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## Tip vortex instability triggered by rotor asymmetry for accelerated wake recovery

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### Track 4: Wind turbines and wind plants

#### Introductory Summary

The breakdown of tip vortices in the wake of a wind turbine is the crucial first step of wake mixing and recovery. Capitalizing on inherent instabilities in the vortex system to promote interaction between adjacent vortices can accelerate this breakdown process. One way to trigger vortex instability is to introduce an asymmetry to the rotor by modifying one or two of the blades. The current study uses water channel experiments and simulations to investigate the effects of different types of rotor asymmetry on the wake. Results show that rotor asymmetry successfully triggers vortex instabilities, though some types of asymmetry are more effective than others. These findings suggest rotor asymmetry could be used as a type of passive flow control to mitigate the detrimental effects of wakes on downstream turbines in a wind farm.

**Keywords:** *Tip vortex instability, wake recovery, passive flow control*

#### Introduction

Previous studies have shown that wind turbine wake effects are responsible for some of the largest losses in wind plant energy production [1] and significant increases in fatigue loading on downstream turbines [2]. The near wake, within 1-4 rotor diameters of the turbine depending on the inflow turbulence level, is characterized by coherent vortical structures shed from the turbine tower, nacelle, blade roots, and blade tips. Mixing between the wake and the surrounding flow increases substantially once these structures start to break down, particularly those shed from the blade tips [3]. This mixing re-energizes the flow in the wake, providing more available power to downstream turbines. In addition to their role in delaying wake recovery, coherent structures can be responsible for strong structural loading events on downstream turbines [2]. Therefore, accelerating the breakdown of such structures can help minimize the detrimental impacts of wind turbine wakes on downstream machines.

Lignarolo et al. [3] show that tip vortex breakdown occurs after pairing between adjacent vortices. This pairing is caused by the mutual inductance instability in the helical vortex system, which occurs when filaments are close enough to experience the induced velocity field of their nearest neighbors. This instability can be triggered by introducing a slight asymmetry to the rotor as a form of passive flow control to offset the tip vortices from their baseline position, demonstrated for a two-bladed rotor by Quaranta et al. [4]. The current study uses water channel experiments and simulations with a multi-fidelity vortex solver to investigate the impact of rotor asymmetry on the wake of a three-bladed rotor, the configuration usually used for horizontal axis wind turbines.

#### Methods

The experiments were conducted in a recirculating free-surface water channel with a 150 cm × 38 cm × 50 cm (length × width × height) test section, the same as that used in [4]. The three-bladed rotor was constructed using additive manufacturing, with separate parts for the hub, nose, and blades, so each blade could be removed and replaced independently. It had a radius of 9.0 cm and a tip chord of 2.3 cm, with blades designed using the Glauert method [5] for the outer 50% of the radius. The NACA2414 airfoil was used for the blade cross-section as a compromise between low-Reynolds number performance and a minimum necessary thickness for additive manufacturing. In the experiments, the rotor rotated at 3 Hz, with a flow speed of 56 cm/s, yielding a tip speed ratio of 3 and a tip-chord-based Reynolds number of 40,000. The wake of the rotor was measured using particle image velocimetry (PIV) and dye visualizations. For each case, one or two of the rotor blades were removed and replaced with blades that were modified in some way, such as a length increase, an out-of-plane deflection, or a combination of both.

To complement the experiments, simulations of a few select cases will be conducted using the MIRAS code, which models the vortices shed from a wind turbine rotor using a hybrid filament-mesh method [6]. These simulations will provide additional information that is not available in the experiments, such as the downstream evolution of the wake beyond the field of view of the water channel test section. Velocity fields from planes positioned where a downstream turbine would be located will elucidate the impact of the perturbed wake on other turbines within a wind farm.

