Critical, Cost-Effective Wind Blade Inspections Using Autonomous Inspection Systems

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Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.
• Rapid and steady increase in wind power installation

• Critical enablers to improve market competition with other electricity sources - Dept. of Energy Wind Vision Roadmap identifies need for continuing declines in wind power costs (blade availability) and improved reliability

• Increase wind farm availability and lower production costs by reducing unplanned maintenance - requires broader adoption of condition monitoring systems

• Better understanding of harsh environments combined with uncertainties in aging phenomena and Damage Tolerance of blades

• Blade maintenance is now a major issue because: 1) the number and age of wind blades in operation continues to grow, 2) larger blades have increased demand/need for more invasive repairs (vs. replacement), 3) operational loads/environment combined with seeded flaws creates the need for in-service inspections

• Navigant Research estimates the cumulative global revenue for wind turbine inspection services will reach nearly $6 billion annually by 2024.
Create the ability for manufacturers to determine the quality of their product before it leaves the factory & to enhance the in-service inspection of wind blades.

Required Relationship Between Structural Integrity and Inspection Sensitivity

Detectable Flaw Size

Nondestructive Inspection

Need this overlap

Damage Tolerance

Allowable Flaw Size
Inspection Areas and Flaw Types of Interest

Flaws include: Ply Waves, Delaminations, Adhesive Voids, Joint Disbonds, Snowflaking and Porosity.
In-Service Inspection of Blades Including Wind Blade Repairs

Damage Sources -
Installation, Lightning Strike, Impact, Erosion, Overstress, Fatigue, Fabrication-Seeded, Environmental

- In-service NDI can improve blade reliability, minimize blade downtime & extend blade life
- Additional access & deployment challenges
- Post-repair inspections

Skin Laminate Fracture
Demand for More Extensive Wind Blade Repairs Requires Pre- and Post-Repair Inspection

- Requires the means to conduct in-service inspections up-tower
- NDI must go beyond visual surface indications and produce deep, subsurface damage assessments
- NDI must be rapid to minimize blade downtime

Severe Growth of Fiber Fracture

Lightning Strike Damage

Scarfed Blade Repair Process

Drone- and Robot-Deployed NDI Systems
Overcome Inspection Challenges

Want to make NDI easier, quicker, more reliable and more sensitive
MAUS P-E UT with Focused Probe (1 MHz/2") and Adjustable Water Path

New “Immersion” Probe Holder Allows for Adjustable Water Path

REF-STD-6-202-250-SNL-1
Pulse-Echo Inspection of Bond Joint

**A-Scan Signals**

- **Spar Cap - 1**
- **Web Squeeze Out - & 2 4**
- **Web Bond Line - 3**

**Images:**
- Ultrasonic Transducer
- Spar cap back wall
- Web squeeze out back wall
- Web bond line back wall (gate set here)
Sandia has focused on a sealed couplant box that:

- Adjusts to slight curvature in surfaces
-Eliminates water flow to open box
-Maximizes signal strength
-Accommodates necessary standoffs for signal clarity
- Easily saves scanned images for reference using a wheel encoder
Olympus 1.5Mhz, 42 element probe

Dry Fiber Areas

REF-STD-4-135-SNL-1 (wrinkles & dry areas)

Resin Rod Induced Waves
An Experiment to Assess Flaw Detection Performance in Wind Turbine Blades (POD)

Purpose
- Generate industry-wide performance curves to quantify:
  - how well current inspection techniques are able to reliably find flaws in wind turbine blades (industry baseline)
  - the degree of improvements possible through integrating more advanced NDI techniques and procedures.

Expected Results - evaluate performance attributes
1) accuracy & sensitivity (hits, misses, false calls, sizing)
2) versatility, portability, complexity, inspection time
3) produce guideline documents to improve inspections
4) introduce advanced NDI where needed

Ensure representative blade construction and materials
Implementation of Wind POD Experiment

- 11 POD specimens with spar cap and shear web geometry
- Thickness ranges from 0.45” to 2.20” thick (with adhesive bond line)
- Blind experiment: type, location and size of flaws are not know by inspector
- All panels painted with wind turbine blade paint (match inspection surface)
- Performance of NDI – hits, misses, false-calls, flaw sizing, human factors, procedures

Specimens designs applicable to various blade construction

Spar Caps & Shear Web

Box Beam
Wind Blade Flaw Detection Experiment – Individual Inspector and Cumulative POD Comparison

