SLATT UNDERGRADUATE RESEARCH FELLOWSHIP
FINAL REPORT

SCHOLAR NAME:	Sean Egan
FACULTY ADVISOR:	Professor David Richter
PROJECT PERIOD:	January 19, 2024 - May 3, 2024
PROJECT TITLE:	Flow and Turbulence Characteristics at Hub Height for Offshore Wind Energy Production
CONNECTION TO ONE OR MORE ENERGY-RELATED RESEARCH AREAS (CHECK ALL THAT APPLY):	**( ) Energy Conversion and Efficiency** **( ) Sustainable and Secure Nuclear** **( ) Smart Storage and Distribution** **( ) Transformation Solar** **( ) Sustainable Bio/Fossil Fuels** **(X) Transformative Wind**

MAJOR GOALS AND ACCOMPLISHMENTS

Summarize your research goals and provide a brief statement of your accomplishments (no more than 1-2 sentences). Indicate whether you were able to accomplish your goals by estimating the percentage completed for each one. Use the next page for your written report.

RESEARCH GOALS	ACTUAL PERFORMANCE AND ACCOMPLISHMENTS	% OF GOAL COMPLETED
Explore current landscape of offshore wind development	Gained a strong understanding of what offshore wind is, the engineering problems facing offshore wind, and economic and social barriers to further development.	100
Explore research that is simulating and analyzing wind-wave interaction	Perused current research journals to understand current simulations that are being run for offshore wind applications, especially those using LES for observing wind-wave interaction and the conditions created by these interactions.	100
Modify Large Eddy Simulation (LES) software in Linux for offshore wind applications	Modified LES code in Linux which involved learning the structure of Linux and how to run and compile complex directories in Linux.	100
Run simulations for offshore wind applications and analyze varying turbulence characteristics	Ran simulations for varying wind speeds and observed the turbulence characteristic from the wind-wave interaction at a common hub height for offshore wind turbines to see the fluctuations that a turbine would experience at hub height.	100

RESEARCH OUTPUT

Please provide any output that may have resulted from your research project. You may leave any and all categories blank or check with your faculty advisor if you are unsure how to respond.

CATEGORY	INFORMATION
EXTERNAL PROPOSALS SUBMITTED	
EXTERNAL AWARDS RECEIVED	
JOURNAL ARTICLES IN PROCESS OR PUBLISHED	
BOOKS AND CHAPTERS RELATED TO YOUR RESEARCH	
PUBLIC PRESENTATIONS YOU MADE ABOUT YOUR RESEARCH	Seventh Annual ND Energy Research Symposium, Flow and Turbulence Characteristics at Hub Height for Offshore Wind Energy Production, April 24, 2024, McKenna Hall
AWARDS OR RECOGNITIONS YOU RECEIVED FOR YOUR RESEARCH PROJECT	
INTERNAL COLLABORATIONS FOSTERED	Professor David Richter, Research Professor Mentor, 1-2 times per week
EXTERNAL COLLABORATIONS FOSTERED	

WEBSITE(S) FEATURING RESEARCH PROJECT	
OTHER PRODUCTS AND SERVICES (e.g., media reports, databases, software, models, curricula, instruments, education programs, outreach for ND Energy and other groups)	

RESEARCH EXPERIENCE

Please let us know what you thought of your research experience: Did this experience meet your expectations? Were lab personnel helpful and responsive to your needs? What else could have been done to improve your experience or achieve additional results?

This experience went above and beyond my expectations. Professor Richter did an amazing job planning out a research project that could be feasibly accomplished within the time constraints of a semester. He helped to take me through the whole research process, from learning background and what is already being done in terms of research with LES for offshore wind, to developing code for our specific applications, to actually running simulations and analyzing the results while still keeping the big picture in mind. The skills and knowledge I gained from this experience are invaluable and far beyond what I could have acquired in a traditional classroom setting or through extracurricular activities. I am deeply grateful for the opportunity to undertake this project and for the guidance and support provided by Professor Richter throughout.

FINAL WRITTEN REPORT

Flow and Turbulence Characteristics at Hub Height for Offshore Wind Energy Production

Sean Egan

Introduction

Interest in offshore wind has continued to grow over the last few decades as a vital component in the renewable energy landscape. The wind speeds offshore are higher and generally more consistent in magnitude and direction owing to the aerodynamically smoother surface of the ocean, and turbines can be built at a larger scale which generates greater and more reliable energy production.

