

VORTEX DYNAMICS AND BREAKDOWN IN THE WAKE OF A WIND TURBINE ROTOR

J.N. Sørensen¹, R.F. Mikkelsen¹, T. Leweke²

¹Department of Wind Energy, Technical University of Denmark, 2800 Lyngby, Denmark,
jnso@dtu.dk

²IRPHE, CNRS, Aix-Marseille Université, Centrale Marseille, 13384 Marseille, France,
leweke@irphe.univ-mrs.fr

ABSTRACT

A century ago, Joukowski proposed an aerodynamic rotor model utilizing an actuator disc with constant circulation. Since then, this model has been the subject of much controversy, as it predicts a power performance that for all tip speed ratios exceeds the Betz limit and that goes to infinity when the tip speed ratio approaches zero. Recently, it was demonstrated that the Joukowski model is fully compatible with the inviscid Euler equations and that the apparent inconsistency can partly be explained by the fact that the model neglects lateral forces due to pressure or friction [1]. Furthermore, CFD computations using an actuator line model have shown that the excessive swirl of the hub vortex at small tip speed ratios generates vortex breakdown on the wake axis, causing a recirculating zone that limits the power yield [2].

In the past years we have studied in detail the flow behavior of Joukowski rotors at small tip speed ratios (TSR). It is shown that the excessive swirl appearing towards the rotor center at small tip speed ratios generates vortex breakdown, causing a recirculating zone in the wake that limits the power yield of the rotor. The appearance of vortex breakdown has a similar effect on the flow behavior as the vortex ring state that usually appears at higher tip speed ratios. Limits to where vortex breakdown might occur with tip speed ratio and rotor loading as parameter are investigated. The limits found correspond to well-known criterion for vortex breakdown onset for swirling flows in general. By applying a criterion for vortex breakdown in combination with the general momentum theory, the power performance always stays below the Betz limit.

In this contribution, we investigate the characteristics of a particular low-TSR rotor through CFD computations, as well as experimentally in a water channel. An 8-bladed Joukowski rotor of diameter 10 cm was designed for operation at TSR = 1 (Fig. 1). Experimental visualizations and velocity measurements reveal the existence of a large recirculation zone behind the rotor (Fig. 2), which is consistent with the prediction based on general momentum theory and a simple vortex breakdown criterion. In Fig. 3 the result of an axisymmetric computation shows the appearance of vortex breakdown in the wake of the rotor disc. The results from these simulations have later been confirmed by full 3-dimensional simulations. Further comparisons between theory, simulation and experiment will be presented.

REFERENCES

- [1] J.N. Sørensen, G.A.M. van Kuik, “General momentum theory for wind turbines at low tip speed ratios”, *Wind Energy* **14**, 821-839, 2011.
- [2] R.F. Mikkelsen, S. Sarmast, D. Henningson, J.N. Sørensen, “Rotor aerodynamic power limits at low tip speed ratio using CFD”, *Journal of Physics: Conference Series* **524**, 012099, 2014.



Figure 1: Rotor geometry

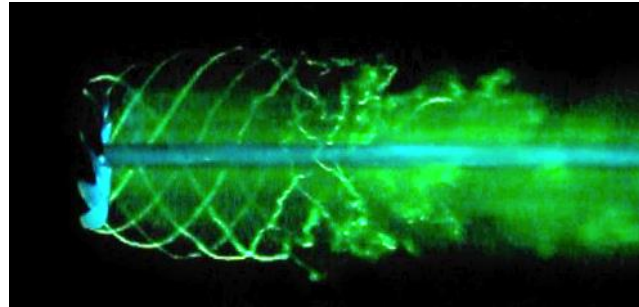


Figure 2: Dye visualization and mean velocity field (streamlines and axial velocity) of the wake for $TSR = 1$.

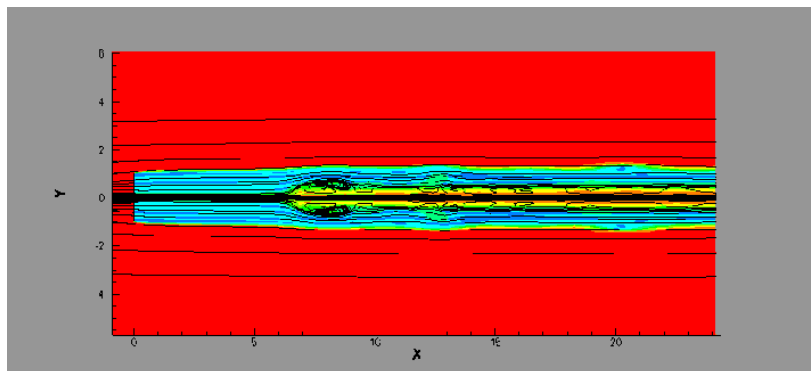
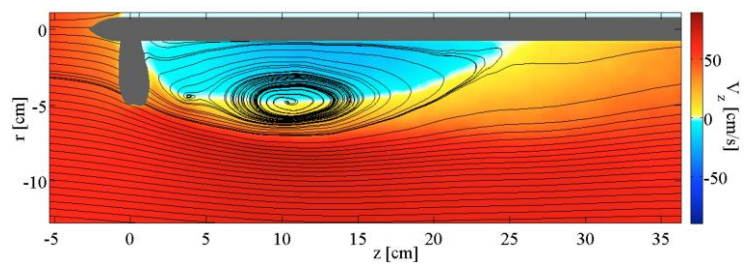


Figure 3: Numerical simulation of vortex breakdown behind rotor disc.