All Panels - Spar Cap with Shear Web and Box Spar Construction Types

Conventional Single Element Pulse-Echo Ultrasonic Inspection Method
Sealed water box and 1.5L16 Phased Array probe was used to detect missing adhesive in bond lines.
Wind Blade In-Service Inspection – Robot-Deployed NDI System

- Automated, remotely-controlled with wireless data transfer to ground station
- Includes Phased Array Ultrasonics for full-penetration damage detection
- Combined with high-fidelity visual inspection using deployed camera
- Real-time health assessment – allows for immediate repairs during a single maintenance stop and rapid return-to-service
- Benefits are escalated for off-shore applications
- Avoid more extensive repairs and even catastrophic blade failures (replacement)
Wind Blade In-Service Inspection – Robot- & Drone-Deployed NDI Systems

- **Goal**: produce a turnkey, automated, remotely-operated inspection system capable of detecting blade damage at all depths (full-penetration) that can rapidly inspect large regions on land-based and offshore wind blades.

- **Benefits**: System will provide cost-effective, routine, surface and subsurface inspections that previously had not been performed and thus, allow blades to reach their design life; accommodate more invasive repairs (post-repair inspection) which will avoid large replacement costs.

- **Background**: U.S. DoE *Wind Vision* roadmap identifies continuing declines in wind power costs and improved reliability will improve market competition with other electricity sources; increased availability (lower production costs) can be achieved by reducing unplanned maintenance through broader deployment of condition monitoring systems.

- **Motivation**: To minimize costly downtime and repair periods and ensure successful functioning of a wind farm, it is necessary to conduct in-service inspections. As the length of blades increase and operational environments produce high stress levels in the blades, it has become increasingly important to detect the onset of damage or the propagation of fabrication defects during blade operation. Detailed NDI is also necessary to firmly establish if repairs are needed and to assess the quality of the repair (post-repair inspections). Small defects can propagate to levels of concern during blade use while fatigue loading, bird/hail impact, lightning strike, erosion and other in-service conditions can lead to new damage in the blades.
Wind Blade In-Service Inspection –
Robot-Deployed NDI System
Component Integration on Robot Superstructure

- DT Black Box for NDI System Data Acquisition
- Lift-Lower Actuator
- Camera for High-Fidelity Visual Inspection & UT Inspection Monitoring
- Raster Arm Stepper Motor (Y-Direction Encoder)
- Water Reservoir for Water Couplant Supply to Shoe
- Raster Arm (Y-direction motion)
- X-Direction Encoder (Robot Motion)
- Spring Loaded for Surface Following
- Water Shoe
- U^T Array Transducer
Wind Blade In-Service Inspection – Robot-Deployed NDI System

Robot increments in small X step and then rastering arm on robot moves DolphiCam head in the Y-direction. Repeat this process to produce a 2-D C-scan.
Wind Blade In-Service Inspection – Robot-Deployed NDI System

Ground Workstation – Data Acquisition & Analysis Plus Control of Robot

Robot Crawling on Vertical Surface

Raster Scan of Area

C-Scan Inspection Image

ON-GROUND ↔ ON-BLADE
Wind Blade In-Service Inspection – Robot-Deployed NDI System

Robot Crawling on Vertical Surface

Raster Scan of Area to Produce C-Scan Inspection Image
Robot-Deployed NDI System – Initial System Validation Testing
Wind Blade In-Service Inspection – Drone-Deployed NDI System
Wind Blade In-Service Inspection – Drone-Deployed NDI System

Thermography Inspection of Subsurface Flaws

Flir IR Camera
(320 X 256 pixels)

LiDAR and GPS Sensors & Computer for Automated Drone Controls

Visual Inspection of Surface Flaws

Digital Camera

LiPo Batteries
Wind Blade In-Service Inspection – Drone-Deployed NDI System

Solar Radiation Thermography

- Heating: Blades Facing Sun
- Cooling: Blades Facing Away from Sun

Foam Core with Fiberglass Skin

Thick Fiberglass Spar Cap

- .330" Deep Flaws Clearly Visible
- .660" Deep Flaws Barely Visible

IR Images of Engineered Damage

Heating Duration: 60s

Heating Duration: 120s
Decrease in Annual Energy Production vs. Mean Wind Speed

Using LiDAR sensors to measure leading edge erosion, predict AEP loss, and provide guidance on performing erosion repairs

Example of Multiple and Single LiDAR Returns
(http://gisgeography.com/lidar-light-detection-and-ranging)

Erosion Example
Wind Blade In-Service Inspection – Drone-Deployed LiDAR and IR Camera Integration

Use NASA’s SuperResolution Algorithm to Process Data

Increase LiDAR Resolution

Measure Relative Changes in 6 DOF state vector

Enables the use of low weight, low resolution solid-state LiDAR sensors to measure IR data at an area of interest over time.

