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Effect of delta wing's leading edge geometry to vortex breakdown

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Abstract

This paper studies the effect of delta wing's leading edge geometry (sharpness and bevel angle) to the vortex breakdown. At the apex, the flow separates and forms apex vortices, which may breakdown if the wing is at high angle of attack. Preliminary studies reveal that the initial circulation and/or swirl of the apex vortices are mostly created at the wing's apex vicinity. This initial circulation is the control parameter of vortex breakdown, and it is changed significantly by the wing's leading edge geometry. Here we study the leading edge sharpness and the bevel angle effects by means of flow visualization. For curvature effect, we compare two delta wings with sharp and rounded leading edges. The delta wing with sharp leading edge results in stronger apex vortices' initial circulation, and that the consequent vortex breakdown happens earlier than the rounded one. For bevel angle effect, we flip the delta wing with sharp leading edge vertically. When the delta wing is flipped, the apex vortices bifurcate into smaller vortices. We label these vortices as: primary, secondary and tertiary vortices. These vortices are convected downstream without breaking down.

Introduction

The vortex breakdown is an abrupt enlargement of a vortex, where the axial filament emanating from the apex of a delta wing suddenly takes a spiral form. At times, a bubble form of the breakdown is also observed. Encapsulated within the spiral or bubble is a limited region of flow reversal near the vortex centerline, which is followed by highly turbulent flow.

Although there have been many theories of vortex breakdown, they mostly ignore the spiral form of the breakdown on the delta wing, which is more common, and instead focus on axisymmetric bubble breakdown in the pipe with swirling flow, because the latter is mathematically tractable. A recent comment (ref. 1) 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." (ref. 2)

Recently, we proposed what we call a self-induction mechanism for the formation of vortex breakdown. Details of the mechanism can be found in Kurosaka (1998) (ref. 3), Srigrarom & Kurosaka (2000a, 2000b) (ref. 4 and 5). According to the theory, it is the initial circulation and/or swirl that causes the negative axial vorticity gradient within the apex vortices itself. Then, by its own self-induction, the apex vortices can pile-up and breakdown.

The apex vortices (and hence, their initial circulation) are created by the flow separation on the wing from the pressure side to the suction side of the delta wing. Consider figures 1 and 2, which show the computed viscous flow around the delta wing (from VSAERO® CFD code). For the delta wing positioned at high angle of attack ($\alpha = 25°$), the incoming flow streamlines at the apex will hit the wing, separate and form the apex vortices (figures 3 and 4). It is the leading edge that controls the vortices' turning radii, and that, their initial swirl. Therefore, we focus our attention to the sharpness and the curvature of the wing. We also consider the effect of the bevel angle by flipping the wing vertically to create different flow pattern. The investigation was done primarily by means of food coloring dye and Laser Induced Fluorescence (LIF) flow visualization in the water tunnel.

Effect of leading edge shape

According to the self-induction mechanism theory, it is the initial vorticity gradient that leads to the chain of events leading to the formation of vortex breakdown. Suppose that we could reduce the initial vorticity gradient, then, theoretically, the vortex breakdown can be delayed or weakened. For the case of the delta wing with a sharp apex, the initial vorticity gradient is associated with the flow separated from the sharp corner at the apex of the wing. Therefore, to reduce the initial vorticity gradient, we could attempt to prevent flow separation by rounding the wing's apex.

To investigate the above concept, we have done pilot experiments by installing a curved wood attached to the apex of the delta wing, and tested at various usual vortex breakdown conditions in the water tunnel. The plexiglass delta wing 12 inches chord length and 1 inch thick (i.e. thickness to chord ratio, t/c = 1/12) with 60-degree swept angle was used. This relatively thick delta wing was used, because we could observe the edge effect more visibly. The wing was set at angle of attack of 20 and 25 degrees, under incoming freestream flow of 5 cm/s, corresponding to Reynolds number of ~15000 based on chord length ($Re \equiv U_{¥}c/n$ ~ 15000). Red food-coloring dye was used for flow visualization. The wing was tested with and without the curved wood attachment for direct visual side-by-side comparison. We compare the results by examining the local flow at the apex, and the location of the vortex breakdown.

