WindSTAR

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

2018 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 sustained support and Membership. The Center has now completed its fourth year with 9 research projects currently being executed. As the awareness and engagement of WindSTAR continues to grow, more people in the wind industry are learning that the Center is a platform that allows universities, industrial partners, and government to collaborate on developing novel solutions to wind energy problems. We are working toward the goal of lowering the LCOE and helping to make the use of wind energy more widespread within the United States and globally. Without leveraging the infrastructure of a National Science Foundation I/UCRC, this level of commitment and value to industry would not be possible. For every dollar coming from a Full IAB member, 15 dollars are invested in the Center from another source. For small business IAB members the leveraging is approximately 40:1.

As we enter our fifth year of operation, we hope to grow the Center, strengthen existing collaborations, and increase awareness of WindSTAR in the wind industry community. The WindSTAR Center is working to meet the challenge of improving performance and reliability of wind energy conversion systems to help drive down the cost of wind-generated electricity. For example, Center members are utilizing research results and custom software to improve blade materials and increase turbine power production, and newly developed monitoring systems for blades and foundations are expected to be field tested in 2019. Results from projects have provided valuable data to Center members who developed large proposals for federal funding; thus, augmenting their R&D capacity. Through continued advancements in technology we believe that wind power will be a major player in the future of the Nation's electricity portfolio. In the ever changing energy business climate, we will look for creative solutions to help grow and expand the Center. 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.
Professor and Chair, Department of Mechanical Engineering
Co-Director, Structural Dynamics and Acoustics Systems Laboratory
Director, WindSTAR I/UCRC
University of Massachusetts Lowell

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

TABLE OF CONTENTS

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 and transmission. 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, Boundary layer and subsonic wind tunnel testing, control system design for wind turbines and wind farms, large rotor design, grid integration and energy storage. The University of Texas at Dallas is a public research university in Richardson, Texas.

CURRENT 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.

2018-2019 IAB Chair
Nicholas Althoff
Sr. Advanced Manufacturing Engineer
GE Renewable Energy

2018-2019 IAB Vice Chair
Neal Fine
CEO
Aquanis, Inc

2017-2018 IAB Chair
Ben Rice
Senior Manager, Operations Engineering
Pattern Energy

2017-2018 IAB Vice Chair
Nicholas Althoff
Sr. Advanced Manufacturing Engineer
GE Renewable Energy

Past IAB Chairs:
2016-2017: Steve Johnson, GE Renewable Energy
2015-2016: Justin Johnson, EDP Renewables
2014-2015: Steve Nolet, TPI Composites, Inc

AQUANIS	bachmann.	edp renewables
GE Renewable Energy	HEXION	HUNTSMAN Enriching lives through innovation
LEEWARD Renewable Energy, LLC	Pattern	TWT Texas Wind Tower
tpi COMPOSITES		

Previous Members include:

Keuka Energy
Maine Composites Alliance
Massachusetts Clean Energy Center
National Instruments
NRG Renew

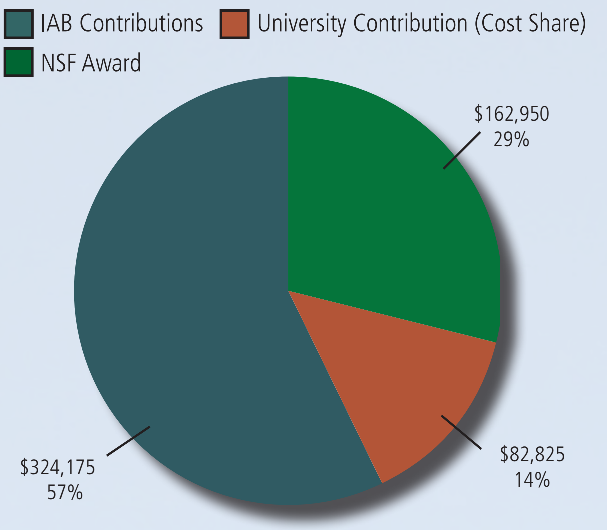
FINANCIAL OVERVIEW: RETURN ON INVESTMENT

MEMBERSHIP LEVELS 2017-2018

Full
$42,400 Annually

Small Business Associate
$15,900 Annually

REVENUE FOR 2017-2018



TOTAL INVESTED: $569,950

CUMULATIVE INVESTMENT
During 4 years of center operation

Cumulative Research Investment by IAB Members
2014-2018: $1,319,175

Cumulative Investment in Center
2014-2018: $2,799,611

UT Dallas invested approximately $5 million to build the Boundary Layer and Subsonic Tunnel (BLAST) which opened this year. The tunnel features two test sections, the boundary layer test section (up to 76 mph with 100 feet of optical access) and the subsonic test section (up to 112 mph). Image shows visualization of air flow past a wind turbine with smoke generator inside BLAST.

2017-2018 PROJECTS

- Curing of Thick Adhesive Joints
  Project ID: A1-17
- Mechanical Properties Enhancement Prediction for Matrix Materials
  Project ID: A2-17
- Intelligent Damage Detection from Wind Turbine Blades Using Acoustic Excitation
  Project ID: B1-17
- Low Cost Optical Fiber Strain Sensor Interrogator for Wind Turbine Blades
  Project ID: B3-17
- Proactive Monitoring of Wind Farm Performance Through Wind LiDAR Data and a Reduced Order Model
  Project ID: C1-17
- Uncertainty quantification of wind farm performance through high fidelity simulations and wind LiDAR measurements
  Project ID: C2-17
- NREL FAST Modeling for Blade Load Control with Plasma Actuators
  Project ID: D2-17
- Wind Turbine Aerodynamics Modified Gurney Flaps
  Project ID: U1-17
- Wind Turbine Foundation Monitoring Sensor Development
  Project ID: U2-17
- Effects of Manufacturing Induced Defects
  Project ID: A4-16

PAST PROJECTS

- Automation for Blade Manufacturing
  Project ID: A3-16
- Mechanical Property Enhancement Prediction for Matrix Materials
  Project ID: A5-16
- Performance Effects of Adhesive Bond Defects
  Project ID: A6-16
- Diagnosis of Electrical Faults of Wind Turbine DFIGs
  Project ID: B1-16
- Proactive Detection of Under-Performing Wind Turbines Combining Numerical Models, LiDAR and SCADA data
  Project ID: C1-16
- Evaluation of Nested Extremum Seeking Wind Farm Control with SWiFT Facility
  Project ID: D1-16
- Low-Cost Wind Turbine Blade Structural Health Monitoring
  Project ID: B1-15
- Design for Composite Wind Turbine Blade Manufacturing
  Project ID: A1-14
- Self-Healing Materials for Wind Turbine Blades
  Project ID: A3-14
- Large Area Turbine Blade Inspection
  Project ID: D1-14
- Extremum Seeking Control for Wind Turbine Power Maximization
  Project ID: E2-14
- Two-layer Optimization for Maximizing Wind Farm Power Output
  Project ID: E3-14

