JOURNAL OF AIRCRAFT
Vol. 42, No. 4, July–August 2005

Engineering Notes

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Impingement of a von Kàrmàn Vortex Street on a Delta Wing

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Introduction

HIGH-PERFORMANCE military aircraft oftentimes employ delta-shaped wings. It is well documented that delta wings at a fixed angle of attack generate lift by separating a shear layer of fluid (air or water) at the leading edge, and this shear layer forms two strong counter-rotating vortices on either side of the wing.[1–5] These leading-edge (LE) vortices are critical to the generation of lift, as they produce a large suction peak on the surface. Under certain conditions, the LE vortices are prone to undergo a change in their coherent structure. The vortex expands around the core, slows down axially, and forms either a bubble or a spiral, with the spiral form being more predominant at Reynolds numbers of interest to aircraft designers. This change, called vortex burst or breakdown, is dependent on the aspect ratio of the wing, angle of attack, pressure gradient, yaw angle, and swirl angle of the vortex, among others.[6–8]

Delta wings have evolved over the years and are now used primarily in the form of leading-edge extensions on many fighter aircraft. As these aircraft become more and more maneuverable, the understanding of the physics of time-dependent unsteady flows is becoming more important. The vortex burst has such a detrimental effect on the lift generation of delta wings that it is important to correctly model the flow, predict it with accuracy, and control the movement of the burst location. If accurate computational models of these maneuvers are to be developed, it is necessary to understand the mechanisms involved in vortex bursting and mixing on the lee side of the delta wing. This is true of so-called "hyperagile" maneuvers (like the Cobra maneuver), where research has been intense.[9–13]

The behavior of the burst location is sensitive to yaw. Aircraft performing the Cobra maneuver (or other high-angle-of-attack maneuvers) can be unstable in yaw.[14–17] Sometimes, the wake of an aircraft's forebody can have vortices at very high angles of attack.[18] In other cases, close proximity of the delta wing to the wake of another aircraft would subject the delta to an external vortical flow. This inspired the authors to consider the effect of an impingement from another set of vortices upon the delta-wing's leading-edge vortices. Because a von Kàrmàn vortex street has a well-known behavior, it was determined to be an ideal candidate for interaction with the delta wing's leading-edge vortex system.

Thus, the objective of this investigation is to test a delta wing under the impingement of a von Kàrmàn vortex wake from a cylinder to obtain qualitative and quantitative data on the effect on the vortex burst location, the mixing, and any other flow features that might occur. For purposes of this paper, the static vortex burst location of a delta wing will be studied as it is being impinged upon by a von Kàrmàn cylinder wake. This will become the baseline; in the future, the test program will expand to include testing of a pitching delta wing under similar conditions.

Experimental Setup

The Water Tunnel at Wichita State University's National Institute for Aviation Research is a 3500-gallon facility with a 2×3 ft (0.61×0.91 m) test section.[19] Installed on this water tunnel is a dynamic pitching, unsteady freestream delta-wing mount. It consists of an aluminum frame and track, on which a carriage is moved by a nylon line and dc motor arrangement. The model is then mounted upside down.[20] For purposes of this test, the tunnel is used as a stagnant water tank, while the towing of the model generated the freestream velocity U_∞.

Attached to the carriage that tows the delta model is a circular, commercially available brass tube $\frac{3}{8}$-in. diameter, with a small fin attached to it on the downstream side. The cylinder (fin's trailing edge) is then located at a distance of 0.25 chord length ahead of the apex of the delta wing when the angle of attack is zero (Fig. 1). The cylinder is held stationary, centered along the root chord of the delta wing, and the fin on the downstream side is set parallel to the freestream direction. Dye is injected at several locations at the base of the side of the fin closest to the camera. Only the von Kàrmàn vortex that sheds on the side of the dye injection ports entrains dye and becomes visible; the vortex on the opposite side (opposite sense of rotation) is not visible.