Offshore wind turbines have a few different substructures for both fixed and floating turbines, with monopile being the most used foundation and over 99% of installed turbines using fixed substructures. However, most of the offshore wind potential for the United States lies in deeper waters, so the future lies in floating structures. For an idea of the size of these turbines, the average hub height (vertical distance from the surface to the hub of the turbine) is around 100 meters, and the average rotor diameter is about 220 meters. Globally, there is about 63 GW being produced with China, the United Kingdom, and Germany leading the way. Comparatively, the United States is lagging far behind, with only three operational offshore wind farms (producing 174 MW) and a few more in the development and permitting phases. High borrowing and inflation rates have created problems for building more offshore wind farms in the U.S. even with the help of the Inflation Reduction Act.

Offshore wind also comes with many risks and disadvantages that have impeded the progress of the energy source. Operating offshore in saltwater significantly complicates both installation and maintenance processes, leading to substantially higher costs. Electrically, there are issues ensuring stable operation, efficient power transmission, and effective management of energy storage systems amidst changing environmental conditions and operational demands. From a structural point of view, there are concerns about the durability in the face of strong and variable weather conditions and minimizing mechanical loading due to wind-wave behavior. Another obvious risk for the turbine is strong winds, especially the conditions created during a hurricane. These risks as well as the high upfront construction costs have held offshore wind development back compared to solar and onshore wind, but many countries including the United States see offshore wind as a crucial piece of the renewable energy landscape for the future, especially for large populations near the coasts, and will continue to invest money in it to push development forward.

A smaller area that is important for turbine design and reducing costs is exploring the conditions created by wind-wave interaction at varying wind speeds. By knowing the fluctuations in wind speed that a turbine will experience across its rotor blades, turbine designers can make more informed decisions regarding the materials used and the forces, vibrations and fatigue, and torques that the blade needs to be designed to withstand. We centered our efforts on this topic and analyzed the turbulence created by these interactions, specifically at hub height of the wind turbine.

Methods

One tool for simulating wind over waves is Large Eddy Simulation (LES). This mathematical model is based on the Navier-Stokes equations which describe the motion of fluid flows, and it is used to simulate turbulent flows. LES is extremely useful for offshore wind applications as it simulates the turbulent conditions that a turbine would experience and facilitates a better understanding of these conditions. Code was compiled and run in Linux, so part of the process was learning the Linux commands needed to accomplish this and then also developing and running these simulations for our specific interest in the wind-wave interaction at hub height. LES resolves the largest scales of turbulence over space and time with small grid cells and time steps, so it requires a lot of computing power and takes a while to run. In order to run this code, we collaborated with the Center for Research Computing (CRC) and ran the code on their computer nodes.

In our simulations, varying wind speeds were blown over a surface of waves, which served as an initial condition for us so that we could observe the effect that the wind speed had on the turbulent conditions that resulted from the wind-wave interactions. A close-up snapshot of the wave-field in the x-z plane is shown below in Figure 1 and a snapshot of the whole wave-field with z contoured over zeta to give an idea of what the wave-field looks like in three dimensions is depicted in Figure 2.

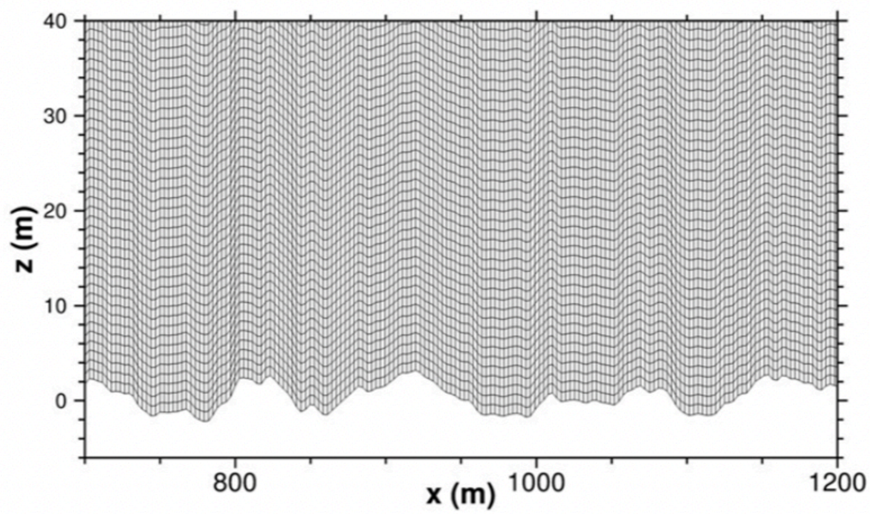

Figure 1: Snapshot of a small part of the grid in the x-z plane from Sullivan [1]. Depicts the surface shape of the waves.

