Proceedings
of the
2nd Workshop on
Probabilistic Prognostics and Health Management of Energy Systems
(PPHMES 2017)

May 15 – 16
Lubbock, TX

PPHMES 2017

The 2nd Workshop on Probabilistic Prognostics and Health Management of Energy Systems

15 – 16 May, 2017
Lubbock, Texas, USA

Hosted by

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Contents

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National Renewable Energy Laboratory, USA

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São Paulo State University, Brazil

Dr. Americo Cunha Jr
Assistant Professor
Rio de Janeiro State University, Brazil

About Workshop

Editorial Note

The objective of the workshop is to bring international expertise together in order to address the prevailing issue of premature failure of energy systems and enhance the prediction tools of remaining useful life (RUL), by which the uncertainty of RUL prediction will be minimal.

The workshop will be held at Texas Tech University in Lubbock, Texas, USA, on May 15-16, 2017. The four topics pertinent to industry research, academia research, and government laboratory research that will be addressed by experts are:

PHM for Off-Shore Energy Systems
Internet-of-Things for PHM
Vibration Based PHM
Emerging Technologies on Sensing and Filtering

The international experts that will come from several countries (from academia, industry, and government laboratories). They will have expertise in the field of mechanical and electrical engineering, mathematics, computer programming, internet of things, renewable energy, modeling, and probabilistic analysis.

The workshop will revisit the state-of-the-art Prognostics and Health Management (PHM) research, the contemporary practice of the energy industry in implementing PHM and the uncertainties involved in predicting RUL.

Program at a Glance

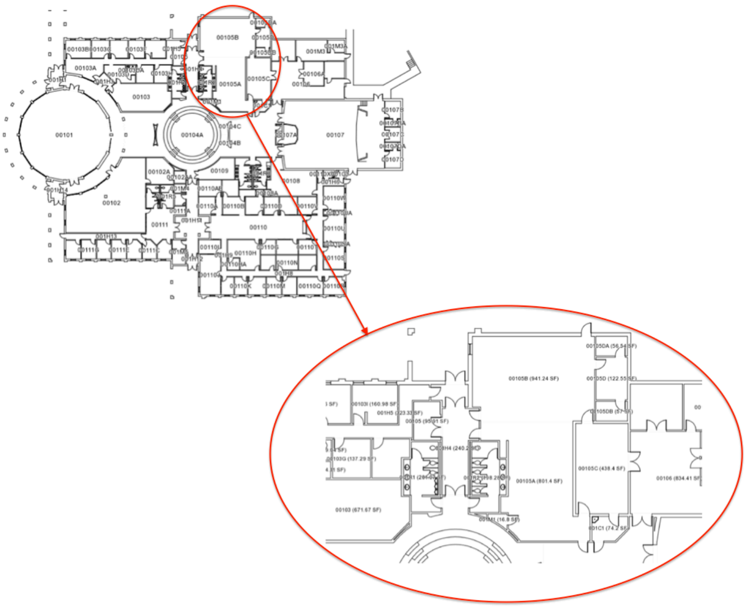
Monday, May 15, 2017	Time	Activities
	8:00:00 AM	Registration
	9:00:00 AM	Welcome/Opening Remarks
Session 1 PHM for Off-Shore Energy Systems **Chair**: Dr. Sheng	**9:10:00 AM**	**Keynote Speak 1**
	10:00:00 AM	Technical Presentation 1.1
	10:30:00 AM	**Coffee Break**
	11:00:00 AM	Technical Presentation 1.2
	11:35:00 AM	Technical Presentation 1.3
	12:05:00 PM	**LUNCHEON**
Session 2 Emerging Technologies on Sensing and Filtering **Chairs**: Drs. Gonçalves/Dias	**1:30:00 PM**	**Keynote Speak 2**
	2:20:00 PM	Technical Presentation 2.1
	2:50:00 PM	**Coffee Break**
	3:20:00 PM	Technical Presentation 2.2
	3:55:00 PM	Technical Presentation 2.3
Panel Discussion **Chair**: Dr. Ekwaro-Osire	4:30:00 PM	*Panel Discussion: New Trends in PPHM*

Tuesday, May 16, 2017	Time	Activities
	8:10:00 AM	Registration
Session 3 Vibration Based PHM **Chair**: Dr. Cunha Jr.	**9:10:00 AM**	**Keynote Speak 3**
	10:00:00 AM	Technical Presentation 3.1
	10:30:00 AM	**Coffee Break**
	11:00:00 AM	Technical Presentation 3.2
	11:35:00 AM	Technical Presentation 3.3
	12:05:00 PM	**LUNCHEON / Sponsors Presentation**
	1:30:00 PM	**Poster Exhibition**
Session 4 Internet-of-Things for PHM **Chair**: Dr. Alemayehu	**2:30:00 PM**	***Keynote Speak 4***
	3:20:00 PM	Technical Presentation 4.1
	3:50:00 PM	**Coffee Break**
	4:20:00 PM	Technical Presentation 4.2
	4:55:00 PM	Technical Presentation 4.3
	5:30:00 PM	Wrap up / Closing Remarks

Workshop Venue

International Cultural Center of Texas Tech University

Texas Tech University, 601 Indiana Avenue, Lubbock, TX 79409, EUA



Room 105A-B

Registration Guide

Visit the Registration Deck located in Room 105A-B of ICC. You can take your ID badge and workshop kit including program book and other information for the workshop.

Use of Internet and Wi-Fi

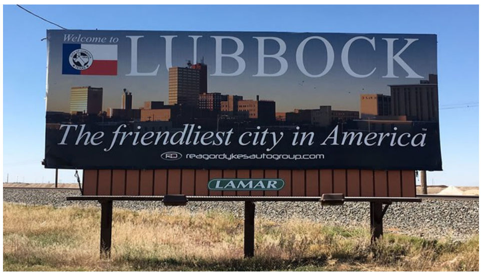
ICC provides Wi-Fi for free. Check the network name and password in Registration Deck.

For Lunch

Lunch will be offered to all workshop participants in both days, starting to be served by 12:05 PM.

About Lubbock

Located at Northwestern Texas (Panhandle), with an estimated population of 249,042 (by 2015 Census), Lubbock is the economic, educational, and health care center of the multicounty region, which had an estimated 2015 population of 311,154. This region, known historically and geographically as the Llano Estacado and ecologically is part of the southern end of the High Plains.



Social Programe

http://www.visitlubbock.org

Red Raiders

http://redraiders.com

Program

Keynote Lectures

Lecture 1 - Fleet monitoring for failure prognosis
Monday, May 15, 2017, 9:10 AM

Speaker: Dr. Jan Helsen (Vrije Universiteit Brussel / OWI-Lab, Belgium)

Chair: Dr. Shuangwen Sheng

Lecture 2 - Stochastic modeling for system remaining life prognosis
Monday, May 15, 2017, 1:30 PM

Speaker: Dr. Robert Gao (Case Western Reserve University, USA)

Chairs: Dr. Aparecido C. Gonçalves and Dr. João Paulo Dias

Lecture 3 - Vibration and wave energy harvesting by exploiting nonlinearities and metamaterials
Tuesday, May 16, 2017, 9:10 AM

Speaker: Dr. Alper Erturk (Georgia Institute of Technology, USA)

Chair: Dr. Americo Cunha Jr

Lecture 4 - When will it break?
Tuesday, May 16, 2017, 2:30 PM

Speaker: Dr. Kai Goebel (NASA Ames Research Center, USA)

Chair: Dr. Fisseha Alemayehu

Technical Sections

Day 1 – Part I
Monday, May 15, 2017

Section 1 - PHM for Off-Shore Energy Systems

Chair: Dr. Shuangwen Sheng

10:00 AM
Cost Reductions for Offshore Wind Plants through Structural Health and Prognostics Management
Dr. D. Todd Griffith (Sandia National Laboratories, USA)

10:30 PM
Coffee-break

11:00 AM
O&M strategy map and costs for U.S. offshore wind
Mr. Tyler Stehly (National Renewable Energy Laboratory, USA)

11:35 AM
Drill string dynamics and uncertainties
Dr. Thiago Gamboa Ritto (Federal University of Rio de Janeiro, Brazil)

12:05 PM
Luncheon

1:00 PM
Luncheon Presentation
Vector-phase analysis of bearing defect on the base of wave health monitoring (WHM) by Mr. Edgard Grant (Advanced Vector Analytics - Latvia)

Technical Sections

Day 1 – Part II
Monday, May 15, 2017

Section 2 - Emerging Technologies on Sensing and Filtering

Chairs: Dr. Aparecido C. Gonçalves and Dr. João Paulo Dias

2:20 PM
Location of Impacts on Composite Plates via Piezoelectric Rosettes
Dr. Vicente Lopes Jr. (São Paulo State University, Brazil)

2:50 PM
Coffee-break

3:20 PM
Next Generation Smart, State-Aware Materials for Enabling Prognostic Health Management
Dr. Douglas Adams (Vanderbilt University, USA)

3:55 PM
Optical sensing for structural dynamics, structural health monitoring, and wind energy
Dr. Christopher Niezrecki (University of Massachusetts, USA)

4:30 PM
Panel Discussion - New Trends in PPHM
Chair: Dr. Stephen Ekwaro-Osire

Participants:
Dr. Douglas Adams (Vanderbilt University)
Dr. Robert Gao (Case Western Reserve University)
Dr. Kai Goebel (NASA Ames Research Center)
Dr. Paulo Sérgio Varoto (São Paulo University)
Dr. Carsten Westergaard (Texas Tech University)

Technical Sections

Day 2 – Part I
Tuesday, May 16, 2017

Section 3 - Vibration Based PHM
Chair: Dr. Americo Cunha Jr.

