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Delta Wing Vortex-Burst Behavior Under a Dynamic Freestream

Ismael Heron*
Bombardier Learjet, Wichita, Kansas 67209
and
Roy Y. Myose†
Wichita State University, Wichita, Kansas 67260-0044

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A series of experiments was performed at Wichita State University's water tunnel on a 70-degree-sweep delta wing using a towing mount. A video camera captured dye-flow visualization images of the vortex burst that were subsequently analyzed using a computer-assisted image analysis software. The aim was to better understand the relationship between the freestream velocity and the time constants involved in the movement of the vortex-burst point. Experiments indicated that a change in the freestream velocity changed the forward progression of the vortex burst. Under pitch-up conditions, deceleration resulted in a momentary retardation in the forward progression of the burst, whereas acceleration resulted in a faster progression toward the apex.

Nomenclature

c	=	wing root chord
dU_∞/dt	=	deceleration rate
Re_c	=	chord Reynolds number, $U_\infty c/\nu$
s	=	coordinate along root chord
U_∞	=	freestream velocity
$U_{\infty,\max}$, $U_{\infty,\min}$	=	velocities before and after acceleration or deceleration
α	=	angle of attack
β	=	yaw angle
κ	=	nondimensional pitch rate, $(d\alpha/dt)c/(2U_\infty)$

Introduction

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. In particular, if accurate computational models of these maneuvers are to be developed, it is necessary to understand the mechanisms involved in features such as vortex bursting and mixing on the delta wing. This is true of so-called hyperagile maneuvers.

It is well documented that delta wings at a fixed angle of attack generate lift by separating a shear layer of air (or fluid, such as 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 undergo small fluctuations in space [6], but remain relatively fixed over the suction side of the delta wing, and are critical to the generation of lift, as they produce a large suction peak on the surface. Two much smaller vortices, the secondary vortices, are also formed, as seen in Fig. 1. In other words, LE vortices are the result of a balance between vorticity being generated at the leading edge and the ability of the flowfield to convect said vorticity along the vortex core.

The LE vortices are not stable, and at some point, their coherent structure will undergo a dramatic change, expanding around the core, slowing down axially, and either forming a bubble or a spiral, with the spiral form being more predominant at Reynolds numbers of interest to delta wing designers. This change, called vortex burst or breakdown, is dependent on the aspect ratio of the wing, angle of attack, pressure gradients, yaw angle, and swirl angle of the vortex, among others [7,8]. The exact reason for this bursting is not known, but research has focused on two general areas:

1) The flows upstream and downstream of the vortex burst are two separate and very different flows, and the vortex burst is a necessary feature, similar to a hydraulic jump [7].

2) The core of the LE vortex serves as a mechanical waveguide for longitudinal waves; these waves either coalesce or become critical, thereby triggering the burst [9].

The effect of the vortex burst is to reduce the lift generated by the delta wing. If the delta wing is pitched to a given angle of attack α and then maintained at that angle until the transient flow features die down, it is said to be tested under static conditions. As this process is repeated at increasing values of α, the vortex-burst point will move forward toward the apex of the wing due to the increasing adverse pressure gradient. This progressively deprives a larger area of the delta from the benefits of the high suction peak.

In most flows, the strength of the vortex is dependent upon the Reynolds number. In delta wing flows, however, the LE vortex-burst behavior on delta wings appears to be less sensitive to Reynolds number when the burst is located over the delta wing. This is most likely due to the fact that the sharp leading edge serves as a fixed separation line. This peculiarity in the burst behavior allows a wide range of static testing of models in different media (air, water, etc.) to be directly compared.

Compare this with the dynamic situation in which the delta wing is continuously pitched, never allowing the flow features to become steady. Under dynamic conditions, in which the delta wing is pitched upward at a given rate, the location of the vortex burst is farther toward the trailing edge compared with the same angle of attack under static conditions (thus, it lags behind the static angle-of-attack location). This produces a phase lag in the burst location, allowing transient values of lift to exceed those obtained during static testing [10–14]. Similarly, pitching down the delta wing moves the vortex-burst location forward. This produces a phase lead (i.e., the vortex burst occurs at a position farther forward during the pitch-down than if it were static for a given angle of attack) and a reduction in lift, compared with the similar static angle of attack. This introduces the notion of a hysteresis effect, or time delay, in which there is a difference in the measured C_L values if the angle of attack is increasing or decreasing [15]. The magnitude of the phase lag/lead

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*Senior Flight Sciences Engineer. Member AIAA.

†Professor, Department of Aerospace Engineering. Associate Fellow AIAA.