JOURNAL OF AIRCRAFT
Vol. 46, No. 1, January–February 2009

Experimental Investigation of Plain- and Flapped-Wing Tip Vortices

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DOI: 10.2514/1.38217

Particle image velocimetry was used in a low-speed wind tunnel to investigate and characterize wing tip vortex structures. A rectangular wing of a subsonic wall interference model was used as a vortex generator in two different configurations: 1) plain wing and 2) flapped wing with the trailing-edge flap extended at 20 degrees. Vortex flow quantities and their dependence on angle of attack at Reynolds numbers of 32.8×10^3 and 43.8×10^3 were evaluated. Assessment of measured data reveals that the peak values of tangential velocities, vortex strength, and vorticities are directly proportional to the angle of attack. The vortex core radius value grows slowly as the angle of attack is increased. Both plain and flapped configurations showed similar trends. The peak tangential velocities and circulation almost doubled when the flapped configuration was used instead of the plain wing.

Introduction

TRAILING vortices behind aircraft are inevitable consequences of the creation of lift. It generates downwash on the aircraft wing, which reduces lift and increases drag. Because trailing vortices tend to persist for many miles behind the aircraft, they pose a potential hazard for the follower aircraft. Wake–vortex encounter is most likely near airport runways, because planes are likely to fly in close proximity when they are near the runway and because the tip vortex circulation is maximal when a plane is taking off or landing (Arndt et al. [1]).

Chow et al. [2] examined the rollup process of wing tip vortices in terms of mean flowfield and Reynolds stress tensor at $x/c = 0.678$ downstream (x is the downstream distance from the trailing edge and c is the chord length) using a seven-hole pressure probe. They found that the axial velocity in the vortex core reached 1.77 times the freestream velocity just upstream of the trailing edge, and turbulence levels in and around the vortex were initially very large but decayed rapidly. Significant tip vortex rollup appears even at the wing trailing edge; Shekarriz et al. [3] graphically showed early rollup of vortex. Although some researchers claim that rollup of the tip vortex can be considered to be completed almost immediately downstream of the trailing edge of the wing ($x/c = 1$), Shekarriz et al. [3], Lombardi and Shinner [4], Birch and Lee [5], Birch et al. [6], and Green and Acosta [7] showed that rollup is essentially completed, on very different wing geometries, within 2–3 chords of the wing trailing edge. Shekarriz et al. [3] also reported that the overall circulation of this vortex remains nearly constant throughout the range $0 < x/c < 6.7$. Birch and Lee [8] measured tip vortex by particle image velocimetry and found that, depending on the angle of attack, the axial velocity in the core could have wakelike or jetlike patterns. Zhang et al. [9] showed that the radial distribution of tangential velocity and vorticity of the wing tip vortex is described reasonably well by the exponential vortex solution.

Schell et al. [10] used hot-wire anemometry to study the wake vortex structure behind a flapped wing. A wing with flaps was investigated by Birch and Lee [8] using a miniature seven-hole pressure probe and hot-wire probe to measure the mean and fluctuating velocity components. The displaced flap produced a more concentrated vortex with higher induced drag of maximum increase by 32% at $\delta = 20$ deg (where δ is the trailing-edge deflection angle) due to the presence of massive flow separation induced by the deflected flap. Many investigations on the wake structure of plain rectangular wings have been performed experimentally and numerically, whereas investigations on wings with flaps are relatively few in number.

Wing tip vortex flows exhibit unsteadiness from sources other than turbulence. Those sources are not clear yet. This implies meandering (wandering) of the tip vortex in space and time downstream of the wing. The vortex core movements in an apparently random fashion were observed by Corsiglia et al. [11] and Baker et al. [12]. Time-averaged Eulerian point measurement at a fixed location is equivalent to spatial averaging over distances several times the vortex core radius. Thus, a primary result of meandering is that fixed-probe measurements of velocity and pressure cannot be trusted at distances more than one chord downstream of the wing. Wandering leads to large uncertainties in mean velocity and turbulence based on point measurement. Baker et al. [12] reported measurement uncertainties up to 35% in peak tangential velocity. Devenport et al. [13] found that tip vortex wandering was typically less than 1% of the chord length and 3% of the vortex core radius, but Corsiglia et al. [11] recorded wandering of many times the core diameter. Zhou et al. [14] investigated tip vortex wandering behind a rectangular wing using particle image velocimetry. They found up to 33% underestimates in maximum streamwise vorticity of the tip vortex if the fixed probe is used to measure the tip vortex. The same investigation showed that wandering of tip vortices is due to the unsteady nature of separation more than to the wind-tunnel unsteadiness.

In addition to the wandering, the wing tip vortices are very sensitive to even very small intrusive probes (Holl et al. [15]).

Aiming for consistently reliable data, particle image velocimetry (PIV) as a minimally intrusive measurement technique is used in this

Received 23 April 2008; revision received 7 August 2008; accepted for publication 8 August 2008.

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