# 3D STEREO PIV STUDY OF TIP VORTEX EVOLUTION ON A VAWT

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## Abstract

The increased application of Wind Turbines in the built environment has lead to the recurrence of Vertical Axis Wind Turbines (VAWT). In highly turbulent urban flow fields, VAWT present several advantages over Horizontal Axis Wind Turbines, mainly due to its insensitivity to yaw and aesthetics. The complex aerodynamics of the VAWT are dominated by three-dimensional unsteady flow effects, including phenomena such as wake-blade interactions, wake deformation in the rotor volume, tip vortex effects, dynamic stall and time-varying induction. The present research paper aims at understanding and quantifying the development of the near wake of a VAWT, by experimentally measuring by 3D-Stereo Particle Image Velocimetry the evolution of the tip vortices and immediately adjacent flow. A two bladed H-Darrieus VAWT model was tested in the low speed/low turbulence wind tunnel at the Technical University of Delft. Stereo-PIV measurements were used to visualize the flow in the near wake focusing on the flow field around four different tip geometries at two different tip speed ratios. The measurement planes cover several section of the rotor volume, allowing for a reconstruction of the evolution of the tip vortex and nearby dynamic stall shed wake. The formation, convection and dissipation for each tip vortex were located and quantified. A comparison the Stereo-PIV Data for the four different tip geometries shows a clear influence of the tip shape on the generation and release of the tip vortex and the influence of the tip speed ratio on the interaction between the dynamic stall and the tip vortices. The experimental results provide a new insight into the development of dynamic stall and vortex formation on VAWTs. The visualization of the flow field for the different cases provides an important database for the validation of numerical dynamic stall and vortex models

Keywords: Vertical Axis Wind Turbine, PIV, Tip Vortex, Wake, Darrieus

1. * Nom	enclature		$U_{\infty}$
c D	airfoil/blade chord, m rotor diameter, m	$\Gamma$ circulation $m^2/s$	
$R \\ Re \\ U_{\infty} \\ U$	rotor radius, m Reynolds number $Re = c.\lambda.U_{\infty}/\nu$ Unperturbed velocity m/s Local flow velocity m/s	<b>2. Introduction</b> One of the results of the development of solutions for the built environment is the reappearance of Verti- cal Axis Wind Turbines (VAWTs). Extensive research	

was conducted until the end of the 1980's, when, due to the increasing success of the application of Horizontal Axis Wind Turbines (HAWTs), it was discontinued. Yet, in the built environment, VAWTs present several advantages over the (presently) more common HAWTs, namely: low sound emission (consequence to its operation at lower tip speed ratios), better esthetics due to its three-dimensionality (more suitable for integration in some architectural projects, since it follows the concept of volume of the building), its insensitivity to yaw and its increased performance in skew (see Mertens et al[1] and Simão Ferreira et al[2],[3]).

The three-dimensionality of the rotor implies that the near wake develops in the rotor volume and flows over the downwind passage of the blade, in bladevortex interaction phenomena.

The designs of VAWT for the built environment tend to favor the H-Darrieus (or derived forms) configuration, thus presenting an aerodynamic behavior where tip vorticity, specially the one generated in the upwind part of the rotation, is paramount.

The present research paper aims at understanding and quantifying the development of the near wake of a VAWT, by experimentally measuring by Stereo PIV the evolution of the tip vortices and immediately adjacent flow. The results focus on the generation, trajectory, evolution and dissipation of tip vortices for four different tip configurations at tip speed ratio  $\lambda = 2$ and  $\lambda = 4$ .

#### 3. Vortex Dynamics of H-Darrieus

Although much is usually mentioned regarding the blade-vortex interaction of the wakes with the downwind passage of the blade, very little consideration has been given to the tip vorticity of the H-Darrieus. The dynamics of the wake (figure 1) are not only a result of BVI and curvature of the wake, but also of a pronounced inboard movement of the tip vortices generated in the most upwind part of the rotation, which have a large impact in the induction at mid-span in the upwind part and in the BVI phenomena in the downwind passage. The dynamic of this inboard movement are proved by the present experimental results.

#### 4. Experimental Setup

#### 4.1. Wind Tunnel facility

The Low-Speed Low-Turbulence Wind Tunnel (LTT) of the Faculty of Aerospace Engineering of Delft University of Technology (TU Delft) has an octagonal test section that is 1.80 m wide, 1.25 m high and 2.60 meters long. This tunnel has a contraction ratio of 17.6, resulting in a maximum test section velocity of 100 m/s and a low turbulence intensity ranging from .015% at 10m/s to .07% at 75m/s.