Let us consider the flow around the rounded leading edge of the curved wood attachment shown in figure 3, which was taken from side view. The wing was set at angle of attack of 25 degree. The flow remains mostly attached at the apex, with a mild separation. Therefore, the apex vortices would have reduced initial swirl, hence lesser axial vorticity gradient, compared to the one with the sharp leading edge case.

Figure 4 shows side-by-side comparison for the case of the wing at 20° angle of attack. Although, there is still vortex breakdown on the one with the curved wood attachment, the vortex breakdown is weaker, as noticeable by the gradual fading of the dye color. The location of the vortex breakdown is also delayed downstream, as observed by comparing $L_1 > L_2$ in figure 4 (both L_1 and L_2 are measured from the delta wing's trailing edge). This means that smoothening the delta wing's apex to reduce the separation helps to lessen the initial vorticity gradient and weaken and delay the vortex breakdown, as expected. We also obtained the same results for the case of the wing at 25° angle of attack (figure 5)

Effect of bevel angle

In the previous section, we discussed the effect of modifying the delta wing's apex shape, by which we could delay the vortex breakdown. The modification was done by rounding the sharp apex to a smooth curved one. Here we look into the effect of the bevel angle. We may change the delta wing apex and/or the leading edge, such that the incoming flow needs not to turn around the acute angle (see figure 6), which has smaller turning radius, and that, creates the apex vortices with causes strong initial swirl (circulation). Instead, the flow bends around the obtuse angle (milder turn), corresponding to larger turning radius, and that, creates the apex vortices causes weaker initial swirl (circulation). We achieve this change by flipping it vertically flipped, as shown schematically, in figure 6.

Here we used the same delta wing with 12 inches chord length and 1 inch thick (i.e. thickness to chord ratio, $t/c = 1/12$), and 60 degree swept angle ($\phi = 60°$) in the water tunnel. The incoming flow speed was 5 cm/s. The delta wing was at 25 degree angle of attack ($\alpha = 25°$). We first present the baseline result corresponding to its normal position as figure 7, which corresponds to strong swirl in apex vortex (on each side of the wing), and that where the usual vortex breakdown is observed.

For the delta wing at vertically flipped position as shown in figure 8, in comparison to the normal position wing as shown in figure 7, the flow at the apex turns at lesser angle, having larger turning radius, and that, apex vortex (on each side) has lesser initial swirl. Therefore, vortex breakdown is suppressed, as predicted by this changing the bevel angle manner.

Furthermore, for the case of vertically flipped wing, the apex vortices stay close to the wing and bifurcate into to multiple vortices, as shown in figures 9 and 10. We identify the multiple vortices as the primary, secondary and tertiary apex vortices, as shown schematically in figure 11.

Figures 12-15 taken by dye and figures 16-17 by LIF shows the eruption of the fluid near the wall. In general, it is well known that when a vortex is located in the vicinity of a solid surface, the boundary layer over the surface is drawn towards the vortex in an eruptive manner and forms a secondary vortex, which, for exactly the same reason, induces the tertiary vortex in turn. It is in this context that we interpret these figures. It should also be noted that, for all primary, secondary, and tertiary vortices, they are just convected downstream without breaking down.

Conclusions

From the flow visualization results, we have studied the effect of leading edge's sharpness and bevel angle to the apex vortex. For curvature effect, we compare two delta wings with sharp and rounded leading edges. The delta wing with sharp leading edge results in stronger apex vortices' initial circulation, and that the consequent vortex breakdown happens earlier than the rounded one. For bevel angle effect, we flip the delta wing with sharp leading edge vertically flipped. When the delta wing is flipped, the apex vortices bifurcate into smaller vortices, labelled as: primary, secondary and tertiary vortices. These vortices are convected downstream without breaking down.