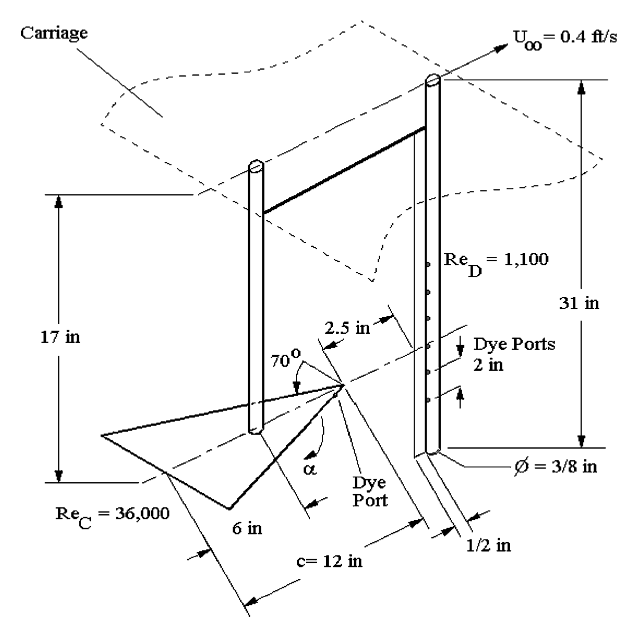

Fig. 1 Overview of experimental setup.

Presented as Paper 2004-4731 at the 22nd Applied Aerodynamics Conference, Providence, RI, 16–19 August 2004; received 19 October 2004; revision received 1 February 2005; accepted for publication 4 February 2005.

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The delta-wing model has a root chord c of 12 in., a sweepback angle of 70 deg, a thickness of $\frac{1}{8}$ in., and sharp leading edge beveled at a 30-deg angle. The wing is towed at 4.95 in./s (0.41 ft/s) with a maximum peak-to-peak velocity deviation of $\pm 5\%$. This results in a von Kàrmàn shedding frequency of 3 Hz, producing sufficient separation between the von Kàrmàn vortex filaments for the video analysis tool to reliably distinguish them.

The images are obtained using the setup as shown in Fig. 2. A camera is placed looking through the side window perpendicular to the path of the delta wing. The images from the camera are mixed along with angle of attack α and velocity U_∞ information and recorded on S-VHS videotape for analysis. The videotape is analyzed each frame (1/30 s) using a VisualBASIC code that identifies the length of the root chord of the wing and the vortex-burst (VB) location of the leading-edge vortex.

There are a few limitations with this experimental setup that need to be acknowledged:

1) Because the angle of attack will change, so does the angle at which the von Kàrmàn vortex street impinges upon the delta wing.

2) The location of the vortex burst is accomplished by identifying where the core flares out (bubble burst) or the location of the first sharp kink (spiral burst). The identified location might or might not coincide with the actual core stagnation point.

3) Some of the features observed (e.g., the distortion of the LE vortex in the presence of the wake filament) cannot be explored further using this (flow-visualization only) system. A certain amount of interpretation must be exercised.

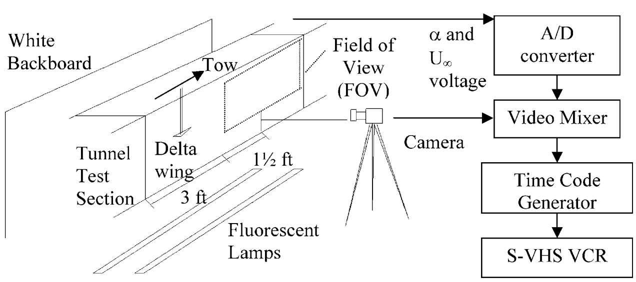

Fig. 2 Overview of the data gathering setup.

4) The uncertainty in burst position is calculated based on repeated measurements of baseline cases. The burst point can be detected to within $\pm 0.02c$.

Quantitative Results

The first set of results is illustrated by plots of the time histories of the vortex-burst position at different angles of attack (Fig. 3). These plots are obtained from a 3-s time window around the center of the field of view (FOV), that is, the time history starts 1.5 s to the left of the center of the FOV, and ends 1.5 s to the right of center. They are then aligned so that the first valley is shown at the left of the plot ($t = 0$). The apex is the $x = 0$ location, where the coordinate is horizontal and parallel to the freestream velocity. Three runs at every angle of attack were performed. Subsequent plots (Fig. 4) only show one of the three time histories measured and analyzed for each angle of attack.

