WindSTAR

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

2021 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. We're proud of what we've accomplished having faculty and students work side by side with company members. We have finished our second year as a Phase II Center having 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 eighth 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 2022, we believe there will be many new growth opportunities due to increased interest in the decarbonization of the electric grid and the planned U.S. procurements for offshore wind energy.

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 various 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 and enable new applications of this renewable source of energy. 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, Mechanical Engineering
Co-Director, RIST Institute for Sustainability and Energy
Co-Director, Structural Dynamics and Acoustics Systems Laboratory
Director, WindSTAR I/UCRC
University of Massachusetts Lowell

Mario A. Rotea, Ph.D., F. IEEE
Professor, Mechanical Engineering
Professor (affiliate), Electrical and Computer Engineering
Director, Center for Wind Energy (UTD Wind)
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.

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, transmission and zero-carbon fuel generation. The University of Massachusetts Lowell is a public national research university in Lowell, Massachusetts.

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.

2021-2022 IAB Chair
Brian Hill
General Manager North America
Bachmann Electronic Corp

2021-2022 IAB Vice Chair
Brandon Fitchett
Program Manager, Wind Power R&D
Electric Power Research Institute (EPRI)

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

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

Past IAB Chairs:
2019-2020: Neal Fine, Arctura
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

ARCTURA

AVANGRID RENEWABLES

bachmann.

edp renewables

EPRI ELECTRIC POWER RESEARCH INSTITUTE

GE Renewable Energy

HEXION™

LEEWARD renewable energy

MASSACHUSETTS CLEAN ENERGY CENTER

Olin™ EPOXY

Pattern

TWT Texas Wind Tower

tpi COMPOSITES

WindESCo

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

FINANCIAL OVERVIEW: RETURN ON INVESTMENT

MEMBERSHIP LEVELS 2020-2021

Full Membership
$44,944 Annually

Small Business Associate
$16,856 Annually

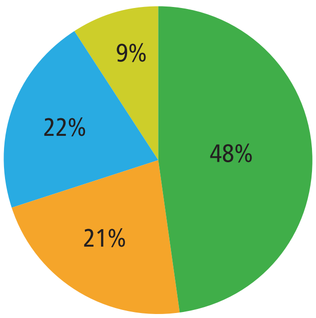
CUMULATIVE INVESTMENT

NSF Award
$1,201,654

University Contribution (Cost Share)
$1,235,527

IAB Contributions
$2,755,451

In-Kind
$ 527,508



TOTAL INVESTMENT: $5,720,140

2020-2021 PROJECTS

- » Developing a Multi-physical Computational Model for Predicting Process-Induced Residual Stress and Distortion In Fiber Reinforced Composites, Project ID: A1-20
- » Structural Wind Blade Repair Optimization, Project ID: A3-20
- » Cure Cycle Optimization of Low CTE Adhesives for Wind Turbine Blade Bondlines, Project ID: A4-20
- » Development of a Next-Generation Low-power Acoustic Sensor for Wind Turbine Blade Structural Health Monitoring, Project ID: B1-20
- » Data Driven Remaining Useful Lifetime Modelling of Inverters in Renewable Energy Applications, Project ID: B2-20
- » Assessment and Improvement of Industry-standard Wind Farm Models based on Physics-informed Reduced Order Model, Project ID: C2-20
- » Decision Support with OpenFAST Digital Twin - Case Studies Applied to IAB-owned Assets, Project ID: C3-20
- » Fatigue Loading Effects and Power Flucuations Due to Wake Steering Within A Wind Farm-A Wind Tunnel Study, Project ID: D1-20
- » Design of UHPC Towers for Offshore Wind Turbine, Project ID: F1-20

PAST PROJECTS

Composites and Blade Manufacturing (A)

- » Adhesion Test Device for Evaluating Adhesive/Sealant for Lap Joints in Wind Turbine Blades
- » Structural Repair of Wind Turbine Blades
- » Cure Cycle Optimization of Wind Turbine Blades Adhesive Bondlines
- » 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 (B)

- » Long Duration Testing of the Acoustic Blade Monitoring System
- » 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 (C)

- » Data-driven Reduced Order Model Based on LiDAR Measurements for Predictions of Wind-Farm Annual Energy Production
- » Decision Support Using FAST Aero-elastic Models of Operating Wind Turbines
- » Modeling of Power Losses due to Leading Edge Erosion
- » 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 (D)

- » Development of a Computational Tool to Maximize Wind Farm AEP by Yaw Angle Optimization
- » 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 (F)

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

Developing a Multiphysical Computational Model for Predicting Process-Induced Residual Stress and Distortion in Fiber-Reinforced Composites

Principal Investigators:
Dong Qian, Hongbing Lu (University of Texas at Dallas)

Student Researchers:
Runyu Zhang, Yingjian Liu, Vijay Kulkarni
(University of Texas at Dallas)

IAB Mentors:
Steve Nolet (TPI Composites)
Yi Ling "Ivan" Liang, Huifeng Qian (Olin)
Paul Ubrich, Nathan Bruno, Mirna Robles (Hexion)

Polymer matrix composites (PMC) such as glass fiber reinforced epoxy composites have dominated the manufacturing of wind turbine blades due to the combination of high strength/stiffness, low mass density, and ease of manufacturing. These blades including various structural components such as the spar cap are typically manufactured using vacuum-assisted resin infusion molding (VARIM). Residual stress and micro-distortion of fibers and fiber tow in spar cap may develop during the VARIM process. Defects occur more often on the thickest section of the spar cap component and at or near peak exotherm temperature. Such kind of manufacturing defect leads to reduced compressive strength and long-term cycle life. Residual stress/distortion can be alleviated by increasing cure time and lowering temperature; however, these will extend the manufacturing cycle. Replicating such a phenomenon in the lab is challenging. Understanding the mechanism and the effects of the process is the key for the blade manufacturing industry to reduce defective parts and increase productivity. In this project, a multiphysics computational approach has been established for predicting the process-induced residual stress and distortion in PMC spar caps. Detailed mechanisms of residual stress and micro-distortion of fibers and fiber tow in glass fiber composite were studied. Multiple VARIM experiments of different setups were performed in the lab and mechanical properties of the finished composite parts were characterized. Micro-distortion was observed in the VARIM process of thin composite plates with 3-ply glass fiber. Based on the simulation and experimental studies, it is concluded that the differential curing leads to the temperature gradient and provides the main mechanism of micro-distortion when combined with the high aspect ratio of the composite spar cap.