10:00 AM
Performance Analysis of a Multi Degree of Freedom Piezoelastic Energy Harvester from Structural Vibrations
Dr. Paulo Sérgio Varoto (University of São Paulo, Brazil)

10:30 PM
Coffee-break

11:00 AM
Reference-free detection of minute, non-visible, damage using full-field, high-resolution mode shapes output-only identified from digital videos of structures
Dr. Chuck Farrar (Los Alamos Laboratory, USA)

11:35 AM
Time-frequency MUSIC beamforming for nondestructive evaluations of shell structures using ultrasonic Lamb waves
Dr. Yong-Joe Kim (Texas A&M University, USA)

12:05 PM
Luncheon

1:00 PM
Sponsor Presentation
An overview of TTU's Global laboratory for energy asset management and manufacturing initiatives by Annette Sobel (Director GLEAMM)

1:30 PM
Poster Exhibition

Technical Sections

Day 2 – Part II
Tuesday, May 16, 2017

Section 4 - Internet-of-Things for PHM

Chair: Dr. Fisseha Alemayehu

3:20 PM
Creating meaningful physics based analysis of large data sets in wind energy
Dr. Carsten Westergaard (Texas Tech University, USA)

3:50 PM
Coffee-break

4:20 PM
Big data-enabled PHM for wind turbines: opportunities and challenges
Dr. Shuangwen Sheng (National Renewable Energy Laboratory, USA)

4:55 PM
Characterization and simulation of inhomogeneous and non-stationary turbulent wind fields for assessment of wind turbine reliability
Dr. Jason McNeill (Envision Energy, USA)

5:30 PM
Wrap up/Closing Remarks

Extended Abstracts

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O&M Strategy Map and Costs for U.S. Offshore Wind

T. Stehly[1*], A. Dewan[2], N. Saraswati[2], A. Delmarre[2]
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[2]*Energy Research Centre of the Netherlands (ECN) – Petten, the Netherlands*
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Keywords: O&M, Offshore, Wind

1. INTRODUCTION

The U.S. Department of Energy has adopted Wind Vision [1] to support the develpment of an offshore wind industry in the United States. The strategy calls for 3 GW by 2020, 22 GW by 2030, and 86 GW by 2050 cumulative offshore wind capcity in the central study scenario. With these levels of projected deployment, it is important to understand the life cycle costs for offshore wind in the U.S. This work focuses on the operations and maintenance (O&M) portion of life cycle costs.

2. METHODOLOGY

National Renewable Energy Laboratory (NREL) and Energy Research Centre of the Netherlands (ECN) have teamed to model six potential offshore wind sites in the North Atlantic, Mid-Atlantic, Gulf of Mexico, Pacific, Great Lakes, and Hawaii (Figure 1) using the latest O&M model developed by ECN. Using ECN's O&M model, an optimal O&M strategy is determined for each of the sites and key performance indicators (KPIs) are calculated. The KPIs include O&M cost, accessibility, and wind plant availability. The offshore wind plants in U.S. waters require different O&M strategies due to differences in site conditions (e.g., distance from port) and metocean conditions (e.g. wave height).

The analysis considers four different types of access strategies and two types of large component replacement. Helicopter assistance was modeled for each of the four access strategies to determine if further O&M cost reductions could be obtained.

The four access stategies include:

1. Crew Transfer Vessel (CTV): typical vessel used to transport technicians from the O&M port to the wind site for inspection and small repairs;
2. Advanced CTV: faster more capable vessel of operating in higher sea states than the standard CTV;
3. Surface Effect Ship (SES): vessel with an integrated air cushion to handle harsher sea states than the advanced CTV and can reach higher tranport speeds; and,
4. Service Operations Vessel (SOV): large vessel that is designed to sustain long periods of time out at sea in harsh sea conditions while hosting a high number of technicians.

The two large turbine component replacement strategies include:

1. In situ strategy: where a jackup repair vessel conducts the large component repair/replacement at the turbine location (used for fixed-bottom substructures), and
2. Tow to shore strategy: where large component repair/replacement is conducted port side by towing the turbine from its moored location to the O&M port (used for floating substructures).

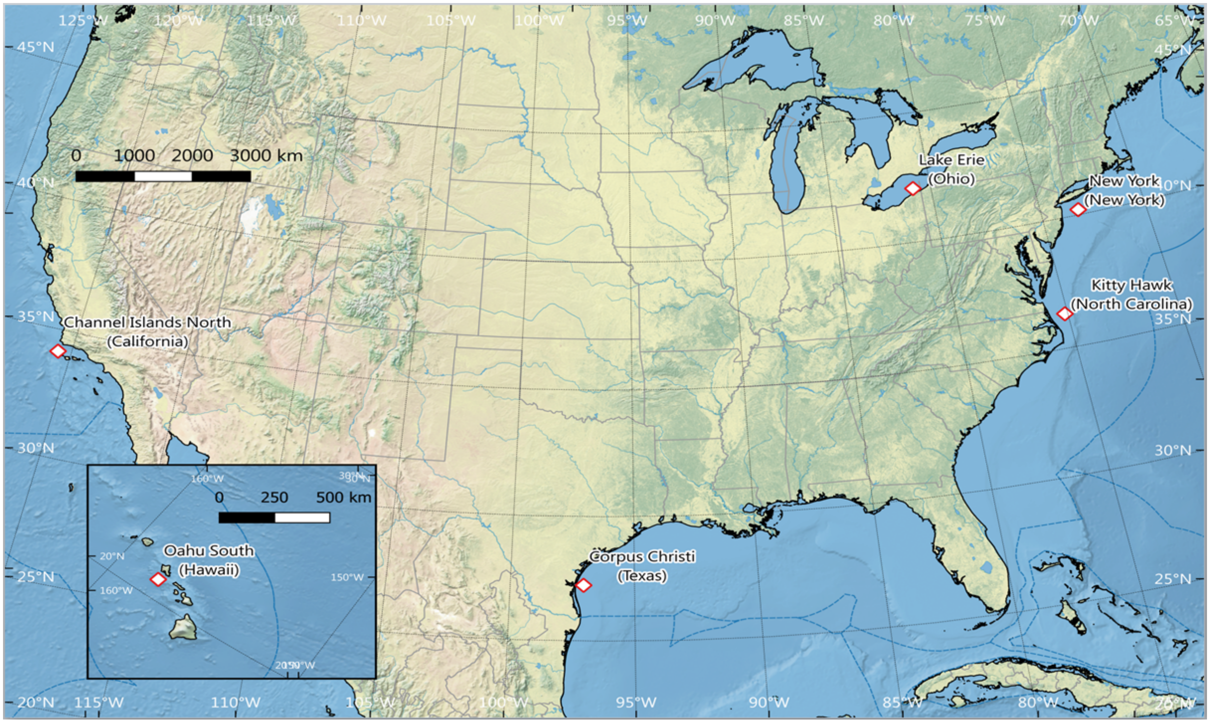

Figure 1. Map of U.S. sites and their optimal O&M strategy [2]

3. RESULTS

Preliminary estimated O&M costs, availability, and identified O&M strategy for each of the six U.S. offshore site are summarized in Table 1.

Table 1. Summary of Results for Six U.S. Offshore Sites

U.S. Site Name	*Optimal O&M Strategy*	*O&M Cost ($cent/kWh)*	*Availability in Time (%)*
North Atlantic, New York	SES	1.94	95.1
Mid-Atlantic, Kitty Hawk	SOV	2.34	95.7
Gulf of Mexico, Galviston	SES	1.82	95.3
Great Lakes, Lake Erie	CTV + Helicopter	4.27	93.0
Pacific, Southern California	SOV	1.31	95.2
Hawaii, Oahu	Advanced CTV	1.35	96.0

4. CONCLUSIONS

Each of the six wind sites selected for the U.S. have different site characteristics and metocean conditions that drive the selection of an optimal O&M strategy. A description of the optimal O&M strategy and the factors driving it are described for each of the six sites.

North Atlantic
The surface effect ship (SES) is the most cost effective O&M strategy for the North Atlantic site. Since the distance from the O&M port to the offshore wind plant is about 70 km a vessel with a fast transit speed is required to transport technicians for maintenance activities. A standard crew transfer vessel (CTV) does not have a fast enough transport speed and would have increased time at sea for technician transport and higher O&M cost.

Mid-Atlantic
The Mid-Atlantic site is around 143 km from the O&M port. This large distance translates to about 4.5 hours of tranport time (one way) for technicians to reach the site using an SES. Therefore, the Service Operations Vessel (SOV) strategy is considered. Since the SOV resides at sea near the wind plant the high travel time is reduced. While the costs for the SES and SOV strategies are similar the well being of the technicians are considered so the SOV is more suited for this site.

Gulf of Mexico
The Gulf of Mexico site tends to be milder metocean conditions. A standard CTV is capable of transporting crew under these conditions. However, since the site in the Gulf is 60 km from shore, the faster SES results in lower O&M costs.

Great Lakes
One unique characteristic of the Great Lakes is the tendency of the fresh water to form ice during the winter months. Hence, the great lakes result in higher O&M cost than the other sites considered. This impacts the ability for technicians to get to a down turbine in th winter and reduces the energy production of the wind plant. One solution to this is a combination of a standard CTV (since the metocean condition is mild and the site is not far from the O&M port) used to transport technicians during the times when ice is not present on the lake and a helicopter for times when a CTV cannot tranport technicians.

Pacific
The water depth in the Pacific exceed the capabilities of fixed-bottom substructrue technology; therefore, the turbines are placed on floating substructures. If the turbine requires a large component repair or replacement the turbine is assumed to be towed back to the O&M port for the repair. The severe metocean conditions (i.e., average significant wave height 2.3 m) nearly exceed the wave limit of an SES and the long distance from the O&M port (i.e., 127 km) introduce long transport times. The SOV strategy is optimal considering the well being of the technician and harsh sea conditions.

Hawaii
The offshore coast of Hawaii have deeper waters and requires floating substructures. Therefore, large componant repairs or replacements are done by towing the turbine from the site to the O&M port. The O&M port is located 30 km from the wind plant and the metocian

conditions are considered to be moderate; hence, an advanced CTV strategy for small repairs and inspections of the turbines is most cost effective and results in the highest wind plant availability.

A summary of the optimized O&M strategy for the six sites are shown in Figure 2.

