Experimental Wind-tunnel Study of a Sensing Skin for Damage Detection on a Wind Turbine Blade

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September 27th 2017

Overview

Contents

Failure of a 49 meter wind turbine blade wind-watch

Objective

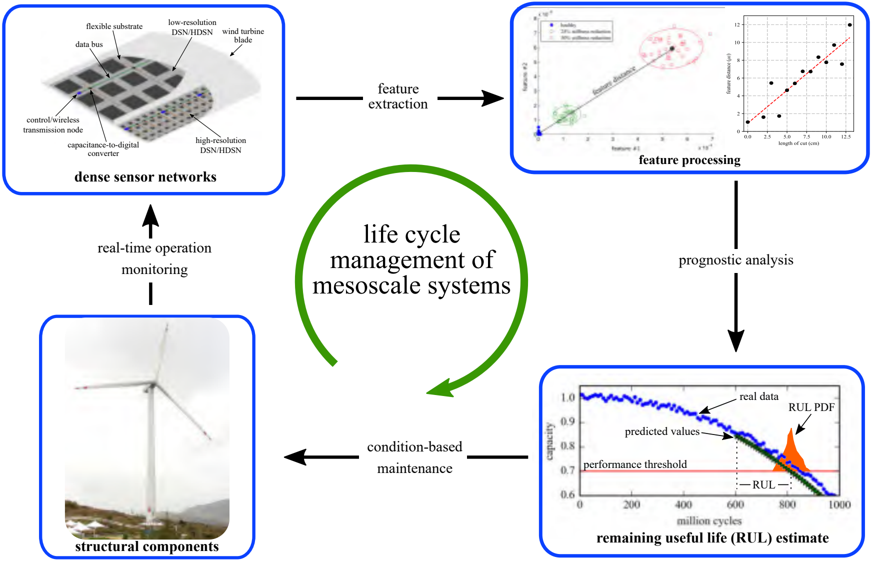
To enable the life cycle management of mesoscale systems through the use of dense sensor networks (DSN)

Data extracted from a DSN can enable:

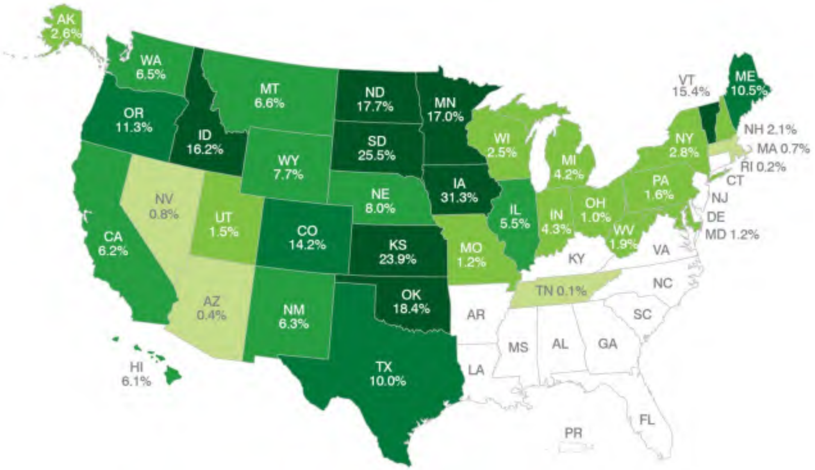
- Condition Based Maintenance (CBM)
- Smarter load management
- Prognostics and health management (PHM)
- Reduced operations and maintenance (O&M) cost

Life cycle management of wind turbines

Utilizing DSNs to enable life cycle management of mesoscale systems



Iowa, a center for wind



US wind energy share of electricity generation during 2015 iowa.gov

Towards 50% wind energy

FUTURE TENSE THE CITIZEN'S GUIDE TO THE FUTURE. SEPT. 12 2016 2:38 PM

FROM SLATE, NEW AMERICA, AND ASU

The Most Impressive State for Clean Energy

It's Iowa. Really!

By Daniel Gross

7.9k 190 112

Iowa has been one of the epicenters of America's wind boom.