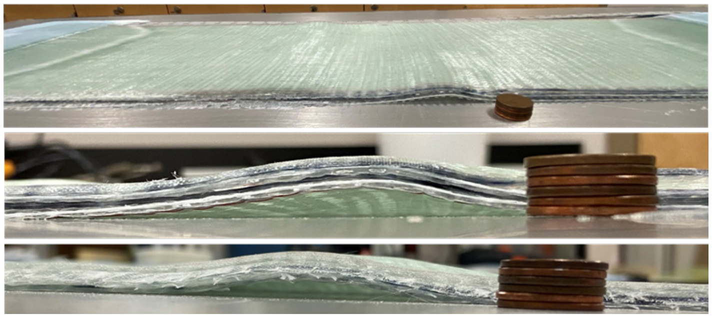


Figure 1. Experimental observations of buckling in a thin composite plate made by VARIM process.

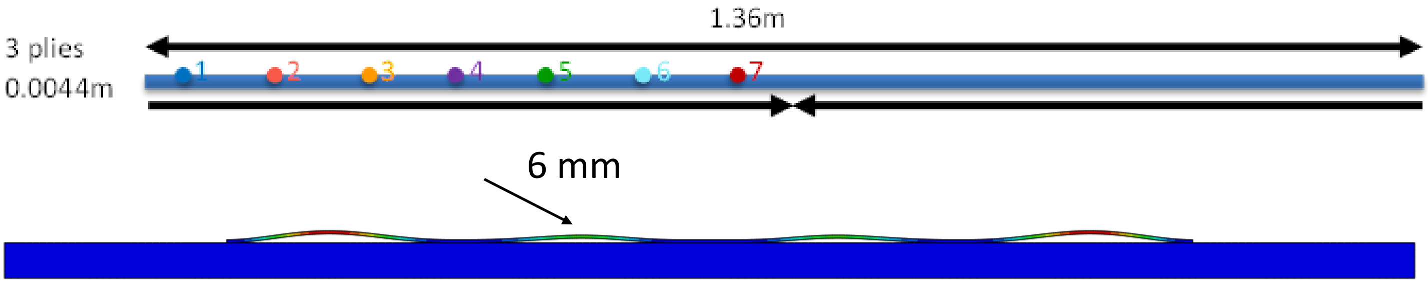


Figure 2. Multiphysics model simulation results (Top: CAE model for a 3-ply composite with 7 points marked for temperature and curing monitoring. Bottom: Multiphysics simulation of micro-distortion/local buckling in 3-ply composite).

PROJECT ID: A1-20

Structural Wind Blade Repair Optimization

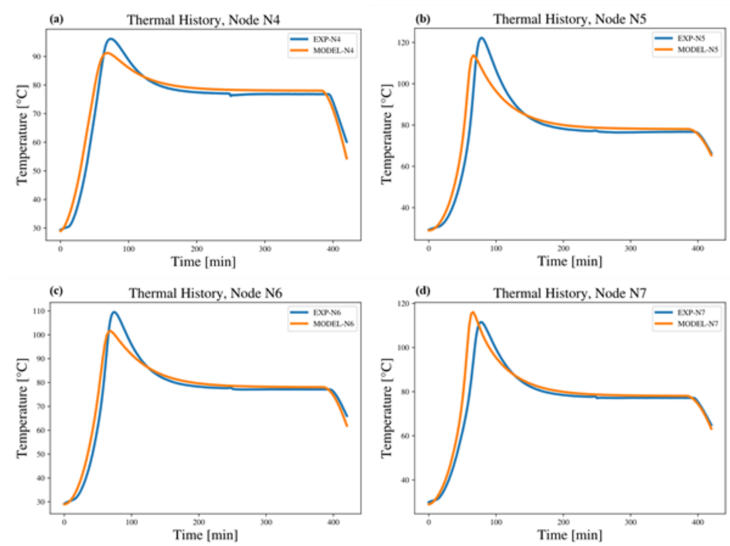
Principal Investigator:
Mariana Maiaru (University of Massachusetts Lowell)

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

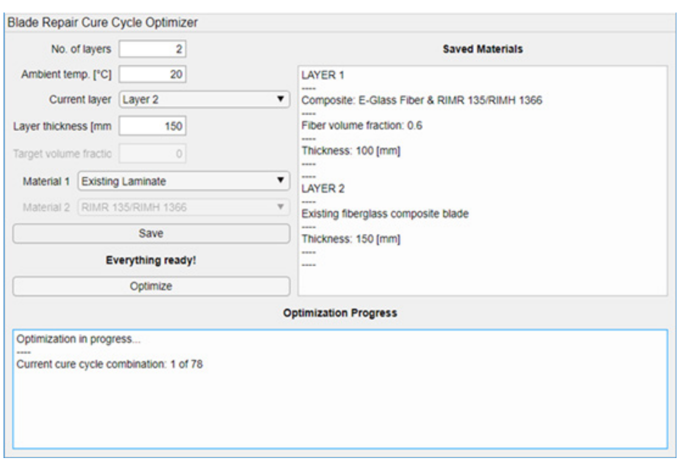
Student Researchers:
Michael Olaya (University of Massachusetts Lowell)
Joseph McDonald (University of Texas at Dallas)

IAB Mentors:
Steve Nolet, Amir Salimi, Alexander Krimmer (TPI Composites)
Paul Ubrich, Nathan Bruno, Mirna Robles (Hexion)
Ben Rice (Pattern Energy)
Jian Lahir (EDP Renewables)
Nicholas Althoff (GE Renewable Energy)
Ron Grife (Leeward Renewable Energy)
Rajesh Turakhia, Yi Ling Liang (Olin)