Curing of Thick Adhesive Joints

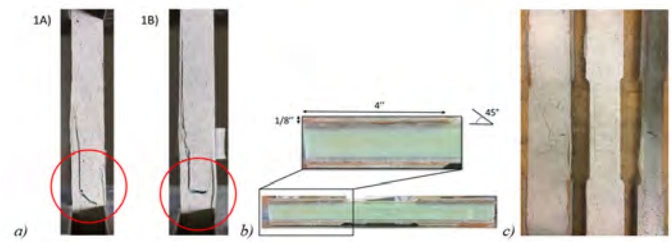
Principal Investigator:
Scott Stapleton, University of Massachusetts Lowell

Co-Principal Investigators:
Marianna Maiaru, University of Massachusetts Lowell
Christopher Hansen, University of Massachusetts Lowell

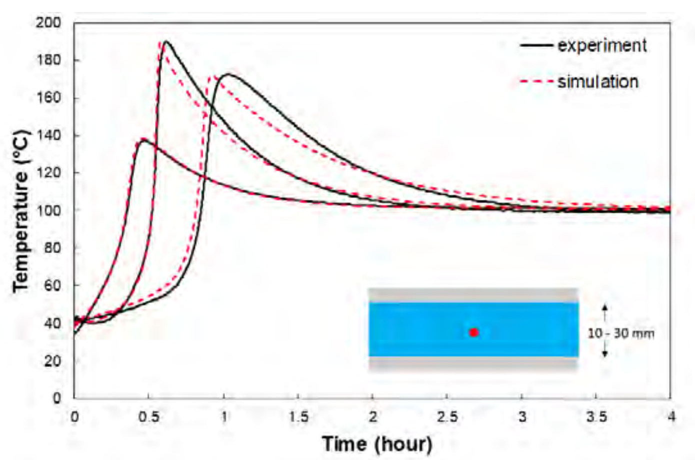
Student Researcher:
Alessandro Cassano, University of Massachusetts Lowell

IAB Mentors:
Nicholas Althoff, GE Renewable Energy
Paul Ubrich, Hexion
Christopher Savio, GE Renewable Energy
Amir Riahi, GE Renewable Energy

Bondline failure is a key critical failure mode in wind turbine blades. Substantial variation in bondline thickness can result in different thermal histories for the adhesive layer due to the exothermic curing of common adhesives. Predictive guidance regarding the impact of this variability in adhesive cure temperature cycles is extremely limited. Without guidelines of acceptable variability, excess resources may be placed into avoiding damage by processing at excessively low temperatures and longer processing cycles, which produce no discernible benefits. This project focuses on the characterization of adhesive bonded joints as a function of the curing temperature and adhesive thickness. In order to take into account the thickness influence, a series of experiments are conducted in a bonded joint configuration. Two sets of specimens for each thickness (10/20/30 mm) have been manufactured using recommended cure cycles and an elevated temperature cure cycle. A series of tensile and fatigue tests is performed on the joint specimens to determine the mechanical properties and the thickness-temperature influence on the bonded joint performance. Moreover, due to the exothermic nature of the cure of most adhesives, thicker regions result in elevated temperatures during curing which, beyond a critical threshold, lead to a degradation of adhesive properties. These regions with degraded properties are often visibly indiscernible from adhesive cured at recommended temperatures. Little research has been conducted to characterize the effect of temperatures and exothermic reaction levels on adhesive quality for thick joints. Additionally, the effect of bondline thickness on curing temperatures is also poorly understood, and predictive capabilities in this field are presently unavailable. Therefore, a finite element model capable of tracing the thermal and conversion histories in thick adhesive bondlines is presented. The cure kinetics of the bonding paste has been successfully characterized using isothermal DSC analysis. The finite element model is validated with experimental results from temperature sensors embedded in the adhesive centerline of 10, 20 and 30 mm specimens. Finally, an example of curing cycle optimization on a geometry representative of the trailing edge of a wind turbine blade is proposed.



Failure due to stress concentrations near the gripping area b) tabs geometry b) failure of 10, 20 and 30 mm thick adhesive specimens with tabs



Temperature sensor reading (continuous lines) vs. FE model predicted values (dashed lines) at adhesive centerline for 10/20/30 mm thick adhesive joint specimens.

PROJECT ID: A1-17

Mechanical Properties Enhancement Prediction for Matrix Materials

Principal Investigator:
Marianna Maiaru, University of Massachusetts Lowell

Co-Principal Investigators:
Alireza Amirkhizi, University of Massachusetts Lowell
Christopher Hansen, University of Massachusetts Lowell

Student Researcher:
Sagar Shah, University of Massachusetts Lowell

IAB Mentors:
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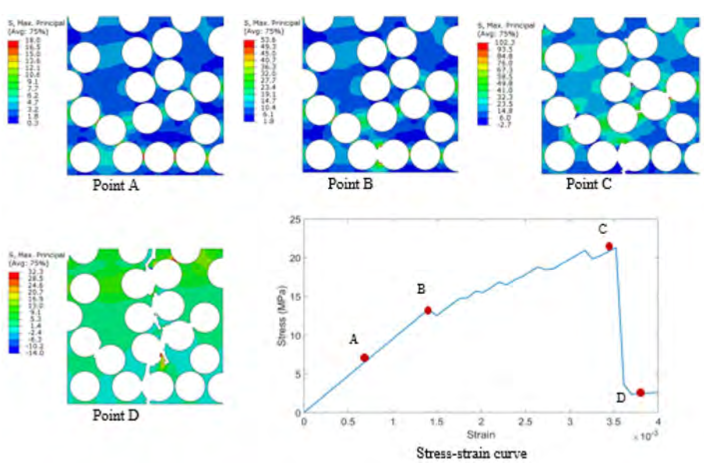
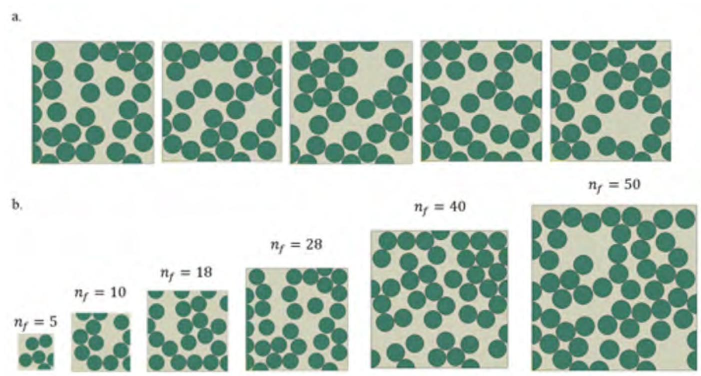
Amir Salimi, TPI Composites
Hui Zhou, Huntsman

Uniform curing of matrix material during wind turbine blade manufacturing is a challenge as the thermal field is spatially dependent and non-uniform. The potential for localized, non-uniform cure states could affect blade performance and result in premature failure. Resin material is primarily responsible for the transverse response of the composite materials used in blade manufacturing. The blade can undergo high transverse and shear stresses which can cause delamination or trailing edge splitting. Micromechanical analysis to predict the transverse response of the composite as a function of degree of cure of the resin material was the focus of this project.