#### 4.2. The rotor

The rotor model is a two bladed H-Darrieus Vertical Axis Wind Turbine. The blades are NACA0015and NACA0018 profiled, with four different tip configurations (see figure 2).



Fig. 1: Numerical simulation with 3D Unsteady Panel Model of the experimental model and conditions.



Fig. 2: Schematic of the two blades with four different tips.

The tips are designed to follow a elliptical decrease of chord to 1/3 at the tip, starting at a distance from the tip of 1/7 of the span. The description *leading edge, trailing edge* or *quarter chord* identifies which reference line remains straight throughout the tip (thus resulting in different tip shapes). The *flat chord* corresponds to a straight rectangular tip with no decrease of chord.

The rotor is D = 0.575m diameter and H = 0.7m span and a c = 0.06m chord at mid section. The blades are supported to the rotor axis by two spars and two tension wires. The rotor was placed in the center of the test section (in z and y directions, see Figure 3).

The experimental work was performed at Reynolds  $Re = 8 * 10^4$  and and tip speed ratio  $\lambda = 2$  and 4. The Reynolds numbers is calculated using the blade's chord and rotational velocity as reference scales  $Re = \frac{R \cdot \Omega \cdot c}{\nu}$ , where  $\nu$  is the kinematic viscosity of air.

#### 4.3. Diagnostic apparatus

The flow was continuously seeded with approximately one micrometer droplets generated by a fog machine. The particle tracers are illuminated by a light sheet introduced vertically from the test section, perpendicular to the blade and located at its mid span. The laser light sheet was generated by a *Quantec CFR 200* Nd: YAG laser (200 mJ/ pulse), and is



Fig. 3: Schematic of the experimental setup at the TUDelft LTT.

approximately 2 - 3mm thick at the field of view (FOV). Two CCD cameras set at 1200 \* 1040 pixels were used with a narrowband green filter for daylight interference. The reference FOV is approximately 150mm \* 120mm and the time interval between exposures was set to obtain an eight pixel displacement at  $4U_{\infty}$ . Approximately 30 samples were acquired per azimuthal position. The images were analyzed with the iterative multi-grid window, with an integration window size of 16 pixels and overlap factor of 50%.

#### 5. Phase averaging of the velocity field

The analysis of the flow and tip vortex development is performed assuming the existence of a dominant phase locked average flow field, determined by the azimuthal position of the blade. The instantaneous flow can be regarded as the result of a mean flow, a phase averaged flow and a random fluctuating term, following the traditional triple decomposition. The predominance and asymmetry of the phase averaged flow, and the importance of the vorticity development in terms of rotor induction, imply that the analysis of a time averaged mean flow is irrelevant for physical insight. Thus, the analysis will focus on the phase averaged flow components.

#### 6. Tip vortex evolution

The trajectory, shape and intensity of the tip vortices is one of the main outputs of the experimental campaign.

Figure 4 shows the evolution of the tip vortex of the quarter chord tip at seven planes perpendicular to y, at y = -0.18m, y = -0.12m, y = -0.06m, y = 0.0m, y = 0.06m, y = 0.12m and y = 0.18m; the results are taking at each plane at different azimuthal moments of rotation ( $\theta$ ,  $\Theta$ ) for each plane. The evolution of vorticity indicates three main aspects:



Fig. 4: Evolution of the tip vortex over upwind part of the rotation (vorticity contours).

- The displacement in the *z* direction is dependent of the plane (and thus, of the moment of rotation)
- As the vortices are closer to the y = 0.0m plane, they experience a more pronounced movement movement. inboard into the rotor volume.
- The tip vortex expands very rapidly immediately in the near wake.

Figure 5 show the projection in the xz plane of the core of the tip vortices during the rotation in the near wake region. The significant inboard movement of the tip vortex is clearly visible. This inboard movement can be explained by the curvature of the trajectory of the blade and thus, the U-shape of the wake; this U-shape, results in a tip vorticity segment on the most upwind part of the rotation that is perpendicular to the tip vortex segment on the side of the rotor. These segments induce a inboard velocity to the upwind segment, resulting that the vortice core at the planes in the vicinity of y = 0.0m move inboard. There is a dynamic effect in this process, that makes the displacement of the vortices not only proportional to the induced velocities, but also to the duration of this acceleration effect. During the rotation, as the blade moves upwind, the previously shed vortices induce a inboard acceleration on the newly shed wake. This induction increases in strength as the circulation of the shed vortices increases with increasing angle of attack (until dynamic stall occurs) and increasing angle between vortex segments.