DarcyMaulsby/Thinkstock

Wind XI will add 1000 2-megawatt machines. slate.com

MidAmerican Energy To Invest $3.6 Billion In 2 GW Wind Project

April 19th, 2016 by Joshua S Hill

US energy company MidAmerican Energy has announced a commitment to invest $3.6 billion to build the 2 GW Wind XI project in Iowa.

The MidAmerican Energy Company announced last week that it had filed a request with the Iowa Utilities Board to build the 2 GW Wind XI, a project that will add 2 GW of wind energy capacity to Iowa. The project, which will cost a proposed $3.6 billion, is the largest economic development project in the state's history, and the largest wind project MidAmerican Energy has ever undertaken, and the company hopes to avoid increasing customer rates or seeking financial assistance.

MIDAMERICAN ENERGY

The project is a big step towards the company's goal of 100% renewable energy for all its Iowa customers.

"We have a bold vision for our energy future," said Bill Fehrman, CEO and president of MidAmerican Energy. "We don't know of another US energy provider that has staked out this

The project is a big step towards the companys goal of 100% renewable energy for all its Iowa customers. cleantechnica.com

Taller towers

Iowa has the tallest land-based (US) wind turbine (115 meter hub height)
Donnelle Eller

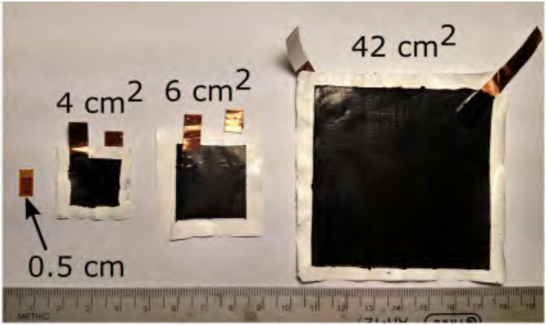
Iowa State University is working on the development of hexagon concrete towers.
news.iastate.edu

Bigger blades

Enercon 73 meter blade Wind Energy

Soft Elastomeric Capacitor (SEC)

Large area electronics consisting of a strain-sensitive Soft Elastomeric Capacitor (SEC)



SECs of varying size compared to a resistive strain gauge (RSG).

Highly elastic sensing membrane.

Laflamme et al., "Robust Flexible Capacitive Surface Sensor for Structural Health Monitoring Applications".

Implementation

- Deployable inside wind turbine blades/towers
- Retrofit or OEM
- Useful for other large structures, e.g. buildings, bridges, aircraft.

Inside a 45 meter GE blade Austin Downey

Damage cases

Typical damage cases found on wind turbine blades

1) fracture; 2-3) edge split; 4) impact. Austin Downey

SEC electromechanical model

Electromechanical for the SEC for converting capacitance to strain

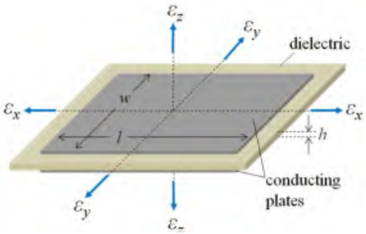
Parallel plate capacitor

$$\Delta C = \epsilon_r \epsilon_0 \frac{\Delta A}{t} \tag{1}$$

ϵ_r is the relative static permittivity and ϵ_0 is the dielectric constant. Using hooks law;

$$\frac{\Delta C}{C} = \lambda(\varepsilon_x + \varepsilon_y) \tag{2}$$

where ε_x is the strain in the x direction, ε_y is the strain in the y direction and λ is the sec's gauge factor ≈ 2 for mechanical excitation under < 15 hz.

