PIV Investigation of the Flow Across a Darrius Water Turbine

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The growing interest for affordable and efficient energy production systems leads to the design of large wind and water turbines in areas where significant winds or currents are available. At smaller scale, Vertical Axis Wind, or Water Turbines (VAWTs) can be seen as complementary solutions for local autonomous systems, or in areas where the wind or currents are subject to direction and intensity changes.

The dynamics of VAWTs of Darrieus type are highly unsteady, involving intricate lift and stall effects affected by the dynamic stall phenomenon (McCroskey 1981, Fujisawa et al. 2001, Ferreira et al. 2009). The optimal operating stages of such turbines then strongly depend on their solidity, tip speed ratio and Reynolds number. Additionally, the occurrence of dynamic stall generates strong vortices that interact with the blades, resulting in a complex unsteady wake.

The flow over a 4-bladed Darrius water turbine of H type with a solidity of 0.533 was investigated using phase-locked 2D Particle Image Velocimetry in a towing tank as shown in Fig.1. The rotor was mast-free, held from a top circular stainless-steel flange attached to the generator shaft. A bottom PMMA transparent flange allows for PIV imaging of the rotor mid-plane. The generator shaft is equipped with torque sensors and angular indexes. The device was operated between \(V_o=0.5\,\text{m/s}\) and \(1.5\,\text{m/s}\) for tip-speed ratio ranging from 0.5 to 5.

![Fig. 1 Turbine model (left) and laser illumination on the rotor's mid plane during PIV experiment (right)_](image)

The experiments are conducted in a 20m long, 1.5m wide and 1.3m deep towing tank equipped with side and bottom glass windows allowing for optical measurements. The PIV setup comprises a 200m\(^2\) dual-head Nd:YAG laser (Quantel Big 5k) separated in two horizontal sheets on an optic table and entering the towing tank diagonally from a side window. This setup helps limiting the extent of the area over which the rotor is shaded by the blades. Two Tai CV-M2 dual-frame CCD cameras (1600\*1200 pixels, 15 fps max.) situated below the towing tank capture the PIV images on a 1000\*700mm\(^2\) area. The towing procedure is synchronized with the turbine rotation cycle in order to allow reproducible phase-locked torque and PIV measurements. The phasing between the towing carriage and the rotating turbine allows phase-locked measurements to be carried out to an arbitrary angular resolution of 10\(^\circ\) with a level of uncertainty of a few milliseconds. The PIV timing loop are also adjusted so that successive velocity fields correspond to angular displacements that are multiples of 10\(^\circ\), ensuring the full rotation cycle to be covered.

Series of PIV measurements have been obtained for tip speed ratios leading to optimal and non-optimal operating conditions revealed the desired tip-speed ratio (\(\lambda\)) for the model under study is 2 as shown in Fig.2.

![Fig. 2 Turbine model (left) and laser illumination on the rotor's mid plane during PIV experiment (right)_](image)

From the PIV analysis, it is observed that the phenomenon of dynamic stall progressively occurring when the upstream blade crosses the incoming flow. The analysis of the full rotation of the turbines for these different tip speed ratios provides information on the influence of dynamic stall on the efficiency of the turbines, as well as on the effects associated to the blade-vortex interaction occurring in the downstream part of the rotor.

![Fig. 3 Velocity fields at various azimuthal positions of blade for \(V_o=1m/s\)_](image)

Phase-locked PIV measurements of vorticity magnitude on high-concentrated scale (for better visualization) at phase angles of 20 multiples corresponding to respective azimuthal positions of the blade through one complete operation cycle at a tip-speed ratio (\(\lambda\)) of 2 and free-stream velocity (\(V_o\)) of 1m/s. the flow remains attached to the blade for the azimuthal position between 50\(^\circ\) and 100\(^\circ\). At \(\alpha=120\(^\circ\)\), vortex gets detached from the blade surface on its pressure side, and developed and expanded until \(\alpha=220\(^\circ\). Unsteady vortex structures and separation region and blade-vortex interaction were clearly visualized in the PIV results. During this phase, a relatively low-strength trailing edge vortex was seen shedding at \(\alpha=180\(^\circ\). Beyond 240\(^\circ\) of azimuthal position, observed is a progressive reattachment of the flow on to the blade with leading and trailing edge vortices follow the downstream fluid motion. Presence of another vortex was found between \(\alpha=0\) and 40 that disappeared during \(\alpha=40\) to 50\(^\circ\).

PIV Post-processing implies the usage of robust correlation of frames and image merging for prosperous data analysis. Global accuracy of present experimental campaign is appreciable as the results are consistent with the previous studies. In the context of the optimization of Darrieus turbines using blade-pitching strategies, understanding and predicting these behaviors are essential preliminary steps that will also allow the validation of numerical models and the definitions of the most adapted control laws.