Previous WindSTAR work determined the effective composite stiffness dependence on the resin properties by employing the Continuous Periodic Fiber Model (CPFM). A MATLAB tool was created that performed modulus prediction and applied layup adjustments to accurately determine the effective composite properties using several micromechanical models, including CPFM. This was followed by a numerical study to predict the effect on stiffness response of the composite due to the change in stiffness of the resin material. It showed that for a 20% increase in the matrix Young's modulus, the transverse stiffness rose by 16%. This approach, although valuable, can be employed only to estimate the stiffness of the composite based on component properties. To predict failure in the blade as a function of curing, a more sophisticated approach is required, and this has been completed in this project.



Maximum principle stress contour showing the crack initiation and propagation through an 18 fiber RUC composed of 100% cured RIMR 135/RIMH 137 resin and E-glass fibers. Stress strain response indicating Point A: Initial stress build-up during loading, Point B: Crack initiation in the RUC, Point C: Micro-cracking and stress concentration before failure and Point D: Final cracked RUC.



a. Five realizations of randomly distrubuted 28 fiber RUC, b. RUC size variation

A combined experimental-micromechanical analysis approach was employed to characterize the matrix material in-house and use the experimental results for matrix material as an input to the micromechanical model. The characterization began with cure kinetic study to accurately predict the cure of the matrix material when subjected to a thermal cycle. This characterization task was followed by stiffness measurement using a Dynamic Mechanical Analyzer (DMA). Combining the cure kinetics with the DMA, the stiffness of the matrix material as a function of cure was obtained. Finally, the strength of the matrix material was measured by tensile testing specimens subjected to different thermal cycles which eventually yielded strength measurements as a function of cure state. The mechanical response (strength and stiffness) of the neat matrix material for different degrees of cure were used as inputs to the micromechanical model to predict failure of the composite material.

Closely packed fibers act as stress rises which could lead to crack initiation in the composite. Thus, a random fiber distribution was modeled to investigate the effect of fiber packing on the strength and failure of the composite. In order to ensure convergence, the number of fibers were increased from 5 fibers in a repeating unit cell (RUC) to 50 fiber RUC, while keeping the fiber volume fraction constant. Convergence was achieved for the 50 fiber RUC, which could accurately predict the strength and stiffness of the composite material based of individual components. This approach was employed for two different resin formulation, RIMR 135/RIMH 137 and RIMR 135/RIMH 1366, prior being the baseline system for the analysis.

PROJECT ID: A2-17

Intelligent Damage Detection from Wind Turbine Blades Using Acoustic Excitation

Principal Investigator:
Murat Inalpolat, University of Massachusetts Lowell

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

Student Researchers:
Christopher Beale, University of Massachusetts Lowell
Ioannis Smanis, University of Massachusetts Lowell

IAB Mentors:
Adam Johs, EDP Renewables
Ben Rice, Pattern Energy

In this project, a novel acoustic sensing technique was used to detect cracks, holes, delaminations and trailing edge splits from wind turbine blades. Acoustic speakers were used to excite the blade's cavity from internally and aerodynamic noise due to wind from externally. Wireless microphones were used for the cavity-internal passive detection and a single microphone located underneath the nacelle was used for the external active detection of damage. The main focus of this project was on the field tests on a full-scale turbine blade as well as signal processing and machine learning algorithm development to enable this technology.

This project enabled the team further develop a state of the art acoustics-based structural sensing and health monitoring technique, which requires efficient algorithms for operational damage detection from wind turbine blades. The team initially focused on the passive acoustic detection aspect of the project. A renewed passive damage detection test campaign was initiated on a fullscale blade undergoing flapwise fatigue testing at the Wind Technology Testing Center (WTTC) in Charlestown, MA. This approach leverages the energy caused by the wind/flow-induced noise, exterior to the cavity. It is inexpensive, in-situ, and effective to detect holes, cracks and leading/trailing edge splits in bonded surfaces. The blade can be continuously monitored and when damage is originated, the internal acoustic signature should change due to the changes in the transmission loss (caused by the hole or crack) and/or the distorted acoustic pressure field. The sound field inside the blade should be significantly different when the blade cavity is no longer sealed to the fluid passing over the exterior of the blade. A single microphone inside the blade cavity can be used to track the differential noise component caused by the damage, which essentially couples the blade cavity to the exterior airflow.

The team has also worked on the active detection part of the project. For this part of the project, a utility scale turbine blade that exists at the WTTC has been utilized. The blade-internal cavity has been ensonified by acoustic speakers and blade-external microphones have been used to detect any changes in the acoustic transmission loss due to damage. After the aforementioned tests, the team has been developing a suite of preliminary damage detection algorithms that will be used to detect damage under operation.

A close-up of a blade-internal microphone used for in-lab acoustic detection tests.

PROJECT ID: B1-17

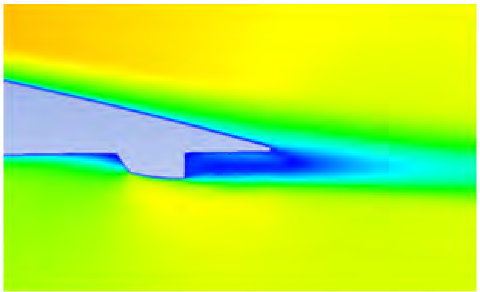
Wind Turbine Aerodynamics Modified Gurney Flaps

Project Instructor:
David Willis, University of Massachusetts Lowell

Student Researchers:
Jessica Ferguson, Richard Horan, Michael Floss, Antonio Monteiro, Joshua Dollen, Corey Berube, David Church, and Robert Monteagudo, University of Massachusetts Lowell

IAB Mentors:
Neal Fine, Aquanis

This Capstone Design project examined different designs of Gurney flaps for wind turbine blades using computation fluid dynamics and wind tunnel experiments. Gurney Flaps have been demonstrated as a viable solution to increasing the efficiency of aircraft wings, race car spoilers and wind turbine blades. However, previous research has only examined the Gurney Flap height, length and installation location. This work examined different Gurney Flap shapes to determine increases in both efficiency and lift force. In much of the previous Gurney Flap research, a simple ninety-degree tab is used as the aerodynamic actuator; however, in this project different Gurney Flap profile shapes are examined, including convex and concave designs. Initial results indicate that convex curves yield improved aerodynamics efficiency and performance.