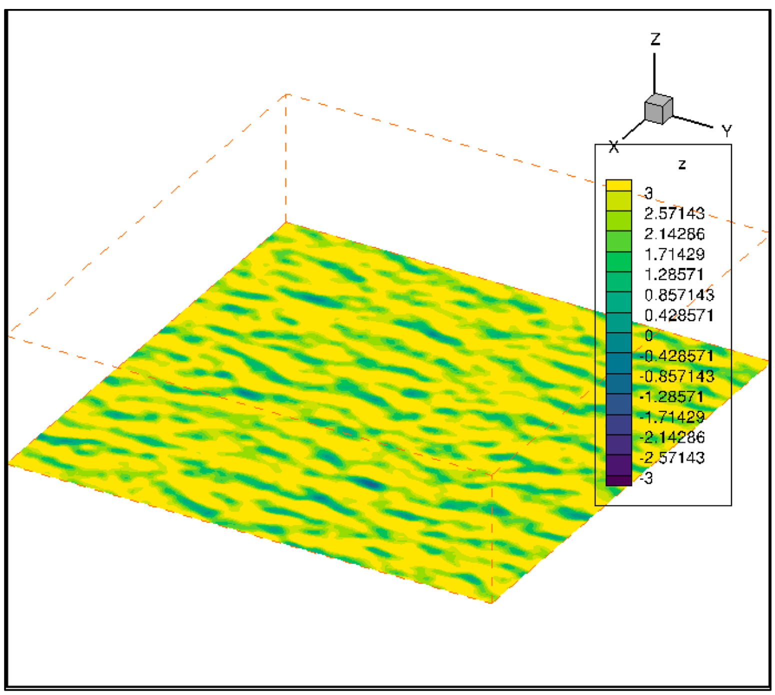

Figure 2: Snapshot of a slice of the wave field at a zeta height of 3 meters.

Results

We ran simulations for low, average, and high wind speeds of 5 m/s, 10 m/s and 25 m/s. The variances of the w velocity at the z height of 105 meters, which is close to standard hub height for a turbine, were 0.1594 for 5 m/s , 0.1602 for 10 m/s, and 0.6486 for 25 m/s. The variances are plotted below in Figure 3 to show the fluctuations that the turbine would experience at hub height in the grid over time and a snapshot of the w-velocities in the x-y plane is included below in Figure 4 to show the flow varying in space as well.

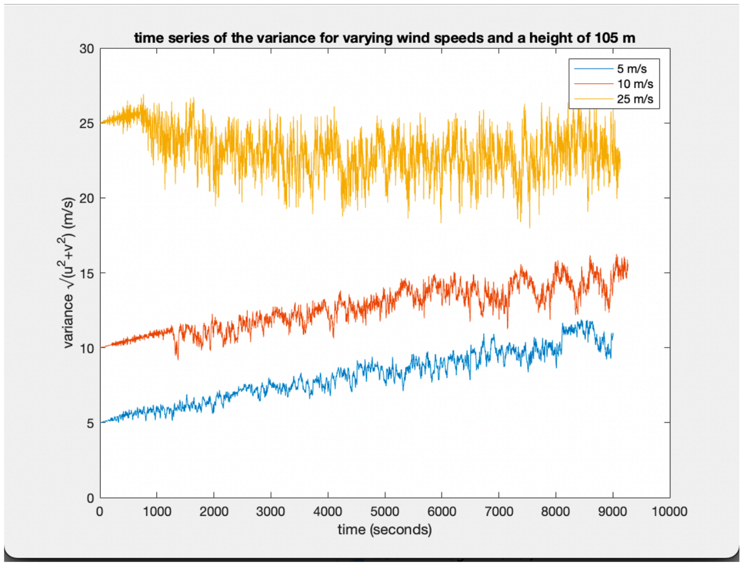

Figure 3: Variances for wind speeds at a z height of 105 meters. Depicts the flow varying temporally at a specific position in the flow.