Acknowledgments

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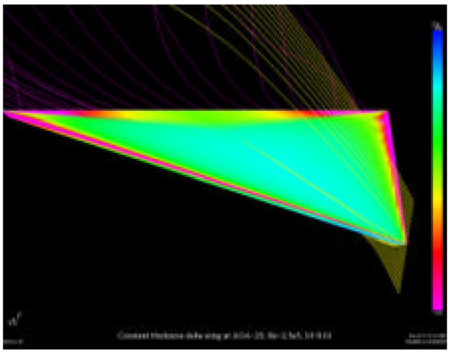
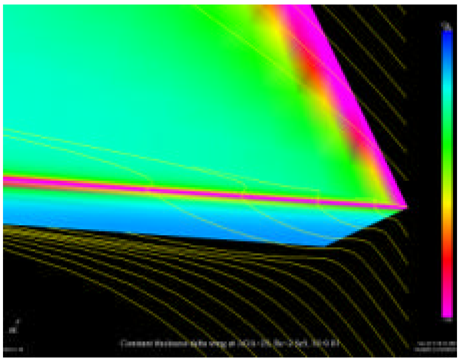
References

1. Spall, R.E., "Transition from Spiral- to Bubble-Type Vortex Breakdown", *Physics of Fluids*, Vol. 8, No.5, 1995, pp. 1330-1332.
2. Faler, J.H., and Leibovich, S., "Disrupted States of Vortex Flow and Vortex Breakdown", Physics of Fluids, Vol. 20, No.9, 1977, pp. 1385-1400.
3. Kurosaka, M., "Spiralling Shear Layers as a Cause of Vortex Breakdown", *Proceedings of the 8th International Symposium on Flow Visualization* [CD-ROM], National Library of Scotland, 1998.
4. Srigrarom, S., and Kurosaka, M., "Shaping of Delta-Wing Planform to Suppress Vortex Breakdown", *AIAA Journal*, Vol. 38, No.1, 2000, pp.183-185.
5. Srigrarom, S., and Kurosaka, M., "Surface Shaping to Suppress Vortex Breakdown on Delta Wings", *AIAA Journal*, Vol. 38, No.1, 2000, pp. 185-187.
6. Srigrarom, S., "On the Formation of Vortex Breakdown over Delta Wings", *Ph.D. Dissertation*, University of Washington, 2001

Figures

Figures 1 (left) and 2 (right): CFD results (VSAERO® CFD code) of flow around delta wing (left) and at the wing's apex (right).

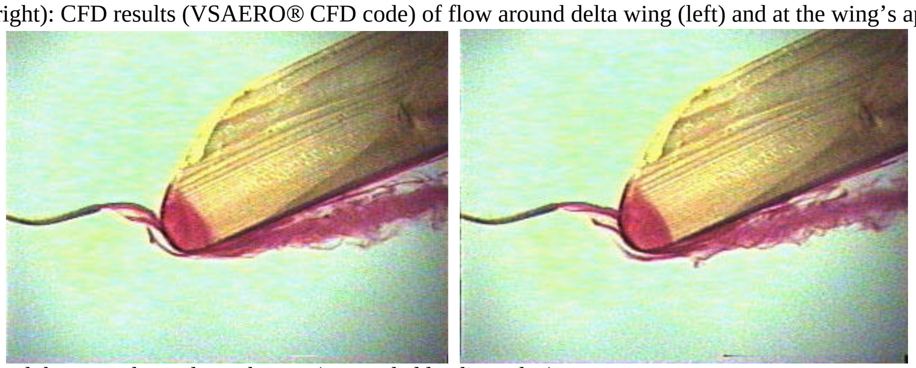


Figure 3: The flow around the curved wood attachment (= rounded leading edge).

