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Technical Notes

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Shaping of Delta-Wing Planform to Suppress Vortex Breakdown

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I. Introduction

On high-performance military aircraft the sharp-cornered wing and body junction generates a vortex, which becomes the core of the vortex system emanating from the wing leading edge. Serious problems arise at high angles of attack when the core vortex breaks down, which can easily be detected by the telltale characteristic of backflow.

The troublesome aspect of the vortex breakdown is the high levels of organized unsteadiness with a dominant frequency associated with a helical disturbance in the downstream of the breakdown. When the helical frequency coincides with the natural frequency of the empennage, a resonant structural oscillation can rapidly lead to fatigue damage.

The lateral separation of the tails in a twin-tailed aircraft brings them closer to the path of the vortex, when compared to a single tail. This proximity in the tail results in tail buffet problems, which have plagued the F-18 (Ref. 1).

A fix currently in use in the F/A-18 C/D is to install fences near its leading-edge extension. Its purported function is that the primary vortex emanating from the leading edge generates secondary vortices on the fence[2]; the mutual induction between the two is such that the vortices move themselves away from the tail. The fence is, however, only an exigent fix, having the adverse side effects of increasing radar cross section and drag.

Although theories of vortex breakdown abound (and here we define the theory in a narrow sense as based on a simple conceptual model rather than numerical simulation), almost all of them ignore the spiral form of the breakdown and instead focus on axisymmetric bubble breakdown. Even in this limited scope, we still cannot explain, in simple physical terms, why vortex breakdown occurs at all. A recent comment[3] stating that "a comprehensive theory of vortex breakdown still does not exist" echoes similar comments made in 1977: "The embarrassing number of different theoretical notions has not, it must be admitted, led to satisfactory understanding of the flows observed."[4] The argument can be made that this lack of fundamental understanding has thwarted a successful search for alternative and viable means of suppression.

II. Spiraling Shear Layer and Self-Induction Theory

Quite recently, we proposed what we call a self-induction mechanism[5] for the formation of vortex breakdown. The new theory is based on four crucial observations: 1) upstream of the vortex breakdown, the vortex core is straight and of constant diameter; 2) the core is dominated by a structure, a spiraling shear layer; and 3) unlike other shear flow structures, the spiraling shear layer does not display any appreciable growth; and 4) the reason for observation 3 is that the conical vortex sheet emanating from the entire leading edge, within which the core is folded, imposes a physical constraint and stunts such a growth.

As far as the spiraling shear layer is concerned, Payne et al.[6] and Lowson[7] appear to be the first ones to report its presence over a delta wing, which the former called striated secondary vortices, the latter tassel vortices. The fact that the cross section maintains a constant diameter before breakdown is likewise noted.[6] Their presence is also noticed in swirling pipe flows,[8] where the pipe wall imposes a constraint to restrain the growth, similar to the conical vortex sheet.

The spiraling shear layer we visualized using laser-induced fluorescence in a water tunnel (to be described in Sec. III) is shown in Fig. 1. As the laser sheet, almost parallel to the x–y plane and away from the wing (a), is brought closer to the wing (c), the direction of the strands changes. For the sheet position (b), placed between (a) and (c), strands run in both directions. Therefore (a–c) as a whole implies the presence of a spiraling structure wrapping around the core, as sketched at the top of Fig. 1.

Although these spiraling shear structures are known to exist, their role as a direct cause of the vortex breakdown does not appear to have been explicitly recognized.

According to the self-induction mechanism,[5] this spiraling shear around the core carries the very seed of the vortex breakdown. Consider the pitch-up motion of a delta wing whose angle of attack is suddenly increased from zero, forming a transient spiraling shear layer. One can argue that the self-induction caused by the vorticity of the spiraling shear and the straight line of the vortex core results in backflow; this in turn triggers the onset of the vortex breakdown. The details of the self-inductive scenario will be described in the following successive steps.

