WindSTAR

Wind-Energy Science, Technology, and Research
Industry/University Cooperative Research Center

2020 ANNUAL REPORT

UMass Lowell ✦ UT Dallas

MESSAGE FROM OUR CENTER DIRECTORS

Center Director
Christopher Niezrecki, Ph.D.
University of Massachusetts Lowell

Site Director
Mario Rotea, Ph.D.
University of Texas at Dallas

Dear IAB Members,

On behalf of the WindSTAR I/UCRC Directors and Faculty members, we would like to thank you for your continued support and membership. The Center has completed (Phase I) and we're proud of what we've accomplished having faculty and students work side by side with company members. During Phase I, the Center completed dozens of projects, published numerous papers, had multiple M.S. and Ph.D. students graduate (several have been hired by member companies and national labs), implemented several software and hardware systems that are in use by the WindSTAR company members, and created a new WindSTAR Webinar Series. For every dollar coming from a Full IAB member, ~16 dollars are invested in the Center from another source. For small business IAB members, the leveraging is approximately 48:1. Without operating through the National Science Foundation's I/UCRC program, this level of commitment and value to industry would not be possible.

Every year WindSTAR continues to grow and more people in the wind industry are learning that the Center is a platform that enables universities, industrial partners, and government to collaborate on developing novel solutions to wind energy problems. As we progress through our seventh year of operation (Phase II), we will continue to grow the Center, strengthen existing collaborations, and increase awareness of WindSTAR within the wind industry. In 2021, we believe there will be many new growth opportunities due to increased interest in the decarbonization of the electric grid.

The WindSTAR Center is working to improve the performance and availability of wind energy conversion systems. The Center's efforts will help drive down the cost of wind-generated electricity and make the use of wind energy more widespread within the United States and globally. Results from projects have provided valuable data to Center members who have acquired several multi-million dollar grants augmenting their R&D capacity. Through continued advancements in technology we believe that wind power will be a major player in improving the sustainability of the Nation's electricity portfolio. We are happy you are participating in the WindSTAR I/UCRC and look forward to working with you in the years to come.

Sincerely,
Christopher Niezrecki, Ph.D.
Distinguished University Professor and Chair, Department of Mechanical Engineering
Co-Director, Structural Dynamics and Acoustics Systems Laboratory
Director, WindSTAR I/UCRC
University of Massachusetts Lowell

Mario A. Rotea, Ph.D.
Erik Jonsson Chair in Engineering and Computer Science
Professor, Department of Mechanical Engineering
Site Director, WindSTAR I/UCRC
University of Texas Dallas

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A NATIONAL SCIENCE FOUNDATION SUPPORTED INDUSTRY-UNIVERSITY COLLABORATION DRIVING DOWN THE COST OF WIND POWER

MISSION STATEMENT

The mission of WindSTAR is to bring together university and industry researchers to conduct basic and applied research on topics important to wind industry members. The Center combines capabilities, facilities, and knowledge to execute projects of interest to industry partners, train students in advanced technologies, and foster a community for industry/university networking and collaboration.

WindSTAR is an NSF-funded Industry/University Cooperative Research Center for Wind Energy, Science, Technology and Research, established in 2014. A collaboration between UMass Lowell, the University of Texas at Dallas, and its members, the Center aims to solve the pressing needs of the wind industry.

UMASS LOWELL

The University of Massachusetts Lowell is the lead WindSTAR site and focuses on projects that advance the materials, manufacturing, reliability, testing, modeling, and monitoring of turbines as well as energy storage and transmission. The University of Massachusetts Lowell is a public national research university in Lowell, Massachusetts.

UT DALLAS
The University of Texas at Dallas

The University of Texas at Dallas is a WindSTAR site with foci on high-fidelity simulation of wind power systems and components, LiDAR measurements and analysis of wind fields for diagnostics and model validation, wind tunnel testing, control system design for wind turbines and wind farms, large rotor design, grid integration and energy storage, data analytics for forecasting, performance and health assessment. The University of Texas at Dallas is a public research university in Richardson, Texas.

IAB MEMBER COMPANIES

WindSTAR's industry membership is diverse across the wind energy supply chain, including wind farm owner and operators; turbine, blade and tower manufacturers; material suppliers; condition monitoring & control electronics manufacturers; actuator technology developers; and other organizations with a stake in the growth of the wind energy market.

2020-2021 IAB Chair
Nathan Bruno
Composites Manager - Epoxy
Hexion

2020-2021 IAB Vice Chair
Brian Hill
General Manager North America
Bachmann Electric Corp

2019-2020 IAB Chair
Neal Fine
CEO
Arctura

2019-2020 IAB Vice Chair
Nathan Bruno
Composites Manager - Epoxy
Hexion

Past IAB Chairs:
2018-2019: Nicholas Althoff, GE Renewable Energy
2017-2018: Ben Rice, Pattern Energy
2016-2017: Steve Johnson, GE Renewable Energy
2015-2016: Justin Johnson, EDP Renewables
2014-2015: Steve Nolet, TPI Composites, Inc

Previous Members include:
Huntsman
Keuka Energy
Maine Composites Alliance
National Instruments
NRG Renew

FINANCIAL OVERVIEW: RETURN ON INVESTMENT

MEMBERSHIP LEVELS 2019-2020

Full Membership
$42,400 Annually

Small Business Associate
$15,900 Annually

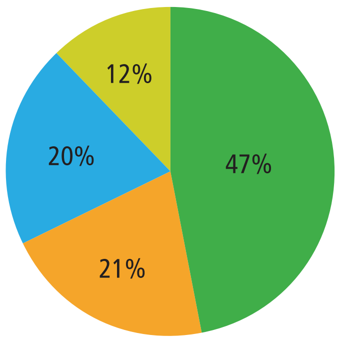
CUMULATIVE INVESTMENT

NSF Award
$929,338

University Contribution (Cost Share)
$993,448

IAB Contributions
$2,234,850

In-Kind
$582,207



TOTAL INVESTMENT: $4,739,843

2019-2020 PROJECTS

- Mechanical Properties Enhancement Prediction for Matrix Materials
  Project ID: A1-19
- Cure Cycle Optimization of Wind Turbine Blades Adhesive Bondlines
  Project ID: A2-19
- Structural Repair of Wind Turbine Blades
  Project ID: A3-19
- Long Duration Testing of the Acoustic Blade Monitoring System
  Project ID: B1-19
- Data-driven Reduced Order Model Based on LiDAR Measurements for Predictions of Wind-Farm Annual Energy Production
  Project ID: C1-19
- Decision Support Using FAST Aero-elastic Models of Operating Wind Turbines
  Project ID: C2-19
- Modeling of Power Losses due to Leading Edge Erosion
  Project ID: C3-19
- Development of a Computational Tool to Maximize Wind Farm AEP by Yaw Angle Optimization
  Project ID: D1-19
- Wind Turbine Foundation Monitoring Sensor Development
  Project ID: U3-19
- Adhesion Test Device for Evaluating Adhesive/Sealant for Lap Joints in Wind Turbine Blades
  Project ID: U1-20