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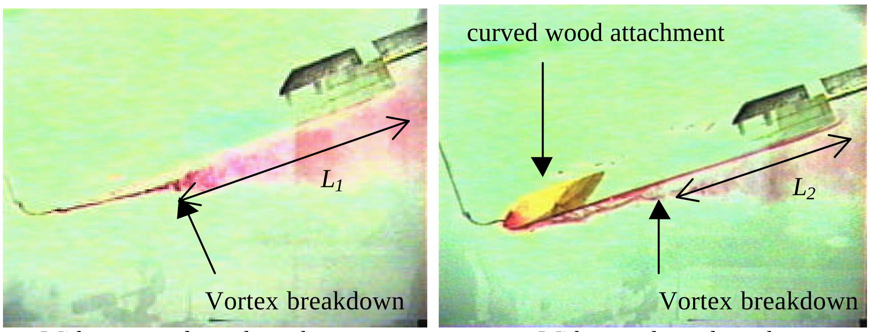


Without curved wood attachment With curved wood attachment

Figure 4: Vortex breakdowns on the wing, at $\alpha = 20°$ with curved wood attachment = rounded L.E. (right) and without = sharp L.E. (left).

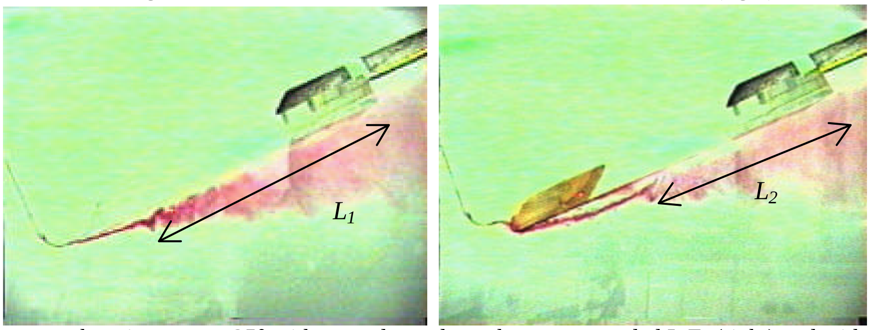
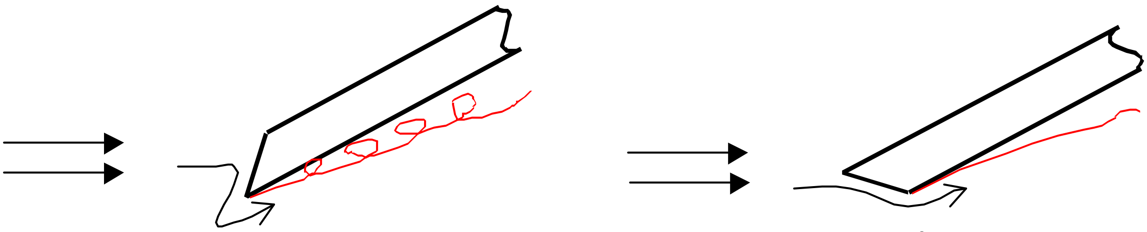


Figure 5: Vortex breakdowns on the wing, at $\alpha = 25°$ with curved wood attachment = rounded L.E. (right) and without = sharp L.E. (left).



Delta wing in normal position
Flow turns around acute angle (small turning radius)
Gives apex vortex strong swirl

Delta wing in vertically flipped position
Flow bends around obtuse angle (large turn radius)
Gives apex vortex weaker swirl

Figure 6: Schematic diagram: Flipping the delta wing vertically flipped results in changing initial circulation/swirl in apex vortex.