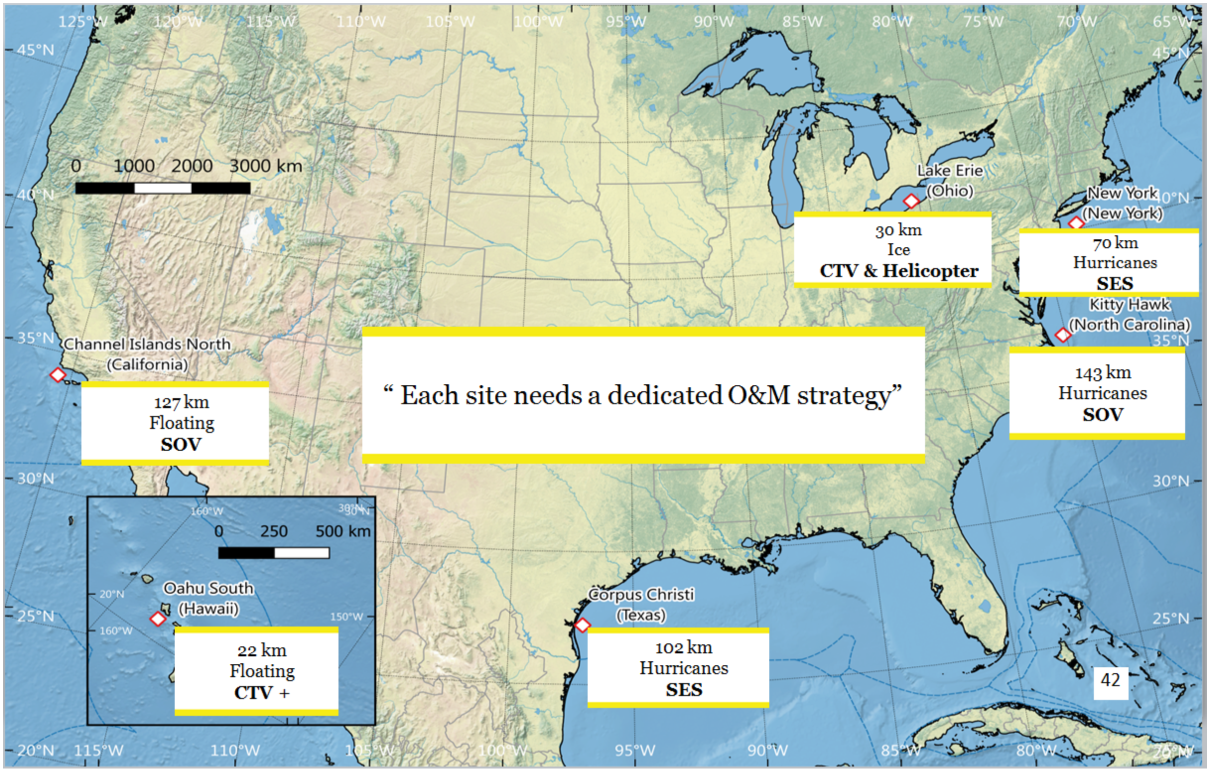

Figure 2. Map of U.S. sites and their optimal O&M strategy [2]

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Cost Reductions for Offshore Wind Plants through Structural Health and Prognostics Management

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[1]*Wind Energy Technologies Department, Sandia National Laboratories, Albuquerque, NM, USA*
[*]Corresponding author: dgriffi@sandia.gov

Keywords: structural health monitoring, condition based monitoring, prognostics health management, offshore wind energy, wind turbine blade, smart loads management

1. INTRODUCTION

One of the key challenges facing the wind energy industry is to develop reliable methods to detect damage in the rotor blades and to detect them early enough to impact operations and repair/maintenance decisions leading to optimized revenues – through reduced costs and increased energy capture. To address this challenge, Sandia National Laboratories has been performing research in the areas of structural health monitoring (SHM) and prognostics management. A particular motivation for this research, when considering siting in the offshore environment, is to address unique environmental conditions to mitigate the large rise in costs for offshore operations and maintenance (O&M) due to accessibility difficulty, weather, high sea states, etc. (which are illustrated in Figure 1). Through a combined application of structural health monitoring and prognostics management, multiple cost reductions are achievable including reduced O&M costs, improved wind-plant reliability, and increased energy capture – all targeted to reduce levelized cost of energy (LCOE).


Figure 1. Illustration of Offshore Wind Accessibility Challenges (Weather, High Sea States and Remote Access) that Motivate the Need for Structural Health & Prognostics Management

2. TECHNICAL APPROACH

The Sandia research program (funded by the US Department of Energy's Wind & Water Power Technologies Office) was implemented over multiple years, from 2011 to 2015, as described in the following paragraphs.

In the first year, 2011, the technical approach was to identify the major causes of turbine downtime in the rotor and then perform a simulation of damage case study for one type of damage to determine the extent to which blade damage could be detected using sensors and operational monitoring. An initial roadmap for structural health and prognostics management technology was developed and a case study of blade trailing edge disbond damage was analyzed [Refs. 1, 2, 5] to demonstrate the simulation-based approach and illustrate the initial roadmap.

In 2012, additional blade downtime issues (i.e. shear web disbond & rotor imbalance) were identified and evaluated within the established simulation of damage framework [Refs. 3,4,6,7] . In 2012, an updated technology roadmap was produced to map-out the multi-year strategy and objectives for the research. The technical work in 2013 (and continuing to 2014) focused on refined sensitivity of damage studies in the presence of variable inflow conditions to evaluate the viability and robustness of the proposed damage detection strategies in the presence of realistic inflow conditions (i.e. varying wind speeds, turbulence, shear, etc.) [Refs. 10,11, 12]. Inflow variability studies with a probability of detection (POD) analysis were conducted to evaluate and quantify the robustness of the developed damage detection strategies under these realistic and variable inflow conditions.

In addition, in 2014, life extension strategies were investigated – damage mitigation (e.g. mitigation of damage initiation or damage growth) was considered through a smart loads management approach (i.e. controls) [Refs. 8,9,13] for life extension and increase of uptime. A progressive damage model was applied and validated for blade disbonds in the trailing edge and shear web. The impact of derating was quantified by comparing strain energy release rates for normal operation and derated operation. Economic impacts of SHPM were evaluated, with focus on the impact of derating on improving energy capture (or AEP, Annual Energy Production). The variation of AEP with several variables (i.e. seasonal variations in wind resource, derating type, derating level, and site characteristics) was quantified. The analysis was useful to understand the opportunities for increased AEP and the overall economics of derating including the most suitable derating strategy and best derating level as well as the best derating time. As an example to illustrate the potential economic benefit of SHPM-enabled smart loads management, it was found that safely operating a damaged turbine for one week with loads limited to 50% of nominal values (i.e. 50% derating) could increase the AEP by 1-2.5%, a range depending on seasonable wind speeds, versus a one-week maintenance shutdown of the turbine.

In 2015, a comprehensive final report was published [Ref. 11].

3. CONCLUSIONS AND SUMMARY OF MAIN FINDINGS FROM THE SANDIA STRUCTURAL HEALTH AND PROGNOSTICS MANAGEMENT PROGRAM

With the overall goals to significantly reduce O&M costs and increase energy capture, the motivations behind this research were to develop and evaluate new strategies – robust and cost effective structural health and prognostics management (SHPM) strategies that can provide the following features (of varying complexity):

1. to ensure operations in a desired (designed) safe state of health,
2. to aid in planning of maintenance processes versus more costly unplanned servicing,
3. to avoid catastrophic failures through advance warning, and/or
4. to improve energy capture by avoiding unnecessary shutdown and increasing overall plant availability.

These overall goals for cost reduction were addressed specifically through the following main findings and contributions of this research program, which are documented in Reference 11. The principal contributions are:

1. A Comprehensive Technical Roadmap for SHPM Technology was Developed
2. A Multi-scale Damage Modeling and Simulation Methodology was Developed
3. Damage Detection Strategies Using Onboard Sensing were Developed and Simulated for Common Damage Types
4. The State of Health of Damaged Turbines was Assessed
5. Damage Models for Wind Turbine Blade Analysis were Improved
6. Smart Loads Management (e.g. Derating, Damage Mitigating Controls) were Proposed and Demonstrated
7. Optimized Maintenance Process Concepts were Proposed
8. SHPM Economics Analysis Based on Smart Loads Management was Performed
9. Damage Detection Strategies were Tested under Realistic & Variable Inflow Conditions including a Probability of Detection Study
10. A Framework for SHPM Decision-making was Proposed.

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Drill String Dynamics and Uncertainties

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Corresponding author: tritto@mecanica.ufrj.br

Keywords: drill string nonlinear dynamics, stochastic modeling, uncertainty quantification

The drill-string dynamic problem considers many physical aspects, such as bit–rock interaction, fluid-structure interaction, geometric nonlinearity, impact and rubbing, model and parameter uncertainties, and rigid body motions. In addition, from the economic perspective, it is very important to understand the drill-string dynamics for prognostics and healthy management. For instance: (a) mitigation of undesirable vibrations to avoid failures (environmental included), and (b) optimization of the system's performance. A computational model for the drill string must include the main forces acting on the system, which depend on the type of formation, type of bit, etc.

This paper tackles the drill-string dynamic modeling and simulation, including stochastic analysis for vertical [1-9,11-15] and horizontal rigs [10,16]. A complete model [9] considers axial, lateral, and torsional vibrations; nonlinear bit-rock interaction; impact; and fluid-structure interaction.

Uncertainties are taken into account both for the system parameters and the bit-rock interaction model [7-13]. Strategies for stochastic identification [9] (including the Bayesian approach [11]) and robust optimization [8] are presented. Finally, field data of a 5 km drill-string [12] is used to (a) partially validate the torsional vibration model and (b) identify a proposed stochastic model for the nonlinear bit-rock interaction.

The above models might be used for prognostic and health management. It is common to use the stability map [12], with controlled parameters (a) weight-on-bit and (b) top speed, to avoid a combination of parameters that leads to an unstable regime. Also, given a bad operation condition, where there are stick-slip oscillations, for instance, one should apply a strategy to mitigate these undesirable conditions [1-2].

The drill-string stochastic dynamics is depicted in many forms; nevertheless, there are still many aspects to explore in this nonlinear dynamical model.

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Next Generation Smart, State-Aware Materials for Enabling Prognostic Health Management

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Keywords: Smart materials, nanoparticles, photoluminescence, material state monitoring

1. INTRODUCTION

There is a trend in the research community that is reflected in Table 1, which was built using data from Google Scholar from 1980 to 2015. This data focuses on structural systems as a subset of engineered systems. In the early part of this time period, the data shows the emphasis in research was on *observing* structures – i.e., structural monitoring. Observations included operational loading and environmental conditions [1]. As time has progressed, the emphasis of the research community shifted from *observing* to *understanding* the condition of the structure – i.e., structural health monitoring. This trend has been driven by the needs of stakeholders – owners and operators of infrastructure who have defined their needs around decisions about cost, safety, etc. The process of structural health monitoring can be described as a process in pattern recognition (see Farrar and Worden [2]). Building from observing to understanding structures, the most recent trend is towards developing *awareness* that extends into the future for prognosis of structural health [3]. This abstract discusses a next generation smart, state-aware material that aims to enable prognostic health management in this way.