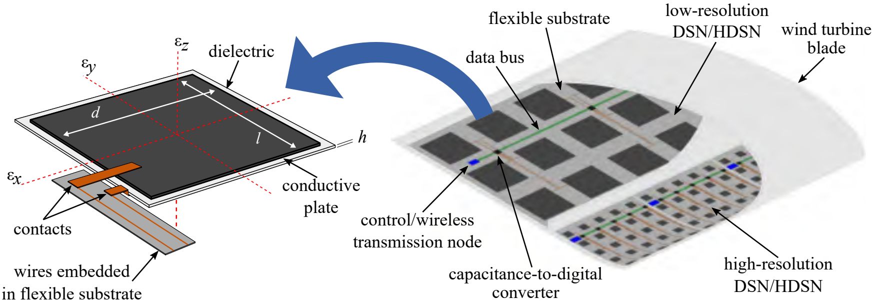


SEC sensor

Laflamme et al., "Dynamic Characterization of a Soft Elastomeric Capacitor for Structural Health Monitoring".

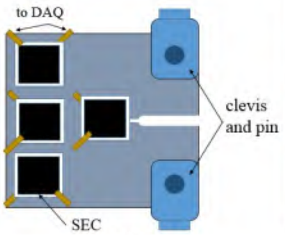
Fully integrated SEC-based dense sensor network

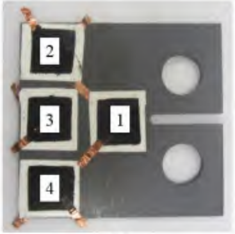
A fully integrated SEC-based dense sensor network consisting of sensors, data acquisition, and power management all preassembled on a polyimide sheet

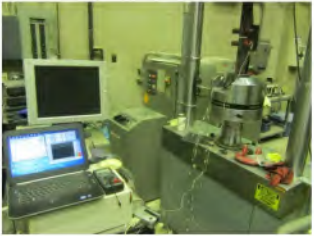


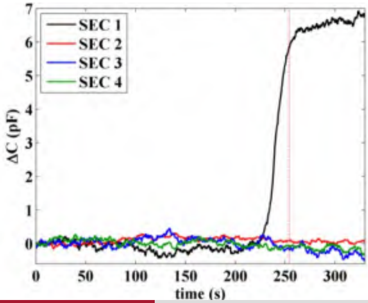
Downey, Laflamme, and Ubertini, "Experimental wind tunnel study of a smart sensing skin for condition evaluation of a wind turbine blade".

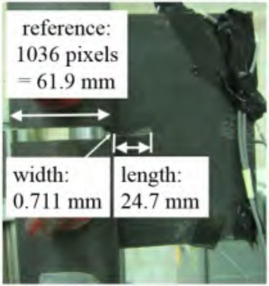
Dense sensor network for fatigue crack detection





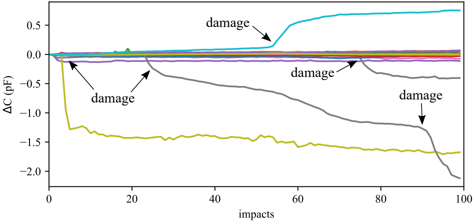






Direct damage detection

A DSN of SECs is capable of spatial and temporal damage detection



impact testing

Link

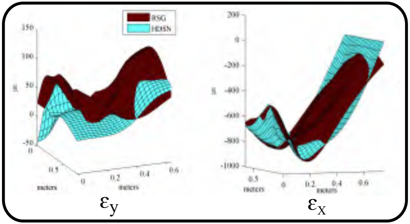
Decompose the SEC's additive strain signal

An algorithm was developed generate unidirectional strain maps

First a model is developed by:

- Assuming a shape function
- Imposing boundary conditions

then the model is solved by calculating the function parameters via a least squares estimation



Decomposed strain maps developed for an experimental DSN with 20 SECs and 10 RSGs

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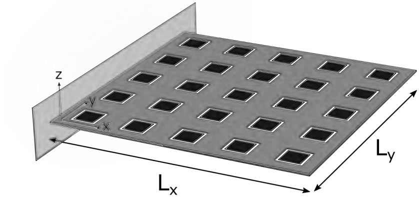
Downey, Laflamme, and Ubertini, "Reconstruction of in-plane strain maps using hybrid dense sensor network composed of sensing skin".