The plots show periodic fluctuations in the vortex-burst location. These fluctuations are nonsymmetrical, and their nature changes with angle of attack. At the lower values of α tested (Figs. 3 and 4a), the vortex burst appears to jump to some location forward towards the apex and then moves gradually in the direction of the trailing edge. As the angle of attack increases (Figs. 4b and 4c), the range between the forward-most and rear-most positions of the vortex burst decreases. This range is large (greater than $0.1c$) at $\alpha = 35$ deg. Eventually, it diminishes to about $0.05c$ at the highest angle of attack tested.

The von Kàrmàn vortex filaments are tracked over several frames (from shedding until the dye becomes too faint to follow) and plotted in terms of their horizontal distance x. The filament's time histories are extrapolated up to the apex of the delta wing based on this observed behavior. When the time histories of the LE burst location are plotted and the wake filaments are extrapolated, it can be observed that the passing of the wake vortex filament provokes a jump towards the apex of the LE burst. The burst then moves aft at approximately the same velocity as the passing of the filament. This relationship holds best at $\alpha = 40$ deg, but is still evident at the highest α tested.

Figure 5 shows the VB position in terms of distance s along the root chord. (Note that a coordinate transformation is required between x and s for nonzero angles of attack.) The average vortex-burst

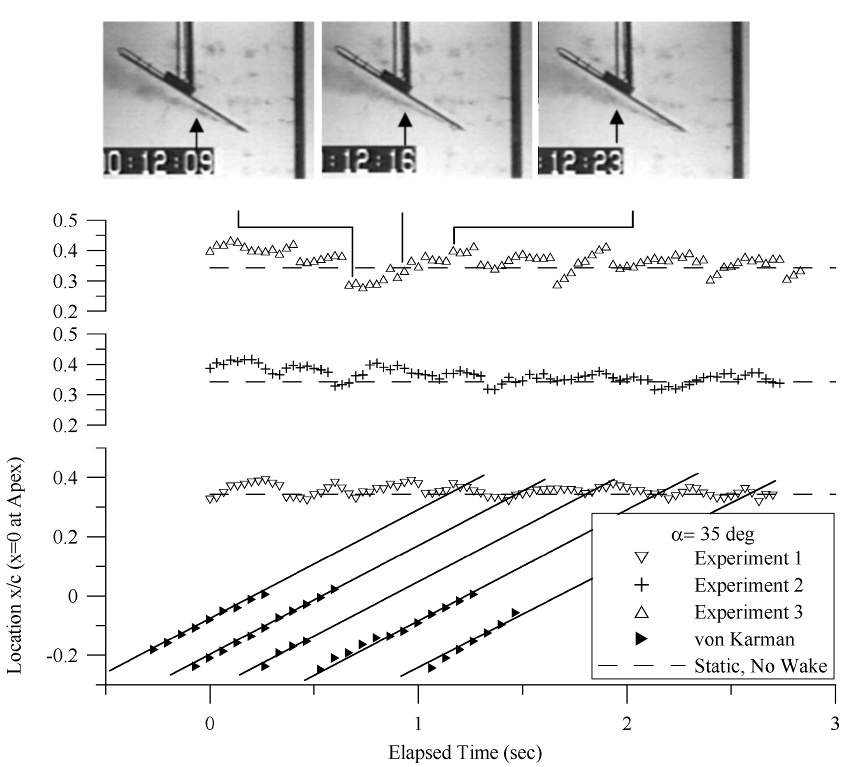

Fig. 3 Vortex-burst time history; $\alpha = 35$ deg.