Damaged wind turbine blades are typically repaired on-site and up-tower, which can take several days to complete. The time-consuming repair process can be attributed to the complexity and difficulty in accessing the damaged sections, as well as the need to replace and cure the fiber-reinforced composite (FRC) materials used in state-of-the-art blade design. As repairs are performed on-site, environmental conditions such as the temperature and relative humidity can have an impact on the steps necessary to rehabilitate the blade, and ultimately on the final properties of the restored structure. Currently, there are no best practices to repair damaged blades effectively, and each repair varies with respect to environmental conditions as well as the unique geometry and FRC materials used in each repair. Insights on the effect of these parameters thus presents opportunities for repair optimization to reduce the turbine downtime. This work builds upon the material characterization of resin systems (infusion, hand lamination, bonding paste) commonly used in turbine blade repairs the computational tools developed in the previous years of this project. Four tasks which coupled experimental and computational work were executed during this year's project. Cure kinetics of a new Hexion cold temperature resin, which is suitable for processing at temperatures as low as 5°C, were characterized. Long-term absorption quantification of a composite substrate was performed to set a baseline for worst-case scenarios when evaluating the effect of moisture on adhesion of repairs to the existing blade structure. A larger and more complex lab-scale experiment designed to be representative of real-world repair geometries was performed, and validation of the computational tools developed in previous years and advanced in this years' work was performed. The knowledge gleaned from these tasks has been studied and implemented in ongoing development of the on-site repair tool/application for on-demand cure cycle optimization. The app now features a preliminary graphical user interface (GUI) designed for ease-of-use by repair personnel, and work continues on migration to an open-source platform more mobile device usage. This work continues to address and contribute to providing insight into factors which influence every repair, including environmental conditions, extent of the damaged area, and material systems used in state-of-the-art blade rehabilitation efforts. Ultimately, an understanding of these critical parameters offers a way to analyze and optimize each repair in a way that has never been done before. Through computation and experiment, the potential of extended repair season and thus cost savings for owners and operators is possible.



Comparison of the thermal history between the FE process model and experiment for four nodes.



Preliminary GUI developed for interacting with the on-site repair analysis showcasing simplistic user inputs and cure cycle optimization.

PROJECT ID: A3-20

Development of a Next-Generation Low-power Acoustic Sensor for Wind Turbine Blade Structural Health Monitoring

Principal Investigator:
Murat Inalpolat (University of Massachusetts Lowell)

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

Student Researchers:
Caleb Traylor, Fei Zhou (University of Massachusetts Lowell)

IAB Mentors:
Adam Johs (EDP Renewables)
Ben Rice (Pattern Energy)
Ron Grife (Leeward Renewable Energy)
Lothar Breuss (Bachmann Electronic Corp)

High operational loads cause significant bending and shear and thus are detrimental to wind turbine blades. Currently available condition monitoring systems are not capable of detecting different types and severity levels of damage and defects such as leading and trailing edge splits, holes and cracks. A comprehensive damage detection system that can monitor the blades for leading and trailing edge splits, delaminations, cracks and holes is currently not available. Consequently, it is vital to provide a low cost yet highly capable condition monitoring solution that will reduce the need for unscheduled maintenance. Deployment of a previously developed wind turbine blade acoustic monitoring system requires complete understanding and mitigation of the mechanical, electrical and structural problems associated with the installation and operation of the system. This project is on further development of a blade damage detection and monitoring system. The project team will continue the efforts from our previous project, which has successfully shown the feasibility of the proposed technique in the laboratory environment as well as in the field (at the WTTC). This year's project entails integration of this novel acoustic monitoring system on a full scale operational turbine blade and mitigating the potential problems with the system and the blade interface. After the aforementioned tests, the team has focused on improving the sensor design and will deploy the new sensor on a full-scale wind turbine in a wind farm under the next project cycle. The final report will highlights the sensor development related research activities. Lessons learned will be leveraged in order to improve the current system design and its integration. The team will focus on the field tests on a full-scale turbine as well as improving and implementing the developed signal processing and machine learning algorithms to enable this technology in the near future.

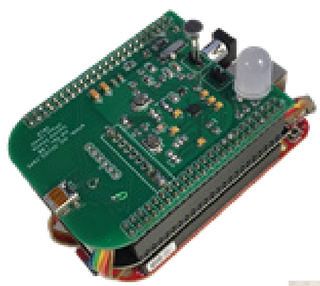


Figure 1. Acoustic sensing node circuitry.

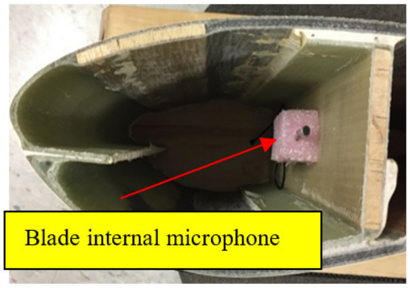


Figure 2. A close-up view of the blade-internal acoustic sensor (microphone) from a lab test.

PROJECT ID: B1-20

RECENT CENTER EVENTS

Webinar Series:

» Data-driven Wind Farm Modeling Based on Wind LiDAR Measurements, Giacomo Valerio Iungo, March 24, 2021
» Curent Status and Future Directions in Wind Farm Modeling, Stefano Leonardi, November 4, 2020
» Control of Wind Energy Systems, Mario Rotea, June 19, 2020

IAB Meetings:

» University of Massachusetts Lowell (Virtual), June 16-17, 2021
» University of Texas at Dallas (Virtual), February 3-4, 2021

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

Data Driven Remaining Useful Lifetime Modeling of Inverters in Renewable Energy Applications

Principal Investigator:
Bilal Akin (University of Texas at Dallas)

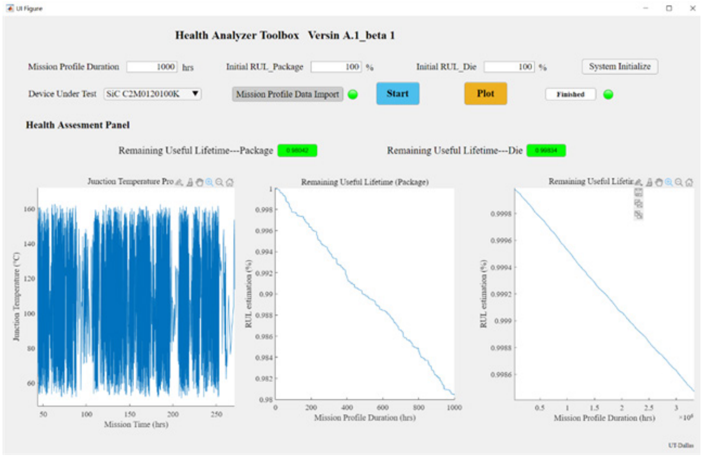
IAB Mentors:
Adam Johs, Aditya Krishna (EDP Renewables)

Student Researchers:
Shi Pu, Saurabh Kumar (University of Texas at Dallas)