Step 1: Deceleration of Axially Induced Velocity

Figure 2 shows a vortex core just starting to form, where two rows of alternating vortices (bottom picture) correspond to the cuts of spiral shear layer on the meridional plane (top). For the starting vortex (1) of the top row, where there is no vortex on its right, the induction in the axial direction comes from all of the upstream vortices in the bottom row, but the majority of the contribution comes from only a few neighboring vortices, e.g., (1) and (2) of the bottom row. For vortex (2) of the top row, now the starting vortex of the bottom row participates in the induction, together with the neighboring vortices (2) and (3) of the bottom row. Thus the induced velocity at (2) is higher than at (1), and similarly the induced velocity at (3) is higher than (2). (For vortices farther upstream the induced velocity approaches a plateau level.) In other words the induced axial velocity decelerates toward the starting vortex. Such deceleration is observable in a numerical simulation of a pitching delta wing.[9] The deceleration is connected with the straight line of the vortex core, by which the induced velocity can add up linearly.

Step 2: Pile Up of Vorticity

The upstream part of the spiraling vortices thus starts to catch up with the downstream part. Near the starting vortex the pitch of the

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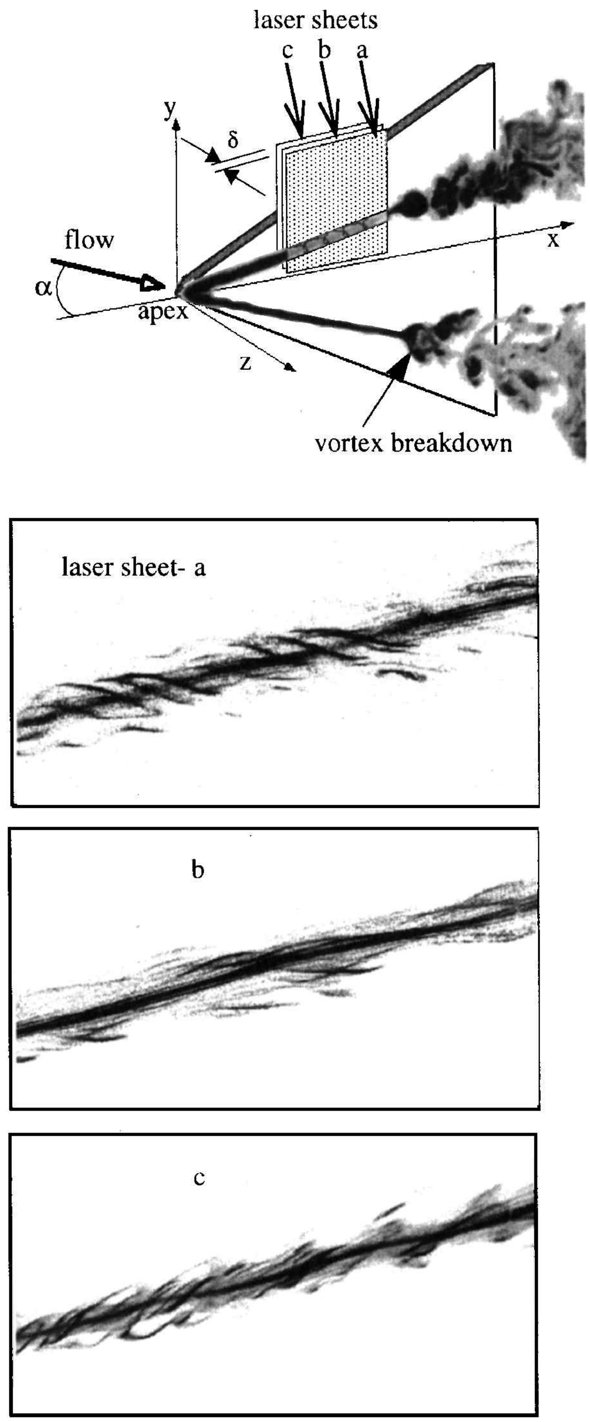

Fig. 1 Spiraling structure: $\alpha = 30$ deg and $\delta/C = 3.3 \times 10^{-3}$.