Table 1. Comparison of Structural Monitoring, Structural Health Monitoring and Prognostics Health Management (Google Scholar trends in the literature from 1980 to 2015).

Dates	Structural Monitoring	Structural Health Monitoring	Prognostic Health Management
1980-1990	374	259	24
1980-1995	859	768	38
1980-2000	1870	2610	116
1980-2005	4120	10400	463

1980-2010	9120	22100	2230
1980-2015	15900	55400	9390

2. METHODOLOGY

As the trend in Table 1 has played out, the need has emerged for enhanced sensing capabilities that reduce the dependence on external sources of power, extensive wiring harnesses, and complex algorithms for interpreting sensor signals. A method for enhanced sensing is proposed herein that leverages ultra-small white light emitting CdSe quantum dots to achieve photoluminescent smart materials with state-aware characteristics. These quantum dots were synthesized as in previous studies by the authors [4]. Both bulk and surface coated specimens were fabricated. These specimens were fabricated by forming a layer of epoxy mixed with CdSe solution containing 1% by weight of quantum dots on an aluminum flat bar. The specimens were cured overnight in an oven at 70°C under a vacuum.

3. RESULTS

As described in [5], tensile tests were performed on the specimens coated with epoxy encapsulated with white light emitting quantum dots. The coating was excited with a 20mW laser, and emission data was acquired using a CDS 600 CCD-based spectrometer. Figure 1 shows that as external load is applied to the tensile specimens, the spectral emission is thought to result in the removal of surface ligands in the quantum dots, quenching their emission. Surface ligands would be broken as strain occurs across the interface between the epoxy matrix and the quantum dots.

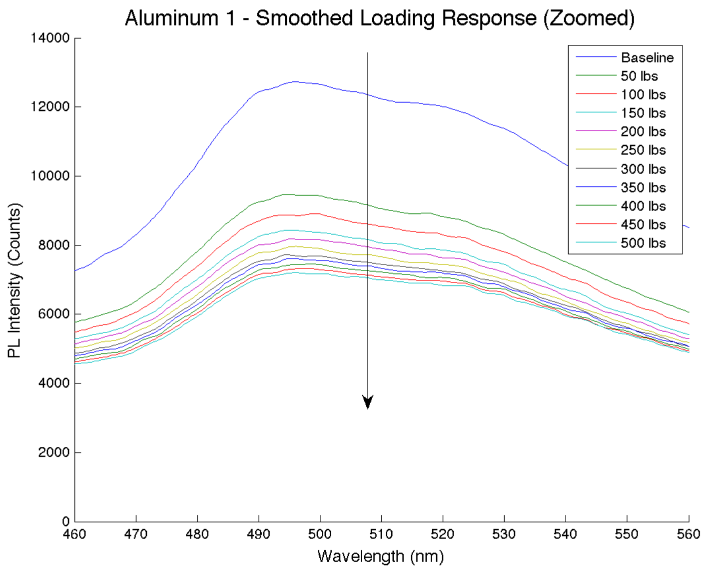

Figure 1. Photoluminscent emission measured on surface of specimen coated with epoxy containing quantum dots under tensile load suggesting quenching of emission (result in [5]).

4. CONCLUSIONS

The ability to incorporate and utilize nanomaterials to realize next generation smart, state-aware materials to enable prognostic health management was discussed through an illustrative example involving tensile specimens with surface coatings containing quantum dots. By encapsulating nanomaterials in precursor filaments, the ability to 3D print a new generation of such smart materials has also been demonstrated subsequently. By harnessing the unique characteristics of quantum dots, this research is demonstrating that such smart materials could potentially be used to achieve structural state awareness through their optical properties.

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Location of Impacts on Composite Plates via Piezoelectric Rosettes

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Keywords: Impact location, structural health monitoring, composite materials, piezoelectric rosettes.

1. INTRODUCTION

Composite materials have become widely used in many areas of engineering, including aerospace, marine, automotive, railway and sports industries. They are a material of choice in light-weight applications, due to their high strength to weight and stiffness to weight ratio. The major drawback of composite materials is their susceptibility to impact damage. Impacts can occur from many sources. For instance, in the aerospace scenario, it could be caused by the drop of a hand tool on a wing, collision with birds, foreign object debris or even impacts with ground support equipment. Such damage can be barely visible and may go undetected, but its effect on the degradation of the composite structure strength can be dramatic [1].

In the efforts to characterize such eventual damage, when the existence and position of an impact event is known with a certain precision, the inspection of the laminate can be limited to this region and may significantly reduce the complexity of a damage identification problem [2]. Traditionally, impact location is based on the time-of-flight (TOF) triangulation of wave measurements taken at multiple receiving points [3]. However, it requires knowledge of the wave velocity in the test material, used to translate arrival time measurements into source location. This becomes a limitation when monitoring anisotropic structures, where the velocity is dependent upon propagation direction.

Another approach, based on PZT rosettes was proposed and demonstrated earlier for pencil-lead breaks on small composite panels [4] and on damage progression monitoring in a composite aerospace panel [5]. The rosettes exploit the highly directional response of macro-fiber composites piezoelectric patches (MFC) to obtain the direction of incoming waves, essentially like a dynamic version of the electrical resistance strain gages (ERSG) rosette. Since no wave velocity information or complex modelling is required, the technique is very suitable for impact and acoustic emission (AE) location on anisotropic and complex structures. This article extends the study to low-velocity impacts carried on by a hand-held hammer, simulating realistic impacts suffered by an in-service structure.

2. METHODOLOGY

Considering a rectangular MFC-P2 sensor (Smart Material Corportation, Sarasota, FL) with dimensions *l* x *b*, as shown in Figure 1(a), the strain field from the incoming AE wave, *S*, can be divided into a longitudinal sensitivity factor, *S1*, and a transverse sensitivity factor, *S2*:

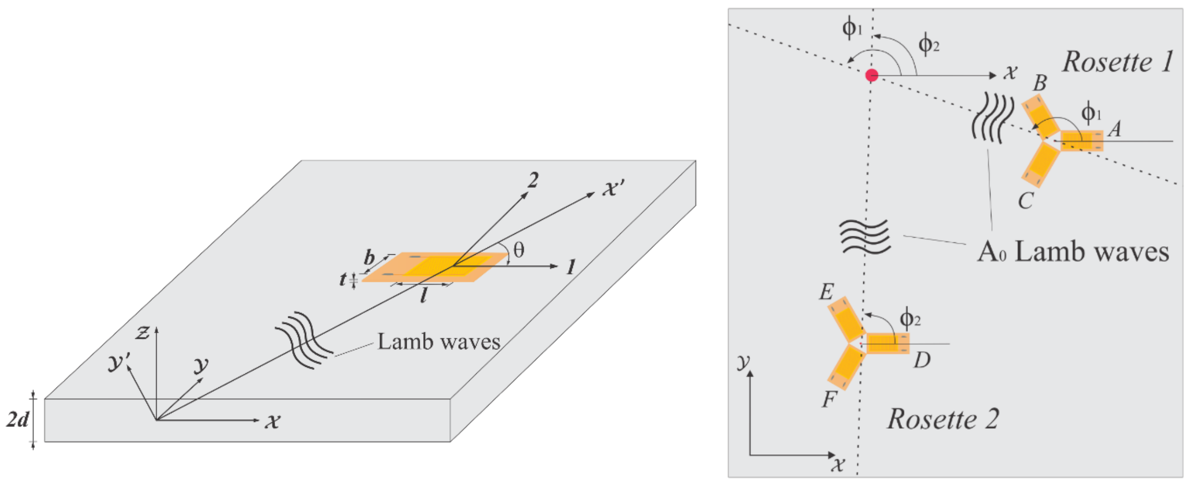
$$S \approx S_1 \cos^2\theta + S_2 \sin^2\theta \tag{1}$$

where θ is the wave propagation direction relative to the sensor's lengthwise direction. The longitudinal and transverse sensitivity factors are defined for waves propagating along the sensors's lengthwise and widthwise directions, respectively, given by [4]:

$$S_1 = S\big|_{\theta=0^\circ} = \frac{2t(d_{31}E_1 + d_{32}\nu_{12}E_2)\sin\left(\frac{kl}{2}\right)}{lk\left[(1-\nu_{21}\nu_{12})e_{33}^{\sigma} - (d_{31}^2E_1 + 2d_{31}d_{32}\nu_{12}E_2 + d_{32}^2E_2\right]} \quad \text{(2-a)}$$

$$S_2 = S\big|_{\theta=90^\circ} = \frac{2t(d_{31}\nu_{12}E_2 + d_{32}E_2)\sin\left(\frac{kb}{2}\right)}{bk\left[(1-\nu_{21}\nu_{12})e_{33}^{\sigma} - (d_{31}^2E_1 + 2d_{31}d_{32}\nu_{12}E_2 + d_{32}^2E_2\right]} \quad \text{(2-b)}$$

where *d31* and *d32* are the sensor's piezoelectric constants, *E1* and *E2* are the sensor's in-plane Young's moduli along the 1 and 2 directions, *v12* and *v21* are the respective Poisson's ratios. *e33σ* is the sensor's dielectric permitivity along the throush-thickness electrical poling direction, *t* is the sensor's thickness and *k* is the AE wavenumber.



(a) (b)

Figure 1. (a) General oblique incidence of Lamb waves in a MFC sensor. (b) Concept of piezoelectric rosettes computing the principal strain angles of the wave.

Equation (1) allows the construction of a dynamic rosette, using at least 3 MFC sensors[4]. Using conventional ERSG rosette reduction equations for principal strain direction, each rosette yelds the principal strain angle of the incoming wave, ϕ, as a function of the Cartesian strain components, where

$$\tan(2\phi) = \frac{\gamma_{xy}}{\varepsilon_{xx} - \varepsilon_{yy}} \qquad (3)$$

Evaluation of the source location in a plane is readly achieved by the intersection of the principal directions determined by at least two rosettes, as shown in Figure 1(b).

A carbon fiber reinforced polymer (CFRP) plate with 13 plain-weave layers stacked in a [0°,90°] sequence, with dimensions 1060x1100x2mm was used for the experiment. Two, three-element MFC rosettes (model M-2814-P2), arranged in a delta orientation were surface-bonded to the composite plate. The impacts were non-destructive and carried out manually (different forces applied) using a small hammer with a hardened metal tip. A National Instruments USB-6251 device was used for the data acquisition, with a sampling rate of 100kHz per channel. The sampled sensor's signals were stored and processed afterwards, using a MATLAB® code developed by the authors.