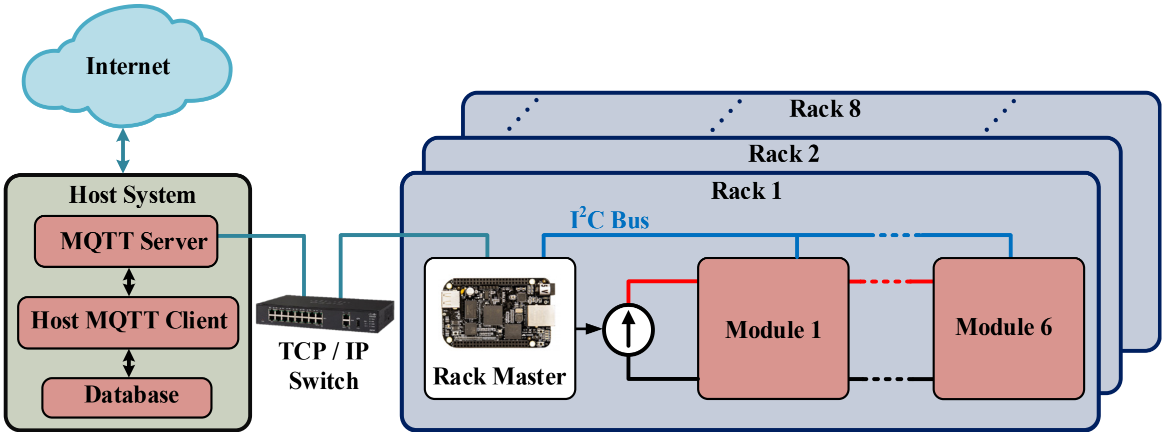
The world is adding wind/solar energy capacity at a rapid pace as the serious consequences of climate change are becoming increasingly obvious. Given the remoteness of most wind and solar farms, reliable and predictable operation of wind turbines is very critical. For this purpose, we propose remaining useful lifetime (RUL) estimation for power converters used in wind turbines and solar systems simply by processing Scada data.

In power converters, the power modules including IGBTs / PowerFETs are one of the most fault prone components. To prevent unexpected system down-time, several switch health monitoring and early warning techniques have been proposed in literature. Most of the techniques require access to internal converter hardware. However, wind EPCs and operators may not have low level access to the power converters. Therefore, it is important to develop system level converter health monitoring and RUL techniques that minimize the need for low-level hardware access. The proposed technology can potentially be leveraged by EPCs and operators to reduce O&M costs and provide value-added-services. The equipment agnostic nature of proposed methods allows supplier optimization without compromising on monitoring features.

Moreover, the decoupling of power conversion and inverter health monitoring functions allows independent, incremental and scalable testing of next-gen smart monitoring features without them being subject to the typically long design cycles of power inverters.



GUI of developed toolbox when analyzing process is finished.



High level schematic of the proposed large-scale DC power cycling test bench.

PROJECT ID: B2-20

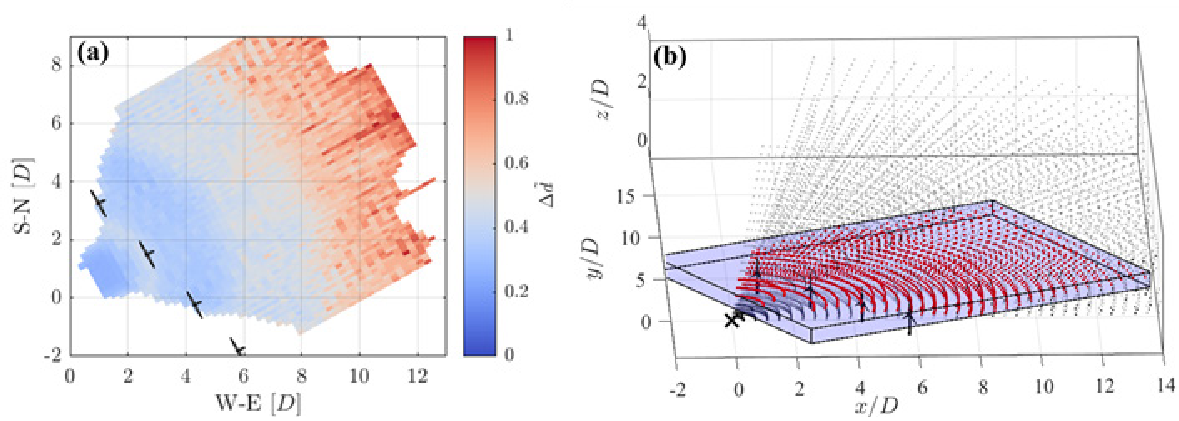
Assessment and Improvement of Industry-standard Wind Farm Models based on Physics-informed Reduced-Order Model

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

Student Researchers:
Stefano Letizia, Coleman Fuller Moss (University of Texas at Dallas)

IAB Mentors:
Samuel Davoust, Nicholas Althoff (GE Renewable Energy)
Lothar Breuss (Bachmann Electronic Corp)
Brandon Fitchett (EPRI)
Adams Johs (EDP Renewables)
Benjamin Rice (Pattern Energy)
Patrick Climer (Leeward Renewable Energy)

There is an increasing awareness in the wind energy industry that pressure-induced effects due to the interaction between wind turbine rotors and the incoming atmospheric boundary layer (ABL), such as blockage and speedups, have a significant impact on the performance of the wind turbines and annual energy production (AEP) of the entire wind power plant. These phenomena, which have been long disregarded by wind farm modelers, require new modeling paradigms based on high-quality experimental data to characterize robustly the relatively subtle effects of the pressure field, yet leading to significant effects on power capture. This project aims at investigating experimentally the impact on the wind resource of a wind farm induction field. To this aim, an field LiDAR campaign has been carried out at an onshore wind farm before and after the commissioning of a multi-MW project. In a first phase of the project, the pre-construction wind data collected by five profiling LiDARs are analyzed to identify possible flow heterogeneity induced by the site topography or the local micro-climatology as a function of wind direction, wind speed, and atmospheric stability conditions. In a second phase, the accuracy of the various remote sensing instruments is quantified through simultaneous and co-located measurements. Finally, the wind resource is investigated again after the construction of the wind power plant, also including the use of a scanning Doppler wind LiDAR. For the latter, the measurement scans are optimally designed through the LiSBOA procedure. The blockage and speedups observed in the preliminary results are a valuable source of information for the development and calibration of a reduced-order wind farm model.