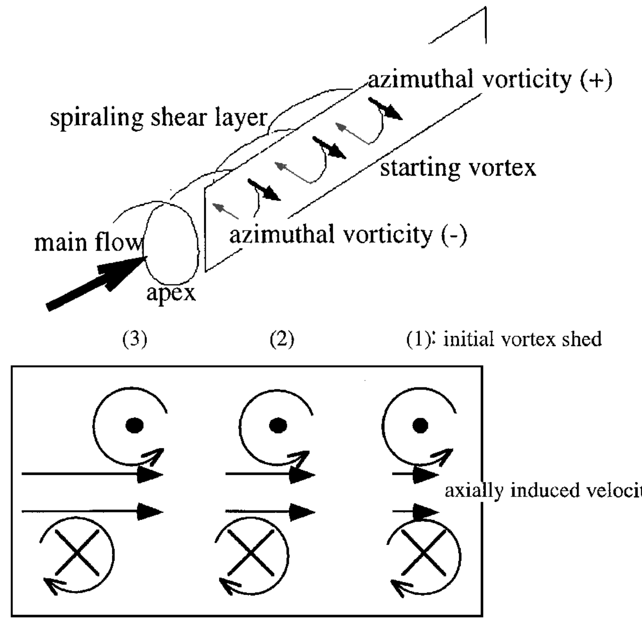

Fig. 2 Induction by azimuthal vorticity.

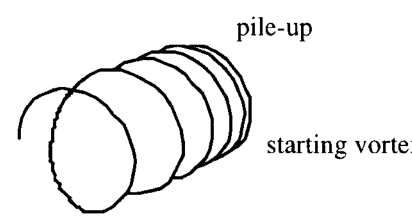

Fig. 3 Pile up of vorticity.

spiraling vortices becomes smaller and smaller like a compressed coil. As the pitch becomes smaller, the inductive effect becomes larger, and the process becomes accentuated; the vorticity near the starting vortex piles up (Fig. 3). The pile up could be avoided if the spiraling shear layer were allowed to expand radially so that the mutual induction would not be linearly additive. However, here such radial relief is prevented by a tightening constraint: a radial pressure gradient imposed on the core by the enclosing and swirling conical vortex sheet.

Step 3: Induced Azimuthal Velocity Decreases

For the same reason as step 1, the self-induction caused by the axial vorticity of the spiraling shear layer is such that the azimuthally induced velocity or swirl decreases similarly toward the starting vortex.

Step 4: Onset of Backflow

The less the swirl is, the higher the pressure at the center of the core; thus, the center pressure for vortex (1) is higher than that of (3). This downstream rise of the core pressure does set off the backflow.

Step 5: Onset of Radial Enlargement

The collision between the backflow and streamwise flow forces the core to expand radially despite the constraint. This is the onset of the vortex breakdown, which now alters the flowfield globally.

Step 6: Postbreakdown Induction

Once the radial enlargement occurs, there should be a switch in the sign of azimuth vorticity downstream of the breakdown point.[10] As a vorticity vector is convected downstream along a radially diverging stream surface, the decrease of swirl at larger radii causes the vorticity vector to tilt azimuthally in a direction opposite to the swirl. Because of the sign switch, the direction of the self-induced flow downstream of the breakdown point also switches from step 1, and it opposes the main flow. The sign switch, the presence of which has been confirmed in experiments,[11] provides a postbreakdown feedback mechanism to the backflow.[10]

For simplicity, we ignored the feeding of the vorticity from the conical vortex sheet to its core in the preceding explanation; the continuous supply of vorticity from the surrounding conical vortex sheet and its downstream convection can further promote the pile up.

