Graduate Research Plan Statement

Introduction. Recent years have seen global growth in wind energy capacity and wind farm density. As the number of wind farms increases, so do concerns over the impact of long-lasting turbine wakes. This is especially a problem in offshore wind, where siting locations can already be limited by water depth and environmental factors. Turbine wakes are usually thought to dissipate before reaching an adjacent farm, but recent research suggests that they can persist for very long distances; one study found wakes extending more than 50km [1]. These wakes can reduce a downwind farm's energy yield, though the extent of the impact is still being studied. The simplest solution is to spread wind farms farther apart, but as wind energy becomes a larger source of grid energy, doing so will only decrease the amount of usable space and lower the capacity of wind energy across the world. A more reliable solution is to find a way to mitigate the wakes' impact. One possibility is to intentionally excite instabilities in the blade tip vortices to accelerate their dissipation and shorten the wakes. To accomplish this, **I propose to investigate the use of active flaps near the wind turbine blade tips that will excite instabilities in the tip vortices to cause them to dissipate faster, thus reducing the farm-to-farm wake effects.**

Turbine wakes are a result of harvesting energy from the wind, causing low speeds and turbulence downstream of the turbine. While this turbulence is known to negatively affect the performance of nearby downwind turbines [2], it was recently discovered that these wakes can travel much farther than previously thought, impacting wind farms miles away. The dominant feature of wind turbine wakes are the vortices that form at the tips of each blade [3]. These tip vortices are formed from the pressure differential between the pressure and suction sides of the turbine blade. The tip vortices can be quite stable, so the challenge is finding a way to destabilize them and cause them to dissipate over shorter distances. There are three modes of instabilities in tip vortices: short wave, long wave, and mutual inductance [4]. To lessen the impact of wakes, one can attempt to disrupt the mutual inductance instabilities of tip vortices, which has been shown in simulations to hasten their dissipation and reduce their impact on downwind turbines [5]. In the proposed study, I will focus on exciting the mutual inductance instability by increasing size of the vortex core using Gurney flaps [4]. In Huang, X., et al. [6], simulations show that flaps can result in mutual inductance vortex destabilization in as little as five blade radii from the turbine, representing roughly a 50% reduction in dissipation distance.

Gurney flaps are small protuberances that are mounted near the trailing edge on the pressure side of lifting surfaces. They have been used for many years to increase the lift of airfoils. Arctura and Brown University investigated the use of active "controllable" Gurney flaps near the trailing edge of turbine blades to control sectional lift and pitching moment [7]. Using a similar idea, I will add controllable Gurney flaps to excite the instabilities in tip vortices of wind turbines, with a goal of forcing the wakes to dissipate faster. Because I previously worked with Gurney flaps for active lift control, I have the appropriate background knowledge to conduct this project.

Objective 1: Literature Review and Model Design. I will begin with a thorough review of the literature surrounding the theoretical and experimental study of tip vortex aero and hydrodynamics, with an emphasis on vortex instabilities. A model wing will then be designed along with prototype Gurney flaps. The wing will be designed to accept a variety of flap designs. Candidate flap designs (including the size, shape, mounting location, and actuation method) will be developed using past research and simulations, found during the literature review. Since I have first-hand experience with testing Gurney flaps on wind turbine blades at Arctura, Inc., I am prepared to create a solid blueprint for the initial designs.

Objective 2: Wind Tunnel Testing. After the model wing and Gurney flaps are designed, they will be 3D printed and assembled for testing in the Brown University wind tunnel. A Particle Image Velocimetry (PIV) system will be used to evaluate the behavior and evolution of the tip vortex. Hotwire measurements will also be used to measure velocities downstream of the tip to determine the instability and turbulence of the wind. Using a force transducer, lift, drag, and moment forces will be measured to evaluate changes in performance, a torque transducer will be used to evaluate effect on loads. Results will be compared to a baseline where a wing section is tested without flap modifications. Gurney flap designs will also be compared to each other, based on the length till dissipation, found using the PIV and hotwire results. A range of Reynolds numbers (up to a maximum of roughly 500,000) and angles of attack will be studied. My work in the industry will be useful in this step, as I have experience testing Gurney flaps on wing sections in wind tunnels.