Optimally-designed lidar scan according to the LiSBOA guidelines: (a) Local data spacing, where low values indicate an adequate spatial sampling of the features of interest in the flow; (b) geometry of the scan, with the red dots indicating points falling inside the volume under investigation.

PROJECT ID: C2-20

Decision Support Digital Twin – Case Studies Applied to IAB Assets

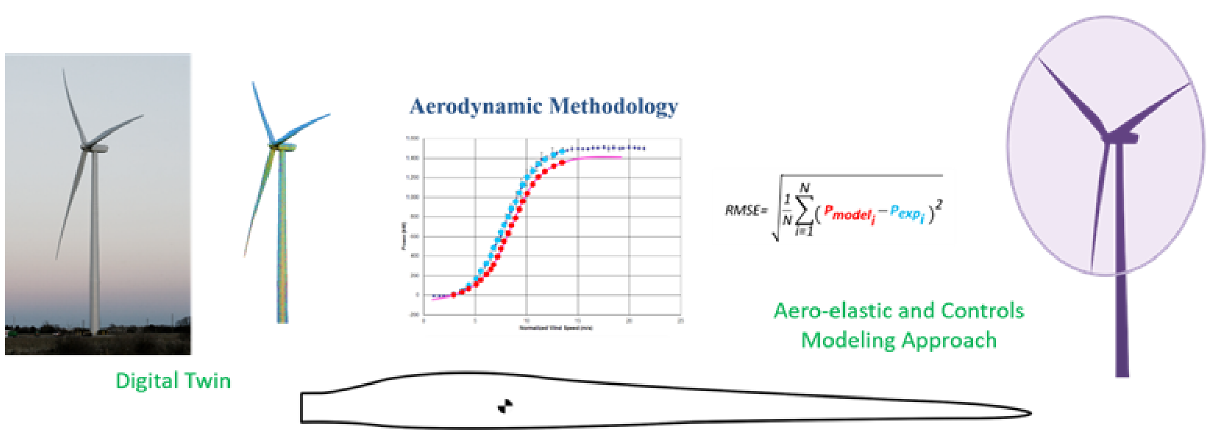
Principal Investigator:
Todd Griffith (University of Texas at Dallas)

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

Student Researchers:
Liliana Haus, Chang Liu, Ipsita Mishra (University of Texas at Dallas)

IAB Mentors:
Adam Johs (EDP Renewables)
Brandon Fitchett (EPRI)
Lothar Breuss (Bachmann Electronic Corp)
Ron Grife (Leeward Renewable Energy)
Benjamin Rice (Pattern Energy)
Neal Fine (Arctura)
Nathan Post (WindSECo)

Accurate numerical tools for both 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 C3-20 project addresses this need by developing and evaluating a new approach for creating an aero-servo-elastic digital twin model. The overall aim of this project is to deliver wind turbine aero-elastic models for existing turbines to support decision-making in wind farm operations. Maximizing the revenue of an operating wind fleet requires making decisions involving power performance, component maintenance costs, and selection of performance upgrades. In the developed 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 of interest. A key focus in the current study for the C3-20 project has been how to accomplish an accurate digital twin model for the case of having limited experimental data sets or limited turbine specifications. 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. In addition, a study was performed to gain further confidence in the model accuracy by analyzing the sensitivity of the model response (e.g.; sensitivity of blade deflections or tower loads) to changes in the calibrated model input parameters.



Graphic representation of the digital twin model development process. Experimental data (such as power curve data) is used to calibrate model parameters for the aerodynamic, structural, and control system elements of the aero-servo-elastic model.

PROJECT ID: C3-20

Fatigue Loading Effects And Power Fluctuations Due To Wake Steering Within A Wind Farm-A Wind Tunnel Study

Principal Investigator:
Yaqing Jin (University of Texas at Dallas)

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

Student Researchers:
Emmanuvel Joseph Aju, Devesh Kumar (University of Texas at Dallas)

IAB Mentors:
Neal Fine (Arctura)
Ben Rice (Pattern Energy)
Brandon Fitchett (EPRI)
Adam Johs (EDP Renewables)

Wake steering has proven to be effective for increasing the power output of a wind farm. However, practical control strategies for turbine yaw angles and induced fatigue loading effects remain less understood. In this work, systematic wind tunnel experiments were conducted to characterize the wake dynamics, power outputs and wind loading of turbines within a wind farm under wake steering. Model wind turbines with yaw control capability and power coefficients similar to utility-scale turbines were fabricated and tested in the Boundary Layer and Subsonic Tunnel at UT Dallas. High-resolution force load and time-resolved particle image velocimetry system were applied to measure the variation of wind loads and wake flows across time. Our measurements show that, with the growth of turbine yaw angles in the front row, the wake flows can be significantly deflected and therefore increase the effective incoming flow velocity impiniging the downstream turbines. For a wind farm with aligned turbine layout and five times rotor diameter distance in streamwise direction, the maximum wind farm power output is achieved with the first row yawing at 30o and second row at 20o in the same direction. This results in ~8.5% power output growth compared to the baseline case (without wake steering). Comparatively, the impact of wake steering control on staggered wind farm is less distinctive with maximum of ~2.5% power increase. Measurements on the instantaneous wind loading of turbines in the first row reveal that the growth of yaw angle increases the fatigue loading in the side-force direction across all frequency components. A state-of-the-art Log-of-Power Extremum Seeking Control (LP-ESC) is also implemented in this project to determine optimal yaw angles from power measurements autonomoulsy. LP-ESC is applied to most upstream turbines only to maximize the power of properly defined clusters of turbines. The experimental results show that LP-ESC matches the measurements from power output static maps for both aligned and staggered layouts; thus, optimizing wind farm power output in real-time with no models.

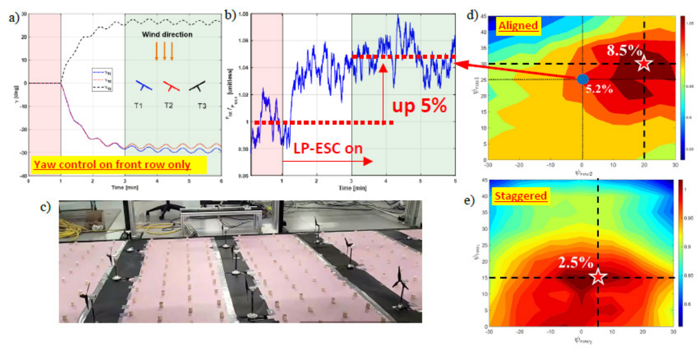


Figure 1: Wake steering control for maximizing the power output of wind farms. a) Variation of turbine yaw angles under LP-ESC; b) Instantaneous wind farm power output under LP-ESC; c) Photograph of model wind farm; d-e) Static map of power output with aligned and staggered turbine layouts; LP-ESC on first row only in agreement with optimum from static map (marked with a star in figure 1d).