3. RESULTS

The results of the impact tests are summarized in Figure 2. The actual impact location is represented by filled blue circles, while the predicted impact location is represented by unfilled pink circles.

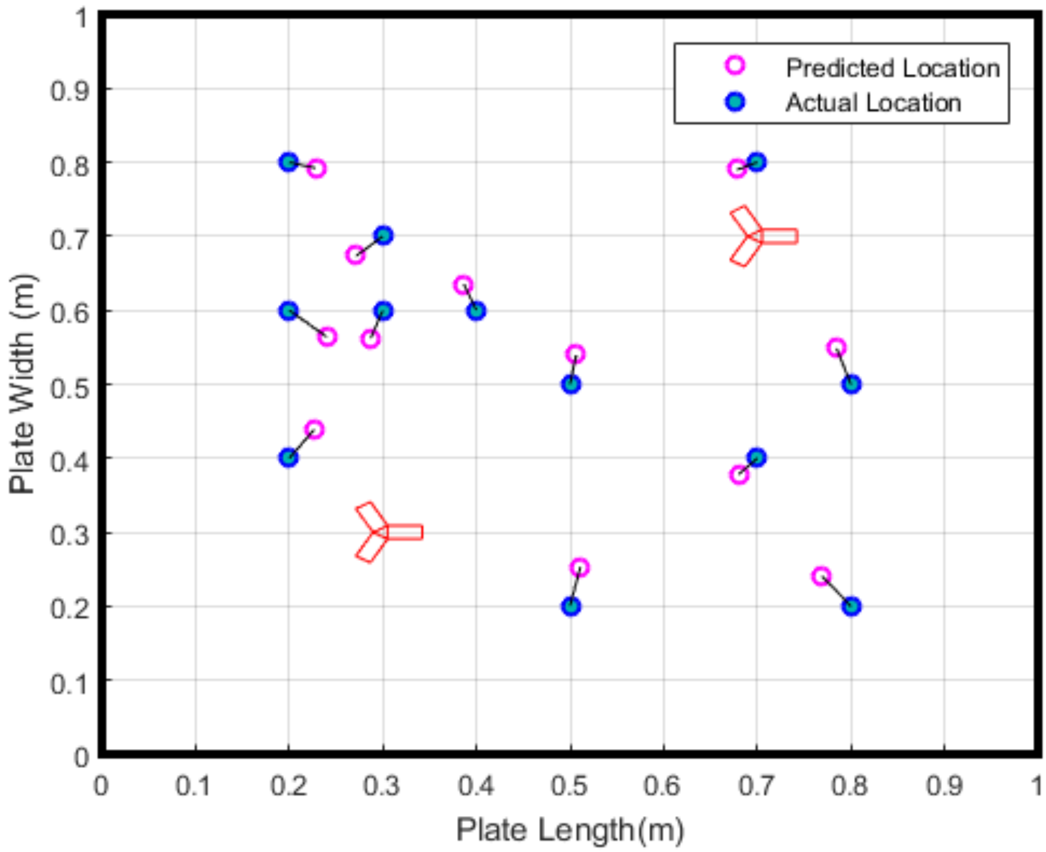


Figure 2. Results of the impact location from MFC rosettes measurements.

The error was calculated for each impact using Equation (4):

$$Error=xactual-xpredicted2+yactual-ypredicted2 \quad (4)$$

The average location error, based on 12 impacts, was of 41.44mm, with an average impact location error of 4.1%, which can be considered very satisfactory for a composite plate.

4. CONCLUSIONS

This study has shown that the piezoelectric rosettes technique using MFC transducers offers good results locating low-velocities impacts in a composite structure, with an average location error of 4.1%. On the experimental setup, the rosettes were approximately 565mm apart, which is a much greater distance than used in previous experiments carried on using the same technique [4,5]. Also, increased accuracy of the impact location can be achieved using additional rosettes, which provide additional information.

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Performance Analysis of a Multi Degree of Freedom Piezoelastic Energy Harvester from Structural Vibrations

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Keywords: Piezoelectric Energy Harvesting, Structural Vibrations, Harvesting Efficiency

1. INTRODUCTION

Recent technological developments have increased the demand for alternative energy sources to power electronic devices for a large variety of applications ranging from aerospace systems and civil engineering structures up to micro-electromechanical systems. In this context, novel methods of electrical energy generation from a large variety of natural phenomena have been widely investigated in the past decades, a process that, in general can be referred to as energy harvesting [1]. In the particular case where the energy source consists of structural vibration signals coming from environmental sources, the use of piezoelectric materials have been extensively used in the mechanical to electrical conversion process, commonly referred to as piezoelectric vibration energy harvesting.

Commonly employed energy harvesting methods use mechanically resonant devices to increase the amount of usable electrical energy in the conversion process such as the well known cantilever beam model [1,5]. A crucial issue in the harvester's design is the need for tuning of the harvester's to the input frequency of the acquired vibration signal. Several methods have been recently proposed to increase and optimize the frequency bandwidth of cantilever based energy harvesters operating in the vicinity of the fundamental resonant mode of vibration [1,5], as well as in multi-degree of freedom (MDOF) models [2,4].

The main goal of this article is to assess the performance of a MDOF piezoelastic energy harvester composed by a combination of beam segments partially covered with piezoceramic layers and connected by lumped masses forming an L-shape structure. Numerical and experimental results indicate that different output voltages are obtained for the proposed device when different design configurations are considered. Particular geometric configurations of the harvester may exhibit modal interactions between commensurable natural frequencies as previously observed [3] thus enhancing the energy generation capabilities of the harvesting system.

2. METHODOLOGY

In the present section main theoretical and experimental aspects of the energy harvesting system studied are summarized. Figure 1 depicts the proposed harvester physical model that consists of two slender beams carrying lumped masses (M_1 and M_2) and connected in a L-shape geometry. The proposed geometric arrangement shown in Fig. 1 is similar to [2] and inspired in the previous work by Haddow [1], except that in this case purely mechanical linear and nonlinear dynamic characteristics were studied. The harvester design proposed shown in Fig. 1 employs segmented piezoelectric layers partially covering one (unimorph) or two (bimorph) surfaces of each beam segment according to the specified locations (P_1, P_2, and P_3, respectively). The lumped mass M_1 is used to connect the horizontal and vertical beam segments. A second lumped mass M_2 is used and its position along the vertical beam span can be varied such that different natural frequencies can be obtained for the energy harvesting system.

The design geometry proposed here has three major advantages: (*i*) Proper design leads to multiple modes of vibration having natural frequencies within the desired frequency range, increasing the tuning capabilities of the device; (ii) For a given geometric configuration optimization techniques can be used [5] to adjust the piezoelectric material and location such that maximum output electrical power generation can be achieved; (iii) The harvester can exhibit linear and nonlinear dynamic behavior depending on the geometric configuration used.

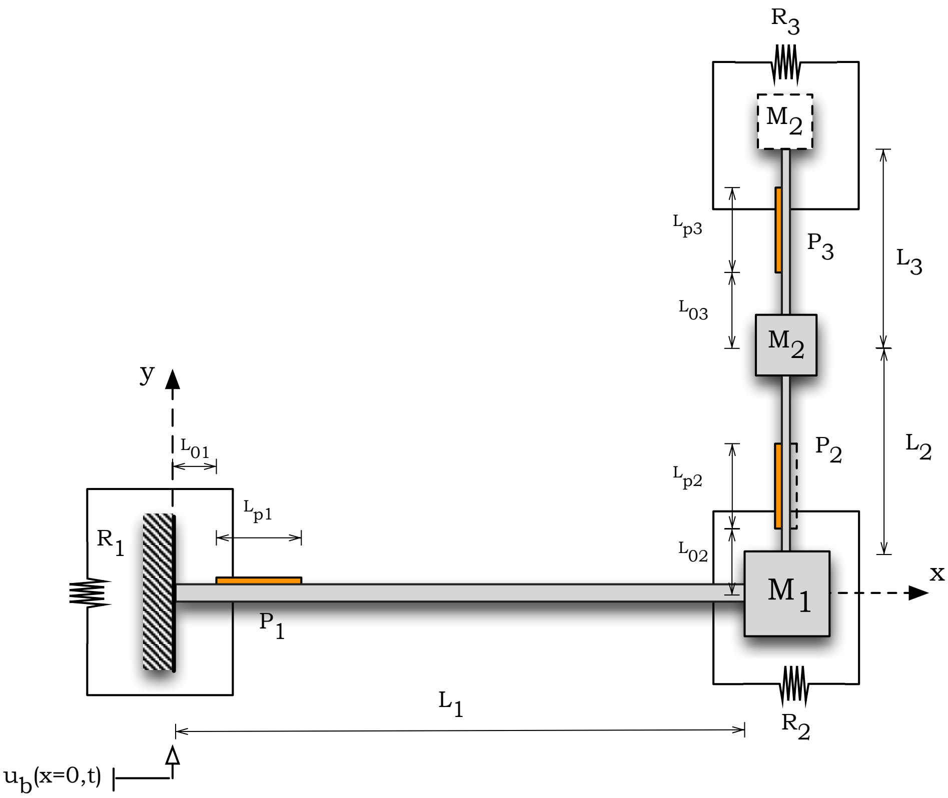

Figure 1. Model of multi-degree of freedom piezoelectric energy harvesting

Following a similar procedure adopted in [2] the frequency domain complex valued output voltages V_k are obtained from the solution of a system of linear equations in the frequency domain for each value of the excitation frequency according to

$$\sum_{k=1}^{p} Q_{mk} V_{ak} = P_m \quad m = 1,2,\ldots,p \tag{1}$$

where the complex valued and frequency dependent coefficients Q_{mk} and P_m are obtained from the modal and electric properties of the harvester and it is given as

$$Q_{mk}(\omega) = \frac{1}{R_l} + j\omega\left(C_p\right)_m \delta_{mk} + \sum_{p=1}^{2} \frac{j\omega\psi_{mp}\chi_{kp}}{\omega_p^2 - \omega^2 + j\omega 2\varsigma_p\omega_p\omega} \tag{2}$$

$$P_m = \sum_{p=1}^{2} \frac{j\omega\psi_{mp}\lambda_{kp}}{\omega_p^2 - \omega^2 + j\omega 2\varsigma_p\omega_p\omega} \tag{3}$$

and finally the frequency domain output electric power can be obtained for a unit amplitude input base acceleration signal $u_b(x=0,t)$ from

$$P_l = \frac{|V|^2}{R_l} \tag{4}$$

where R_l is the load resistance. It should be noticed that solution of Eq. 1 gives the output voltage for each individual piezoelectric layer. The total voltage for the harvesting electromechanical circuit can be easily obtained by summing these individual voltages. In this case the mode cancelation phenomenon [2] must be accounted for in evaluating the harvester's dynamic performance.