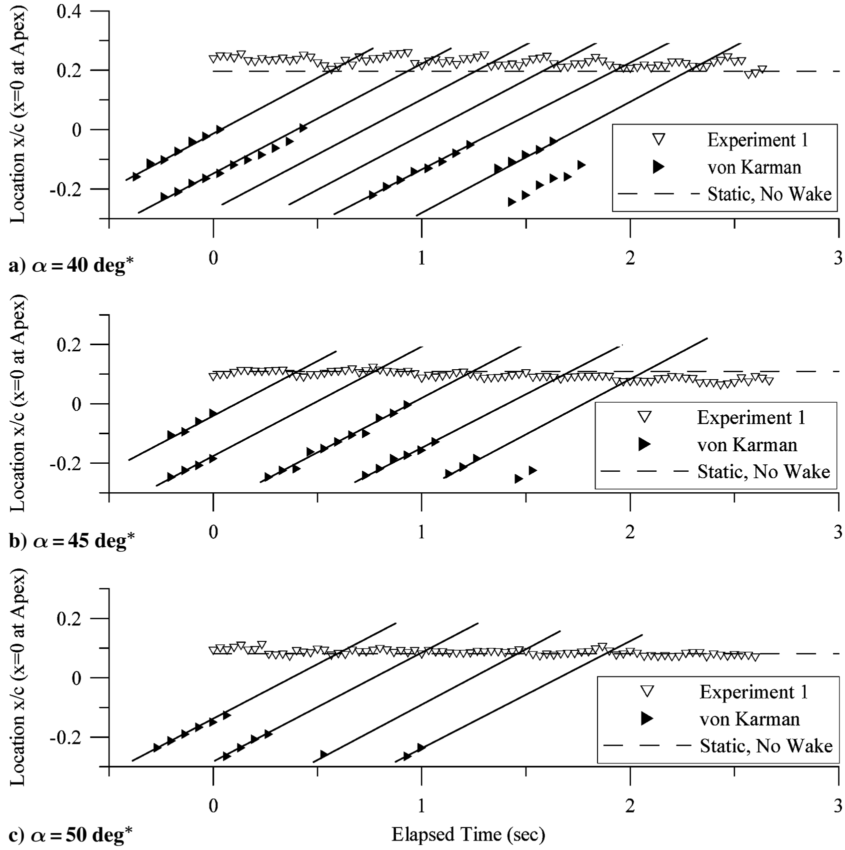

Fig. 4 Vortex-burst time history; 40 < α < 50 deg. (*Only one run per angle is shown, other runs are similar.)

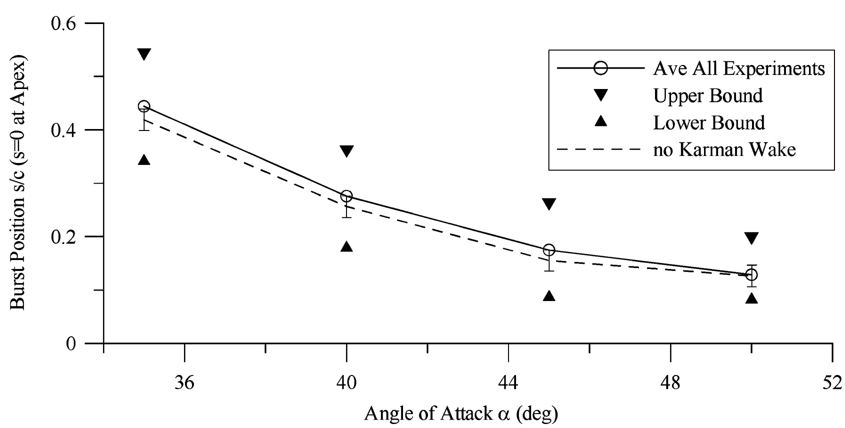

Fig. 5 Angle-of-attack behavior comparison.

position under the wake impingement regime approximately coincides with the static-burst position for this delta wing, in this mount, under unperturbed freestream conditions. The range of motion of the vortex burst under the wake impingement remains relatively constant on either side of the average. There is a slight reduction in the range at the highest α tested, particularly in the lower bound.