Temperature vs. Time history is needed to use Thermal Wave Imaging's TSR algorithm.
The goal is to produce an automated Damage Assessment and Maintenance Plan with actionable recommendations for Owner/Operators.

Establish Damage Severity Levels:
- **High**: LE erosion has penetrated into the blade structure exposing the underlying laminate of the leading edge.
- **Medium**: LE erosion has removed the protective gelcoat and begun to penetrate into the bond and had exposed the underlying laminate of the leading edge.
- **Low**: LE erosion has removed the protective gelcoat and begun to minimally penetrate into the bond.
- **Minimal**: LE erosion has begun and appears to be superficially limited to the outer protective gelcoat.

Use Image Augmentation Techniques to Increase the Size of the Training Set.

Train and Validate Damage Classification Neural Network.

Next Phase: Add NDI methods to develop a more advanced damage classification system.

Challenge: Acquiring enough images of damage to create a strong training set.
Wind Blade Flaw Detection Needs – Role of Inspection in Production and Operation

- **Need for accurate NDI** becomes more important as the cost per blade, and lost revenue from downtime, grows

- **Many Inspection Challenges** - very thick and attentive spar cap structures, porous bond lines, varying core material & different manuf./in-service defects

- **NDI Practices Vary Widely** – differing levels of rigor & methods used

- **In-Service Inspection Needs** - damage from transportation, installation, stress, erosion, impact, lightning strike, and fluid ingress

- **In-Service Inspection Considerations** - NDI fidelity beyond what can be provided by visual methods is required; time, cost, & sensitivity needs (minimize production, maintenance and operation costs)

- **Sandia Labs NDI Evolution** – WBFDE (POD) quantitatively assessed performance of NDI to allow for optimum deployment of more sophisticated inspection methods; there are sensitive & rapid NDI options available - automation

- Results can produce **improvements** in both quality assurance measures during blade production and damage detection during operation in the field - improve sensitivity, accuracy, repeatability & speed of inspection coverage

- Detection of fabrication defects helps enhance plant reliability while improved inspection of operating blades can result in efficient blade maintenance - **increase blade life; facilitate repairs before critical damage levels are reached and minimize turbine downtime**
Program Thrusts to Improve Wind NDI

- Use of NDI reference standards to form sound basis of comparison & ensure proper equipment set-up
- Use of material property & calibration curves (attenuation, velocity)
- Human factors – adjust procedures
- Improved flaw detection: Hybrid inspection approach - stack multiple methods which address array of flaw types (data fusion)

Enhance factory reliability, facilitate repairs before $a_{critical}$ is reached, minimize turbine downtime & increase blade lifetime
Different Flaw Types Engineered into NDI Performance Assessment Specimens

- Glass Beads
- Grease
- Mold Release
- Pillow Insert

*Materials inserted into multiple layers*

- Voids in bond joint
- Pull tabs in bond joint
- Glass beads in bond joint
- Waviness produced by pre-cured resin rods
- Dry fabric areas
Wind Blade NDI Probability of Detection Experiment

- Blind experiment: type, location and size of flaws are not know by inspector
- Statistically relevant flaw distribution – Probability of Detection (POD)
- Used to analytically determine the performance of NDI techniques – hits, misses, false-calls, flaw sizing, human factors, procedures

Experimental Design Parameters
- Representative design and manufacturing
- Various parts of blade such as spar cap, bonded joints, leading and trailing edge
- Statistically valid POD (number, size of flaws and inspection area)
- Random flaw location
- Maximum of two days to perform experiment
- Deployment

Specimens designs applicable to various blade construction
Robot-Deployed NDI System – Schematic of Power, Controls and Data Transfer

![Diagram of Robot-Deployed NDI System](image-url)
Through Sandia’s New Mexico Small Business Assistance (NMSBA) program, we partnered with Emerging Technology Ventures to develop a plan for integrating NDI sensors with aerodynamics modeling and machine learning.

The goal is to produce an automated Damage Assessment and Maintenance Plan with actionable recommendations for Owner/Operators.