The unique features of the present scenario are steps 1–5, whose key point is the self-induction upstream of the vortex breakdown as a trigger to set off the backflow; this in turn initiates the radial spread. In the past only one report[12] appears to refer to this prebreakdown induction, and even then no connection was made with the breakdown itself. If instead of the starting vortex one reapplies the argument of step 1 to near the apex, self-induction of the vortex core should result in acceleration. By appealing to this, Erickson[12] explained the observed downstream increase of the core flow (upstream of the breakdown point). By the acceleration, however, one cannot explain the vortex breakdown, which is caused by deceleration.

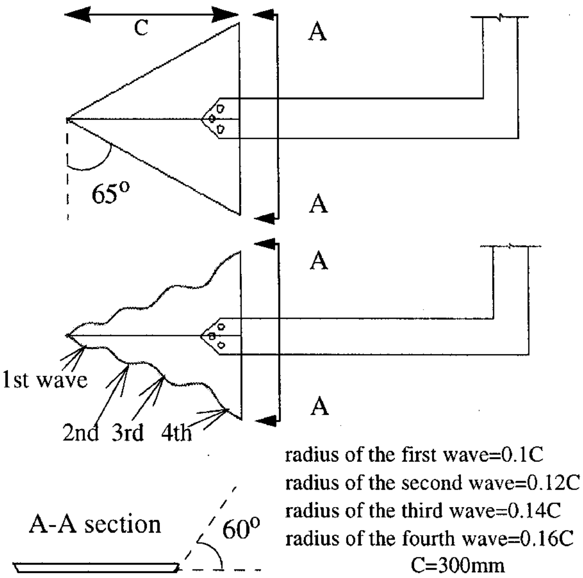

Fig. 4 Straight (top) and shaped (middle) planform.

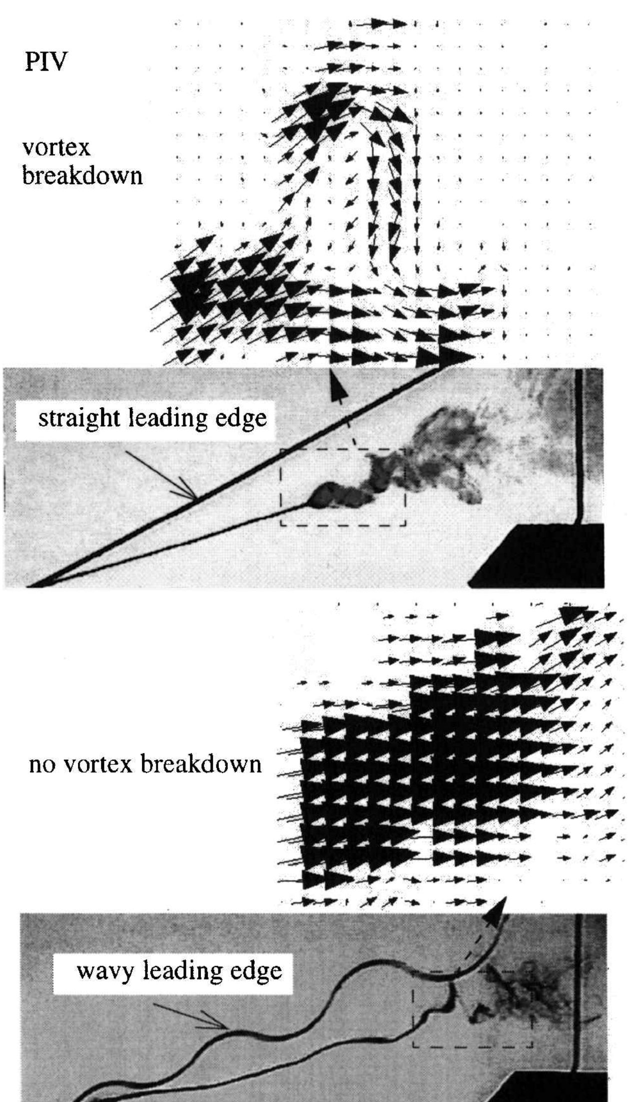

Fig. 5 PIV and dye results for straight and wavy planform: plan view; $\alpha = 30$ deg, tunnel velocity = 4 cm/s, and Reynolds number based on $C = 1.2 \times 10^4$.