PROJECT ID: U1-17

Low Cost Optical Fiber Strain Sensor Interrogator for Wind Turbine Blades

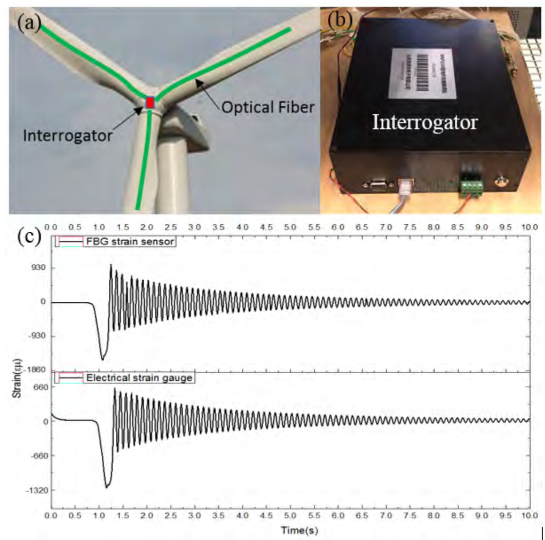
Principal Investigator:
Xingwei Wang, University of Massachusetts Lowell

Co-Principal Investigator:
Christopher Niezrecki, University of Massachusetts Lowell

Student Researchers:
Cong Du, University of Massachusetts Lowell

IAB Mentors:
Bernard Landa, GE Renewable Energy
Nicholas Althoff, GE Renewable Energy

Sensing and control improvements in the blades of wind turbines plays a vital role in improving their power production efficiency and reliability. However, the blades suffer from exposure to harsh environments and continuous dynamic loads. It is important to utilize structural health monitoring sensors for operation monitoring and condition based maintenance and repair.Fiber Bragg grating (FBG) technology has the potential to be being widely used in wind turbine structural health monitoring. It has several advantages compared to other incumbent technologies, due to its small size, distributed sensing properties over long distances (20-120 km), immunity to electromagnetic interference, resilience to harsh environments, and capability of monitoring structural behavior of new composite materials in bending loads. To perform demodulation of FBG sensors, optical fiber sensor interrogator technology has been used for many years. In this project, a low-cost self-powered interrogation system that can be simultaneously operated by multiple optical fiber strain sensing elements is proposed. The interrogator dimensions are smaller than conventional systems (i.e. ~6" by 6" in size). The interrogation system being developed includes a low power-consumption tunable laser, photodiodes, controller and integrated data storage. The Field Programmable Gate Array (FPGA) technique is applied to conduct the high-speed scanning for the FBG wavelength. Vertical Cavity Surface Emitting Laser (VCSEL) is utilized for reducing power consumption. The 24 channels are divided from a laser source using a 1-24 optical splitter. 24 FBGs were mounted on three fiberglass panels to test the performance of the interrogator in the detection of strain and temperature. The electrical strain gauges were used as a reference during testing in operation. The results indicate the successful validation of interrogator in the laboratory and this optical fiber strain sensor methodology is found to be promising for detecting dynamic strain and temperature on utility-scale turbine blades.



The low cost optical fiber strain sensor interrogator for wind turbine blades: (a) the schematic of strain detection using FBG interrogator. (b) FBG interrogator. (c) The FBG strain sensors vs electrical strain gage.

PROJECT ID: B3-17

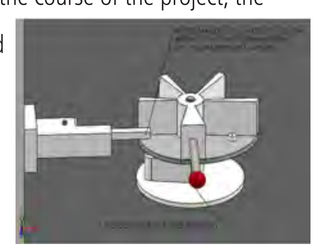
Wind Turbine Foundation Monitoring Sensor Development

Project Instuctor:
Christopher Niezrecki, University of Massachusetts Lowell

Student Researchers:
Joshua Bennett, Catherine Clarke, Brennan Kickery, Albert Todd, University of Massachusetts

IAB Mentors:
Ron Grife, Leeward Energy
Diogo Silva, EDP Renewables
Adam Johs, EDP Renewables

The motivation behind this Capstone Design project was to develop a low-cost motion indicator to monitor the displacements that can occur in the foundation of utility-scale wind turbines. Currently there are limitations with visual inspection and even if technicians are properly trained they may miss a foundation in the early stages of failure. Likewise, electronic monitoring is cost prohibitive. The goal for this project was to create a sensor that would record motion, be easy for the technician to read, and indicate vertical and horizontal deflections in a range of .015"- .05". The team developed two designs that fulfilled the requirements for indicating tower displacements as small as 1 mm up to 6 mm. The project has led to an invention disclosure and a provisional patent application. During the course of the project, the developed models were prototyped and are currently going through further optimization in anticipation for field trials.



PROJECT ID: U2-17

Proactive Monitoring of Wind Farm Performance Through Wind LiDAR Data and a Reduced Order Model

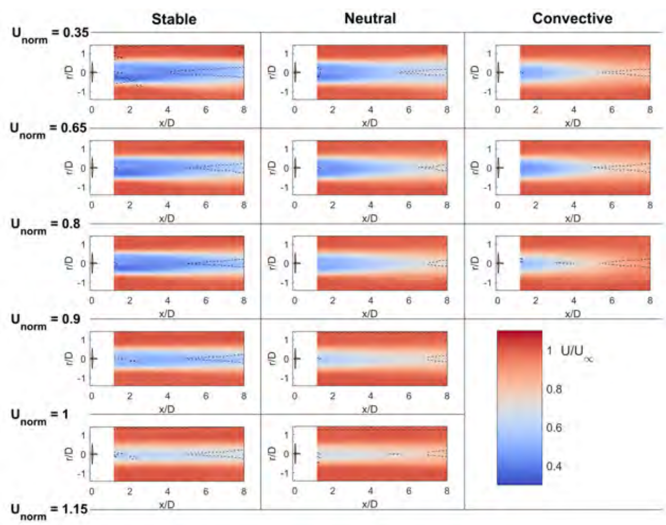
Principal Investigator:
Giacomo Valerio Iungo, University of Texas at Dallas

Co-Principal Investigator:
Stefano Leonardi, University of Texas at Dallas

Student Researchers:
Stefano Letizia, University of Texas at Dallas
Christian Santoni, University of Texas at Dallas

IAB Mentors:
Ron Grife, Leeward Renewable Energy
Bernard Landa, GE Renewable Energy
Patrick Pyle, Pattern
Neha Marahate, EDP Renewables

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. This CFD tool is based on the Reynolds-averaged Navier-Stokes (RANS) equations, which are solved parabolically in order to reduce the computational costs. Calibration and assessment of this code has been performed by leveraging LiDAR measurements of wind turbine wakes, SCADA and meteorological data collected for a wind farm in North Texas deployed over a relatively flat terrain. For this test case, the CFD tool showed an accuracy of 7% with a confidence level of 90% for estimates of power capture from individual turbines. Among different features, the CFD tool provides a data-driven calibration of the turbulence closure in order to mimic variability in wake recovery due to different regimes of the atmospheric stability. Furthermore, the thrust force over the turbine blades is experimentally estimated by coupling LiDAR data and RANS simulations. The current challenge for this project consists in extending the range of applicability of this CFD tool to wind farms on complex terrain. To this aim, a new LiDAR field campaign is under execution for a wind farm in Colorado. This new experimental dataset will allow us to single out potential weaknesses of the CFD tool in presence of topographic effects and, hopefully, to overcome those through further developments of the tool. Mesoscale simulations with ad-hoc wind farm modeling have been executed for the wind farm in North Texas, showing a good accuracy in predicting the wind field around and within the wind farm, while estimating power capture at the turbine level as well.