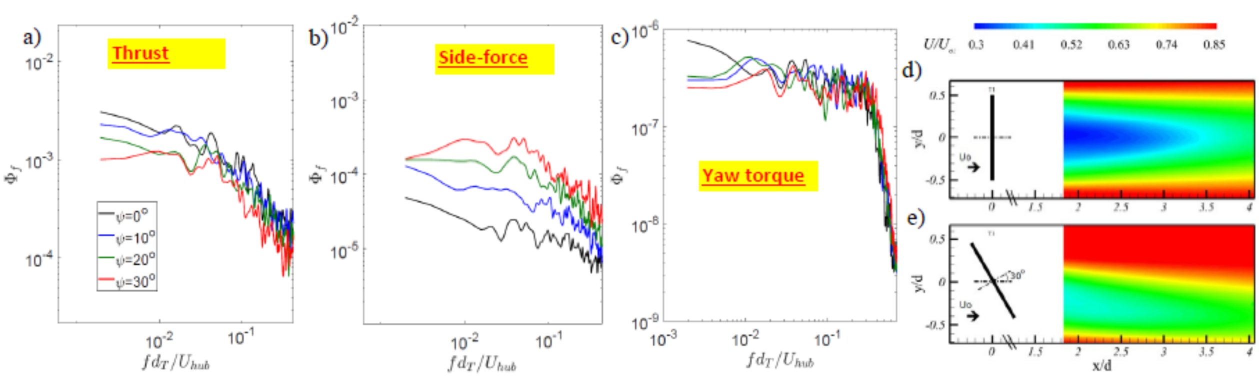


Figure 2: Fatigue loading and wake dynamics of turbines under wake steering. a-c) Spectrum of thrust load, side-force and yaw torque across yaw angles for turbine located in the first row; d) and e) are time-averaged streamwise wake velocities for turbine located in first row under no misalignment and yaw angle at 30o.

PROJECT ID: D1-20

Design of UHPC Floating Support Structure for Offshore Wind Turbine

Principal Investigators:
Dong Qian, Hongbing Lu (University of Texas at Dallas)

Student Researchers:
Ning Bian, Yingjian Liu (University of Texas at Dallas)

IAB Mentors:
Pierre Liagre, Wouter Haans, Nick Smith (Shell)
John Buttles (Texas Wind Tower)

Ultra-High Performance Concrete (UHPC) is a relatively new construction material that is mainly composed of high-performance concrete and fiber materials. The combination of higher binder and fiber dosage with low water to binder ratio provides UHPC with exceptional mechanical properties such as high strength, energy absorption capability, strong resistance to a corrosive environment, and excellent durability. While these outstanding properties make UHPC an ideal structural material for offshore applications, studies on the potential benefit of developing offshore UHPC wind towers remain elusive. In this project, a combined experimental/modeling approach has been established to study the application of UHPC for offshore wind tower applications. The experimental work focused on key material properties such as stiffness, compressive strength, flexural strengths, fatigue endurance limit, water absorption, and resistance to crack imitation and propagation. To mimic the effects of offshore environment, UHPC samples have been immersed in saline solution after cast and measured properties are compared to the ones that have not been treated with saltwater. The bulk density of 3% steel fiber volume fraction UHPC is 2,405 kg/m3. The permeability test results show that water absorption of 3% steel fiber volume fraction UHPC is 0.45%, while the volume of permeable voids of UHPC is 1.2%. The 28-day cured UHPC has a compressive strength of 159 MPa with a modulus of elasticity of 36 GPa, and Poisson's ratio of 0.22. Three-point bending testing results indicate that the average flexural strength of 3% steel fiber volume fraction UHPC is 35 MPa. Fatigue experiments provide fatigue endurance limit of UHPC of around 70% of flexural strength. Based on the experimental results, modeling work focused on the design analysis of a 15MW offshore UHPC wind tower. Using finite element (FEM) analysis, initial design parameters were obtained by considering static, dynamic loading conditions and fatigue. The initial design was further optimized to reduce material consumption. The optimized design was then evaluated in terms of the total cost based on the material consumption. Comparisons were made to the conventional concrete and all-steel offshore towers and UHPC design provided significant cost savings. Aside from the economic benefit, the dimensions of the UHPC tower were comparable to those for the steel tower due to its excellent mechanical properties. Construction solutions were recommended based on the optimized dimension.

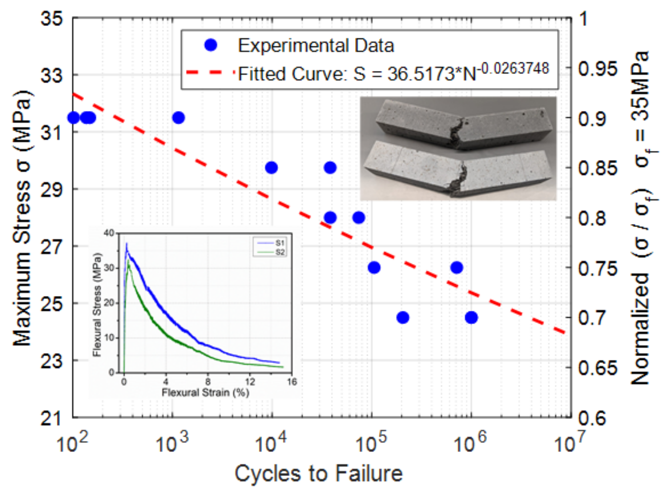


Figure 1. UHPC has high fatigue strength and endurance limit.