Wu et al., "Network of flexible capacitive strain gauges for the reconstruction of surface strain".

Shape function

A two-term polynomial is used to derive ε_x and ε_y



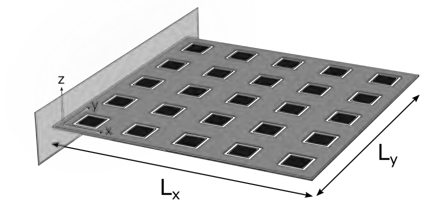
schematic representation of cantilever plate with SEC array

$$\begin{gathered} a \\ x + y \\ x^2 + xy + y^2 \\ x^3 + x^2y + xy^2 + y^3 \\ x^4 + x^3y + x^2y^2 + xy^3 + y^4 \end{gathered}$$

Pascals Triangle for displacement function

Shape function

A two-term polynomial is used to derive ε_x and ε_y



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Pascals Triangle for displacement function

Kirchroff's theory of thin plates

$$\varepsilon_x(x,y) = -\frac{c}{2}\frac{\partial^2 z}{\partial x^2} = -\frac{c}{2}\left(2a_2 + 2a_5 y + 6a_6 x + 2a_9 y^2 + 6a_{10} xy + 12a_{11} x^2\right)$$

$$\varepsilon_y(x,y) = -\frac{c}{2}\frac{\partial^2 z}{\partial y^2} = -\frac{c}{2}\left(2a_3 + 2a_4 x + 6a_7 y + 6a_8 xy + 2a_9 x^2 + 12a_{12} y^2\right)$$

Unidirectional strain maps

The least squares estimator (LSE) is used to solve for the estimated unidirectional strain maps

$$\hat{\varepsilon_x}(x,y) = \hat{b}_1 + \hat{b}_2 x + \hat{b}_3 y + \hat{b}_4 x^2 + \hat{b}_5 xy + \hat{b}_6 y^2$$
$$\hat{\varepsilon_y}(x,y) = \hat{b}_7 + \hat{b}_8 x + \hat{b}_9 y + \hat{b}_{10} x^2 + \hat{b}_{11} xy + \hat{b}_{12} y^2$$

Unidirectional strain maps

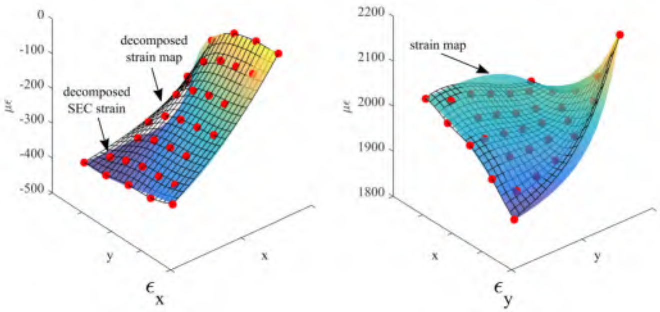
The least squares estimator (LSE) is used to solve for the estimated unidirectional strain maps

$$\hat{\varepsilon_x}(x,y) = \hat{b}_1 + \hat{b}_2 x + \hat{b}_3 y + \hat{b}_4 x^2 + \hat{b}_5 xy + \hat{b}_6 y^2$$

$$\hat{\varepsilon_y}(x,y) = \hat{b}_7 + \hat{b}_8 x + \hat{b}_9 y + \hat{b}_{10} x^2 + \hat{b}_{11} xy + \hat{b}_{12} y^2$$

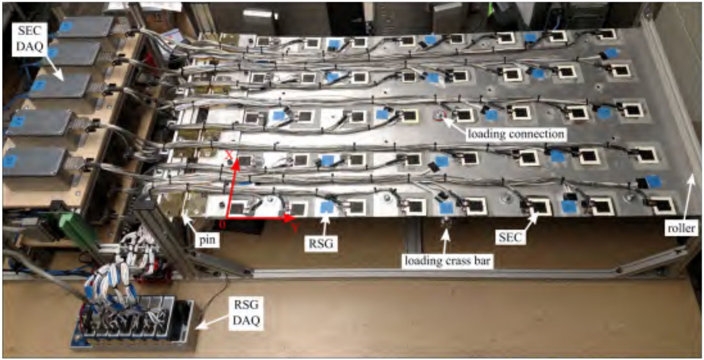
solve for b using least squares estimator (LSE):

$$\hat{\mathbf{B}} = \frac{1}{\lambda}(\mathbf{H}^T\mathbf{H})^{-1}\mathbf{H}^T\mathbf{S}$$