A second feature of the present scenario is in its approach to track the transient development of the breakdown, and in this spirit it is analogous to the more familiar explanation of a supersonic shock as coalescence of small-amplitude waves. (By following this analogy further, we may regard such steady theories as the conjugate flow[13] as similar to the treatment of shocks as a sudden jump.) The transient treatment led us to consider the vortex core as finite length (rather than the usual infinite or semi-infinite one), where the vortices near the starting vortex play the key role of deceleration. Third, the importance of the constraint imposed on the vortex core by the surrounding conical vortex sheet, which acts to hinder the radial enlargement of the vortex core, is explicitly brought forth.

If the proposed self-induction mechanism of vortex breakdown, which hinges on the straight trajectory of the vortex core, is indeed correct, one may be able to suppress the vortex breakdown by forcing the path of the core to deviate from a straight line. This can be achieved, for instance, by reconfiguring the leading edge of a delta wing from a straight to a contoured shape.

III. Shaped-Wing Planform

With this in mind, we designed and tested a delta wing with a wavy-shaped leading edge, shown in Fig. 4 (bottom), together with a straight leading edge (top). Except for the waviness of the leading edge, the two wings are the same. The tests were performed in a water tunnel at the University of Washington. Results are presented in Fig. 5 for $\alpha = 30$ deg in the form of velocity vector plots obtained by particle image velocimetry (PIV) as well as dye-flow-visualization pictures. A detailed description of the water tunnel and PIV technique is available.[14]

Although vortex breakdowns are observed for the straight leading edge both in the backflow of PIV data and in dye tests, for the wavy leading edge vortex breakdowns are suppressed. Though the dye tends to get caught in the swirl of the wavy vortex sheet originating from the wavy leading edge and appears to show a disruptive pattern, PIV data reveal an orderly velocity distribution without backflow, confirming that there is no vortex breakdown.

Upstream of the vortex breakdown region, whereas the trajectories are straight for the straight leading edge, for the wavy leading edge the trajectories are expectably undulating; it is this very waviness that prevents the formation of the vortex breakdown. The effectiveness of the wavy wing appears to persist until around $\alpha = 40$ deg.

IV. Conclusions

Based on the self-induction theory where the spiraling shear layer and the straight path of the vortex core are regarded as the cause of the vortex breakdown, it is demonstrated that the vortex breakdown can be suppressed by reconfiguring the delta-wing planform from a conventional straight leading edge to a shaped form. The wavy wing tested is just one example of such a shaped planform, of which there may be many possible variations. For instance, even with only the first and second wave, the same results are likely to be achieved. (After the initial submission of the present Note, this expectation was indeed confirmed by us.)

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Surface Shaping to Suppress Vortex Breakdown on Delta Wings

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I. Introduction

IN an accompanying Note[1] we presented evidence of vortex-breakdown suppression by reconfiguring the planform of a delta wing from straight leading edges to a shaped form. The underlying rationale for such a change in wing geometry is based on the so-called self-induction mechanism[1,2] of vortex breakdown for the straight leading edge: in the transient formative stage of vortex breakdown, self-induction in the shear layers spiraling around the straight vortex core causes the pile up of vorticity, which in turn induces backflow and radial enlargement of stream surfaces (Fig. 1).

If the proposed self-induction mechanism of vortex breakdown, which hinges on the straightness of the vortex core, is indeed correct, one may be able to suppress the vortex breakdown by forcing the path of the core to deviate from a straight line (Fig. 2). In the preceding Note[1] this was achieved by shaping the leading edge of a delta wing that resulted in a spanwise perturbation to the vortex core.

Even for a delta wing with straight leading edges, a requisite disturbance may be generated by wing surface shaping or bulges. Such bulges would create a perturbation normal to the wing surface, which induces similar deviation of the core from a straight line.

