On yaw-misaligned wind turbine aerodynamics at full dynamic similarity - A coupled experimental and momentum-blade theory approach

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Modern utility scale wind turbines operate at diameter-based Reynolds numbers between 10^7-10^8 and tip-speed ratios between 4-7. Replicating these conditions in experiments or computations remains a major challenge for investigations on wind turbine aerodynamics and performance. Thus, the foundation of our current understanding on wind turbine performance is built on studies at lower than operational Reynolds numbers and unrealistic rotor parameters that do not match in-field counterparts, creating knowledge gaps that limit efficiency improvements. In the present study, experiments are carried out in the High Reynolds number Test Facility at Princeton University, where by varying pressure in place of velocity, operational Reynolds numbers (4×10^6) and tip-speed ratios ($3.5-7.5$) relevant for commercial wind turbines was achieved. The model was rotated between $-45°$ and $45°$ in $5°$ increments to represent a yaw-misalignment of a wind turbine to incident wind. The turbine performance is characterized through measurements of the thrust force and power for each tip-speed ratio and yaw angle combination. The results reveal existence of an optimal tip-speed ratio for maximizing wind turbine power, which decreases with increased yaw-misalignment. Key trends in thrust and power coefficients, in addition to the optimal tip-speed ratio with yaw-misalignment show good agreement with values predicted using a Unified Blade Element Momentum Model (UBEM) for rotors at arbitrary yaw-misalignments and thrust coefficients. The best agreement between experimental and model-predicted wind turbine power is obtained at the optimal tip-speed ratio, and lessens away from the optimal value. The UBEM model predictions show significant improvement over classical momentum theory, and in conjunction with the experimental results, demonstrates the capability of joint yaw and tip-speed ratio control for farm-level power production optimization. The alignment between experimental and model results also establishes confidence in the employed experimental methodology for study of high Reynolds number aerodynamics of wind turbines under yaw-misalignment.

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