3. RESULTS

As previously stated, an advantage of using the system shown in Fig. 1 is the fact that by varying the position of mass M_2 along the vertical beam length different natural frequencies can be obtained for the first two modes of vibration of the harvesting system. Hence, the system shown in Fig. 1 is suitable either in running numerical simulations or in an experimental analysis on an actual prototype. In the present work, extensively numerical analysis was performed in MATLAB environment and a comprehensive experimental investigation was conducted on a physical prototype. The L-shaped harvester was manufactured using carbon steel for the beam segments, with lengths of $L_1 = 192$ *mm* and $L_2 = 182$ *mm* for the horizontal and vertical beams and thickness of *1.65 mm* and *2.50 mm*, respectively. The beams were partially covered with piezoelectric patches according to positions P_i ($i=1, \ldots,3$) as shown in Fig. 1. Aluminum rigid blocks were used as lumped masses attached to the beam segments. The harvester was rigidly attached to a clamping device and the assembly was then mounted on the armature of an electromagnetic vibration exciter that was used to simulate the input vibration signal, that in most of the experimental analysis consisted of a broadband random signal. The experiments were conducted for different load resistance values ranging from a very low value of *10 Ω* up to *1 MΩ* in order to simulate the short and open circuit conditions of the electrical harvesting circuit [1].

A sample of the results obtained from the numerical and experimental analysis is shown in Fig. 2. The results depicted here corresponds to two intermediate values of the load resistance R_l=*100 kΩ* and R_l=*500 kΩ*. In both cases the measured voltage transmissibility frequency response function was compared to the corresponding numerically obtained result. Figures 2a and 2b show the corresponding results for signals obtained from the horizontal and vertical beams for one of the geometric configurations investigated. As seen from these results an excellent agreement occurs between measured and calculated signals, indicating that the analytical model developed is suitable for designing of further configuration scenarios of the energy harvesting system.

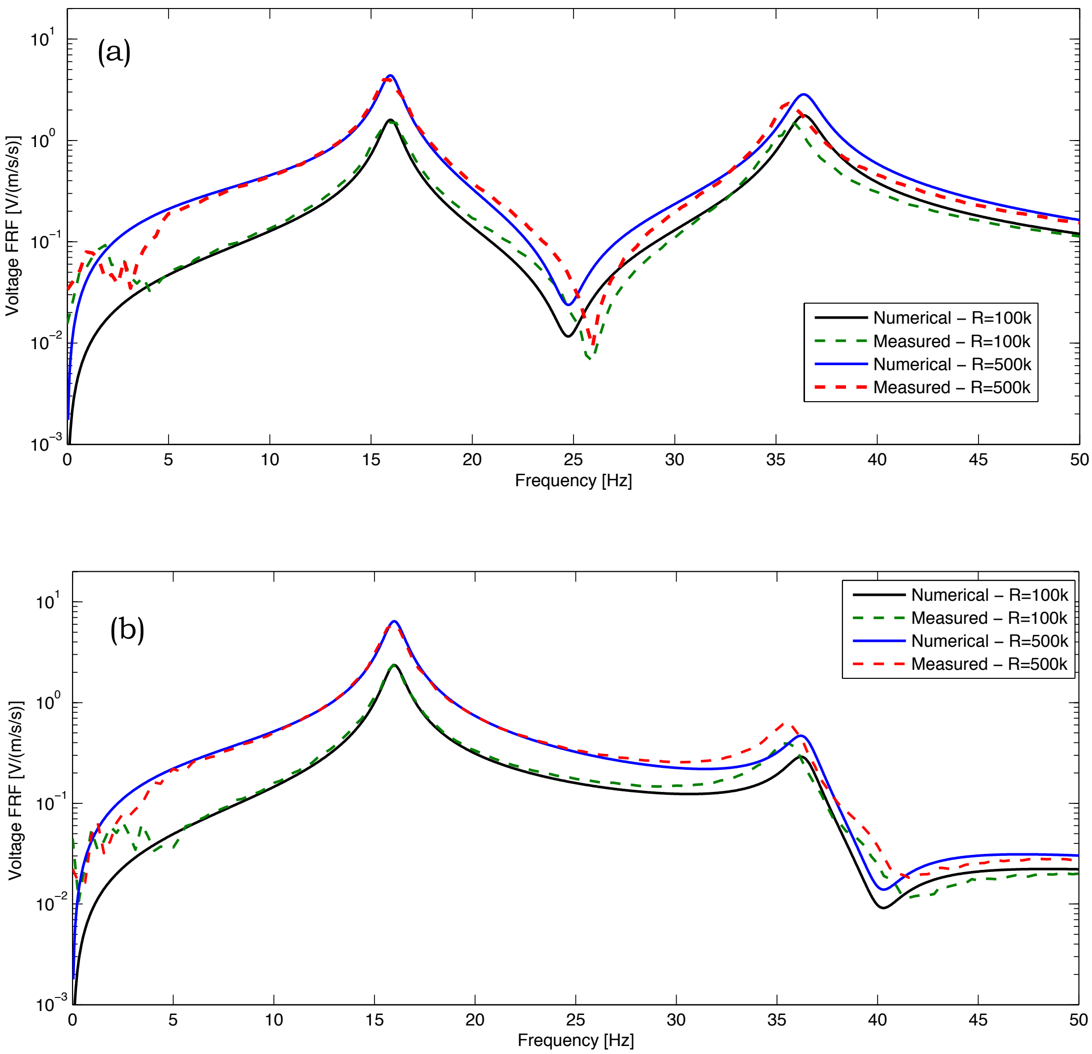

Figure 2. Results from experimental validation of MDOF piezoelectric energy harvesting model: (a) horizontal beam (b) vertical beam

4. CONCLUSIONS

This article explores the dynamic performance of a multi-degree-of-freedom piezoelastic vibration energy harvester. A dynamic model of a L-shaped harvester is studied in either numerical and experimental analysis. The harvester's model was derived such that different harvesting scenarios can be considered from the geometric characteristics and piezoelectric material usage. Numerical simulations were carried out and a physical prototype was constructed and tested. Good agreement was observed between numerical and measured signals for different configurations of the harvesting systems, what include a scenario where the first two natural frequencies are commensurable allowing the harvester to exhibit modal interactions between the corresponding modes of vibration and consequently energy transfer between these modes, thus allowing an extra amount of electrical energy being harvested.

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Time-Frequency MUSIC Beamforming for Nondestructive Evaluations of Shell Structures Using Ultrasonic Lamb Waves

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Keywords: shell structures, nondestructive evaluation, time-frequency MUltiple SIgnal Classification (MUSIC) beamforming, ultrasonic Lamb waves, and ultrasonic piezoelectric sensor/actuator array

1. INTRODUCTION

Guided ultrasonic waves such as Lamb waves in shell structures can propagate long distances with small spatial dissipation rates so that they have gained significant interest for many Non-Destructive Evaluation (NDE) applications. In this NDE application, a Lamb wave can be generated by using a piezoelectric actuator and then propagates in a shell system. When there is a structural defect in the system, the wave is then reflected from the defect. By measuring the reflective waves using an array of ultrasonic piezoelectric sensors, the structural defect location can be identified. The latter procedure can be implemented to scan a large structural area with a relatively small number of the sensors due to the long propagation distance of the guided wave. Recently, acoustic beamforming based NDE procedures have emerged for the applications of "simple" and "ideal" shell structures: e.g., infinite-size and uniform-thickness shell structures. Combined with the Lamb wave excitation, these NDE procedures can scan large areas to identify the locations, shapes, and sizes of structural damages, while most existing NDE procedures require undamaged baseline data or a large number of scanning measurements. However, in a "real" system, high-level waves are reflected from discontinuous features such as reinforced stiffener joints or boundaries. Therefore, it is difficult to apply the existing beamforming based techniques to "real" discontinuous systems.

2. METHODOLOGY

For the purpose of eliminating the effects of direct excitation signals as well as boundary-reflected wave signals, it is proposed to improve a conventional MUSIC beamforming procedure by processing the measured array signals in the time–frequency domain [1]. Figure 1 shows one of the experimental setup to validate the proposed time-frequency beamforming algorithm. In this setup, the cross-shaped array of 21 piezoelectric sensors/actuators was attached on a 2.03 mm thick aluminum panel using superglue. Then, coins were glued on the aluminum panel to simulate structural defects. A burst sinusoidal signal with the center frequency of 20 kHz was used to excite the panel at the array center. Then, the other piezoelectric sensors were used to measure the direct and reflective waves. The other setup with a steel pipe and its results will be presented during the workshop.

3. RESULTS

As shown in Fig. 2, the maximum beamforming power locations at the three different instants match closely with the locations of the simulated structure defects (i.e., the coins).

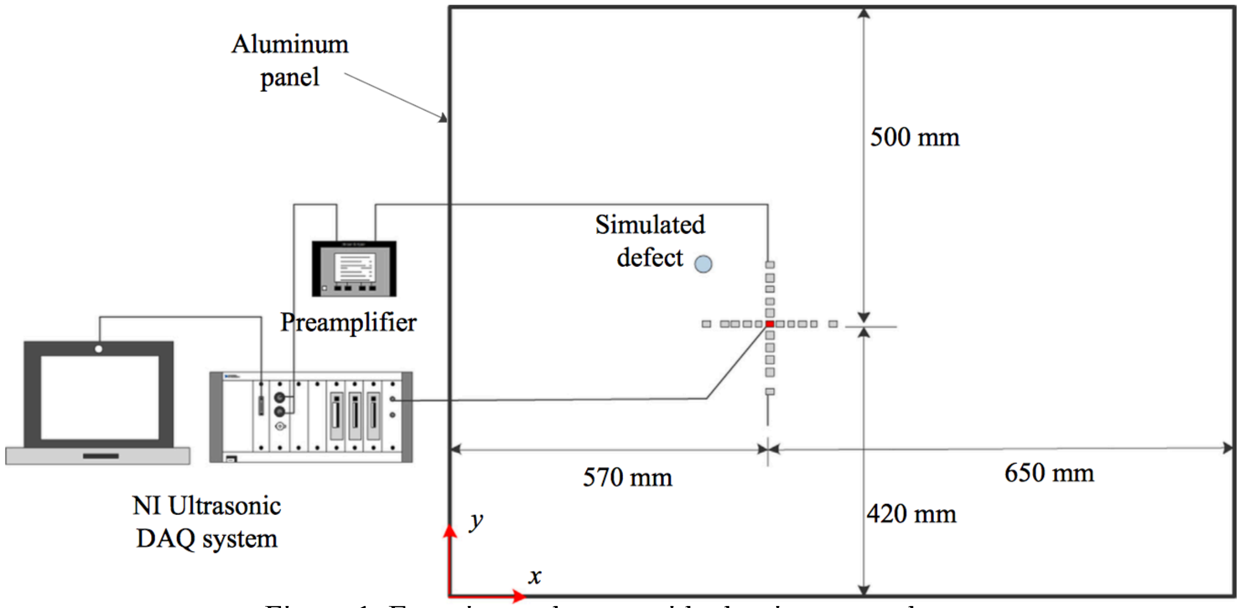

Figure 1. Experimental setup with aluminum panel.