PAST PROJECTS

Composites and Blade Manufacturing

- Mechanical Properties Enhancement Prediction for Matrix Material
- Engineered Sandwich Core Construction: Experiment and Evaluation
- Structural Wind Blade Repair Optimization
- Residual Stresses in Thick Paste Adhesive Bondlines
- Curing of Thick Adhesive Joints
- Mechanical Properties Enhancement Prediction for Matrix Materials
- Automation for Blade Manufacturing
- Effects of Manufacturing Induced Defects
- Mechanical Property Enhancement Prediction for Matrix Materials
- Performance Effects of Adhesive Bond Defects
- Design for Composite Wind Turbine Blade Manufacturing
- Self-Healing Materials for Wind Turbine Blades
- Development of a Unique Fiber-Optic Resin Cure Sensor
- Large Area Turbine Blade Inspection

Structural Health Monitoring, Non-Destructive Inspections, and Testing

- Monitoring of Wind Turbine-Foundation and Technology Assessment
- System integration of a Wind Turbine Blade Acoustic Monitoring System
- Intelligent Damage Detection from Wind Turbine Blades Using Acoustic Excitation
- Low Cost Optical Fiber Strain Sensor Interrogator for Wind Turbine Blades
- Low-Cost Wind Turbine Blade Structural Health Monitoring
- Diagnosis of Electrical Faults of Wind Turbine DFIGs

Wind Farm Modeling and Measurement Campaign

- Proactive Monitoring of Wind Farm Performance Through Wind LiDAR Data and a Reduced Order Model
- Uncertainty quantification of wind farm performance through high fidelity simulations and wind LiDAR measurements
- Proactive Detection of Under-Performing Wind Turbines Combining Numerical Models, LiDAR and SCADA Data

Control Systems for Turbines and Farms

- Advanced Control System for Evaluation of on-Blade Load Mitigation Technologies
- NREL FAST Modeling for Blade Load Control with Plasma Actuators
- Evaluation of Nested Extremum Seeking Wind Farm Control with SWiFT Facility
- Extremum Seeking Control for Wind Turbine Power Maximization
- Two-layer Optimization for Maximizing Wind Farm, Power Output
- Wind Turbine Aerodynamics Modified Gurney Flaps
- Wind Turbine Characterization and Design of High-Efficiency DC Motors

Foundations and Towers

- Mechanical Properties, Micro-structure Property Relationship and Manufacturing/Construction Methods for UHPFRC for Both the Foundation and Towers
- Wind Turbine Foundation Monitoring Sensor Development

2019-2020 PROJECT HIGHLIGHTS

Mechanical Properties Enhancement Prediction for Matrix Materials

Principal Investigator:
Marianna Maiaru (University of Massachusetts Lowell)

Co-Principal Investigators:
Alireza Amirkhizi (University of Massachusetts Lowell)
Todd Griffith (University of Texas at Dallas)

Student Researchers:
Sagar Shah (University of Massachusetts Lowell)

IAB Mentors:
Steve Nolet & Amir Salimi (TPI Composites)
Paul Ubrich, Nathan Bruno & Mirna Robles (Hexion)

Establishing the cost/performance trade-off of new resin systems for modern blades manufacturing is prevented by the limited understanding of the resin in-situ behavior during curing. The effect of heterogeneous and under-cured resins is of particular importance in evaluation of new formulations. Accurate understanding of the curing process is fundamental to reduce processing induced defects and to estimate the effect of in-situ properties on the cost/performance trade-off. The objective of this work is to enable the industry to make more accurate estimates of resin dominated performance measures, such as in-situ composite stiffness and strength, for a given/proposed set of resins and/or curing agents and to determine if there is potential for blade cost reduction minimizing composites defects occurrence including the effects of voids. This project achieved substantial improvements in the prediction of resin-dominated stiffness and transverse strength. We leveraged high-fidelity FEM micro- and meso-scale models to enhance the prediction of matrix dominated properties. Comprehensive thermo-mechanical characterization of Hexion resin systems as functions of degree of cure has been performed and used the data to analyze statistically equivalent Representative Volume Elements (RVEs) of different volume fractions. Mechanical testing has been performed to validate stiffness and strength prediction at the microscale. The void morphology resulting from resin infusion in TPI composites has been characterized using micro-CT. Macroscale FEM simulations linked to cost analysis performed in collaboration with UTD has shown potential for blade cost reduction.

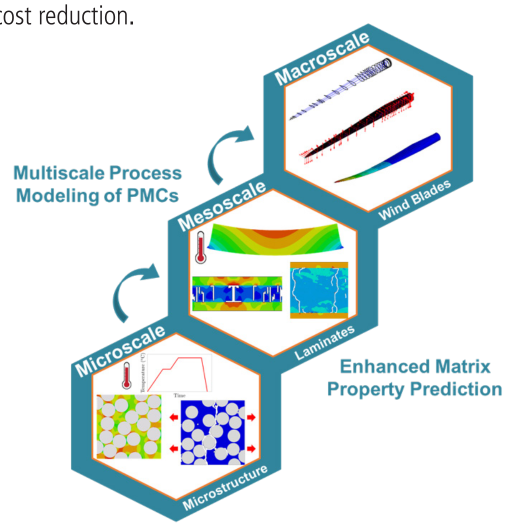


Figure 1: Multiscale approach for enhanced matrix property prediction.

PROJECT ID: A1-19

CENTER EVENTS

IAB Meetings:

- University of Massachusetts Lowell (Virtual), June 10-11, 2020
- University of Texas at Dallas, February 3-4, 2020

Events:

- Dinner with John Lavelle, GE Renewable Energy, CEO Offshore Wind, June 5, 2018
- Mt. Major Hike, June 5, 2018
- Mts. Lafayette, Lincoln, & Little Haystack Hike, June 13, 2017
- Mt. Washington Hike, June 24, 2016
- Mt. Katahdin Hike, June 23, 2015

Webinar Series:

- Control of Wind Energy Systems, Mario Rotea, June 19, 2020
- Curent Status and Future Directions in Wind Farm Modeling, Stefano Leonardi, November 4, 2020

Invited Keynote Speakers for Center Banquets:

- Dr. Paul Veers, Chief Engineer NREL National Wind Technology Center, Is Wind Energy Done? Remaining Grand Challenges in the Science of Wind Energy, February 3, 2020
- Daniel Shreve, Wood Mackenzie Power & Renewables, June 5, 2019
- Dr. Daniel Laird, NREL, January 30, 2019
- Dr. Danielle Merfeld, GE Renewable Energy, June 6, 2018
- Walt Musial, NREL, January, 31, 2018
- John Douglas McDonald, GE Grid Solutions, January 18, 2017
- Dr. Rebecca Barthelmie, Cornell University, February 3, 2016
- Dr. Mike Robinson, NREL/DOE, January 28, 2015
- Daniel Shreve, MAKE Consulting, July 10, 2014

Cure Cycle Optimization of Wind Turbine Blades Adhesive Bondlines

Principal Investigator:
Scott Stapleton (University of Massachusetts Lowell)

Co-Principal Investigators:
Mariana Maiaru (University of Massachusetts Lowell)

Student Researchers:
Alessandro Cassano, Sam Hurvitz, & Sara Najafian
(University of Massachusetts Lowell)

IAB Mentors:
Paul Ubrich (Hexion)
Steve Nolet & Amir Salimi (TPI Composites)

Adhesive bondlines in wind turbine blades are crucial to maintaining the operation and safety of wind farms. Therefore, manufacturers are very careful to ensure that bonds are fully cured and as pristine as possible during manufacturing. To ensure the quality of bonds, conservative approaches to bondline curing are taken to ensure the bondlines are fully cured and do not reach high temperatures during cure. However, bonding of blades can be a manufacturing bottleneck, tying up molds and space in factories while waiting for cure. Since manufacturing time is directly related to the cost of production, manufacturers would like to reduce this curing time as much as possible. To reduce the cure time, heaters are utilized to speed up cure, but they must be careful not to cause the highly exothermic reaction of thick adhesives to carry temperatures into ranges where heat damage may occur. Therefore, manufacturers are have two competing goals: a conservative cure and a quick cure.

To help find the balance between these goals and achieve a cure that is optimized for speed but avoids excessively high temperatures, cure kinetics simulations have been developed. Past work has been done to characterize materials and show the accuracy of such models by comparing with laboratory experiments. While this is a good first step, the shop floor of manufacturing facilities contains many unknowns, and comparisons with highly controlled experiments may not be sufficient to predict actual curing of wind turbine blade bondlines. Therefore, in this project, the model was "taken to the shop floor". Researchers traveled to manufacturing facilities and took measurements about different uncertainties found on the shop floor. Small, instrumented experiments were conducted within wind turbine blades using shop-floor conditions and materials and compared with models. Furthermore, a low-fidelity finite element model was created and a study was made to see how all of the uncertainties in geometric and environmental conditions propagate out and influence the time to cure and the peak temperature. Using this approach, manufacturers can input their uncertainties for a certain material system and cure cycle and ensure that it not only the "nominal" cure will stay within acceptable temperatures, but can give probabilities of proper temperatures and full cure using output statistics.

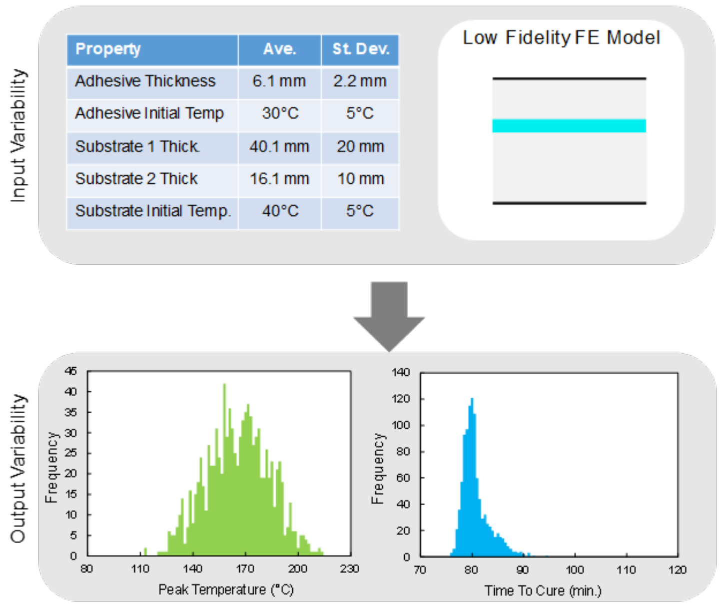


Figure 1: A low fidelity finite element model with cure kinetics was created, and a random selection of substrate and adhesive temperatures and thicknesses within a normal distribution were selected and virtually cured to get a distribution of outputs such as time to cure and peak temperature.

PROJECT ID: A2-19

Structural Repair of Wind Turbine Blades

Principal Investigator:
Marianna Maiaru (University of Massachusetts Lowell)

Co-Principal Investigators:
Scott Stapleton (University of Massachusetts Lowell)
Christopher Hansen (University of Massachusetts Lowell)

Student Researchers:
Sagar Shah, Michael Olaya, Joseph McDonald, Kalima Bukenya, Evgenia Plaka (University of Massachusetts Lowell)

IAB Mentors:
Steve Nolet & Amir Salimi (TPI Composites)
Paul Ubrich & Nathan Bruno (Hexion)
Ben Rice (Pattern Energy)
Jian Lahiri (EDP Renewables)

The objective of this project is to provide the IAB with the knowledge and tools to analyze wind turbine blade repairs and optimize the repair cure cycle to minimize the downtime of the turbines. With a growing number of composite wind turbine blades in service, rotor blade repair is becoming a significant issue. Wind blades can undergo damage during operation due to demanding mechanical loads, environmental conditions, and manufacturing defects. If material damage is not extensive, the structural repair is a cost-effective option to recover strength. Scarf parches can be used to restore the damaged portion of the blade. Up-tower repairs are significantly affected by weather conditions and can cause turbine downtime longer than 24 h depending on the size of the damaged area. Currently, there are no best practices to repair damaged blades effectively. Optimizing the repair cure cycle is needed to reduce the turbine downtime. Insights on the effect of curing parameters are required to schedule repairs in optimal conditions. This work builds upon the material characterization of infusion and hand lamination resin systems and the computational tools developed in the previous year of this project. Five tasks are proposed to perform this work. First, our team will characterize a new Hexion repair system that operates in cold temperatures. Then, we will extend the substrate treatment study to understand the effect of moisture on adhesion. We will further develop and validate the repair app. The app will be translated from Matlab to Python to facilitate the access of the IAB to the tool. Finally, we will study more complex repair procedures that include balsa parts, which will be validated against actual repairs. Outcomes of this work will be insights into optimum procedures for repair as a function of the environmental conditions and the extent of the damaged area, together with the analysis of new resin systems with potential to extend the repair season for owners and operators, thereby providing cost savings. This work will also contribute to creating a tool for cure cycle optimization and a material database for the repair tool.