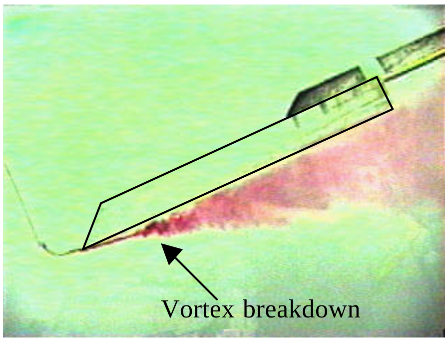


Figure 7: The $\phi = 60°$ delta wing with $t/c = 1/12$, mounted at normal position, at $\alpha = 25°$. The line is drawn to indicate wing for clarity. The dye probe is visible at the left of the wing. The apex vortex has strong swirl and breaks down immediately.

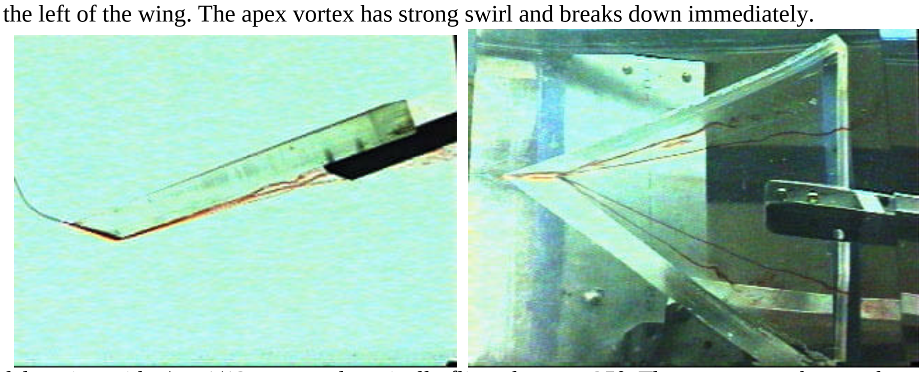


Figure 8: The $\phi = 60°$ delta wing with $t/c = 1/12$, mounted vertically flipped, at $\alpha = 25°$. The apex vortex has weaker swirl, and that, no vortex breakdown exists. (Left: side view, Right: bottom view of the left figure).

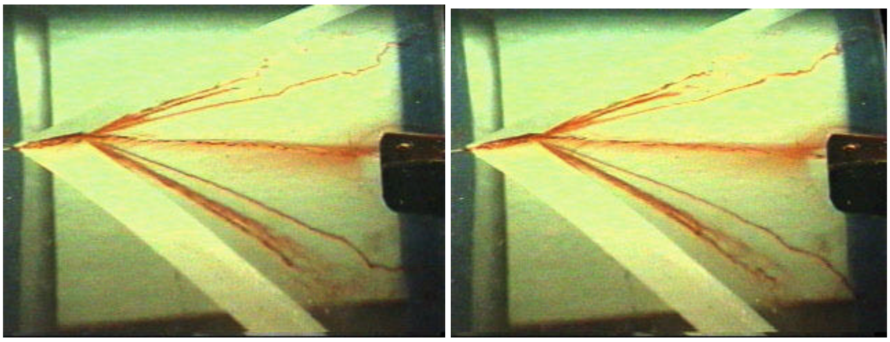


Figure 9: The vertically flipped $f = 60°$ delta wing with $t/c = 1/12$ at $\alpha = 25°$., entire view.

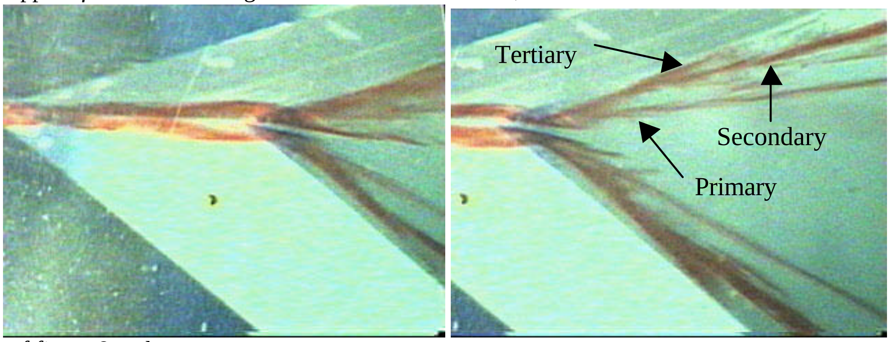


Figure 10: Close-up look of figure 9 at the apex.