## 7. The influence of tip shape

The shape of the blade tip influences the location of the point where the trailing vorticity at the tip starts to concentrate and form the main core of the tip vortex. Figure 6 shows the illuminated seeding particles for four moments of the rotation at the plane y = 0.0m. The images are then a smoke visualization of the tip vortex and it is possible to recognize the location of



Fig. 5: Trajectory of the tip vortex in the xz plane during upwind part of the rotation (quarter chord tip).



Fig. 8: Near wake trajectory and evolution of the tip vortex for trailing edge and quarter chord tips (vorticity contours).

the tip core by the absence of particles. In the cases of a straight trailing edge (*flat tip* and *trailing edge*), the generation of the tip vortex is at the extremity of tip, and the trajectory of the released tip vortex more outboard. For the *quarter chord* and *leading edge*, the generation of the tip vortex is more inboard and the released tip vortex moved more into the rotor volume.

Figure 7 shows the vorticity field for the same cases.

This difference of trajectory and near wake acceleration can be seen on the projection of the trajectory in the xz plane presented in figure 8 for the cases of the *trailing edge* tip and *quarter chord* tip.

The PIV data allows the calculation of the strength of the tip vortex by integrating the circulation inside a contour defined by a residual limit of vorticity. the definition of this limit contour is a source of uncertainty of the method, since the option for high resolution close to the vortex core results in higher uncertainty in the lower speed regions at the edge of the vortex, where pixel displacement of the particles is smaller. An uncertainty ranging 10% of the calculated tip vortex strength can preliminarly be assumed to be associated with the results. Figure 9 presents the



Fig. 9: Vortex strength (circulation) evolution for four different tip shapes at y = 0.

strength of the tip vortex at the y = 0.0m plane for the four different tips. The results immediately show a gap in the results associated with the NACA0015 profiled blade (upper lines, (*flat tip* and *trailing edge*)) and the NACA0018 blades. Notice that this plane occurs after the stall angle of the blades, for which the different stall behavior of the two blades can justify this difference.

For the four tips, the evolution of the strength of the tip vortex shows two different moments: an initial increase of the intensity, probably associated with the rolling up of part of the vorticity shed by the remaining trailing edge and a subsequent decrease of intensity when the tip vortex can be considered as developing as a free vortex.

## 8. The effect of tip speed ratio

The operation of VAWT in urban environments implies that, due to the high level of turbulence, associated with fast wind speed changes, the rotor will operate in an out of optimal tip speed ratio, and operation at low tip sped ratios with high effect of dynamic stall can be frequent. Figure 10 presents a comparison for two tips of the vorticy field at y = 0.0mm at  $\lambda = 4$  and  $\lambda = 2$ . For  $\lambda = 2$ , the occurrence of large dynamic stall induces a strong shed vorticity that interacts with the trailing vorticity of the tip vortex. This recults in a blob of vorticity being shed over the span of the tip.

The shape of this vorticity blob is also depending on the shape of the vortex tip. Figures 11 and 12 show a comparison the trajectory and contour shape for the tip vorticity at  $\lambda = 4$  and  $\lambda = 2$  for the *trailing edge* and *quarter chord* tips. The contours show that the lower tip speed ratio, the vorticity is not only distributed more spanwise, its trajectory is more inboard.

#### 9. Conclusions

The experimental research of the tip vorticity of the H-Darrieus VAWT using Stereo PIV proved successful in detailing and qualifying the evolution the evolution of tip vortices in the near wake. The results show the inboard movement of tip vortices due to the curvature of the wake, and the deformation of the near wake



Fig. 6: Particle visualization of the development of the tip vortex at z/R = 0, for four different tips.



Fig. 7: Vorticity field development at z/R = 0, for four different tips.

![](_page_6_Figure_0.jpeg)

Fig. 10: Vorticity field development at y/R = 0, for two different tips at  $\lambda = 4$  and  $\lambda = 2$ .

![](_page_7_Figure_0.jpeg)

Fig. 11: Near wake trajectory and evolution of the tip vortex for quarter chord tip at  $\lambda = 4$  and  $\lambda = 2$  (vorticity contours at y/R = 0).

as a function of azimuth angle and time. The PIV data allows the quantification of the strength of the vortex, its expansion and dissipation. The data also confirms the influence of the tip shape on the generation loci, trajectory and strength of the vortices This data is of great value for the validation of numerical models, specially those based on the simulation of vorticity, such as panel methods.

## **10. Recommendations and Outline of Future** Work

Future work aims at understanding the effect of skew angle on the evolution of the near wake and asymmetry in span direction.

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![](_page_7_Figure_9.jpeg)

Fig. 12: Near wake trajectory and evolution of the tip vortex for trailing edge tip at  $\lambda = 4$  and  $\lambda = 2$  (vorticity contours at y/R = 0).