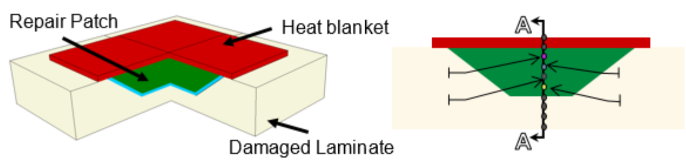


Figure 1: 3D and 1D discretization of repair patch for repair optimization study

PROJECT ID: A3-19

Wind Turbine Foundation Monitoring Sensor Development

Project Instructors:
Christopher Niezrecki
(University of Massachusetts Lowell)

Student Researchers:
Endi Agalliu,Shawn Doolin, Anton San (University of Massachusetts Lowell)

IAB Mentor:
Ron Grife (Leeward Energy)
Adam Johs (EDP Renewables)

PROJECT ID: U3-19

Wind turbine foundations are exposed to a combination of loading which can cause movement and eventually failure. Maintenance inspections are periodically conducted to prevent failure but are generally inconsistent and expensive. A low cost (less than $10) displacement indicator is required. The objective of this indicator is to reveal the displacement between the concrete and tower. Continuing off of a design provided from a previous capstone group, the knowledge gained through research was used to optimize this design while accounting for the design specifications. Two different variations of this product were created; one with an adjustable stopper and one with an adjustable CAM. With minimal changes to the overall functionality of the displacement indicator, prototyping was the next step towards selecting the final design. Instillation time, cost, visibility of product and functionality were all analyzed to optimize its purpose and account for any errors and malfunctions. The final indicator is designed with injection molding in mind and is successful in providing a positive indication that a movement in excess of the specification [0.040" (+/- 0.010")] has occurred.

Long Duration Testing of the Acoustic Blade Monitoring System

Principal Investigator:
Murat Inalpolat (University of Massachusetts Lowell)

Co-Principal Investigator:
Yan Luo (University of Massachusetts Lowell)
Christopher Niezrecki (University of Massachusetts Lowell)

Student Researchers:
Caleb Traylor & Chenxi Wang (University of Massachusetts Lowell)

IAB Mentors:
Adam Johs (EDP Renewables)
Ben Rice (Pattern Energy)
Ron Grife (Leeward Renewable Energy)
Nicholas Althoff (GE Renewable Energy)

Project B1-19 builds off previous projects to develop a low cost highly capable wind turbine blade structural health monitoring system. Wind turbine blade failures can be a significant contributor to the operation and maintenance expenses for wind farm operators. By identifying damage in the early stages, unscheduled blade replacements and major repairs can be replaced by scheduled minor repairs. This approach uses acoustic monitoring of the sound in the blade internal cavities to identify anomalies that could be indicative of damage and has been verified with a blade subsection in a wind tunnel. This project is focused on deployment of acoustic sensors to operational wind turbines for long-duration testing, as well as continued development of the machine learning techniques to identify damage and improvement of the sensor node. Sensors were first deployed inside blades undergoing fatigue testing at the WTTC. This allowed for testing of the node performance and provided valuable data for analysis. Analysis of this data demonstrated how machine learning could successfully identify clusters corresponding to different blade conditions. Improved performance of the machine learning algorithm was then achieved using data collected during wind tunnel experiments for a previous WindSTAR project. In this analysis, the anomaly identification capabilities of the machine learning algorithm were highlighted, as damage location and size could be identified, providing a valuable benchmark in preparing for operational wind turbine data. A new version of the sensor node has been developed that is more reliable, and its acoustic performance was tested and verified inside an anechoic chamber. The power supply plan was improved for implementation in the hub and blades of an operational wind turbine. Seven sensors have been shipped for a deployment on a wind turbine in Texas. According to the deployment plan, two sensor would be placed in each of the three blades of the turbine, and one sensor would be placed at the base of the tower. These will provide valuable data for analysis of wind turbine acoustics. In addition, the process of deploying at a wind farm resulted in answering practical questions regarding implementation which are being incorporated into an improved design. This project was successful in setting up long-duration testing, and the data collected will be of great value in future projects.

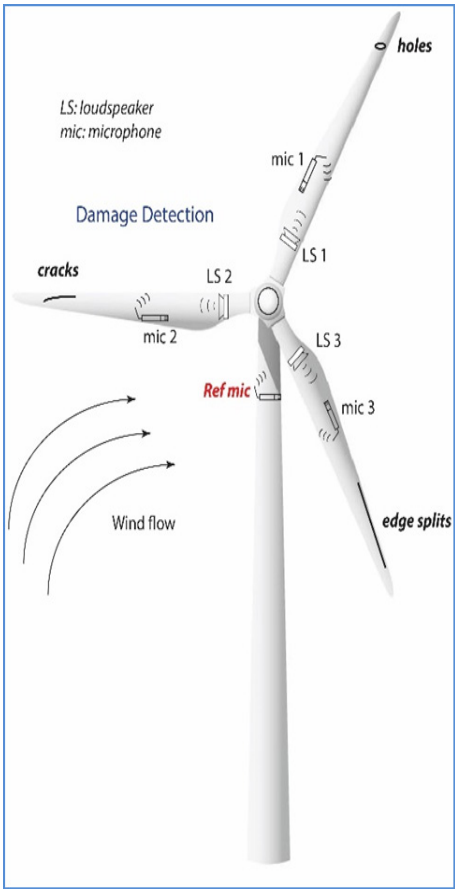


Figure 1: Acoustics based blade structural health monitoring approach. Microphones identify changes in sound pressure, which is used to detect damage.

PROJECT ID: B1-19

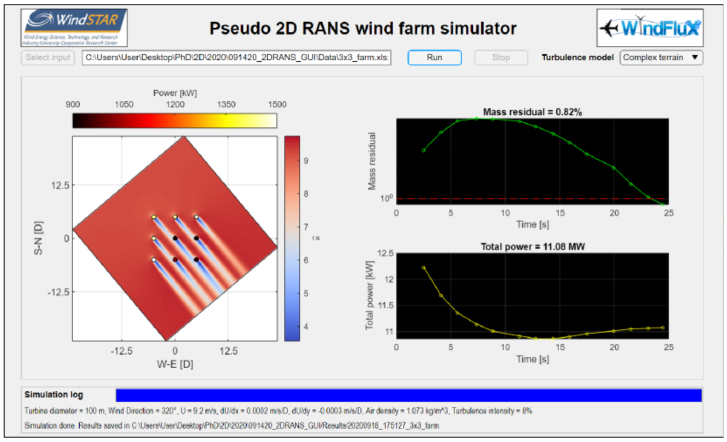
Data-driven Reduced Order Model Based on LiDAR Measurements for Predictions of Wind-Farm Annual Energy Production

Principal Investigator:
Giacomo Valerio Iungo (University of Texas at Dallas)

Student Researchers:
Stefano Letizia (University of Texas at Dallas)