Dynamic reconstruction of unidirectional strain maps

40 SEC DSN on a custom built test bench designed for controlled dynamic loading

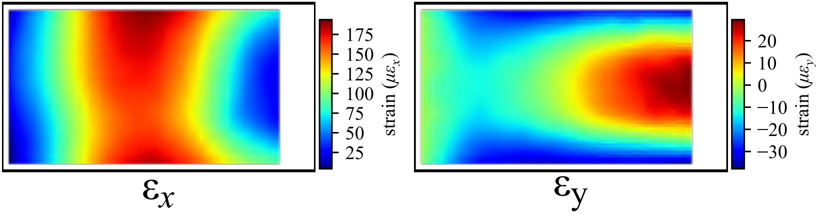


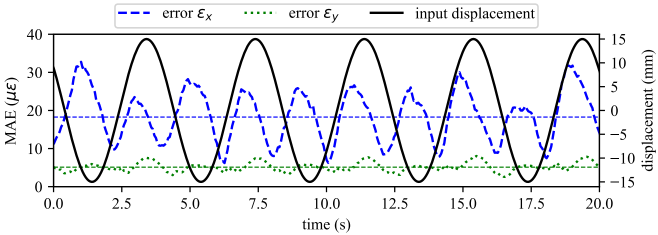
Strain maps (simulation) Dynamic excitation

Downey et al., “Dynamic Reconstruction of In-plane Strain Maps Using a Two-dimensional Sensing Skin”.

Unidirectional strain maps

Dynamic strain maps reconstructed from a 40 SEC DSN on a test bench





Downey et al., "Dynamic Reconstruction of In-plane Strain Maps Using a Two-dimensional Sensing Skin".

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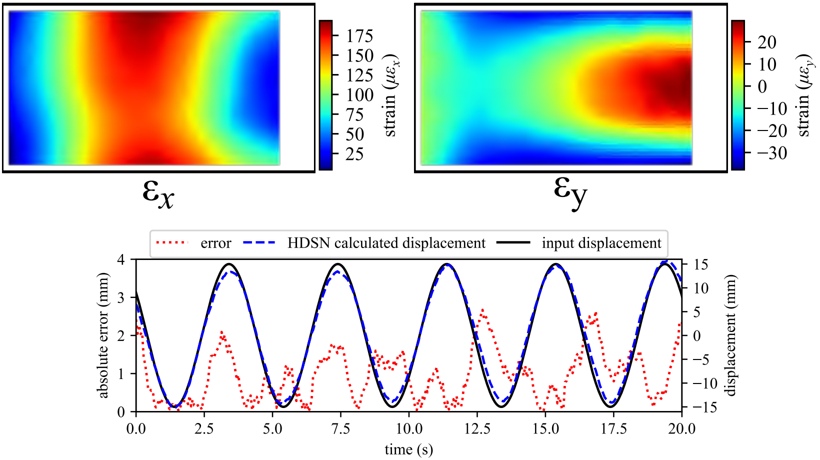
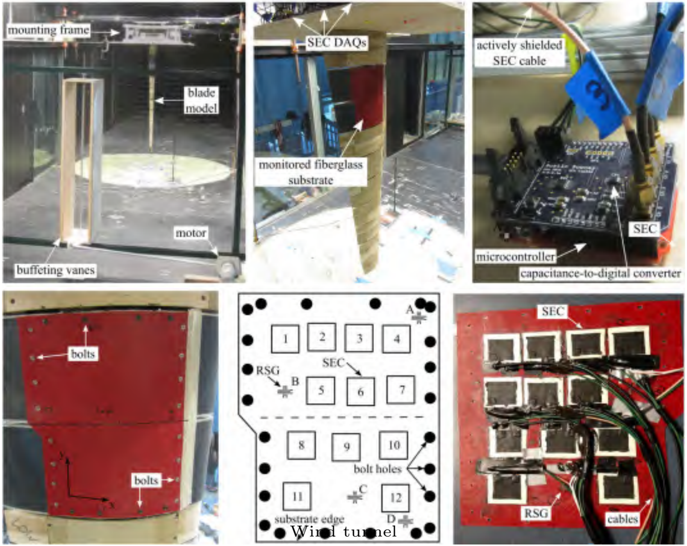


