compares the curve of the top plot with a curve representing vortex breakdown position on the stationary wing. Increase and decrease in core length prior to breakdown, as well as complete loss of the core are indicated using the stationary wing characteristic as a reference.

Clearly, the degree to which these observations persist at other values of pitching axis location, reduced frequency, and amplitude of oscillation remains to be quantified. However, the basic features shown herein are expected to exert a significant influence on the wing loading over a substantial range.

Acknowledgment

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Extrapolation of Velocity for Inviscid Solid Boundary Conditions

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Introduction

IN the computation of an inviscid flow, the solid boundary condition requires that there be no flux across the boundary, that is,

$$V \cdot n = 0 \tag{1}$$

where V is the velocity vector and n the normal vector at the solid-body surface. Equation (1) prescribes only the direction of a resultant velocity, which is sufficient for ensuring the conservation of mass and momentum. However, the magnitude of the velocity components on the body surface is very often needed for the numerical calculation for a one-sided differencing scheme or sometimes for the calculation of pressure or other flow properties, depending upon the scheme used in the calculation. An additional numerical condition is required to decompose the components of velocity on the surface.

A simple way to implement the additional numerical condition is to assume that the points near the body are close enough so that an extrapolation can be used. Nevertheless, an extrapolation is only an approximation. There are two points concerning extrapolation that must be addressed. The first is the order of extrapolation. One can employ various forms of extrapolation, for instance, a linear or higher order of ex-