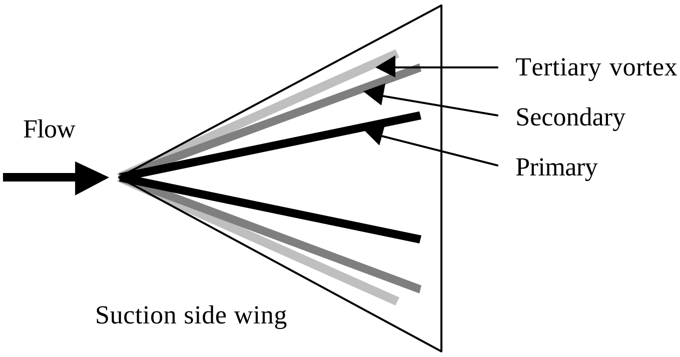
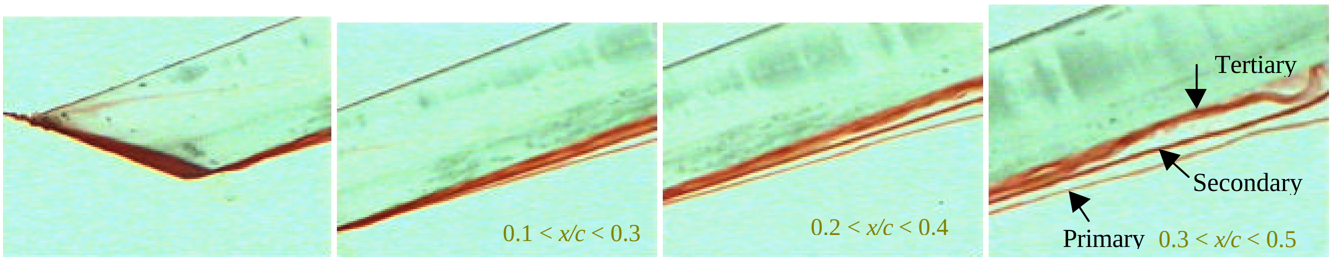
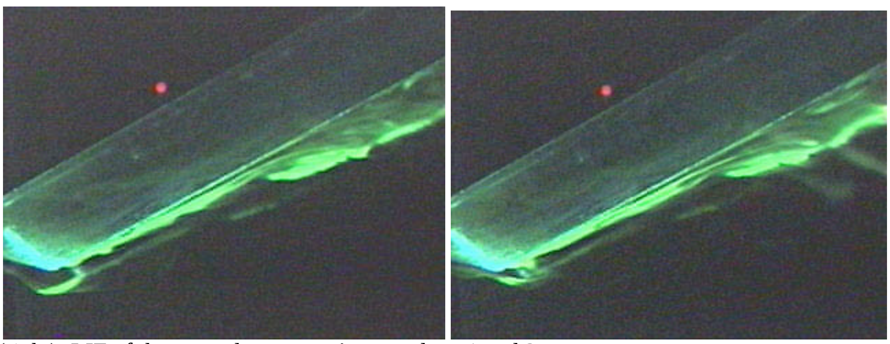


Figure 11: The diagram showing the primary, secondary and tertiary apex vortices.



Figures 12,13,14 and 15: The same wing as in figs. 9 and 10, close-up 1,2, 3 and 4 consecutively.



Figures 16 (left) and 17 (right): LIF of the secondary vortex's core plane 1 and 2.