Bonded Variability of the wake velocity field for different incoming wind speed and regime of the atmospheric stability.

Deployment of the UTD mobile LiDAR station at a wind farm on complex terrain in Colorado

PROJECT ID: C1-17

NREL FAST Modeling for Blade Load Control with Plasma Actuators

Principal Investigator:
Mario Rotea, University of Texas at Dallas

Co-Principal Investigator:
Yaoyu Li, University of Texas at Dallas

Student Researcher:
Chang Liu, University of Texas at Dallas

IAB Mentors:
Neal Fine, Aquanis
Nicholas Althoff, GE Renewable Energy
Steve Nolet, TPI Composites

Reducing extreme and fatigue loads on the rotor blades of a wind turbine lowers the Levelized Cost of Energy, which is critical for future wind turbines equipped with longer and more flexible blades. With larger rotors, the span-wise variability of the wind challenges the capabilities of the blade load control strategies of current operational systems. Active flow control (AFC) has emerged as an appealing solution to fast and localized rotor control for load mitigation. Among the existing AFC devices, plasma actuators have drawn attention due to their mechanical simplicity (no moving parts), fast response time and low cost. This project developed a simulation tool for design of plasma-based AFC systems for blade load reduction. The tool is based on the industry standard NREL FAST code. The FAST module with integrated plasma actuation is demonstrated using the NREL 5-MW reference turbine model. With the feedback of blade-root flapwise bending moments, a Coleman transformation based controller is used to drive the voltage commands to the plasma actuators. Load reduction is demonstrated without noticeable penalty in turbine performance as measured by rotor speed and power errors in Region 3.

Figure 1 shows a segmented blade planform where the aerodynamics of each segment is simulated using FAST. The plasma actuators are modeled as changes in local lift coefficient ΔCL in the outer span of the blade (sections 12 to 17 in the segmented blade). The controllable lift coefficients are modulated by voltage signals (one per blade) generated by a feedback controller that measures selected blade loads to calculate the voltage commands for each blade, referred as Individual Blade Voltage Control (IBVC) in the figure. Figure 2 demonstrates the reduction of the measured loads (blade-root flap-wise bending moments) for the case with vertical shear and no turbulence. Figure 3 demonstrates the reduction of blade loads at the rotor angular frequency when both vertical shear (non-uniform flow) and turbulence (unsteady flow) are present. Damage equivalent loads (DEL) under vertical shear can be reduced from 30% (no turbulence) to 10%-15%, approximately, when turbulence intensity is increased to 15%.

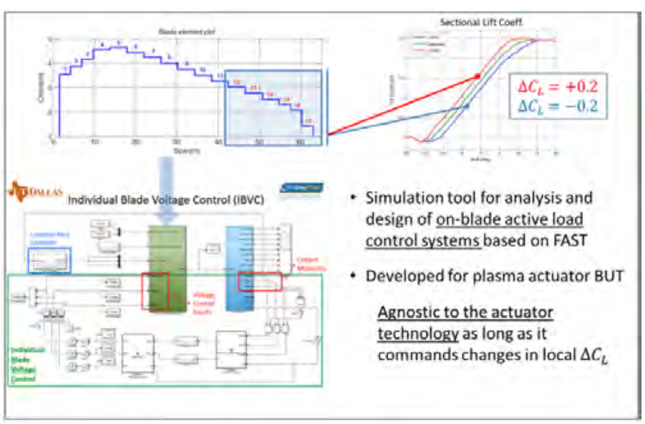


Figure 1: 5MW NREL ref turbine blade showing controllable local lift coefficients (Top). Simulink diagram of NREL FAST tool with controllable sectional lift coefficients (bottom left).

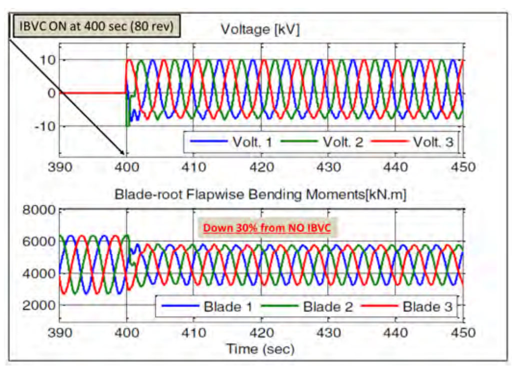


Figure 2: Time series of voltage commands to plasma actuators (one command per blade) and response of measured loads for the 5 MW NREL reference turbine at 18 m/s wind speed and with vertical wind shear.

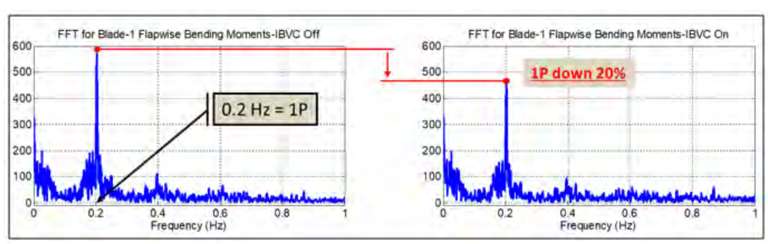


Figure 3: Frequency response of load signal with IBVC off (left) and IBVC on (right) for the 5 MW NREL reference turbine at 18 m/s wind speed, vertical wind shear and 15% turbulence intensity. Rated rotor angular speed is 12.1 rpm (1P).

PROJECT ID: D2-17

Uncertainty quantification of wind farm performance through high fidelity simulations and wind LiDAR measurements

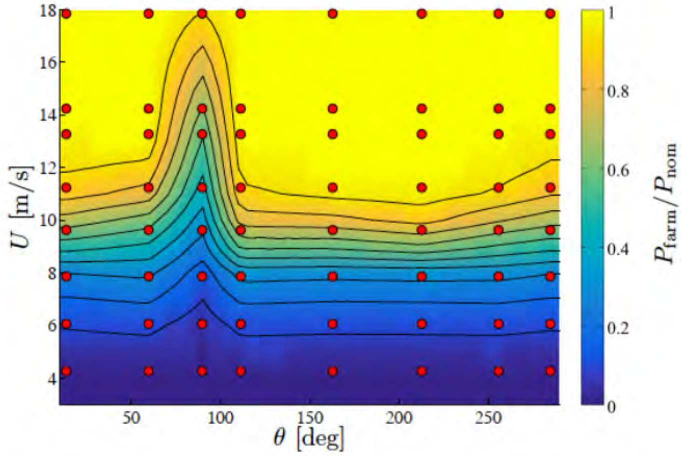
Principal Investigator:
Stefano Leonardi, University of Texas at Dallas