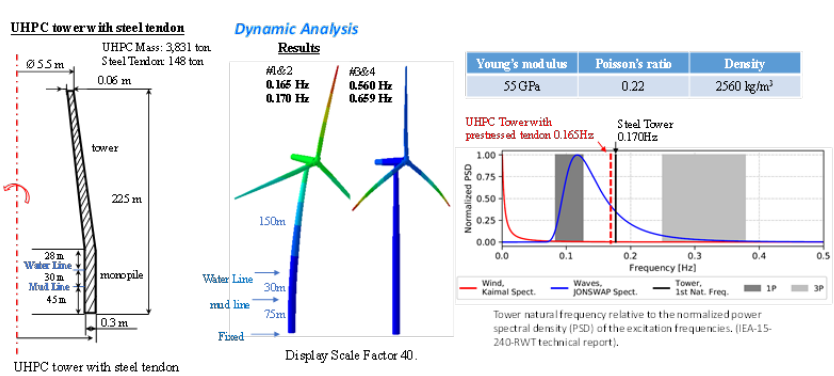


Figure 2. UHPC tower with post-tensioned tendons satisfies static and dynamic requirements.

PROJECT ID: F1-20

2019-2021 OUTCOMES

Through August 31, 2021

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

Products:

1. Software: Multiphysical computational model for predicting process-induced residual stress and distortion in fiber-reinforced composites
2. Software: FAST Model V1.0: Aero-elastic Model
3. 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.
4. 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.
5. 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.
6. 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
7. Software: A Matlab based GUI for prediction of power production and wind turbine wakes for the Panhandle Phase II wind farm.
8. Software: Simulink code for Extremum Seeking Control of NREL CART3 (Controls Advanced Research Turbine, 3-bladed).
9. Patent: Foundation and Deflection Monitoring Device #10808374, Awarded 10/20/20.
10. Hardware: Fiber Optic Interrogator for Strain Monitoring
11. Hardware: Passive Acoustic Damage Detection System for Blades
12. Hardware: Active Acoustic Damage Detection System for Blades

Journal Papers:

1. Cao, D., Malakooti, S., Kulkarni, V. N., Ren, Y., Liu, Y., Nie, X., Qian, D., Griffith, D. T., & Lu, H. (2021). The effect of resin uptake on the flexural properties of compression molded sandwich composites. Wind Energy.
2. Letizia, S., Zhan, L., & Iungo, G. V. (2021). LiSBOA (LiDAR statistical Barnes objective analysis) for optimal design of lidar scans and retrieval of wind statistics-part 1: Theoretical framework. Atmospheric Measurement Techniques, 14(3), 2065-2093.
3. Letizia, S., Zhan, L., & Iungo, G. V. (2021). LiSBOA (LiDAR statistical Barnes objective analysis) for optimal design of lidar scans and retrieval of wind statistics-part 2: Applications to lidar measurements of wind turbine wakes. Atmospheric Measurement Techniques, 14(3), 2095-2113.
4. S. P. Shah and M. Maiarù, "Effect of Manufacturing on the Transverse Response of Polymer Matrix Composites," Polymers, vol. 13, no. 15, Art. no. 15, Jan. 2021.
5. 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.
6. Solimine, J., Niezrecki, C., and Inalpolat, M., "An experimental investigation into passive acoustic damage detection for structural health monitoring of wind turbine blades," Structural Health Monitoring, January 3, 2020.
7. 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.
8. Zhan, Lu, Stefano Letizia, Giacomo Valerio Iungo. "Optimal tuning of engineering wake models through LiDAR measurements." Wind Energy Science 5.4 (2020): 1601-1622.
9. Zhan, Lu, Stefano Letizia, 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.
10. C. Santoni, E.J. Garcia-Cartagena, U. Ciri, L. Zhan, G.V. Iungo and S. Leonardi. One-way mesoscale-microscale coupling for simulating a wind farm in North Texas: Assessment against SCADA and LiDAR data; Wind Energy, 23 (3), 691-710, 2020.
11. Beale, C., Willis, D. J., Niezrecki, C., & Inalpolat, M. "Passive acoustic damage detection of structural cavities using flow-induced acoustic excitations." Structural Health Monitoring, 2019.
12. Beale, C., Inalpolat, M., & Niezrecki, C. Active acoustic damage detection of structural cavities using internal acoustic excitations. Structural Health Monitoring, 2019.
13. Morris J., Hansen C. J., Amirkhizi, A. V. "Improved approximation of transverse and shear stiffness for high volume fraction uniaxial composites," Mechanics of Materials, Vol. 129, 230-235, 2019.
14. Xiao, Y., Li, Y. and Rotea, M.A. "CART3 Field Tests for Wind Turbine Region-2 Operation with Extremum Seeking Controllers," IEEE Transactions on Control Systems Technology, Vol. 27, No. 4, pp. 1744 - 1752, July 2019.

Conference Papers:

1. Bush, B., Chen, Y., Ofori-Boateng, D. & Gel, Y.R. (2021). Topological Machine Learning Methods for Power System Responses to Contingencies. Proc. of the AAAI Conference on Artificial Intelligence, IA track (AAAI-IAAA-21), 35(17), 15278-15285.
2. Yang, F., Pu, S., Akin, B., Butler, S. W., & Wang, G. (2021). Package degradation's impact on SIC mosfets loss: A comparison of Kelvin and Non-Kelvin Designs. 2021 IEEE Applied Power Electronics Conference and Exposition (APEC).
3. Zhang, N., Pu, S., & Akin, B. (2021). An automated multi-device characterization system for Reliability Assessment of Power Semiconductors. 2021 IEEE 13th International Symposium
4. Gondle, Raj K., Pradeep U. Kurup, and Christopher Niezrecki. "Evaluation of Wind Turbine-Foundation Degradation." In International Conference of the International Association for Computer Methods and Advances in Geomechanics, pp. 21-28. Springer, Cham, 2021.
5. Shah, Sagar, Evgenia Plaka, Mathew Schey, Jie Hu, Fuqiang Liu, Tibor Beke, Scott E. Stapleton, and Marianna Maiaru. "Quantification of Thermoset Composite Microstructures for Process Modeling." In AIAA Scitech 2021 Forum, p. 1774. 2021.
6. Sagar Shah, Marianna Maiaru – Effect of Manufacturing on the Transverse Response of Polymer Matrix Composites, ASC 2021, Proceedings of American Society for Composites
7. 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.
8. Inalpolat, Murat, and Christopher Niezrecki. "Acoustic Sensing Based Operational Monitoring of Wind Turbine Blades." Journal of Physics: Conference Series 1452.1 (2020): 012050.
9. 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.
10. 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: Conf. Series, vol. 1452, 012077, 2020.
11. 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.
12. Zhan, Lu, Stefano Letizia, and Giacomo Valerio Iungo. "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. No. 1. 2020.