IAB Mentors:
Ron Grife (Leeward Renewable Energy)
Nicholas Althoff (GE Renewable Energy)
Patrick Pyle (Pattern Energy)
Adam Johs & Brandon Fitchett (EPRI)
Neal Fine (Aquanis)

This project aims to develop a CFD tool for accurate predictions of wind turbine wakes and power capture at the turbine level by reproducing the typical variability during the daily cycle of the atmospheric stability and flow distortion due to the complex terrain. This CFD tool is based on the Reynolds-averaged Navier-Stokes (RANS) equations by leveraging rotor-heights averaging, which are solved parabolically to reduce the computational costs. The model has been validated against real wind farm data with a 10-minute time resolution. The latest upgrade of the CFD tool showed an accuracy of 10% with a confidence level of 95% for estimates of power capture from individual turbines. Among different features, the CFD tool provides a data-driven calibration of the turbulence closure to mimic variability in wake recovery due to different regimes of atmospheric stability. Furthermore, the thrust force over the turbine blades is experimentally estimated by coupling LiDAR data and RANS simulations. A GUI for simulations of wind farms with a generic layout and turbine power curve has been delivered to the IAB members.



Snippet of the Pseudo 2D RANS GUI at the end of a simulation of a farm operating during NW wind.

PROJECT ID: C1-19

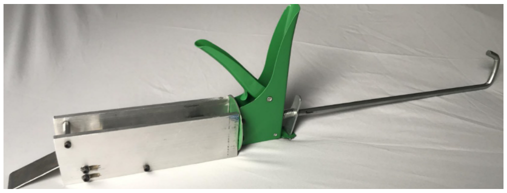
Adhesion Test Device for Evaluating Adhesive/Sealant for Lap Joints in Wind Turbine Blades

Project Instructors:
Scott Stapleton
(University of Massachusetts Lowell)

Student Researchers:
Samuel Munnelly, Zachary Moore, Aidan Burbridge, Gaetan Deschenes
(University of Massachusetts Lowell)

IAB Mentors:
Tomas Muchenik Cena & Murray Fisher (LM Wind Power)

The size and weight of a wind turbine blade directly affect the power production capabilities of the turbine. Blades with lighter materials can be made larger. During manufacturing, the blade shells are joined together with copious amounts of adhesive. The large volume of adhesive adds weight. Testing potential adhesives is vital in the constant search for a more effective, lighter adhesive. One inexpensive and quick preliminary test method is described in the ASTM standard D3808-01. The student team developed a test device to be used following a procedure comparable to that described in ASTM standard D3808-01. Repeatability and portability have been achieved through a simplistic, all mechanical, light weight design involving few moving parts. The device is handheld and meant to be operated by one researcher. The test is carried out by using the energy created by the compression of a spring to scrape through a dot of adhesive. The test device designed allows for repeatable quantitative data to be collected on the bond strength of adhesives.



PROJECT ID: U1-20

Decision Support Using FAST Aero-elastic Models of Operating Wind Turbines

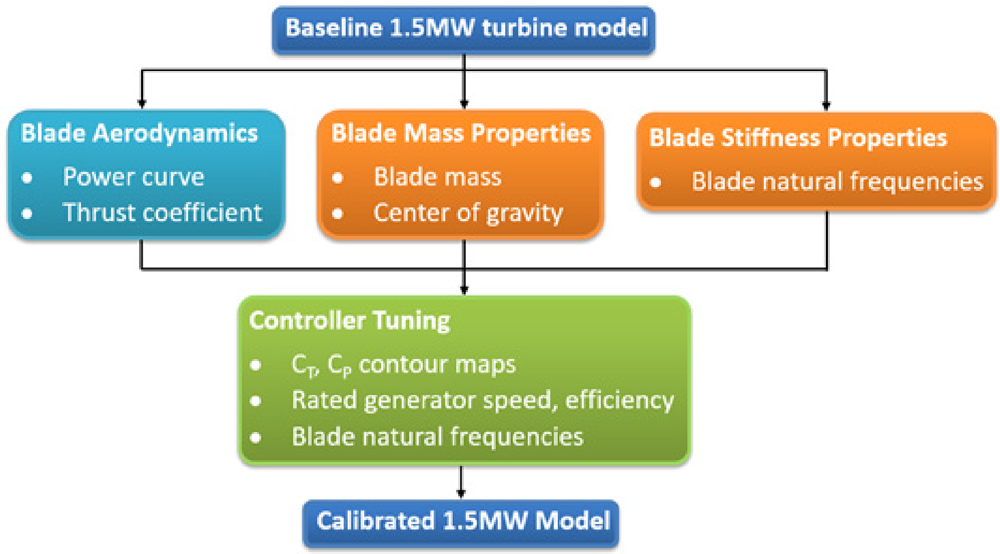
Principal Investigator:
Todd Griffith (University of Texas at Dallas)

Co-Principal Investigator:
Mario Rotea (University of Texas at Dallas)

Student Researchers:
Liliana Haus & Chang Liu (University of Texas at Dallas)

IAB Mentors:
Adam Johs (EDP Renewables)
Brandon Fitchett (EPRI)
Lothar Breuss (Bachmann)
Ron Grife (Leeward Renewable Energy)
Benjamin Rice (Pattern Energy)
Neal Fine (Aquanis)

In modern wind turbines, the wind energy industry looks to the development of new technologies and/or new processes to achieve goals for profitability in producing electricity at a competitive market rate. In this respect, validated tools for design and asset management are one of the key needs for achieving and maintaining a market-competitive levelized cost of energy (LCOE) throughout the lifetime of the turbine. The C2-19 project addresses this need by focusing on a new approach for developing an aero-elasto-servo digital twin model of an operating utility-scale 1.5MW wind turbine. In this technique, experimental data from an operating wind turbine is used to calibrate the properties of a baseline turbine model to represent the loads and dynamic behavior of the target wind turbine. The blade aerodynamics and structural dynamics are the primary focus of this technique. For the aerodynamic model, the power curve and thrust coefficient data of an experimental turbine is used to calibrate the digital twin's blade aerodynamic properties. For the structural model, experimental data on the blade center of gravity, total mass, and natural frequencies is used to calibrate the digital twin's blade mass and stiffness property distributions. The digital twin model was created as an OpenFAST (FAST) model and the turbine's controller was created in Simulink and tuned to maintain the desired operating properties of the digital twin. A primary benefit of this methodology is its versatility of implementation in the creation of models of multiple similar turbines (such as those in a fleet) once a baseline model is in place. Finally, the model is used to perform a de-rating case study and a fatigue case study to illustrate some of the many potential uses of this digital twin in asset management for decision support in wind farm operations. The overarching goal of the project is to provide and explore a new and simple model development methodology to create a digital twin, and explore its uses and potential benefits for LCOE reduction and overall fleet management.