#### Results and Conclusions

Experimental results show that rotor asymmetry causes vortex pairing to occur earlier (further upstream) than it would without the perturbation. The location of this pairing can be observed in the swapping of the axial positions of adjacent helices, whose downstream distance is indicated by the arrow on the dye visualizations of the blade tip vortices depicted in figure 1. The type of rotor asymmetry affects the onset of pairing, with some perturbations significantly more effective than others of the same magnitude. For example, the white blade in figure 1(b) is longer than the other two blades by 5% of the distance between neighboring vortex loops,  $h$ , and deflected upstream by 5% of  $h$ , while the white blade in figure 1(c) is lengthened and

deflected by the same magnitude, but in the downstream direction. Clearly, the perturbation shown in figure 1(c) induces vortex pairing much earlier than that in figure 1(b). The difference in effectiveness of these two asymmetries of the same magnitude is related to the direction of the mutually-induced strain in a system of co-rotating vortices [7]. With 14 different rotor asymmetries tested, many additional conclusions can be drawn about the most effective perturbations for triggering the mutual inductance instability in the helical tip vortex system.

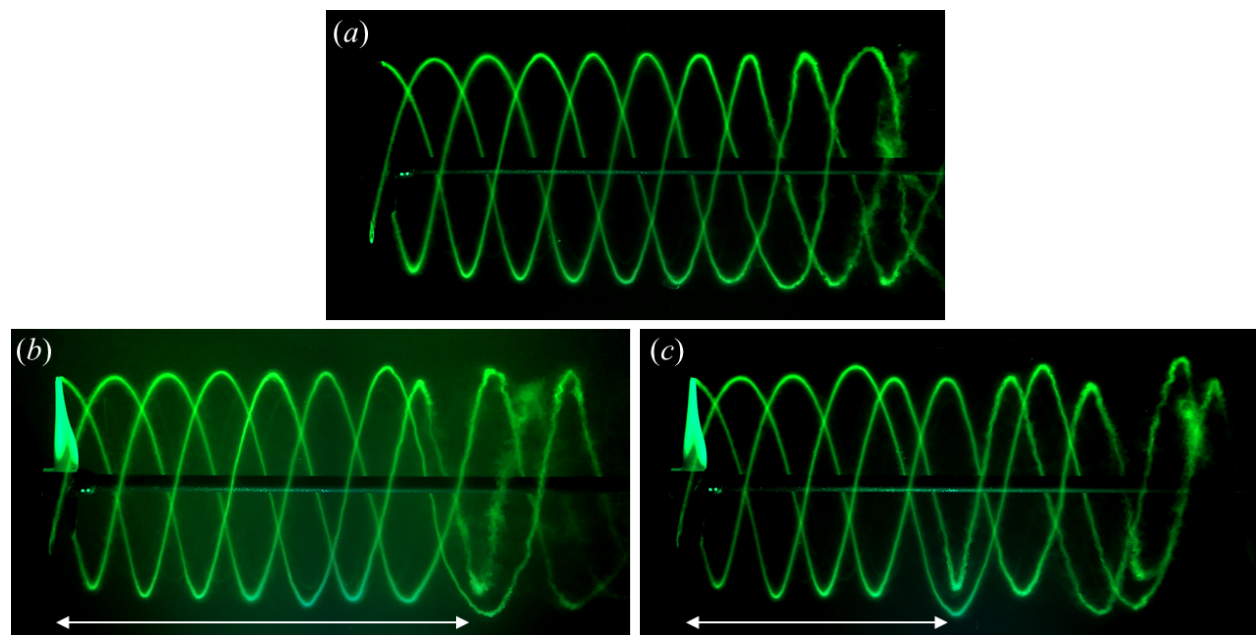


Figure 1: Dye visualizations of blade tip vortices in the wake of a three-bladed rotor, including (a) the baseline symmetric case with an entirely black rotor, (b) the case with one blade (in white, pointing upwards) extended and deflected upstream relative to the other two blades, and (c) the case with one blade (in white, pointing upwards) extended and deflected downstream. The white arrows in (b) and (c) indicate the distance from the rotor plane to the location of vortex pairing.

These findings can be used to design turbines with wakes that break down faster, thereby reducing their negative impact on downstream machines within a wind farm. With the increasing interest in segmented blade technology [8], a blade tip generating the desired vortex perturbation could be implemented on new or existing turbines. To explore the feasibility of implementation, investigation into the impact on the loading of the asymmetric turbine itself and quantification of the effect of the perturbed wake on a downstream turbine are currently underway.

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