Qualitative Observations

During the experiment, the authors observed two phenomena as the LE vortex is impinged by the von Kàrmàn wake. They are illustrated in Fig. 6. First, there is distortion of the LE core in the form of waves that travel along the core. The distortions are not uniform in amplitude, nor do they appear at regular intervals. Second, close observation of the LE vortex core shows that the dye clumps into small, but regularly spaced concentrations. These areas are convected along the core up to the burst. Although no attempt was made to correlate the location of these dye concentration areas with the wake vortex filaments (their dye in the wake filaments has become too faint to reliably accomplish this), it is fair to assume, by virtue of their regularity, that they are related.

After close observation of the wake vortex filaments and the LE vortex core, it appears they become interlaced as the vortex core entrains the wake filaments as shown in Fig. 7. It appears the wake vortex filaments are wrapped around the LE vortex core by the shear layer, such that there is substantial deformation of the wake filament. Further detailed study of this interaction is warranted.

Although the results are not sufficient to put forth a complete picture of the flow mechanics responsible for the behavior, a possibility suggested by the regular dye concentrations in Fig. 6a is that the vorticity of the entrained filaments induces changes in the axial velocity of the vortex core, resulting in a periodic change in swirl angle.

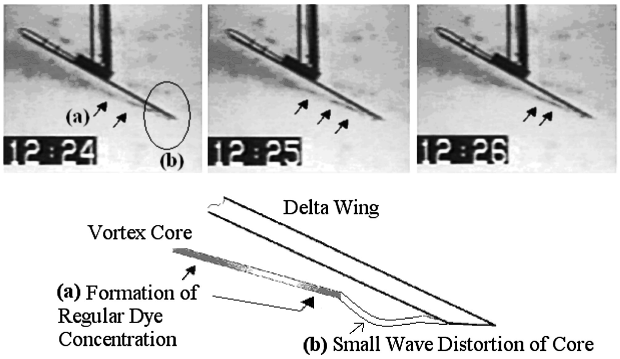

Fig. 6 Observed vortex core distortion modes; $\alpha = 35$ deg.

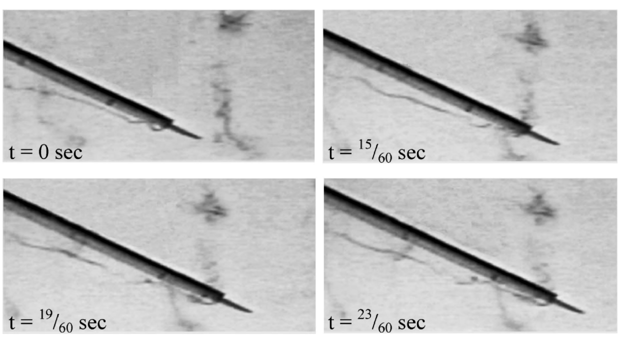

Fig. 7 Entrainment of von Kàrmàn vortex filament in shear layer; $\alpha = 35$ deg.

Even though only one LE vortex was tracked, an asymmetric interaction, where the opposite LE vortex has a mirror-image response, would be expected. This is based on the fact that alternating von Kàrmàn filaments of different sense of rotation are convected downstream. This induces an alternating crossflow velocity field that could be similar to that found on delta wings subjected to periodic yaw oscillations. Although the initial arrival of a von Kàrmàn vortex. precipitates a forward jump, the fact that the burst point moves aft suggests some mechanism to move the burst aft in a periodic manner might be possible.

Summary

A series of experiments, where a von Kàrmàn vortex street wake was made to impinge upon a 70-deg delta wing, was conducted at Wichita State University using a towing mount. There was a temporal correlation to the burst location of the delta wing's leading-edge (LE) vortices, which indicated modulation of the burst location. The LE vortex burst location moved forward towards the apex with the passing of the filaments. This jump was most noticeable at lower angles of attack. It was also found that the average vortex-burst location remained approximately the same whether the freestream flow was clean or in the wake. Qualitatively, as the von Kàrmàn vortex filaments were entrained by the shear layer, they appeared to wrap themselves around the core. Additionally, there was a small-amplitude wave distortion of the LE core. Dye concentrations at regular intervals were also observed in the LE vortex core.

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