Pictorial representation of the model calibration process. The process begins with an uncalibrated baseline model. The baseline aerodynamic and structural properties are tuned separately using experimental data and then the controller is tuned to maintain desired turbine properties during operation.

PROJECT ID: C2-19

Modeling of Power Losses due to Leading Edge Erosion

Principal Investigator:
Giacomo Valerio Iungo (University of Texas at Dallas)

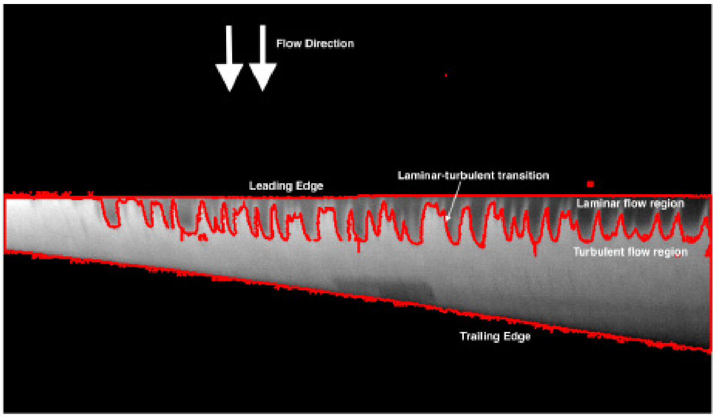
Student Researcher:
Keshav Panthi (University of Texas at Dallas)

IAB Mentors:
Murray Fisher (LM Wind Power)
Nicholas Althoff (GE Renewable Energy)
Ron Grife (Leeward Renewable Energy)

Due to operation under harsh conditions, rotor blades suffer from soiling and erosion of the leading edge, which can be detrimental for the aerodynamic performance of blade airfoils and, in turn, power capture. The presence of asperities over the blade skin in proximity of the leading edge causes a premature laminar-turbulent transition of the boundary layer leading to a reduction of lift force and an increase in drag. Although the leading-edge erosion is known to have significant effects on wind turbine performance, a model for proactive detection of leading-edge erosion is still missing.

Leading-edge contamination is known to have a significant effect on wind turbine performance; however, automated quantification of the leading-edge contamination is missing. To determine the rotor blade surface condition, a semi-automated contactless measurement method has been developed, which is based on the thermographic determination of the laminar-turbulent transition location. The surface blade is scanned with infrared cameras during normal operations to sense the location of the laminar-turbulent transition. The extent of leading edge contamination is calculated by comparing the natural transition location with the actual transition location influenced by local leading edge surface imperfections.

A quantification of both the extent of the contamination and the impact on wind turbine performance is difficult and calculations are based on estimates. A method for assessing the power loss due to leading edge contamination is proposed for this project. The method is based on thermographic flow measurements along the rotor blade and the automated determination of the laminar-turbulent transition location. A comparison with the expected natural transition of the clean rotor blade position enables the extent of the leading-edge contamination to be quantified. This project includes collection of field data on the degradation of the blade skin due to the leading-edge erosion through infrared (IR) cameras. An experiment was conducted on March 11-12, 2020, at the Cedar Creek wind farm. Turbine blades with different levels of leading-edge erosion were scanned to provide information about the actual location of the laminar-turbulent transition. The IR scans, such as those reported in the figure below, were performed for different incoming wind speed, wind shear and atmospheric stability regimes to cover the broad range of operative conditions of the wind turbines. The experimental IR data will be used to inform XFOIL simulations of the airfoils under examination. The location of the laminar-turbulent transition will be prescribed at the locations observed from the IR data to estimate effects on lift and drag forces. The impact on the annual energy production (AEP) will then be evaluated using a Blade Element Momentum (BEM) model using the modified polar data obtained from XFOIL simulations. The BEM calculations will be coupled with the SCADA data to quantify power losses due to different levels of leading-edge erosion. However, the current analysis of SCADA and meteorological does not show evident impact of LE erosion on the power capture over a duration of three years. The ultimate goal of the project consists in providing an engineering model for proactive detection of the advancement of the leading-edge erosion to predict and avoid the occurrence of significant power losses and support decision-making for economically efficient maintenance of the leading-edge erosion.



Sample of IR image collected at the Cedar Creek wind farm and detection of the laminar/turbulent transition.

PROJECT ID: C3-19

Development of a Computational Tool to Maximize Wind Farm AEP by Yaw Angle Optimization

Principal Investigator:
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Ron Grife (Leeward Energy)
Johs Adams (EDP Renewables)
Brian Hill (Bachmann Electronic)
Ben Rice (Pattern Energy)

Recent studies have demonstrated promising results for control strategies such as intentional yaw misalignment to mitigate wake interactions and optimize wind farm efficiency (Figure 1). Most studies have been carried out in "idealized conditions," i.e. typically assuming fixed wind speed and direction. In a realistic scenario, wind speed and direction vary over time, including conditions where there is little to no value added for optimization (e.g., above-rated wind speeds). Therefore, the efficiency improvements obtained with idealized studies will likely be lower when measured in terms of annual energy production (AEP). In this project, we have developed a methodology to move beyond ideal studies and estimate the impact of yaw control on AEP.

The methodology is based on high-fidelity simulations and generalized polynomial chaos. High-fidelity simulations are used to minimize the uncertainties in predicting wind farm performance. Parameterizing wake deflection by yaw (which is the key mechanism for yaw control, a.k.a intentuional yaw misaligment) is still an open issue in wind energy research, and the use of low-fidelity models may result in uncertainties of the same order of the predicted performance improvement. Coupling the high-fidelity simulations with the polynomial chaos technique provide an accurate and computationally efficient surrogate model to compute wind farm power production as a function of wind speed and direction. The surrogate model is used to estimate AEP for different control strategies (in particular, baseline vs. intentional missaligments).

The procedure has been applied to relatively small wind farm consisting of 9 turbines (Figure 2). The wind farm is sited in a complex terrain, reproduced in the high-fidelity simulations, which significantly affects performance as a function of wind direction. A surrogate model for the baseline control strategy (i.e. no yaw control) is first obtained to compute the benchmark AEP. Nested extremum-seeking control is then used to find the yaw misalignment angles to optimize power production for each wind direction. The resulting surrogate model is used to estimate the optimized AEP, which provide an improvement of about 3% for this test case. In addition, the study reveals that the improvement on individual turbines may be larger than for the entire farm. This different sensitivity could be exploited for more advanced and tailored control approaches.

Calculation of optimal yaw angles using a genetic algorithm (GA) with the polynomial chaos surrogate model has also been performed to compare with the results from extremum seeking control (ESC). Table 1 shows the optimal misalignment angles of three turbines (T13, T14, T

Table 1: Comparison of intentional yaw misalignment angles for three turbines from Figure 2.

