Multi-Level Investigation of Blade Aerodynamics and Wake Dynamics in Vertical Axis Wind Turbines: Design and Array Deployment Strategies

Abstract

Vertical axis wind turbines (VAWTs) are promising for decentralized wind energy applications in urban, mountainous, and space-constrained environments, where the incoming wind is often unsteady and directionally variable. Savonius turbines offer reliable self-starting capability, omnidirectional operation, simple construction, and low maintenance, but their efficiency is limited by adverse torque on the returning blade. Hybrid Savonius–Darrieus turbines combine the self-starting capability of Savonius rotors with the higher efficiency of Darrieus rotors; however, their performance deteriorates at higher tip-speed ratios due to aerodynamic interference between the internal and external rotors. In addition, accurate prediction of wake recovery, wake asymmetry, and downstream momentum availability is essential for compact VAWT array deployment. Motivated by these challenges, this thesis presents a multi-level computational investigation of blade aerodynamics, rotor performance, and wake dynamics of Savonius and hybrid Savonius–Darrieus VAWTs.

A hierarchy of computational approaches is employed, including two-dimensional and three-dimensional unsteady Reynolds-averaged Navier–Stokes simulations with the SST $k-\omega$turbulence model and sliding mesh approach, proper orthogonal decomposition, and a 2.5-D large eddy simulation framework with the WALE sub-grid scale model. The computational models are validated against available experimental and numerical results before detailed analyses.

At the rotor level, Savonius turbine performance is improved through blade geometry modification and omnidirectional flow augmentation. A high-shape-factor Bach rotor with varying overlap ratio is examined over a tip-speed ratio range of 0.4–1.3. The overlap ratio strongly influences the inter-blade pressure distribution and promotes suction-driven flow towards the returning blade. An axisymmetric omnidirectional deflector is then applied to the Bach rotor to improve pressure loading on the advancing blade while preserving omnidirectional operation. The Bach-AOD rotor achieves a maximum power coefficient of 0.249 at a tip-speed ratio of 1.0 and gives a maximum power coefficient increase of 42.68% over the conventional semicircular Savonius rotor at a tip-speed ratio of 0.4.

The aerodynamic performance of hybrid Savonius–Darrieus turbines is examined with emphasis on improving high tip-speed-ratio operation. The effects of internal Savonius blade shape, external Darrieus blade profile, collapsed internal rotor configuration, and reduced internal rotor velocity are investigated. Replacing the semicircular internal Savonius rotor with an elliptical rotor does not improve performance because of increased adverse blade–vortex interactions with the external Darrieus blades. In contrast, changing the external rotor from NACA 0021 to the thinner NACA 0018 profile improves performance at higher tip-speed ratios by approximately 12%. A collapsed internal rotor improves the power coefficient by 5–7% for tip-speed ratios above 2.3 by reducing vortex shedding from the internal rotor. The reduced internal rotor velocity configuration is found to be the most effective strategy, producing a peak power coefficient of 0.3354, which exceeds that of the standalone Darrieus turbine considered in the study. Based on these results, a dynamic hybrid turbine design strategy involving blade-thickness modification and reduced internal rotor velocity is proposed.

At the wake level, three-dimensional simulations show that the Savonius turbine wake exhibits strong lateral asymmetry and tip-speed-ratio-dependent recovery. For a tip-speed ratio of 1.0, approximately 50% and 75% streamwise velocity recovery occur at downstream distances of 4D and 7D, respectively. A total momentum flux-based integral approach is developed to identify favourable downstream turbine locations without explicitly simulating turbine pairs. The analysis suggests that downstream distances of approximately 6D–7D are suitable for turbine placement, while laterally shifted locations may provide favourable momentum availability at shorter distances. An asymmetric wake estimation approach based on a hyperbolic secant function is also proposed and assessed against simulated wake profiles.

The discrepancy between two-dimensional and three-dimensional wake predictions is examined using POD of the wake velocity components. The first few POD modes contain most of the wake energy, with more than 99% of the streamwise component energy captured by the first five modes. The streamwise and lateral velocity modes are mainly associated with vortex shedding, while the vertical velocity modes are linked to rotational frequency and its harmonics or subharmonics. The analysis shows that vortex stretching and vertical transport, which are absent in two-dimensional simulations, are important for near-wake recovery. Vertical transport dominates wake recovery up to approximately 2D downstream, whereas lateral transport becomes more important farther downstream. These findings demonstrate the need for three-dimensional simulations in reliable wake prediction and array-level performance assessment.

Finally, blade-level flow physics is investigated using 2.5-D LES. The analysis examines azimuthal variations of torque coefficient, force magnitude, moment arm, sectional torque contribution, pressure distribution, and rotating-frame streamlines. Concave–convex surface decomposition shows that the convex surface plays a dominant role in positive torque generation through a suction-driven mechanism, while the concave-side pressure contribution decreases with increasing tip-speed ratio. Rotating-frame POD of pressure fluctuations shows that the dominant unsteady loading patterns are captured by a few energetic modes, with the first two modes containing more than 70% and the first four modes more than 90% of the pressure fluctuation variance.

Overall, the thesis provides a unified aerodynamic understanding of VAWTs across blade, rotor, and wake levels. It proposes rotor-level design improvements for Savonius and hybrid turbines, identifies wake recovery mechanisms relevant to compact turbine deployment, explains the limitations of two-dimensional wake simulations, and reveals blade-level torque-generation mechanisms using LES and POD. The findings support the development of improved VAWT designs and wake-informed turbine placement strategies for decentralized wind energy applications.