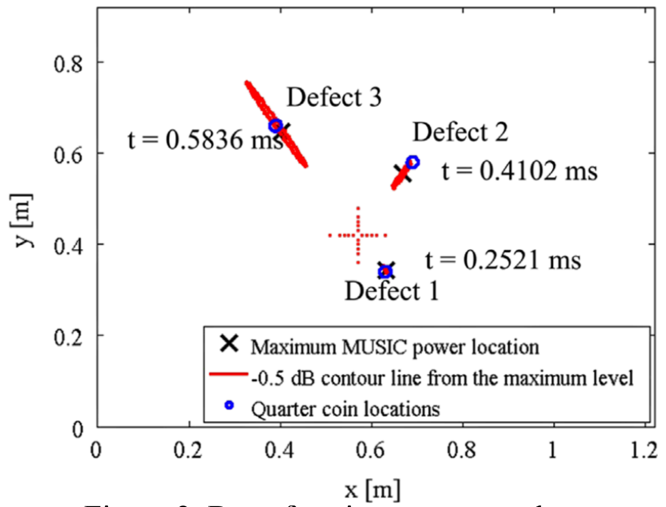

Figure 2. Beamforming power results.

4. CONCLUSIONS

Here, it has been experimentally demonstrated that the proposed time–frequency MUSIC beamforming procedure can be used to identify structural defect locations on the aluminum plate by distinguishing the defect-induced waves from the excitation-generated and boundary-reflected waves.

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Vector-Phase Analysis of Bearing Defect on the Base of Wave Health Monitoring (WHM)

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Keywords: Vector-phase analysis, vibration analysis, Wave Health Monitoring, predictive monitoring

1. INTRODUCTION

Predictive monitoring inevitably deals with strength. Strength is considered by designers on R&D stage. The classical Stress–strain curve based on Hooke's Law links stress to strain and is used to avoid a material reaching a yield point, because after reaching the yield point the structure loses its strength and the failure is about to occur.

Traditional vibration analysis measures strains (deformations) and builds algorithms how to predict the remaining useful life. However, there is one significant drawback of traditional approach: the forces are distributed simultaneously in all directions while single-axis sensors are pre-oriented in some particular direction. The inaccuracy brought by measuring spatial processes with single-axis sensors is multiplied by averaging the real oscillations to obtain some understandable level of signal magnitude. And in the end of the day this information is compared to some statistics-based benchmark to make the decision. This is quite far away from the real processes taking place in the structures.

Some aerospace researchers say, in reality the validity of diagnostics based on vibration analysis is as low as 30 or 40%. Pity, but the more complicated structures will be created the lower will be the method's validity.

The willingness to overcome the main drawbacks of traditional vibration analysis and to raise validity of diagnostics and prognostics was the main driver for the study.

2. METHODOLOGY

The main task in addressing the problem is to introduce on a reasonable basis the corresponding diagnostics parameters for increasing validity of analysis of dynamic condition in terms of spatial stress-and-strain paradigm [1]. The research method (WHM) consists of the following parts:

1. Synchronous capturing of three components of vector of oscillation considering phase shift between them
2. Reconstruction (presenting) of the current spatial stress-strain condition [2] of a structure in a form of a dynamic sequence of phase trajectories
3. Analysis of the spatial phase trajectories (also known as hodographs) for subsequent diagnostics

4. Diagnostics of defects of current operational status based on knowledge about the healthy structure and its potential defects

The phase-sensitive spectrum of measured harmonic oscillations in elastic medium in the form of real trajectories is presented on the figure 1.

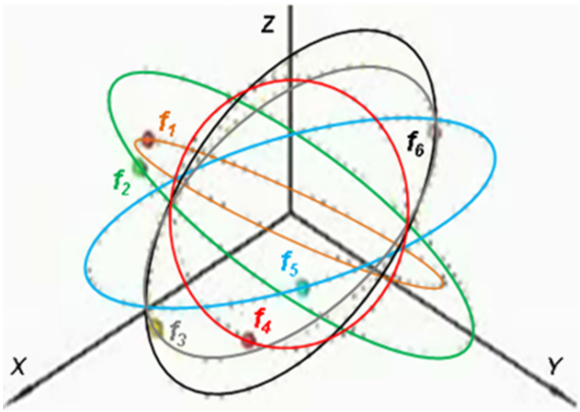

Figure 1. The bunch of six frequencies in the form of spatial phase hodographs' trajectories

The discussed method was applied for a testing of a gas-turbine bearing. The emerging defect of one of the bearing roller was successfully detected and defect development was simulated and observed. The main point of the experiment was to evaluate and compare energetic parameters in the three different modes:

1. Healthy bearing
2. Tiny defect – a 50 µm deep cavern with the areea of 0.5 mm^2 on one of the rollers
3. Developed defect – a 100 µm lateral scratch with the total area of 1.5 mm^2 on one of the rollers

It has been discovered that the most sensitive diagnostics parameter for the particular type of defects is the trend of mechanical energy, see figure 2.

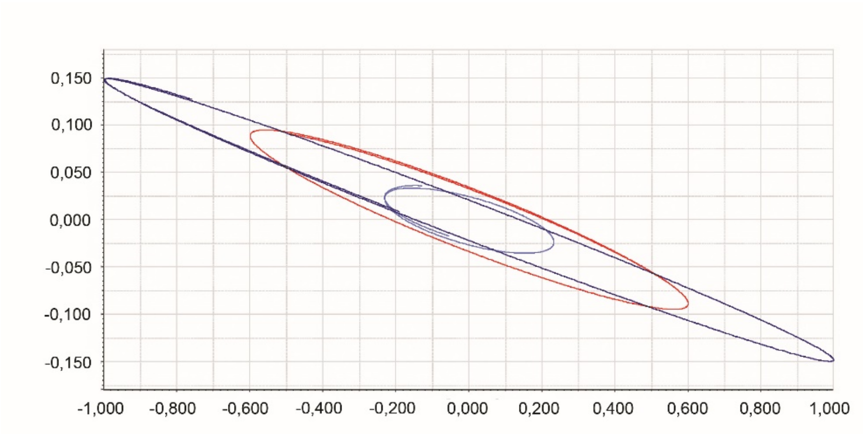

Figure 2. The trajectories of phase hodographs of healthy bearing (light blue), with 50µm cavern (red) and 0.2 mm scratch (dark blue)

3. RESULTS

The standard method of vibration analysis based on amplitude-frequency response failed detecting the first defect. Though, the second defect was detected.

One of the remarkable features of the hodographs is the fact that the area of each hodograph is proportional to the mechanical energy of the oscillation. Mathematically, the area is quadratically dependent on radius, which means the method is quadratically more sensitive comparing to the regular analysis.

Another critical feature of the method is that any point on the hodograph stands for the instantaneous vector of the target point's displacement and therefore, the hodograph's major axis points to the location of the source of the oscillation (excitor).

The method allows to improve noise reduction since noise doesn’t provide elliptical trajectories and therefore the valid signal can be easily filtered out. The mentioned above combination of advantages makes the method very sensitive and valid.

4. CONCLUSIONS

During the experiment it was shown that informative value of the WHM method is significantly higher comparing to the traditional amplitude-frequency approach.

The presented method provides clearer frontier between healthy condition and failure, providing possibility for early fault detection.

The discussed above methods 1-4 provide a perfect ground for the fifth method – prognostics which is developed, yet has not been used during the described test.

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The Importance to Study the Statistical Significance of Wind Turbine Wake States to Improve the RUL and the Prognostics of Wind Turbines Components

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Keywords: wind turbines, wake effect, statistical significance, LIDAR

1. INTRODUCTION

Wind turbines extract kinetic energy of the wind resource to generate electrical energy. A change of the air flow attributes due to turbulence increment is observed downstream the turbine array, besides the wind exiting the turbine contains less kinetic energy. Such effects are called wind turbine wake. Wake effects cause wind energy production losses, but also increase the loads, increasing the unpredicted O&M wind farm. A turbine failure will also impact availability that affects the revenue targets and causes electrical grid instability [1]. Variable inflow and wind turbine operational parameters result in peculiar wind turbine wake states. The impacts and uncertainty of wind turbine wake effect are wide ranging. Wind turbines wakes research are needed to give an opportunity to improve performance, availability and reliability of wind farms. The present work introduces to the Probabilistic Prognostics and Health Management of Energy Systems (PPHMES) field the active TTU research on the wake development of wind turbines to quantify the turbine inflow dynamics with statistically significant data over long periods of time. This work proposes and states the importance of the formulation of a novel methodology to map and to understand the wake instantaneous behavior to reduce the wind turbines prognostics uncertainty related. Further, the present research approach gives an opportunity to develop active wind turbine control strategies, which it will help to extend the remaining use of life (RUL) of wind turbine components.

1.1. The statistical significance of wake states

The literature illustrates that atmospheric stability parameters and turbine settings impact the wind direction and the wind speed variability (turbulence) to the downstream turbines, yet there is no statistically significant data about the exiting wind flow dynamics, the wake states. There is a gap in practical and significantly statistical evidence about the instantaneous characteristics of the wake, which it would help to identify the main parameters responsible for wind turbine loads improving the turbine designs, wind farm sitting, the turbine controls, and the prognostics of a component to failure.
A statistical significance means that a result from an experiment is not likely to occur randomly, but is to be attributable to a specific cause. The literature [1] illustrates a wake is affected by the environmental & site conditions, the boundary layer atmospheric

stratification, and the wind turbine model. Therefore, the present research aims to find the statistical significance of wake states.