The effectiveness of such surface bulges in inducing vortex breakdown is illustrated in this Note.

II. Experiments

The tests were conducted in the water tunnel[1] at the University of Washington. The baseline delta wing with straight leading edges is the same as the one used in the tests described in Ref. 1. Here two bulges are placed on one side of the wing, as shown in Fig. 3.

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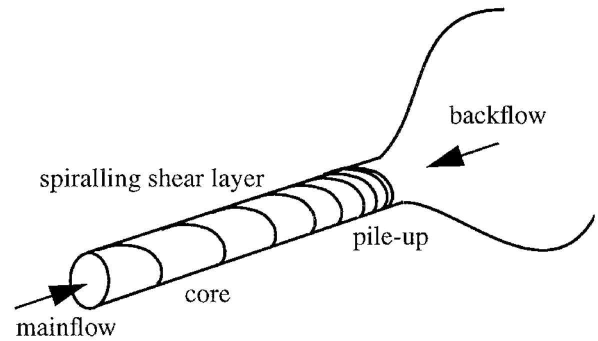

Fig. 1 Vorticity pile up by self-induction.

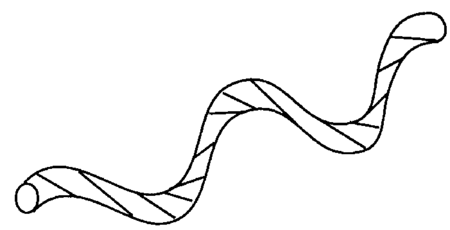

Fig. 2 Departure of the core from a straight line.

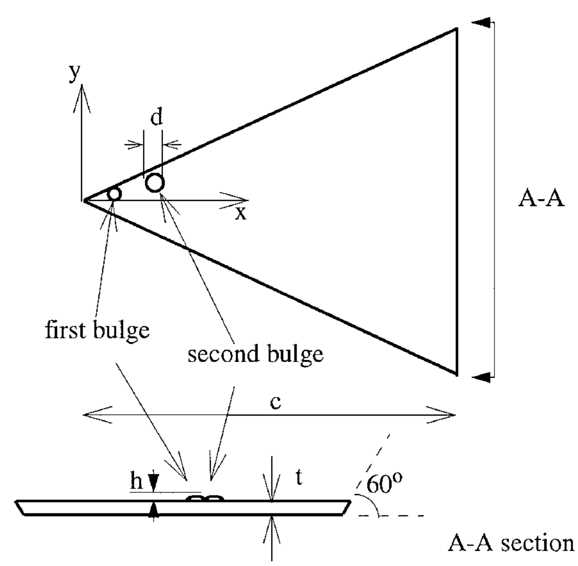

Fig. 3 Bulges.

The center of the first bulge is located at $x_1 = 0.079c$ and $y_1 = 0.0198c$; its diameter $d_1 = 0.033c$, and its height $h_1 = 0.0066c$. The center of the second bulge is located at $x_2 = 0.1914c$ and $y_2 = 0.0495c$; its diameter $d_2 = 0.046c$, and its height $h_2 = 0.0066c$. The chord c is 303 mm, the thickness 6 mm, and the sweep angle 65 deg. The freestream velocity is 4 cm/s, and the estimated accuracy of the particle image velocimetry (PIV) data is 10%. In obtaining PIV measurements the position of the laser sheet is not exactly parallel to the upper surface: the laser sheet touches the apex, and at the trailing edge it is separated from the upper surface by a distance of 0.13c.

In Fig. 4, for the lower part of the wing without bulges, the core is straight, and vortex breakdown with characteristic backflow is present, as observed from PIV data taken over a region shown in a box. For the upper part of the wing with bulges, the core is deflected by the disturbance generated by the bulges, and although the dye becomes diffused, there is no backflow observed in the PIV data. Because of the swirling nature of the flow, the perturbation imparted initially normal to the wing surface by the bulges is seen to induce simultaneously spanwise deviation of the core from the original