AerE545/AerE445: Experimental Fluid Mechanics and Heat Transfer

Lab # 06: Demonstrate Experiment to Study Aeromechanic Performance and Wake Interference of Wind Turbines

Objectives:

1. To get familiar with the experimental setup and operation of large-scale Aerodynamics and Atmospheric Boundary Layer (AABL) wind tunnel.
2. To learn the concepts of wind turbine aeromechanics and turbine wake interferences.
3. To learn about the new concept of dual-rotor wind turbine (DRWT) design and its advantage in harvesting the wind energy from ABL winds.

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Lab #07: Demonstration Experiments of Wind Turbine Aerodynamics

- **Importance of a better understanding of turbine wake characteristics**

A better understanding of the wake characteristics behind a horizontal-axis wind turbine (HAWT) is very essential for optimizing the power output of an individual turbine or in windfarm siting. As depicted schematically in Figure 1, momentum deficits would occur in the turbine wake as the airflow with an Atmospheric Boundary Layer (ABL) profile passes through the turbine rotor. As the wake progresses axially (in X direction), it would undergo expansion. For a rotor of diameter D, the near wake (X < 1.0D) is featured mainly by the advection of helical vortical filaments and the bi-modal velocity deficit distribution behind the turbine. The expanding far-wake region (X > 1.0D) determines the wake recovery process in which the kinetic energy of the wake steadily increases due to turbulent mixing in the shear layer. High-velocity components outside the wake are mixed with the low-velocity components in the wake creating turbulent eddies. Higher levels of blade-driven turbulence intensity in the wake as well as a turbulent ABL increases the mixing efficiency, thus reducing the distance for wake recovery. However, the siting of downstream turbines must be conducted to minimize turbulence-induced blade vibrations in them.

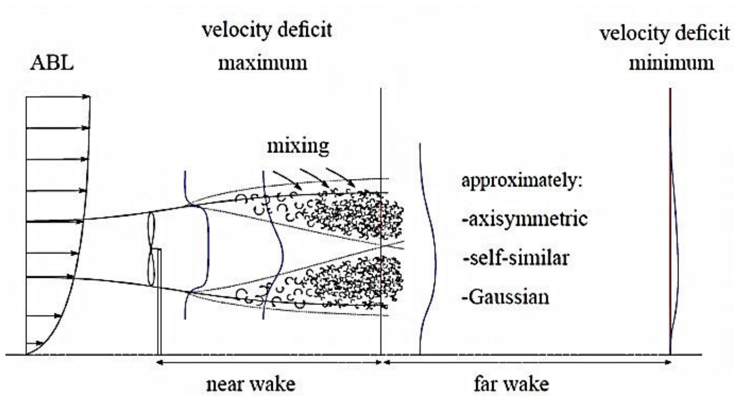

Fig. 1. A schematic of the wake characteristics of a wind turbine.

- **Importance of a better understanding of turbine wake interference**

A modern wind farm usually consists of multiple wind turbines arranged in an organized pattern or array. The wake interferences among the turbines have been found to affect the performance of the turbines significantly. The wind turbines located in the near- and far-wake regions of upstream turbines in a typical wind farm would experience a significantly different surface wind field and wind loadings compared to the ones located upwind due to the wake interferences of the upwind turbines. Since a portion of the wind energy carried by the oncoming wind has already been harvested by the upstream turbines, significant velocity deficits would be generated in the wake flows behind the upstream turbines. As a result, downstream turbines see a considerably lower freestream velocity than the upstream turbines, and thus, less energy is available in the oncoming flows for the downstream turbines. Power losses due to wake interferences among wind turbines were found to be up to 30% of total average power for most large offshore wind farms, depending on the wind turbine array spacing and layout. Extensive experimental and numerical studies have been conducted in recent years to investigate wind turbine aeromechanics and wake interferences among multiple wind turbines in order to gain insight into the underlying physics for higher total power yield and better durability of the wind turbines.

Fig. 2: A picture to show the wake inferences among wind turbines in an offshore wind farm.

- **New concept of dual-rotor wind turbine (DRWT) design**

Modern, utility-scale horizontal axis wind turbine (HAWT) rotor blades are aerodynamically optimized in *outboard region*, whereas blade sections *near turbine hub* (i.e., root of blades) are designed primarily to withstand structural loads (i.e., bending and torsional). Therefore, very high thickness-to-chord ratio airfoils, which are aerodynamically poor, are used near turbine root to provide structural integrity. Such configuration results in a "dead" wind zone near rotor axis where virtually no energy is extracted from the wind. *Up to 5% loss* in wind energy extraction capability is estimated to occur per turbine due to this compromise. These "root losses" occur even in turbines that operate in isolation, i.e., with no other turbine nearby.