Potential Concerns. Adding Gurney flaps close to the tips could negatively impact the fatigue loads experienced by the turbines. This will need to be monitored to make sure the force will not cause failure. If the potential for failure is found, flaps can be redesigned or multiple flaps can be added to offset loads. It will not be possible to match Reynolds number; because of this, Reynolds scaling effects will need to be considered when interpreting results. There are also concerns that arise when thinking of implementing Gurney flaps on wind farms. Retrofitting a turbine with Gurney flaps can take significant time and money to complete. Once the active Gurney flaps are installed on wind farms, the active components risk mechanical failure, which can require high-cost maintenance to repair.

Intellectual Merit. With the increase in construction of wind farms, the topic of intra-farm wake effects is a growing problem. Although blade tip vortices are known to cause negative wake effects on turbines and farms, solving wake effects is still a struggle for most owners and operators. Finding ways to dissipate them, while not negatively impacting production numbers, would be useful for wind energy efficiency, designing farms, and improving predictions of wind farm performance. While there is some research on destabilizing tip vortices, most studies are limited to simulations [5 & 6]. Empirically validating turbine tip vortex destabilization will be valuable for the future of wind energy.

This project will be done at Brown University, which has active wind energy research through their Initiative for Sustainable Energy (ISE). Brown University has the facilities to carry out the experiments. This includes a large wind tunnel, force transducers, a PIV system, model blades and turbines. This project will fit into research themes going on in Brown labs and will broaden the impact of wind energy research. ISE faculty member Dr. Kenneth Breuer will be the advisor during this project.

Broader Impacts. As the US and the world navigate a transition to renewable energy, we must continue to enhance the tools we have to improve the renewable energy industry. Wind energy has been growing exponentially, demanding more space for new construction. Diminishing wake effects will allow wind farms to be built closer together, saving space and lessening maintenance costs. This project will have the potential to increase production in current wind farms by retrofitting blades already in the field and increase potential production in planned wind farms. This will allow the world's climate goals to be achieved more efficiently.

While working on my PhD, I will publish my findings in appropriate journals, Wind Energy and AIAA are two possibilities, and participate in renewable energy conferences and workshops. I will also continue to be involved in outreach clubs, including SWE and OSTEM. By staying involved in both clubs, I will work to encourage other women and LGBTQIA+ people to study engineering. I will use my experience in the industry to help others navigate the engineering field.

Conclusion. My proposed research topic, using Gurney flaps to destabilize blade tip vortices, meshes well with my career experience. From an undergraduate student studying Aerospace and Mechanical Engineering, to an industry research engineer working on active lift control devices on model blades in wind tunnels. Receiving the NSF Graduate Research Fellowship will allow me to perform wind tunnel tests to address important questions about the use of Gurney flaps to reduce wake effects. It will also allow me to advance my career, by giving me the opportunity to go to graduate school and do my own personal research in a field I am invested in.

References. **[1]** Cañadillas, Beatriz, et al Wind Energy 23.5 (2020): 1249-1265. **[2]** González-Longatt, Francisco, Peter Wall, and Vladimir Terzija. Renewable Energy 39.1 (2012): 329-338. **[3]** Soto-Valle, Rodrigo, et al. Wind Energy Science Discussions 2021 (2021): 1-28. **[4]** Widnall, Sheila E. Journal of Fluid Mechanics 54.4 (1972): 641-663. **[5]** Brown, Kenneth, et al. AIAA Journal 60.5 (2022): 3298-3310. **[6]** Huang, X., et al International Journal of Heat and Fluid Flow 77 (2019): 336-351. **[7]** Hao, Siyang, et al. AIAA SCITECH 2022 Forum. 2022.