A Data-driven Approach for Damage Detection in Wind Turbine Blades using a Dense Array of Soft Elastomeric Capacitors

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Overview

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Failure of a 49 meter wind turbine blade wind-watch
Iowa, a center for wind

US wind energy share of electricity generation during 2015 iowa.gov
Towards 50% wind energy

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

The project is a big step towards the company's 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 adds low-wind turbines

Enercon has introduced low-wind speed versions to its 4MW and 2MW onshore wind turbine platform.

Enercon 73 meter blade Wind Energy
Hybrid Dense Sensor Networks (HDSN)

Motivation

Hybrid Dense Sensor Networks (HDSN)

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Conclusion
Structural health monitoring of wind turbine blades
Utilizing large area electronics for global coverage
Soft Elastomeric Capacitor (SEC)

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

Highly elastic sensing membrane.
SEC model

Parallel plate capacitor

\[ \Delta C = \varepsilon_r \varepsilon_0 \frac{\Delta A}{t} \quad (1) \]

\( \varepsilon_r \) is the relative static permittivity and \( \varepsilon_0 \) is the dielectric constant. Using hook's law;

\[ \frac{\Delta C}{C} = \lambda (\varepsilon_x + \varepsilon_y) \quad (2) \]

where \( \varepsilon_x \) is the strain in the \( x \) direction, \( \varepsilon_y \) is the strain in the \( y \) direction and \( \lambda \) is the sec's gauge factor \( \approx 2 \) for mechanical excitation under \( < 15 \text{ hz} \).
Fully integrated SEC based sensing skins for mesosystem monitoring
Implementation

1. Deployable inside wind turbine blades.
2. Retrofit or OEM.
3. Useful for other large structures, e.g. buildings, bridges, aircraft.

Inside a 45 meter GE blade

Austin Downey
Damage cases

Typical damage cases: 1) through crack; 2-3) edge split; 4) impact. Austin Downey
Dense sensor network for fatigue crack detection

[Diagram of a dense sensor network with labels and connections.]

[Image of a network of sensors with numbers 1 to 4.]

[Graph showing data from SEC 1 to SEC 4 over time.]

[Image showing measurement details: reference 1036 pixels = 61.9 mm, width: 0.711 mm, length: 24.7 mm.]
Motivation

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Decompose the additive strain signal into unidirectional strain maps

Develop a model for creating unidirectional surface strain maps:

- Assume a shape function.
- Impose boundary conditions.
- Calculate function parameters via a least square estimation.
Shape function

Schematic representation of cantilever plate with SEC array

\[ a \]

\[
x + y
\]
\[
x^2 + xy + y^2
\]
\[
x^3 + x^2y + xy^2 + y^3
\]
\[
x^4 + x^3y + x^2y^2 + xy^3 + y^4
\]

Pascals Triangle for displacement function
Shape function

schematic representation of cantilever plate with SEC array

\[ a \\
\begin{align*}
x &+ y \\
x^2 + xy + y^2 \\
x^3 + x^2y + xy^2 + y^3 \\
x^4 + x^3y + x^2y^2 + xy^3 + y^4
\end{align*} \]

Pascals Triangle for displacement function

Kirchoff’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

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

\[ \varepsilon_y(x, y) = \hat{b}_7 + \hat{b}_8 x + \hat{b}_9 y + \hat{b}_{10} x^2 + \hat{b}_{11} xy + \hat{b}_{12} y^2 \]
Unidirectional strain maps

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

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

solve for \( b \) using least squares estimator (LSE):

\[ \hat{B} = \frac{1}{\lambda} (H^T H)^{-1} H^T S \]
Real-time unidirectional strain maps

Wind Tunnel Testing

Strain Maps
Network Reconstruction Feature (NeRF)

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Damage detection and localization through a Network Reconstruction Feature (NeRF)
Damage detection and localization through a Network Reconstruction Feature (NeRF)

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

Extract damage features based on the fit of a shape function
Deploying HDSN of SECs and RSGs onto a plate.
Deploying HDSN of SECs and RSGs onto a plate.
Building a HDSN

Deploying HDSN of SECs and RSGs onto a plate.
Building a HDSN

Deploying HDSN of SECs and RSGs onto a plate.
Damage cases

Cantilever plate with damage induced as reduction of stiffness.
Damage cases

Cantilever plate with damage induced as reduction of stiffness.
Damage cases

Cantilever plate with damage induced as reduction of stiffness.
Error detection

Error in strain map reconstitution measured at sensor locations.
Feature extraction

Features extracted from change in fit with increasing shape function complexity
Damage localization

Damage localization on cantilever plate with damage induced as reduction of stiffness.
Damage localization on cantilever plate with damage induced as reduction of stiffness.
Damage localization on cantilever plate with damage induced as reduction of stiffness.
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Experimental wind tunnel validation

Wind turbine blade shaped cantilever plate with damage induced as reduction of stiffness, pressure loading on face.
Leading edge damage

NeRF algorithm results for changing boundary conditions on the leading edge of the monitored substrate.
Changing load paths caused by damage
Cut damage

NeRF algorithm results for cut damage induced into the center of the monitored substrate.
Conclusion

- Low cost measurement system for mesoscale structures.
- Demonstrated capability to detect and localize damage.

Limitations

- Can be difficult to distinguish damage for complex loading.

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

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