Co-Principal Investigator:
G. Valerio Iungo, University of Texas at Dallas

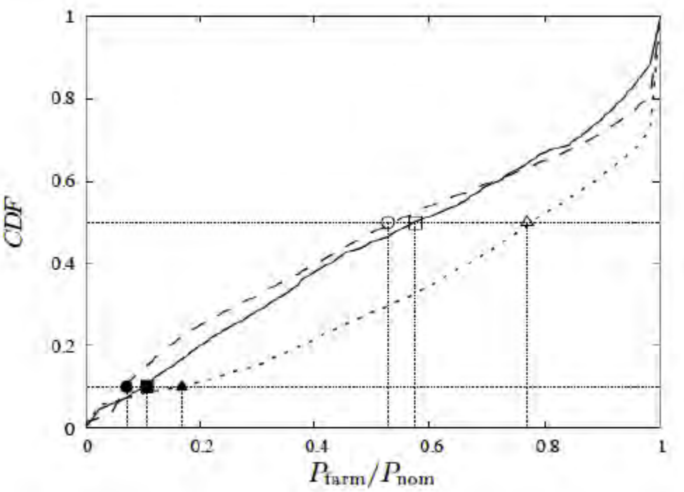
Student Researcher:
Christian Santoni, University of Texas at Dallas

IAB Mentors:
Neal Fine, Aquanis
Benjamin Rice, Pattern Energy

A novel method has been developed to derive a surrogate model for wind farm control. The procedure is based on a stochastic approach using generalized polynomial chaos (PC) and highfidelity simulations. The turbine control law and the incoming wind conditions, such as speed and directions, are treated as uncertain variables. Wind farm power production is then viewed as the random process depending on these uncertain variables. Thus, polynomial chaos expansion can be used to obtain a response function that provides the wind farm power production as a function of the turbine control parameters and the wind speed and direction. The response function is obtained by using a finite set of deterministic realizations, which consist in highfidelity simulations for certain values of wind speed, direction and control parameters,interpolated by polynomials. In PC, the interpolating polynomial basis and the set of realizations are selected according to the probability density function of the uncertain parameters. This allows using a limited number of realizations to obtain an accurate response function and provides uncertainty bounds on the model. Thus, a mapping of the optimal control settings isobtained for any wind speed and direction to be employed for real-time wind farm operations. In this work, the procedure is validated against field measurements in a real wind farm in north Texas. The surrogate model (Fig.1) is obtained by performing 64 simulations with our in-house code interpolated by 7th-order Hermite polynomials. The average power production predicted by the model for six days of operation under stable atmospheric conditions is within 2% accuracy of experimental data. Additionally, other statistical metrics, such as the P50 or P90, are predicted correctly within a 5-10% bound (Fig.2). The results emphasize the importance of the underlying high-fidelity solver used for the development of the model. When the same procedure is applied using an engineering wake model, the error of the surrogate model prediction respect to SCADA data increases of an order of magnitude.



Surrogate model obtained from PC expansion. The red dots indicate the sample points of wind speed and direction.



Cumulative distribution function of the wind farm power production: solid line SCADA data; dashed PC expansion using LES; dotted PC expansion using Jensen model. Symbols indicate the value of P90 (filled symbols) and P50 (empty): square SCADA data; circle PC expansion using LES; triangle PC expansion using Jensen model.

PROJECT ID: C2-17

Effects of Manufacturing Induced Defects

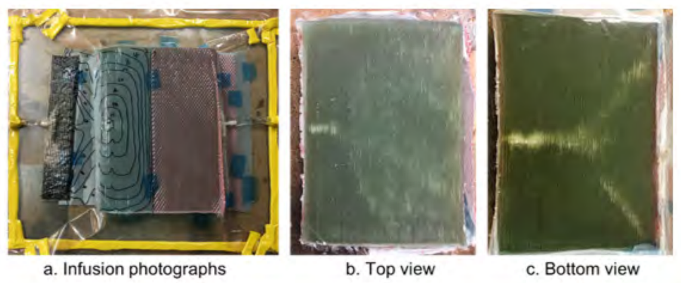
Principal Investigator:
James Sherwood, University of Massachusetts Lowell

Co-Principal Investigator:
Scott Stapleton, University of Massachusetts Lowell

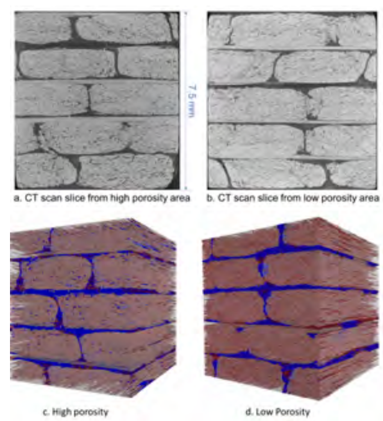
Student Researcher:
Juan Su, University of Massachusetts Lowell
Stephen Johnson, University of Massachusetts Lowel

IAB Mentors:
Stephen Nolet, TPI Composites
Nicholas Althoff, GE Renewable Energy

Manufacturing-induced defects such as local regions of porosity are commonly formed during the resin-infusion step of composite wind blade manufacture, and this porosity is a consequence of air trapped during resin mixing or by nucleation from volatiles. These local regions of porosity can have an adverse impact on the resulting fatigue life of the blade. Due to the absence of any theoretical or empirical models to predict how these local regions of porosity will decrease the nominal fatigue life of a composite wind blade in service, the wind industry is forced to make subjective decisions on the disposition of composite wind turbine blades with regions of high porosity. The current research sought to fill this need for an empirical model to relate state of porosity to the associated fatigue life. A methodology for making composite plates with the various degrees of porosity that can result from the wind blade manufacturing process was developed. These plates were subsequently cut into flexure, compression and fatigue specimens using a water jet saw for large cuts and a wet saw for small cuts. The degree of porosity was investigated using three optical techniques, i.e. optical microscopy, SEM (scanning electron microscope), and micro-CT scanning. Future work in this research will include fatigue testing and the subsequent development of the empirical model(s). These model(s) will enable improved decision making on blade disposition, OEMs and wind farm operators to potentially negotiate reduced price based on the state of porosity, and insurers to tailor the insurance premium to the state of porosity.



Photographs of Sample #4



CT scan slices (a, b) and reconstruction 3D model (c, d)

PROJECT ID: A4-16

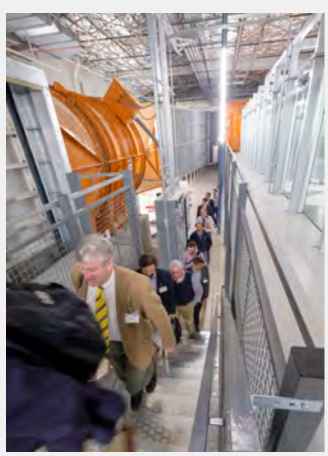
CENTER EVENTS

IAB Meetings:

University of Massachusetts Lowell, June 6-7, 2018
University of Texas at Dallas, January 31 - February 1, 2018

Invited Keynote Speakers for Center Banquets:

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



IAB Members touring BLAST during WindSTAR winter meeting at UT Dallas.

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

WindSTAR members hike at Mt. Major.