Downey et al., "Dynamic Reconstruction of In-plane Strain Maps Using a Two-dimensional Sensing Skin".

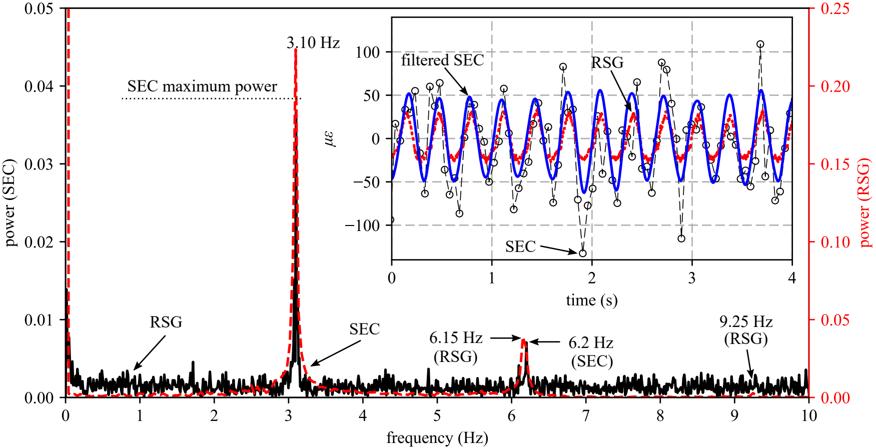
Dynamic reconstruction of unidirectional strain maps

A wind turbine blade application



SEC signal

Time series signal and associated frequency domain for SEC # 8 and RSG B

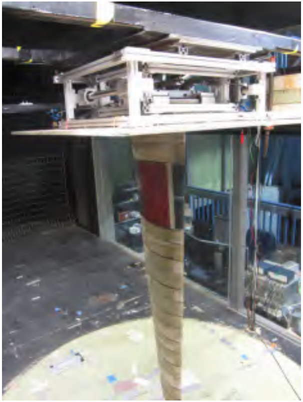


Downey, Laflamme, and Ubertini, "Experimental wind tunnel study of a smart sensing skin for condition evaluation of a wind turbine blade".

Unidirectional strain maps

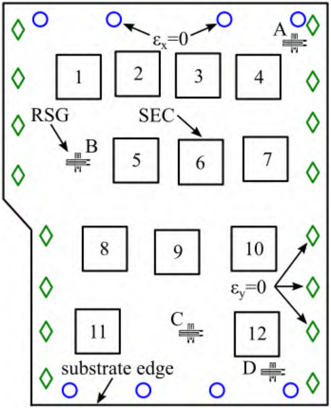
Dynamic unidirectional strain maps generated for a the model wind turbine blade