	T13	T14	T15	Total power change
ESC on high-fidelity model	-8 deg	-5 deg	-10 deg	+ 3%
GA on polynomial chaos model	-11 deg	-12 deg	-12 deg	+ 4%

15 in Figure 2) optimized with ESC in the high-fidelity simulation and the same three turbines optimized with the GA on the surrogate model. While yaw angles are somewhat different, the total wind farm power changes with both optimizations are comparable.

The proposed methodology permits to assess the impact of yaw control in realistic conditions. This will ultimately enable operators to assess the benefit of the control strategy in terms of levelized cost of energy and thus make low-risk informed decisions.

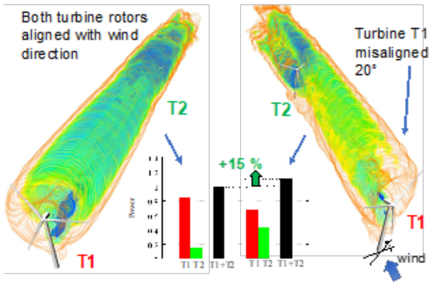

Figure 1: Intentional yaw misalignment to mitigate wake interactions. Visualizations of a two-turbine array (aligned with the wind direction) in baseline operating conditions (no yaw control, left) and with yaw control (right). With a 20° intentional yaw misalignment on T1, the trailing wake is deflected laterally, which reduces the wake interaction on T2. An improvement of 15% is obtained with yaw control for this wind direction.

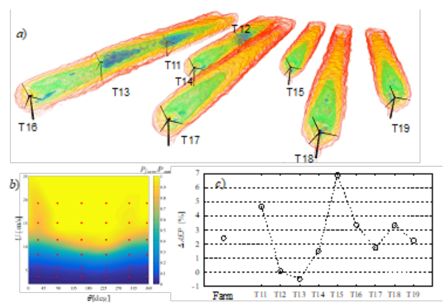

Figure 2: Application of the proposed methodology to estimate the impact of yaw control on annual energy production. Panel a): visualization of turbine wakes at the selected wind farm. Panel b): surrogate model obtained with high-fidelity simulations and polynomial chaos. For each wind speed U and wind direction ⊠, the model provides the power produced by the wind farm. Panel c): improvement of yaw control on annual energy production for the entire farm (≈ 3%) and the individual turbines.

PROJECT ID: D1-19

2018-2020 OUTCOMES

Through August 31, 2020

For a cumulative list of all center outcomes visit uml.edu/windSTAR

Products:

1. Software: FAST Model V1.0: Aero-elastic Model
2. Software: Matlab code for cure optimization as a function of the repair thickness, kinetic of two resin systems as a function of temperature and humidity.
3. Software: A user-based subroutine written in Fortran for use in the finite-element software Abaqus, to calculate the degree of cure and temperature of an adhesive under exothermic curing reaction.
4. Software: A tool to simulate blade active load control systems using NREL FAST and any actuation system (plasma actuators in particular) that can command changes in the local lift coefficient along the blade span.
5. Software: A Matlab-based GUI that can predict the axial, transverse, and shear properties of composite laminates used in wind turbine blades based on CPFM advanced micromechanics model
6. Software: A Matlab based GUI for prediction of power production and wind turbine wakes for the Panhandle Phase II wind farm.
7. Software: Simulink code for Extremum Seeking Control of NREL CART3 (Controls Advanced Research Turbine, 3-bladed).
8. Patent: Foundation and Deflection Monitoring Device #10808374, Awarded 10/20/20.
9. Hardware: Fiber Optic Interrogator for Strain Monitoring
10. Hardware: Passive Acoustic Damage Detection System for Blades
11. Hardware: Active Acoustic Damage Detection System for Blades

Journal Papers:

1. Beale, C., Niezrecki, C., and Inalpolat, M., "An adaptive wavelet packet denoising algorithm for enhanced active acoustic damage detection from wind turbine blades," Mechanical Systems and Signal Processing, Volume 142, August 2020; https://doi.org/10.1016/j.ymssp.2020.106754.
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3. Dongyang Cao, Sadeq Malakooti, Vijay N Kulkarni, Yao Ren, Hongbing Lu, "Nanoindentation measurement of core-skin interphase viscoelastic properties in a sandwich glass composite," Mechanics of Time-Dependent Materials, 2020, DOI: 10.1007/s11043-020-09448-y.pdf
4. Zhan, Lu, Stefano Letizia, and Giacomo Valerio Iungo. "Optimal tuning of engineering wake models through LiDAR measurements." Wind Energy Science 5.4 (2020): 1601-1622.
5. Zhan, Lu, Stefano Letizia, and Giacomo Valerio Iungo. "LiDAR measurements for an onshore wind farm: Wake variability for different incoming wind speeds and atmospheric stability regimes." Wind Energy 23.3 (2020): 501-527. https://doi.org/10.1002/we.2430
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13. Santhanagopalan V., M.A. Rotea, G.V. Iungo, "Performance optimization of a wind turbine column for different incoming wind turbulence," Renewable Energy, Vol. 116, February 2018, pp. 232-24.
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Conference Papers:

1. Gondle, R.K., Kurup, P.U., and Niezrecki, C. "Evaluation of Wind Turbine-Foundation Degradation," Paper accepted to the 16th International Conference of the International Association for Computer Methods and Advances in Geomechanics (IACMAG), Torino, Italy, May 5-8, 2021.
2. Inalpolat, Murat, and Christopher Niezrecki. "Acoustic Sensing Based Operational Monitoring of Wind Turbine Blades." Journal of Physics: Conference Series 1452.1 (2020): 012050.
3. Joe McDonald, Michael Olaya, Sagar Shah, Scott Stapleton, Christopher Hansen, Marianna Maiaru, "Wind Blade Repair Optimization," Presented at ASC Conference Proceedings, session Composites for Wind Blades, ASC 35th Technical (Virtual) Conference, September 17, 2020.
4. Zhan L., Letizia S., Iungo G.V., "Wind LiDAR measurements of wind turbine wakes evolving over flat and complex terrains: Ensemble statistics of the velocity field," Journal of Physics: Conference Series, vol. 1452, 012077, 2020.
5. Liu, Chang, Abhineet Gupta, and Mario Rotea. "Multi-Sectional Lift Actuation for Wind Turbine Load Alleviation." Journal of Physics: Conference Series. Vol. 1618. No. 2. IOP Publishing, 2020.
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9. Santhanagopalan V., Letizia S., Zhan L., Al-Hamidi L.Y., Iungo G.V. "2018 Profitability optimization of a wind power plant performed through different optimization algorithms and a data-driven RANS solver." 2018 Wind Energy Symp., AIAA Scitech Forum AIAA 2018-2018.
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Selected Presentations:

1. S. Letizia, L. Zhan and G.V. Iungo. "Effects of topographic wakes on wind turbine performance." Wind Energy Science Conference 2019, June 17-20, Cork, IR.
2. L. Zhan, S. Letizia and G.V. Iungo. "Ensemble statistics of wind turbine wakes on flat and complex terrains: Wind LiDAR observations." NAWEA WindTech 2019 Conference, October 14-17, 2019, Amherst, MA.
3. Shah, S., "Mechanical Property Enhancement Prediction for Matrix Materials," CAMX, Anaheim, CA, September 2019.
4. Rotea M.A., "Control of Wind Energy Systems," J. Mike Walker '66 Seminar Series, Texas A&M University, February 20, 2019.
5. Letizia S., Zhan L., Iungo G.V., "Effects of topographic wakes on wind turbine performance," Wind Energy Science Conference, June 17-20 2019, Cork, Ireland.
6. Nanos E.M., Letizia S. , Zhan L., Rotea M.A., Bottasso C. and Iungo G.V., "An experimental study of lateral wake interactions within a wind farm," Wind Energy Science Conference, June 17-20 2019, Cork, Ireland.
7. Niezrecki, C., Keynote Address: "Recent Developments in Wind Turbine Sensing for Structural Health Monitoring," World Energy Congress, Boston, MA, August 27-28, 2018.
8. Rotea M.A., Extremum Seeking Control of Wind Energy Systems, AWEA Wind Project O&M and Safety Conference 2018 (largest North American gathering of wind energy O&M industry professionals), San Diego, CA, February 27-28, 2018.

Master of Science Thesis:

1. Haus, L., "New Methods for Digital Twin Modelling of Wave and Wind Energy Systems," MS Thesis, UT-Dallas, July 2020.
2. Behzad Najafi, "Characterization of uniform momentum zones in the atmospheric boundary layer," M.S. in Mechanical Engineering, University of Texas at Dallas, July 2019 (Chair: G.V. Iungo). Now with IAB member Leeward Renewable Energy, LLC.
3. Joshua Morris, "Improving Wind Turbine Blade Transverse and Shear Response Using Advanced Resins," Master of Science Thesis, University of Massachusetts Lowell, 2018. (Advisor: Alireza Amirkhizi).

PhD Dissertations:

1. Christopher Beale, "System Integration of a Wind Turbine Blade Acoustic Monitoring System," PhD in Mechanical Engineering, University of Massachusetts Lowell, 2019. (Advisor: Murat Inalpolat).
2. Umberto Ciri, "Analysis of Model-Free Control of Wind Farms using Large-Eddy Simulations," Ph.D. in Mechanical Engineering, University of Texas at Dallas, July 2019. Now postdoctoral associate at UT Dallas. (Chair: Stefano Leonardi).
3. Lu Zhan, "LiDAR measurements for the characterization of wind turbine wakes, wake interactions and their effects on wind farm performance," Ph.D. in Mechanical Engineering, University of Texas at Dallas, December 2019. Now Postdoctoral Researcher at University of Minnesota. (Chair: G. Valerio Iungo).
4. Siddharth Dev, "Novel Microcapsule Chemistries for Self-Healing Applications in Polymeric Materials," Ph.D. in Mechanical Engineering, Dissertation, University of Massachusetts Lowell, 2018. (Advisor: Christopher Hansen).
5. Cristian Santoni, "Wind Farm Modeling: From the Meso-Scale to the Micro-Scale," Ph.D. in Mechanical Engineering, University of Texas at Dallas, 2018. Now Postdoctoral Associate at Stony Brook University(Chair: Stefano Leonardi).
6. Yan Xiao, "Control of Wind Power Systems for Energy Efficiency and Reliability," Ph.D. in Electrical Engineering, University of Texas at Dallas, 2018. Now with Danfoss, Rockford, IL. (Chair: Mario Rotea, Co-Chairs: Yaoyu Li, Babak Fahimi).

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1. Alessandro Cassano, recipient of WindSTAR NSF INTERN at UMass Lowell, Intern at TPI Composites.
2. Said El-Asha, recipient of WindSTAR NSF REU at UT Dallas, Engineering Intern at Leeward Renewable Energy, LLC.

Students Hired at Member Companies:

1. Liliana Haus, MS from University of Texas at Dallas, EPRI

ACTIVE PROJECTS: 2020-2021

» **Developing a Multi-physical Computational Model for Predicting Process-Induced Residual Stress and Distortion In Fiber Reinforced Composites**
Project ID: A1-20
PI: Dong Qian (University of Texas at Dallas)
Mentors: TPI Composites, Olin Epoxy, Hexion

» **Structural Wind Blade Repair Optimization**
Project ID: A3-20
PI: Marianna Maiaru (University of Massachusetts Lowell)
Mentors: TPI Composites, Hexion, Pattern Energy, EDP Renewables, GE Renewables, Leeward Renewable Energy, Olin Epoxy

» **Cure Cycle Optimization of Low CTE Adhesives for Wind Turbine Blade Bondlines**
Project ID: A4-20
PI: Scott Stapleton (University of Massachusetts Lowell)
Mentors: Hexion, TPI Composites, Olin Epoxy

» **Development of a Next-Generation Low-power Acoustic Sensor for Wind Turbine Blade Structural Health Monitoring**
Project ID: B1-20
PI: Murat Inalpolat (University of Massachusetts Lowell)
Mentors: EDP Renewables, Pattern Energy Group, Leeward Renewable Energy, Bachmann

» **Data Driven Remaining Useful Lifetime Modelling of Inverters in Renewable Energy Applications**
Project ID: B2-20
PI: Bilal Akin (University of Texas at Dallas)
Mentors: EDP Renewables

» **Assessment and Improvement of Industry-standard Wind Farm Models based on Physics-informed Reduced Order Model**
Project ID: C2-20
PI: Giacomo Valerio Iungo (University of Texas at Dallas)
Mentors: GE Renewables, Pattern Energy Group, EPRI, Leeward Renewable Energy, EDP Renewables, Bachmann

» **Decision Support with OpenFAST Digital Twin - Case Studies Applied to IAB-owned Assets**
Project ID: C3-20
PI: Todd Griffith (University of Texas at Dallas)
Mentors: EDP Renewables, Leeward Renewable Energy, Pattern Energy Group, Bachmann, EPRI, Arctura

» **Fatigue Loading Effects and Power Flucuations Due to Wake Steering Within A Wind Farm-A Wind Tunnel Study**
Project ID: D1-20
PI: Yaqing Jin, Mario Rotea (University of Texas at Dallas)
Mentors: Arctura, Pattern Energy Group, EPRI, EDP Renewables

» **Design of UHPC Towers for Offshore Wind Turbine**
Project ID: F1-20
PI: Dong Qian, Hongbing Lu (University of Texas at Dallas)
Mentors: Shell, Texas Wind Tower

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Published 1/25/21

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