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# Vortex formation on squared and rounded tip

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ABSTRACT

The vortical flow originated from the tip of a NACA 0012 rectangular wing is described in its initial formation and development over a rounded and a squared tip. Smoke visualizations show the rolling-up kinematic and evolution of the vortical systems moving the plane towards the trailing edge. The presence of intense secondary vortices affects the primary vortex unsteadiness and shape during the formation and in the early wake. Stereoscopic Particle Image Velocimetry is used to describe vorticity, axial velocity and turbulent kinetic energy distributions of the vortex during the formation and in the early wake at different angles of attack of the wing. The rolling-up of the vorticity sheet around the vortex system is strongly influenced by the vortex shape and the intensity of secondary vortices. Turbulence coming from secondary structures and shear layers is wrapped into the roll-up of the vortex and high levels of turbulence are measured in the vortex core. However, a laminar vortex core is observed for the lower angle of attack in the early wake. Comparing the meandering of the vortex for the two wingtip geometries, two different sources of the vortex fluctuation in the wake are identified: the interaction of secondary vortices moving around the primary vortex and the rolling-up of the vorticity sheet. Lastly, measurements in the wake of the wing at zero incidence are also presented showing a distinctive counter rotating vortex pair.

## 1. Introduction

It is well known that the flow behind a lifting surface, such as a wing, results in a persistent and intense pair of organized vortical structure called trailing vortices or wingtip vortices. Whereas the evolution, the characteristics, the structure of these vortices have been extensively investigated, its origin is often misrepresented. Green [19] explains the occurrence of the tip vortices in three distinctive and complimentary ways. The first and commonly adopted considers the pressure difference between the wing pressure and suction surfaces which accelerates the fluid around the tip. This movement, combined with the streamwise velocity component, produces a vortical structure. A second and more schematic explanation involves Helmholtz vortex laws which present the tip vortices as the connections between the bound vortex (net circulation around the wing, from Kutta–Jukowski's law) and the starting vortex (matching of wing circulation when the wing starts to move, from Kelvin's theorem). A third way to explain tip vortices is in terms of shear layer that exists near the tip. The undisturbed flow and the flow over the wing surfaces are not parallel which implies vorticity approaching the tips. This mechanism allows for two vortices of opposite sign behind each wingtip without producing lift. However, what is observed is that the trailing vortex is more complex than these mechanisms and the flow at the wingtip involves development and interactions of multiple vortical structures, shear layer instabilities, three-dimensional separations and reattachments; in the wake, rolling-up of the vorticity sheet, vortex instabilities, decay and diffusion, vortices interaction and merging are observed. Furthermore the formation and development are strongly affected by several factors such as wing geometry, tip geometry, wing load distribution, vortex circulation and nature of the boundary layer on the wing.

Moreover, many studies focused on the modification and control of the vortex through wingtip devices such as passive (static) methods based on changes in the wing configuration (vortex generators, winglets, wingtip mounted propellers, different tip geometries, splines, spoilers) and active (dynamic) methods. In the latter devices, continuous or periodic controls are adopted such as blowing, active Gurney flaps, boundary layer separation control, active surface mount actuators. However, although many studies on wingtip vortices have been conducted, studies on the detailed flow physics are not that numerous. The complex three-dimensional flow near the tip is not adequately described, especially regarding the vortex unsteadiness and the mechanism of vorticity transport from the near-surface viscous layers into the concentrated trailing vortex.

Chow et al. [6] presented a study on the initial roll-up and early wake evolution of the tip vortex over a rounded wingtip. The secondary and tertiary vortices merge into the primary vortex within one chord from the trailing edge of the wing and the form an

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axial-symmetric vortical structure with axial velocity higher than the freestream (jet-like). As Freymuth et al. [15] stated, flow visualization seems to be the best approach to obtain clues about complex vortical structures and many studies on this phenomenon begin with flow visualizations [6,26,35]. Since the squared tip is a source of singularities in theoretical or numerical analysis, the study of flow over such geometry is particularly significant [14]. Bailey et al. [4] adopted different experimental techniques in order to investigate the evolution of the vortex on a squared tip. The wingtip vortex was found to be formed by three distinct co-rotating vortices. Smoke visualizations performed by Katz and Galdo [26] showed the complex multiple vortices structure and interaction. Secondary vortices are formed on the side of the wing and eventually they climb around the corner contributing to the unsteadiness of the primary vortex. PIV measurements on squared tip by Birch et al. [5] confirmed the multiple vortices structure in the initial rolling-up of the vortex and they showed both axial velocity deficit and excess in the vortex center at a distance of 1.5 chords from the trailing edge. Karakus et al. [25] concluded that the tip region is dominated by the strong interaction between the multiple secondary vortices and the primary vortex. Zuhal and Gharib [38] found this interaction also in the wake up to 3 chords of distance from the wing; they also found a correlation between a higher fluctuation of the primary vortex location and the presence of strong secondary vortices.