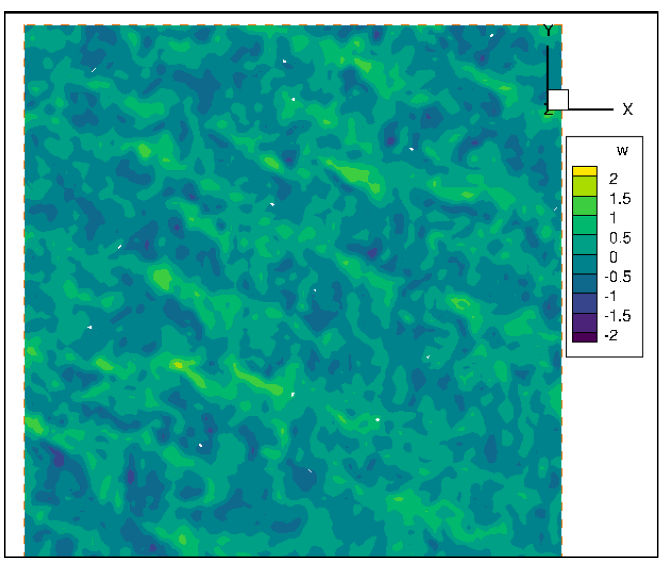

Figure 4: Snapshot of the x-y plane of the w velocities. Depicts the flow varying spatially.

Conclusions

The results of the simulation show that as the wind speed increased, the turbulence or the fluctuations in wind speed also increased in each direction (u, v, and w). This preliminary research scratches the surface of exploration into wind-wave interactions and the turbulence characteristics induced by these interactions and was a preliminary use of LES for offshore wind applications. This area will continue to be important to investigate to affordably build offshore wind turbines in areas that experience higher wind speeds and even hurricanes. Future studies would involve simulating conditions similar to those in a hurricane and including a realistic representation of wind turbines themselves into the model.

References

[1] Sullivan, P. P., McWilliams, J. C., & Patton, E. G. (2014). Large-eddy simulation of marine atmospheric boundary layers above a spectrum of moving waves. *Journal of the Atmospheric Sciences*, *71*(11), 4001–4027. https://doi.org/10.1175/jas-d-14-0095.1

Flow and Turbulence Characteristics at Hub Height for Offshore Wind Energy Production

Sean Egan, David Richter
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INTRODUCTION

Interest in offshore wind has continued to grow over the last few decades as a vital component in the renewable energy landscape. The wind speeds offshore are higher and generally more consistent in magnitude and direction owing to the aerodynamically smoother surface of the ocean, and turbines can be built at a larger scale which generates greater and more reliable energy production. Understanding and harnessing the vast potential of offshore wind is crucial for advancing towards a cleaner and more sustainable energy future.

BACKGROUND OF OFFSHORE WIND

- Most offshore wind turbines use fixed substructures and monopile is the most common foundation
- The future of offshore wind in the US lies in floating structures

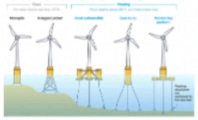

Figure 1: Different substructure types from Razo

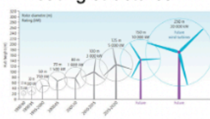

Figure 2: Wind turbine sizes and energy capacity from Padmanathan K.

- Size characteristics – average hub height: 100 meters; average rotor diameter: 220 meters.

Nations around the world are increasingly investing in offshore wind development to meet energy needs sustainably:

- 63 GW produced globally
- China, the UK, and Germany lead the way
- The US lags behind, with only three operational offshore wind farms (producing 174 MW)
- Elevated borrowing and inflation rates hinder further development

There are many engineering challenges that face offshore wind as well:

- Saltwater environment complicates installation and maintenance
- Ensuring electrical stability, efficient power transmission, and effective energy storage management
- Durability in harsh weather and minimizing mechanical stress from wind-wave interaction
- Hurricane-force winds present significant risk to turbine integrity

Figure 3: Turbulent fields behind wind turbines in the Horns Rev 1 offshore wind farm from Steiness.

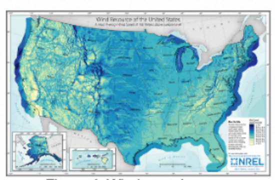

Figure 4: Wind speed across the United States from Roberts at the NREL.