13. Ciri, U., M. A. Rotea, and S. Leonardi. "Increasing wind farm efficiency by yaw control: beyond ideal studies towards a realistic assessment." Journal of Physics: Conference Series. Vol. 1618. No. 2. IOP Publishing, 2020

Selected Presentations:

1. S. Leonardi, "Analysis and Optimization of Wind Farm Performances" International Conference of Energy Harvesting, Storage, and Transfer", May 21-23, 2021, Niagara Falls, Canada Virtual Conference.
2. Aju, E., Rotea, M. A., Jin, Y. On the wake dynamics, flow loading and power output of wind farms under wake steering control: a wind tunnel experiment. (2021) Bulletin of the American Physical Society. Phoenix, AZ
3. Akin, B., "Reliability and Condition Monitoring of Power Electronics Systems," National Renewable Energy Lab (NREL), July 2021, Virtual
4. Akin, B., "Prognostics and Health Management of Power Electronics Systems," Schlumberger, July 2020, Virtual
5. D.T. Griffith, Panel moderator, ASME Wind Digital Solutions Summit, "Digitization vs. Digital Twins – Which One Did We Budget for in 2021?", April 20-21, 2021.
6. G.V. Iungo, WindSTAR Webinar Series: "Data-Driven Wind Farm Modelling Based on Wind LiDAR Measurements," March 24, 2021.
7. M.A. Rotea, "Future of Energy Panel," Moderator, 2021 Single Family Office Symposium, TFOA, April 8, 2021.
8. M.A. Rotea, "Extremum Seeking Control of Wind Energy Systems" TU Delft Wind Energy Institute Lecture, June 24, 2021.
9. S. Letizia, L. Zhan, G.V. Iungo. "Effects of topographic wakes on wind turbine performance." Wind Energy Science Conference 2019, June 17-20, Cork, IR.
10. 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.
11. Shah, S., "Mechanical Property Enhancement Prediction for Matrix Materials," CAMX, Anaheim, CA, September 2019.
12. Rotea M.A., "Control of Wind Energy Systems," J. Mike Walker '66 Seminar Series, Texas A&M University, February 20, 2019.
13. Letizia S., Zhan L., Iungo G.V., "Effects of topographic wakes on wind turbine performance," Wind Energy Science Conference, June2019, Cork, Ireland.
14. 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.

Master of Science Thesis:

1. Diltz, Natalie Lynne. "Monitoring and Assessment of Wind Turbine Foundation Degradation." M.S. Thesis., University of Massachusetts Lowell, 2021.
2. Haus, L., "New Methods for Digital Twin Modelling of Wave and Wind Energy Systems," MS Thesis, UT-Dallas, July 2020.
3. Behzad Najafi, "Characterization of uniform momentum zones in the atmospheric boundary layer," M.S. in Mechanical Engineering, University of Texas at Dallas, July 2019. Now with IAB member Leeward Renewable Energy, LLC.

PhD Dissertations:

1. Stefano Letizia, "Wind farm flow and power capture: optimal design of LiDAR experiments, flow physics, and mid-fidelity modeling," Ph.D. in Mechanical Engineering, University of Texas at Dallas, November 11, 2019.
2. Christopher Beale, "System Integration of a Wind Turbine Blade Acoustic Monitoring System," PhD in Mechanical Engineering, University of Massachusetts Lowell, 2019.
3. 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 Postdoc at UT Dallas.
4. 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 Postdoc at University of Minnesota.

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1. Stefano Letizia, recipient of WindSTAR NSF INTERN at UT Dallas, Intern at EDP Renewables.
2. Alessandro Cassano, recipient of WindSTAR NSF INTERN at UMass Lowell, Intern at TPI Composites.

Students Hired at Member Companies:

1. Liliana Haus, MS,University of Texas at Dallas, EPRI
2. Sara Najafian, PhD, University of Massachusetts Lowell, TPI Composites

ACTIVE PROJECTS: 2021-2022

» **Structural Wind Blade Repair Optimization**
Project ID: A1-21
PI: Marianna Maiaru (University Of Massachusetts Lowell)
Mentors: Olin Epoxy, Hexion

» **Long-Term Environmental Durability of Adhesive Joints**
Project ID: A3-21
PI: Amir Ameli (University of Massachusetts Lowell)
Mentors: TPI Composites, Hexion, 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

» **Design of VARIM Process Based on A Digital Twin Approach**
Project ID: A4-21
PI: Don Qian (University of Texas at Dallas)
Mentors: Hexion, TPI Composites, Olin Epoxy

» **Analysis/Interpretation of Data Collected Using Robust Acoustic Blade Monitoring Sensors**
Project ID: B1-21
PI: Murat Inalpolat (University of Massachusetts Lowell)
Mentors: EDP Renewables, Bachmann, Pattern Energy Group, WindEsco

» **Decision Support OpenFAST Digital Twin-Component Loads and Control System Extensions**
Project ID: B4-21
PI: Todd Griffith (University of Texas at Dallas)
Mentors: Bachmann, Arctura, EDP Renewables, EPRI, WindEsco

» **Observations, Characterization and Modeling of Blockage for Utility-scale Wind Farms**
Project ID: C1-21
PI: Giacomo Valerio Iungo (University of Texas at Dallas)
Mentors: Arctura, EPRI, Bachmann, GE Renewables, Pattern Energy Group

» **Determining Best Practices for YAW Control In Real Window Farms**
Project ID: D1-21
PI: Stephano Leonardi (University of Texas at Dallas)
Mentors: Arctura, Bachmann, EPRI, WindEsco, GE Renewables

» **Wake Steering Control On Complex Terrain Under Time-varying Flow**
Project ID: D2-21
PI: Yaqing Jin (University of Texas at Dallas)
Mentors: Arctura, Bachmann, EDP Renewables, GE Renewables, Shell, WindEsco

» **Co-located Wind Farm and Hydrogen Plant Energy System Study**
Project ID: E1-21
PI: Jie Zhang (University of Texas at Dallas)
Mentors: Arctura, EDP Renewables, Shell

» **Assessment of Wind Turbines' Structural Dynamic and Foundation Integrity Using Optical Motion Amplification**
Project ID: F1-21
PI: Alessandro Sabato (University of Massachusetts Lowell)
Mentors: EDP Renewables, Leeward Energy

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