Wind Tunnel Testing



Link

Strain Maps

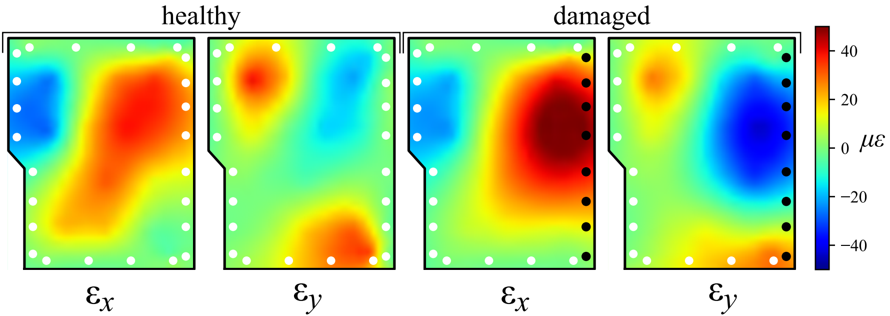


Link

Downey, Laflamme, and Ubertini, "Experimental wind tunnel study of a smart sensing skin for condition evaluation of a wind turbine blade".

Changing load paths

Damage-induced changes in the monitored substrates load path for all bolts removed on the leading edge



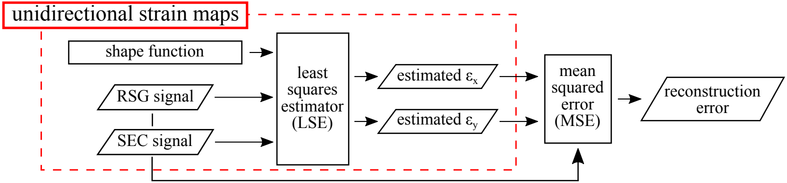
Downey, Laflamme, and Ubertini, "Experimental wind tunnel study of a smart sensing skin for condition evaluation of a wind turbine blade".

Network Reconstruction Feature (NeRF)

A damage detection and localization algorithm specially designed for the SEC-based DSN

The proposed Network Reconstruction Feature (NeRF) algorithm provides:

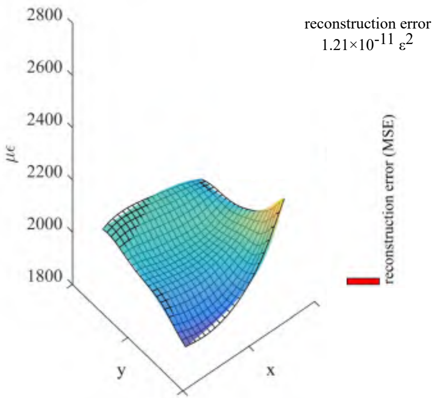
- Data fusion of the additive SEC signal and unidirectional RSG signal.
- Distinguish healthy states form possibly damaged states.
- Capable of damage detection, quantification and localization.
- Can function without historical data set or external models.



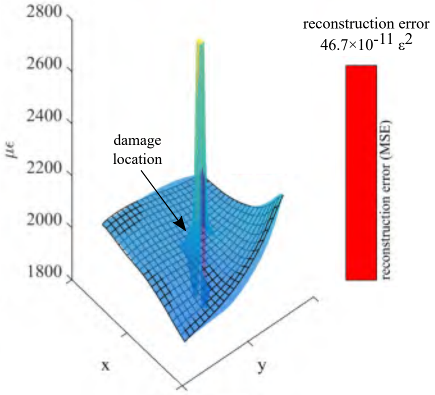
Downey, Ubertini, and Laflamme, "Algorithm for damage detection in wind turbine blades using a hybrid dense sensor network with feature level data fusion".

Error quantification

Quantifies the error between the sensor's measured strain and the decomposed strain maps



ε_y healthy

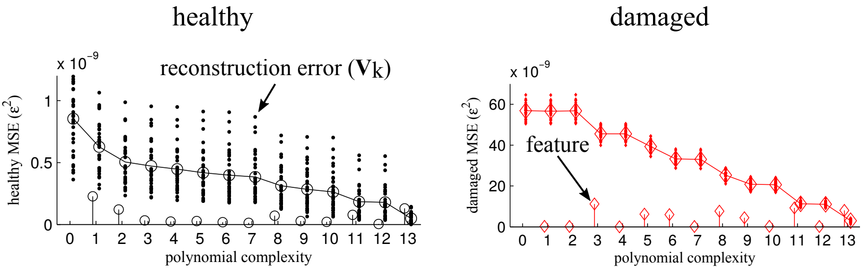


ε_y damaged

Downey, Ubertini, and Laflamme, "Algorithm for damage detection in wind turbine blades using a hybrid dense sensor network with feature level data fusion".