The random movement of the vortex on the plane perpendicular to its axis is commonly known as meandering or wandering and it can be attributed to a variety of reasons including freestream turbulence, vortex instabilities, perturbation due to the rolling-up shear layer and unsteadiness originating on the model [3,22]. Therefore, the understanding of mechanisms and effects of these contributes to the meandering is crucial in the correlation of different experiments and numerical analysis.

The meandering fluctuation is often identified and subtracted from instantaneous flowfields before the average flow is evaluated (e.g. [11,33]). However, this operation does not completely eliminate turbulence in the vortex flow which sources can be found in the boundary layer, viscous wake (streamwise shear), vortex sheet (lateral shear), vortex circulation and atmosphere [36]. The turbulence distribution in the vortex flow and the evolution of the turbulence inside the vortex core have been a matter of many experimental and theoretical studies (e.g. [21,34]). Phillips [30] described the relaminarization process and the resulting solid body rotation of the inner core as the result of high centrifugal forces which dissipate the turbulence at a rapid rate. Cotel and Breidenthal [8] presented a model for stratified entrainment so that turbulent diffusion is limited and the growth of the vortex is essentially dictated by molecular viscosity. Chow et al. [7] presented high turbulence level in and around the vortex core in the early wake coming from the wingtip boundary layers being wrapped during the roll-up of the vortex. They also linked the generation of turbulence with the high radial gradients of the axial velocity within the vortex core.

## 2. Experimental procedure

The wing model tested was a rectangular planform with NACA 0012 profile, 0.76 m chord and 0.75 aspect ratio. Squared and a rounded wingtips were tested. The wing area with the round cap was around 7% greater than the wing area with squared tip. The model was mounted vertically on a circular plate on the floor allowing the angle of attack to be adjusted by rotation about the quarter chord, coincident with the middle plane of the test section.

The reference systems adopted in these experiments are sketched in Fig. 1. A fixed reference system $x$–$y$–$z$ with origin at the trailing edge of the tip at angle of attack $\alpha = 0°$, with $x$ directed as the freestream, was used. An additional coordinate $\tilde{x}$ with origin at the leading edge and directed as the wing chord $c$ was also adopted for the experiments on the vortex formation on the wing.

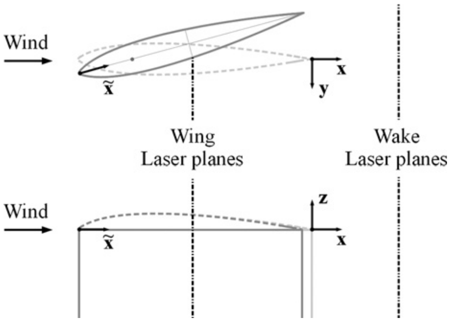

**Fig. 1.** Experimental arrangement.

Two experimental techniques were adopted and two wind tunnels were used for the experiments: a low-speed open circuit wind tunnel for smoke visualizations on the initial roll-up and formation of the vortex on the wing; a subsonic return wind tunnel for Stereoscopic Particle Image Velocimetry on vortex formation on the model and development in the wake.

### *2.1. Smoke visualization technique*

Smoke visualizations were conducted in a purpose built flow visualization wind tunnel with cross section of 0.91 m by 0.91 m. The two tip geometries were tested at a Reynolds number of 3000 at 12° of angle of attack. The smoke lines were illuminated with a continuous laser sheet of 2 mm thickness from a diode laser (5 W power at 532 nm) which was shone from the top of the test section and perpendicular to the freestream flow. A high resolution camera (DALSA 2M30) of 1600 by 1200 pixels with 50 mm focal length lens and $f$-number equal to 4 was mounted 1.5 chords downstream of the trailing edge of the wing and it was used to capture the initial roll-up and the wingtip vortex formation at several locations along the chord. The exposure time was set in a range between 1 and 400 ms so that the vortex system was clearly visible.

The smoke tracer was Shell Ondina EL oil and high pressure carbon dioxide was used as a propellant. The smoke was injected through uniformly distributed orifices of 1 mm of diameter and 6.35 mm step, drilled on a pipe of 12 mm of diameter positioned vertically in the center of the test section inlet (1 chord upstream of the leading edge of the wing). Pressure, density and velocity of the smoke at the orifices were set so that smoke filaments did not show disturbances.

### *2.2. Stereoscopic Particle Image Velocimetry*

The SPIV experiments were conducted in a low-speed, closed-return facility with test section dimensions of 2.65 m wide by 2.04 m high and by 5.60 m long and turbulence level of 0.4%.

Two CCD cameras of 11 Mpixels were mounted on one side of the test section independently from the wind tunnel and 200 mm focal length Nikon lenses were used with $f$-number equal to 8. The angular stereoscopic system in Scheimpflug condition was adopted, as described by Zang and Prasad [37]; the angles between cameras and object plane were between 40° and 47°. These values maintain low errors in the evaluation of both the in-plane and out-of-plane velocity components [28]. A double-frame/single-pulse method [27] was used so that at each time step two images were recorded by each camera in correspondence with two different laser pulses. The time delay used was calculated following