Most utility-scale turbines are deployed in clusters, with multiple turbines operating in proximity of each other. *Array interference (wake) losses* resulting from aerodynamic interaction between turbines in wind farms have been *measured to range between 8 - 40%*, depending on wind farm location (e.g., onshore versus offshore), farm layout, and atmospheric stability condition. The significance of these losses is evident by the magnitudes, which are massive especially when contrasted with the disproportionately small efficiency gains (~0.1%) typically sought by the gas turbine industry. While there is abundant literature documenting root losses and wake losses in wind farms, research on *concepts that can mitigate these losses* are still very inadequate.

A novel dual-rotor wind turbine (DRWT) concept is given in Fig. 1. the DRWT concept will employ a secondary, smaller, co-axial rotor with two objectives: (1) *mitigate losses incurred in the root region* of the main rotor by using an aerodynamically optimized secondary rotor, and (2) *mitigate wake* losses in DRWT wind farms through rapid mixing of turbine wake. Mixing rate of DRWT wake can be enhanced by (a) increasing radial shear in wind velocity in wakes, and (b) using dynamic interaction between primary and secondary rotor tip vortices. Velocity shear in turbine wake can be tailored (by varying secondary rotor loading) to amplify mixing during conditions when wake/array losses are dominant. The increased power capacity due to the secondary rotor can also be availed to extract energy at wind speeds below the current cut-in speeds of conventional SRWT. Given the substantial efficiency improvement potential, success of the proposed concept will transform the wind energy industry and provide a means of sustainably meeting our energy needs.

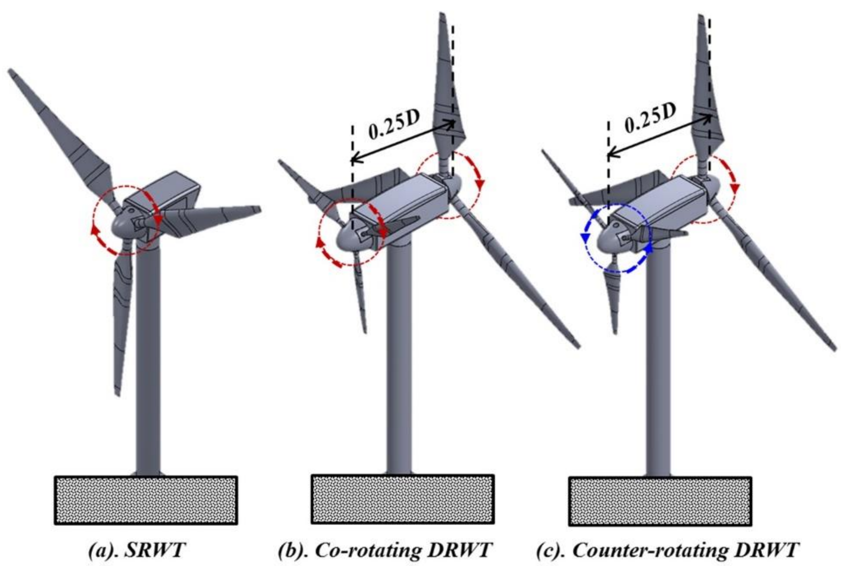

Fig. 3: A schematic of dual-rotor wind turbine (DRWT) concept.

- **The flow field to be measured:**

The experiments will be performed in a closed-circuit atmospheric boundary layer wind tunnel located in the Aerospace Engineering Department of Iowa State University. The tunnel has a test section with an 8 ft wide test section and variable ceiling height. The wind tunnel has a contraction section upstream the test section with honeycomb, screen structures and cooling system installed ahead of the contraction section to provide uniform low turbulent incoming flow to enter the test section.

The experiment consists of an array of 9 wind turbines: 6 dual rotor wind turbines and 3 classic horizontal axis wind turbines.

What you will do during the lab time:

- Visit the Aerodynamics and Atmospheric Boundary Layer Wind Tunnel
- Observe a wind turbine array experiment.

Requirements for the Lab Report

This lab is a demonstration. No report is required for this lab!