Feature extraction

Features are defined as the improvement (reduction) in error from one polynomial complexity to another

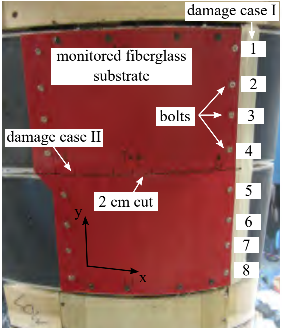


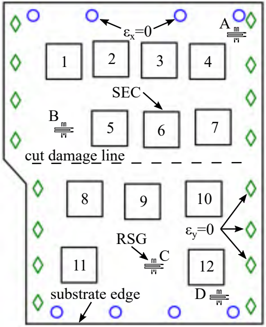
Features extracted from change in fit with increasing shape function complexity

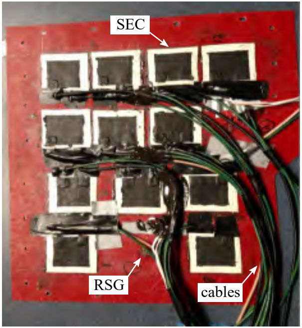
Downey, Ubertini, and Laflamme, “Algorithm for damage detection in wind turbine blades using a hybrid dense sensor network with feature level data fusion”.

Experimental wind tunnel validation

Experimental setup used for testing the DSN in the noisy environment of a wind tunnel



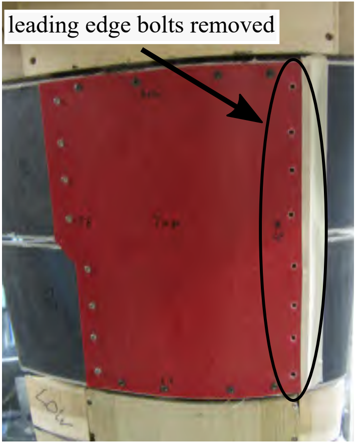


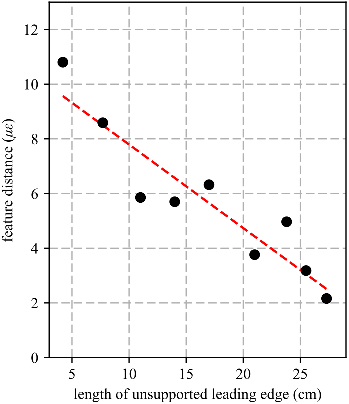


Downey, Laflamme, and Ubertini, "Experimental wind tunnel study of a smart sensing skin for condition evaluation of a wind turbine blade".

Leading edge damage

NeRF algorithm results for changing boundary conditions on the leading edge of the monitored substrate





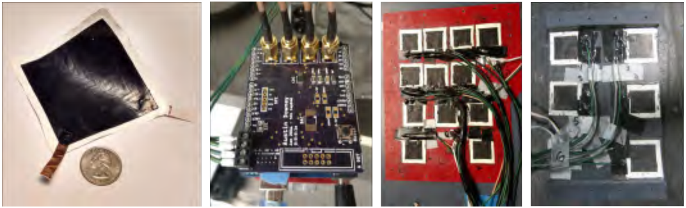
Downey, Laflamme, and Ubertini, "Experimental wind tunnel study of a smart sensing skin for condition evaluation of a wind turbine blade".

Conclusion

Summary of the advances made to the monitoring of mesoscale systems

Key advances made in the current work:

- Proposed a low-cost dense sensor network for mesoscale monitoring
- Demonstrated the dense sensor network's capability to detect and localize damage
- Formulated a simple damage detection algorithm with a high level of data fusion
- Validated the proposed dense sensor network and damage detection algorithms through wind tunnel testing



SEC technology: 1) SEC sensor; 2) 4 channel DAQ; and 3) HDSN; 4) HDSN.

Thank you

Questions?

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