2. METHODOLOGY

To enable a statistically-significant description of the wake instantaneous behavior, this work employs an array of five ground-based light detection and ranging (LIDAR) that has been deployed at the U.S. Department of Energy/Sandia National Laboratories Scaled Wind Farm Technology (SWiFT) site located in Lubbock, TX, beginning November 2016, recording measurements every 5 meters, from 20 to 65 m. The SWiFT site consists of three variable-speed variable pitch modified Vestas V27 wind turbines. Each LIDAR also called SPIDAR (Pentalum Technologies) applies the coherence method with 10 degrees' light of sight which makes the measurement profiles obtained at various lateral locations characterizing the wakes instantaneous states in greater detail.

The project is divided in 3 phases [2]. Primary, the objective is to characterize the wind inflow to be compared with a single wind turbine wake data to be collected in the second phase. The configuration will also permit measuring horizontal variability of the inflow. The SpiDAR array was located in front of the chosen turbine for a period of 3 months. Phase 2 is to place the LIDARs in a row behind the turbine at a distance of 4D (108 m), thus the wake instantaneous dynamics will be observed within the response to the changing wind flow conditions and turbine parameters as yaw misalignment and pitch modes. The purpose of Phase 3 is to characterize the turbine wake cross-section at 2D (54 m) downstream with the same goals as phase 2 but an additional to have a comparison with the literature references regarding near and far wake characteristics.

3. RESULTS

The following results are some of the preliminary findings regarding the Phase 1. The goal of this phase is to understand the extent of the inflow variability.

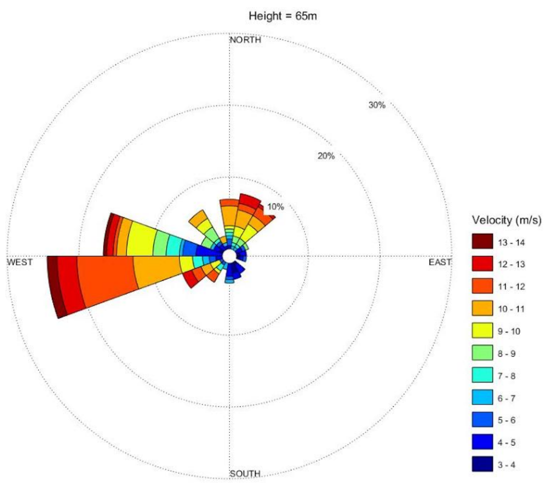

Figure 1. A wind rose with selected heights LIDAR observational data from 12/20/2016 (6:30 pm) to 12/22/2016 (6:30 am)

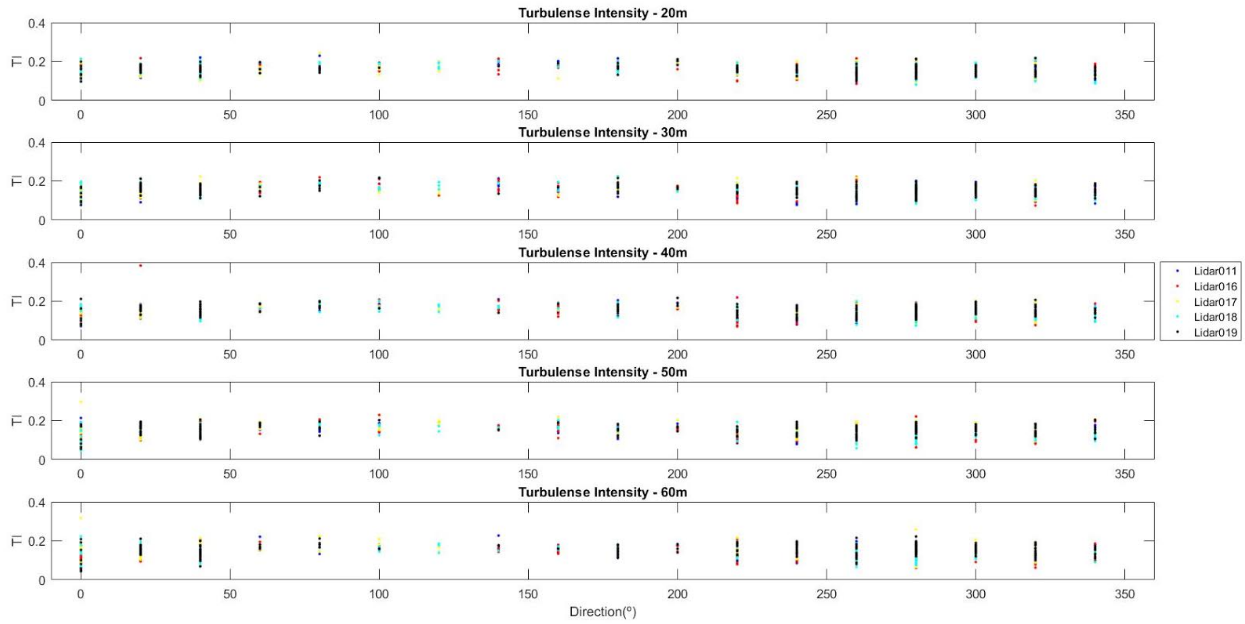

Figure 2. Turbulence intensity – LIDAR array observational data (selected heights) from 12/20/2016 (6:30 pm) to 12/22/2016 (6:30 am)

4. CONCLUSIONS

This work advocates the importance of an innovative approach to measure and quantify wakes states in a statistically significant database that will be beneficial to the wind energy industry. A set of five ground-based LIDAR was deployed at the SWiFT site in November 2016 to perform wind measurements from above, below and across the turbine rotor. The observational data analysis occurs in a conjunction with atmospheric stability conditions and turbine parameters binned appropriately. The preliminary results shown in this work illustrate the research course that will allow to assess the wind turbine wake statistically significance information and its effect on the turbine operation in conjunction with components failure statistics. Furthermore, operational wake control strategies can be developed as a function of the continuously varying inflow by adjusting the turbine parameters to decrease turbine loads.

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Application of Peridynamic

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Keywords: Peridynamic, cracks, numerical methods.

1. INTRODUCTION

This work presents a Peridynamic model that predicts remaining useful life of a beam subjected to vibrations with a crack. The Peridynamic model has been shown to be a promising method to describe crack initiation, growth and propagation on fracture related applications. It has already been applied successfully to model damage problems considering its good accurate predictions on the shape of the crack paths, branching patterns and propagation speed. The main advantages of the Peridynamic model are related with the need to improve PHM techniques in order to reduce costs with unnecessary maintenance procedures and machine downtime; the need to understand the physics of crack propagation better and study its effects on quantification of RUL of system/components subjected to fracture failure; and the need to develop new numerical methods capable to overcome FEM mathematical and computational limitations to model discontinuities such as cracks [1]. In this case, it will be analyzed the problem of a beam to an impulsive force at end. This is a classical problem which the response is known through of the motions equations, considering a homogeneous material. When there is a crack the traditional model do not show in your response the influence of the crack. Thus, it will be used the PD technique to try obtain the real response of the beam.

2. METHODOLOGY

The problem presented by Boubolas et al. [2], considered a two-dimensional straight cantilever beam with a rectangular cross section b x h and length L. A breathing crack of depth *a* exists at position L_c. The crack is located at the upper edge of the beam and forms and angle θ with respect to x axis. An impulsive load is applied transversally at point A.

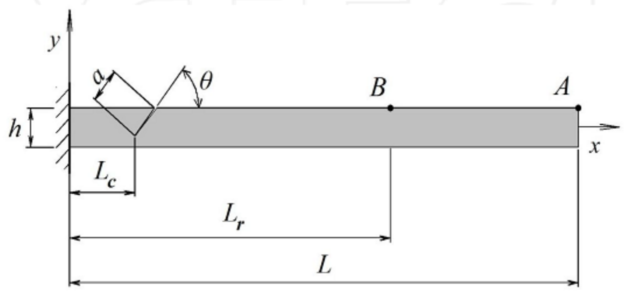

Figure 1 - Cracked two-dimensional beam model (Boubolas et al. [2])

The equilibrium equation governing the dynamic behavior of the model is:

$$M\ddot{u} + C\dot{u} + Ku = R \tag{1}$$

where M , C , and K are the mass, damping, and stiffness matrices, respectively. The time-dependent vectors $\ddot{u}$, $\dot{u}$, u, and R denote the nodal accelerations, velocities, displacements, and external forces, respectively, in terms of a global Cartesian coordinate system x, y . The same problem can be solved by PD theory considering the crack. The PD equation of motion is written as a set of ordinary differential equations for all material points in the system by introducing new fictitious inertia and damping term:

$$D\ddot{u}(X,t) + c\dot{u}(X,t) + ku(X,t) = F(u,u',X,X') \tag{2}$$

where D , C , and K are the mass, damping, and stiffness matrices, respectively. The vectors X and u contain the initial position and displacement of the collocation (material) points, respectively, and they can be expressed as:

$$X = \{X_{(1)}, X_{(2)}, \ldots, X_{(N)}\}^T \tag{3}$$

$$U = \{U(X_{(1)},t) U(X_{(2)},t) \ldots, U(X_{(N)},t)\}^T \tag{4}$$

Where N is the total number of material points in the structure. Finally, the vector F is composed of PD interaction and body forces and its ith component can be expressed as:

$$F_{(i)} = \sum_{j=1}^{N} \left(t_{(i)(j)} - t_{(j)(i)}\right)\left(v_{cj} V_{(j)}\right) + b_{(i)} \tag{5}$$

where $t_{(i)(j)}$ and $t_{(j)(i)}$ are the pairwise force function, [1] which represents the force per unit of volume exerted between the material points inside of the horizon of the peridynamic and b(i) designates a prescribed body-force density field.

3. CONCLUSIONS

Through of the PD theory described by Dias et al., the proposed problem will be solved and it will intend that the PD theory will be interesting tool to identify and to make prognostic to development of the crack. Despite the need of more advances and refinements on PD technique, mainly to deal with more complexes geometries, it will intend to prove that PD is an extremely useful tool on crack modeling, which can be soon incorporated to the PHM routines to determine the remaining useful life (RUL)of systems/components subjected to fatigue loading.

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