2014-2018 OUTCOMES
Through August 31, 2018

Deliverables:

1. 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.
2. 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.
3. 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
4. Software: A Matlab based GUI for prediction of power production and wind turbine wakes for the Panhandle Phase II wind farm.
5. Software: Simulink code for Extremum Seeking Control of NREL CART3 (Controls Advanced Research Turbine, 3-bladed).
6. Patent Filing: Wind Turbine Foundation Motion and Crack Indicator, May 3, 2018
7. Hardware: Fiber Optic Interrogator for Strain Monitoring
8. Hardware: Passive Acoustic Damage Detection System for Blades
9. Hardware: Active Acoustic Damage Detection System for Blades

Journal Papers:

1. Ciri U., M.A. Rotea, and S. Leonardi, "Effect of the turbine scale on yaw control," Wind Energy, first published: August 2018, https://doi.org/10.1002/we.2262.
2. Martin, R., Sabato, A., Giles, R., Schoenberg, A., and Niezrecki, C., "Comparison of nondestructive testing techniques for the inspection of wind turbine blades' spar caps," Wind Energy, http://dx.doi.org/10.1002/we.2208, May, 2018.
3. Xiao Y., Y. Li, and M. A. Rotea, "CART3 Field Tests for Wind Turbine Region-2 Operation with Extremum Seeking Controllers," IEEE Trans. on Control Systems Technology, first published on line: April 2018, doi: 10.1109/TCST.2018.2825450.
4. Iungo G. V., Santhanagopalan V., Ciri U., Viola F., Zhan L., Rotea M. A. and Leonardi S., "Parabolic RANS solver for low-computational-cost simulations of wind turbine wakes," Wind Energy, Vol. 21, No. 3, March 2018, pp. 184-197.
5. 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. 232-243.
6. Willis, D. J., Niezrecki C., Kuchma, D., Hines, E., Arwade, S., Barthelmie, R. J., DiPaola, M., Drane, P. J., Hansen, C. J., Inalpolat, M., Mack, J. H., Meyers, A. T., and Rotea, M., "Wind Energy Research: State-of-the-Art and Future Research Directions, Renewable Energy, Elsevier, vol. 125(C), pages 133-154, 2018.
7. Ciri U., M.A. Rotea and S. Leonardi, "Model-free Control of Wind Farms. A comparative study between individual and coordinated extremum seeking," Renewable Energy, Vol. 113, December 2017, pp. 1033-45.
8. El Asha S., L. Zhan, G.V. Iungo, "Quantification of power losses due to wind turbine wake interactions through SCADA, meteorological and wind LiDAR data," Wind Energy, Vol. 20, No. 11, November 2017, pp. 1823-1839.
9. Ciri U., M.A. Rotea, C. Santoni-Ortiz and S. Leonardi, "Large-Eddy Simulations with Extremum-Seeking Control for wind turbines array power optimization," Wind Energy, Vol. 20, No. 9, September 2017, pp. 1617-1634.

Master of Science Thesis:

1. Joshua Morris, "Improving Wind Turbine Blade Transverse and Shear Response Using Advanced Resins," Master of Science Thesis, University of Massachusetts Lowell, 2018.
2. Martin, R. W., "Analysis of polarimetric terahertz imaging for non-destructive detection of subsurface defects in wind turbine blades," Master of Science Thesis, University of Massachusetts Lowell, 2016.

PhD Dissertations:

1. Cristian Santoni, "Wind Farm Modeling: From the Meso-Scale to the Micro-Scale," Ph.D. in Mechanical Engineering, Dissertation, University of Texas at Dallas, 2018.
2. Yan Xiao, "Control of Wind Power Systems for Energy Efficiency and Reliability," Ph.D. in Electrical Engineering, Dissertation, University of Texas at Dallas, 2018.
3. Siddharth Dev, "Novel Microcapsule Chemistries for Self-Healing Applications in Polymeric Materials," Ph.D. in Mechanical Engineering, Dissertation, University of Massachusetts Lowell, 2018.

Interns at Member Companies:

1. Said El-Asha, recipient of WindSTAR NSF REU at UT Dallas, Engineering Intern at Leeward Renewable Energy, LLC.

Conference Papers:

1. Liu C., Yaoyu Li, John A. Cooney, Neal E. Fine, and Mario A. Rotea, "NREL FAST Modeling for Blade Load Control with Plasma Actuators," 2018 IEEE Conference on Control Technology and Applications (CCTA), pp. 1644-1649, Copenhagen, Denmark, August 21-24, 2018
2. Iungo G.V., S. Letizia and L. Zhan, "Quantification of the axial induction exerted by utility-scale wind turbines by coupling LiDAR measurements and RANS simulations", TORQUE 2018, Milano, Italy, June 20-22 2018, J. Phys.: Conf. Ser. 1037 (7), 072023.
3. Santoni C., E.J. Garcia-Cartagena, U. Ciri, G.V. Iungo and S. Leonardi, "Coupling of mesoscale Weather Research and Forecasting model to a high fidelity Large Eddy Simulation", TORQUE 2018, Milano, Italy, June 20-22 2018, J. Phys.: Conf. Ser. 1037 (6), 062010.
4. Cassano, Hansen, Stapleton, Maiaru "Prediction of Cure Overheating in Thick Adhesive Bondlines for Wind Energy Applications", 2018 Simulia Global User Meeting, Boston, MA, June 18-21, 2018
5. Beale, C., Inalpolat, M., and Niezrecki, N., "An Experimental Investigation into the Interactions between Acoustic Modes and Structural Damage on a Cavity Structure," International Modal Analysis Conference (IMAC XXXVI), Orlando, Florida, February 2018.
6. Fickenwirth, P., Inalpolat, M., "Feature Extraction for Vibration Based Damage Detection Using Spatio-temporal Structural Patterns," International Modal Analysis Conference (IMAC XXXVI), Orlando, Florida, February 2018.
7. V. Santhanagopalan, S. Letizia, L. Zhan, L.Y. Al-Hamidi, G.V. Iungo "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.
8. Su, J., Johnson, S., Stapleton, S., Sherwood, J., Nolet, S., Althoff, N., "Effects of Localized Manufacturing-Induced Defects in Wind Turbine Blades, Proceedings of the American Society for Composites: Thirty-Third Technical Conference, Seattle, WA, 2018.
9. Polcari M, Sherwood J. "Automation for Wind Blade Manufacturing." 3rd International Symposium on Automated Composites Manufacturing. Montreal, 2017.
10. Ciri U., M.A. Rotea and S. Leonardi, "Nested Extremum Seeking Control for Wind Farm Power Optimization," 2017 American Control Conference, Seattle, WA, May 24-26 2017, pp. 25-30.
11. Xiao, Y., Y. Li, M.A. Rotea, "Multi-objective Extremum Seeking Control for Enhancement of Wind Turbine Power Capture with Load Reduction," Journal of Physics: Conference Series, Volume 753 (2016) 052025, The Science of Making Torque from Wind (TORQUE 2016), Munich, Germany, October 5-7, 2016.
12. Polcari M., and Sherwood J. 2016. "Simulation of the Automation of Composite Wind Turbine Blade Manufacture", Proceedings of the American Society for Composites 31st Technical Conference and ASTM Committee D30 Meeting. September 19-12, Williamsburg, VA.