A smaller area that is important for turbine design and reducing costs is exploring the conditions created by wind-wave interaction at varying wind speeds. We centered our efforts on this topic and analyzed the turbulence created by these interactions, specifically at hub height.

METHODS

Utilizing Large Eddy Simulation (LES), our study explores turbulence at hub height:

- Mathematical model based on Navier-Stokes equations
- Simulates turbulent flows, making it valuable for offshore wind applications
- Helps to understand turbulent conditions experienced by turbines
- Simulations involved blowing varying wind speeds over a surface of waves
- Surface of waves served as an initial condition to observe the impact of wind speed on turbulent conditions

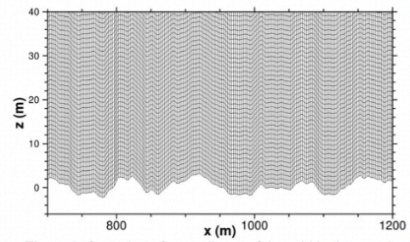

Figure 5: Snapshot of a small part of the grid in the x-z plane from Sullivan. Depicts the surface shape of the waves.

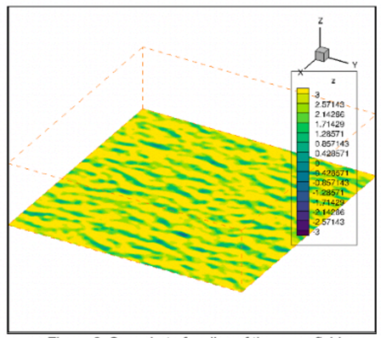

Figure 6: Snapshot of a slice of the wave field.

REFERENCES

Padmanathan, K., Uma, G., Ramachandaramurthy, V. K., P., V., Sudar Oli Selvi, T., & Tamizharasan, T. (2017). *Conceptual Framework of Antecedents to Trends on Permanent Magnet Synchronous Generators for Wind Energy Conversion System.* https://doi.org/10.20944/preprints201707.0057.v1

Razo, Jhasua. *Types of offshore wind turbines.* 19 May 2023. *CNN.*

Roberts, Billy J. *U.S. Wind Power Resource at 100-Meter Hub Height.* 9 Jan. 2023. *WINDExchange.*

Steiness, Christian. *Turbulence field behind Horns Rev 1 offshore wind turbines.* 7 Nov. 2011. *Wind Turbine Syndrome.*

Sullivan, P. P., McWilliams, J. C., & Patton, E. G. (2014). Large-eddy simulation of marine atmospheric boundary layers above a spectrum of moving waves. *Journal of the Atmospheric Sciences, 71*(11), 4001–4027. https://doi.org/10.1175/jas-d-14-0095.1

RESULTS

Simulations were conducted for low, average, and high wind speeds of 5 m/s, 10 m/s, and 25 m/s and the data at a common hub height of 105 meters was extracted to observe the fluctuations in wind speed at this height.

•Variance of the w velocity at z height of 105 meters:

- 5 m/s wind speed: 0.1594
- 10 m/s wind speed: 0.1602
- 25 m/s wind speed: 0.6486

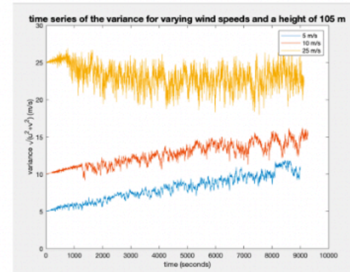

Figure 7: Variances for wind speeds at a z height of 105 meters. Depicts the flow varying temporally at a specific position in the flow.

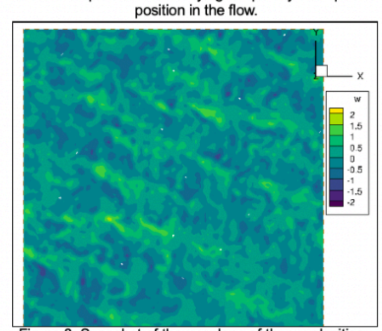

Figure 8: Snapshot of the x-y plane of the w velocities. Depicts the flow varying spatially.

CONCLUSIONS

- As wind speed rose, turbulence (fluctuations in wind speed) increased in all directions (u, v, and w)
- Marks an initial use of LES for offshore wind applications
- Continued investigation is crucial for cost-effective offshore wind turbine construction in regions with hurricane exposure
- Future studies will aim to simulate hurricane-like conditions and incorporate representations of wind turbines in the model