13. Ciri U., M. Rotea, C. Santoni and S. Leonardi, "Large Eddy Simulation for an Array of Turbines with Extremum Seeking Control," 2016 American Control Conference, Boston, MA, July 6-8 2016, pp. 531-536.
14. DiPaola M., D. J. Willis, S. Leonardi, "A Fast Differential Deficit Control Volume Approach for Modeling Turbine-Turbine Interactions," 46th AIAA Fluid Dynamics Conference, 2016, (AIAA 2016-3962), Washington, DC, June 13-17, 2016.
15. Martin, R., Baird, C., Giles, R., Niezrecki, C., "Terahertz ISAR and x-ray imaging of wind turbine blade structures," Proceedings of the SPIE Symposium on Smart Structures & Materials/NDE, Las Vegas, NV, March 20-24, 2016.
16. Iungo G.V., F. Viola, U. Ciri, S. Leonardi, M.A. Rotea, "Reduced order model for optimization of power production from a wind farm," 34th Wind Energy Symposium, AIAA SciTech Forum, (AIAA 2016-2200), San Diego, CA, January 9-13, 2016, pp. 1-9.
17. Ashuri T, M.A. Rotea, C.V. Ponnurangam and Y. Xiao, "Impact of airfoil performance degradation on annual energy production and its mitigation via extremum seeking controls," 34th Wind Energy Symposium, AIAA SciTech, AIAA 2016-1738, San Diego, CA, 4-8 Jan 2016.
18. Xiao, Y., Y. Li, and M.A. Rotea, "Experimental Evaluation of Extremum Seeking Based Region-2 Controller for CART3 Wind Turbine," AIAA 2016 Sci-Tech Wind Energy Symposium, (AIAA 2016-1737), San Diego, CA, January 4-8, 2016.
19. S. Dev, C. Hansen. "Evaluation of self-healing performance in epoxy/glass fiber composites manufactured using VARTM. 20th International Conference on Composite Materials, July 19-24 2015, Copenhagen Denmark
20. Santoni C., U. Ciri, M.A. Rotea, and S. Leonardi, "Development of a high fidelity CFD code for wind farm control," 2015 American Control Conference, Chicago, IL, July 1-3, 2015, pp. 1715-1720.
21. S. Dev and C. Hansen, "Screening Barrier Properties for Robust Double Shell Walled Microcapsules," Fifth International Conference on Self Healing Materials, Durham, North Carolina, NC, USA, June 2015.

Selected Presentations:

1. 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.
2. C. Beale, M. Inalpolat, C. Niezrecki, "A Computational Investigation into the Interactions between Acoustic Mode Shapes and Structural Damage of Composite Subscale Cavity Structures" (244), IMAC XXXVI, Society for Experimental Mechanics, Inc., 12-Feb-2018, Orlando, FL.
3. Joshua Morris, "Micromechanical Modeling of Composites for Shear and Transverse Properties," ASC 32nd Technical Conference, Oct. 2017, West Lafayette, IN.
4. Iungo, G.V., "Proactive monitoring of an onshore wind farm through LiDAR, SCADA and RANS data", Invited presentation at the Mini Symposia "WindFarm2017," Wind Energy Science Conference 2017, June 26-29, 2017, Technical University of Denmark, Lyngby, Denmark.
5. Rotea M.A., S. Leonardi and Y. Li, "Extremum Seeking Control of Wind Turbines and Wind Farms," Invited presentation at the Mini Symposia "WindFarm2017," Wind Energy Science Conference 2017, June 26-29, 2017, Technical University of Denmark, Lyngby, Denmark.
6. Rotea, M.A., Modeling and Control of Wind Energy Systems, Plenary, 2016 IEEE Multi-Conference on Systems and Control (MSC), Buenos Aires, Argentina, September 19-22, 2016.

ACTIVE PROJECTS: 2018-2019

- Mechanical Properties Enhancement Prediction for Matrix Material
  Project ID: A1-18
  PI: Marianna Maiaru (University of Massachusetts Lowell)
  Co PIs: Alireza Amirkhizi, Christopher Hansen
  Mentors: Bruce Burton (Huntsman), Steve Nolet (TPI), Nicholas Althoff (GE), Nathan Bruno (Hexion), Paul Ubrich (Hexion)

- Engineered Sandwich Core Construction: Experiment and Evaluation
  Project ID: A2-18
  PI: Hongbing Lu (University of Texas at Dallas)
  Mentor: Nicholas Althoff (GE)

- Structural Wind Blade Repair Optimization
  Project ID: A3-18
  PI: Marianna Maiaru (University of Massachusetts Lowell)
  Co PIs: Scott Stapleton, Christopher Hansen
  Mentors: Jian Lahir (EDPR), Nathan Bruno (Hexion), Paul Ubrich (Hexion), Nicholas Althoff (GE), Ben Rice (Pattern), Steve Nolet (TPI)

- Residual Stresses in Thick paste Adhesive Bondlines
  Project ID: A4-18
  PI: Scott Stapleton (University of Massachusetts Lowell)
  Co PI: Marianna Maiaru
  Mentors: Steve Nolet (TPI), Nathan Bruno (Hexion), Paul Ubrich (Hexion), Nicholas Althoff (GE)

- Monitoring of Wind Turbine-Foundation and Technology Assessment Survey to Improve Expected Service Life predictions
  Project ID: B1-18
  PI: Pradeep Kurup (University of Massachusetts Lowell)
  Co PIs: Christopher Niezrecki, Raj Gondle
  Mentors: Ron Grife (Leeward), Adam Johs (EDPR), Ben Rice (Pattern), Nicholas Althoff (GE)

- System integration of a Wind Turbine Blade Acoustic Monitoring System
  Project ID: B2-18
  PI: Murat Inalpolat (University of Massachusetts Lowell)
  Co PIs: Christopher Niezrecki, Yan Luo
  Mentors: Ben Rice (Pattern), Ron Grife (Leeward), Adam Johs (EDPR), Jian Lahir (EDPR), GE

- Reduced Order Model developed through LiDAR measurements for Predictions of Wind Turbine Wakes and Power Capture
  Project ID: C1-18
  PI: G. Valerio Iungo (University of Texas at Dallas)
  Mentors: Ron Grife (Leeward), Ben Rice (Pattern), Nicholas Althoff (GE), Neal Fine (Aquanis), Neha Marathe (EDPR)

- Advanced Control System for Evaluation of on-Blade Load Mitigation Technologies
  Project ID: D1-18
  PI: Mario Rotea (University of Texas at Dallas)
  Mentors: John Cooney (Aquanis), Ben Rice (Pattern), Nicholas Althoff (GE)

- Mechanical Properties, Micro-structure Property Relationship and Manufacturing/Construction Methods for UHPFRC for Both the Foundation and Towers
  Project ID: F1-18
  PI: Dong Qian (University of Texas at Dallas)
  Co PI: Hongbing Lu
  Mentors: John Buttles (Texas Wind Tower), Nicholas Althoff (GE)

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