Analysis of Polarimetric Terahertz Imaging for Non-Destructive Detection of Subsurface Defects in Wind Turbine Blades

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Introduction
Fiberglass Defects

- Subsurface defects can form in the interior structure of the blade
- Some defects cannot be detected by visual inspection
- These defects have been shown to cause premature failure of blades in the field [1]

Out-of-plane wave defect.

The terahertz region is typically defined as the frequency band between 100 GHz and 10 THz.

Previous investigations have indicated that terahertz radiation can detect subsurface defects in composite fiberglass.

Both terahertz time domain spectroscopy (TDS) and frequency modulated continuous wave (FMCW) techniques have been used to test fiberglass materials for defects.

Previous investigations have not included collection of fully polarimetric scattering data.
Methodology
Radar Cross Section

- Radar (Scattering) cross section ($\sigma$)

\[ \sigma = \lim_{R \to \infty} 4\pi R^2 \frac{|E^{\text{scat}}|^2}{|E^{\text{inc}}|^2} \]

- Scattering of polarized radiation can be described using the Sinclair matrix

\[
\begin{bmatrix}
E_H^{\text{scat}} \\
E_V^{\text{scat}}
\end{bmatrix} = \left( \frac{e^{-ikR}}{2\sqrt{\pi R}} \right) \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix} \begin{bmatrix}
E_H^{\text{inc}} \\
E_V^{\text{inc}}
\end{bmatrix}
\]

\[ \sigma_{HV} = |S_{HV}|^2 \]
The Sinclair matrix can be diagonalized and meaningful parameters can be extracted

\[ S_D = U^T S U \]

\[ U = \begin{bmatrix} \cos(\psi) \cos(\tau) - i \sin(\psi) \sin(\tau) & - \sin(\psi) \cos(\tau) + i \cos(\psi) \sin(\tau) \\ \sin(\psi) \cos(\tau) + i \cos(\psi) \sin(\tau) & \cos(\psi) \cos(\tau) + i \sin(\psi) \sin(\tau) \end{bmatrix} \]

\[ S_D = \begin{bmatrix} m e^{i2\nu} & 0 \\ 0 & m \tan^2(\gamma)e^{-i2\nu} \end{bmatrix} \]

The parameters \( m, \gamma, \tau, \psi, \text{ and } \nu \) are known as the Euler Parameters
The four angle parameters that contain phenomenological information about the scattering object:

- **$\gamma$**
  - $0^\circ$: Polarizing
  - $45^\circ$: Nonpolarizing

- **$\psi$**
  - $0^\circ$: Horizontal
  - $\pm 90^\circ$: Vertical

- **$\nu$**
  - $0^\circ$: Odd Bounce
  - $\pm 45^\circ$: Even Bounce

- **$\tau$**
  - $0^\circ$: Symmetric
  - $\pm 45^\circ$: Nonsymmetric
A detector with a small aperture can simulate a large aperture by collecting coherent scattering data as it moves along a path.
Alternatively, a small detector can collect scattering data while the sample is rotated to achieve the same effect.

Data collected as a function of frequency and angle azimuth can be Fourier Transformed to an image in range and crossrange.
\[
x - x_0 = (x' - x_0) \cos(\theta) + (y' - y_0) \sin(\theta)
\]
\[
y - y_0 = -(x' - x_0) \sin(\theta) + (y' - y_0) \cos(\theta)
\]
The standard discrete Fourier transform is given by:

\[ F_{x,y} = \frac{1}{N_n N_m} \sum_{n=0}^{N_n-1} \sum_{m=0}^{N_m-1} f_{n,m} e^{-i2\pi \frac{nx}{N_n}} e^{-i2\pi \frac{ym}{N_m}} \]

The coordinate transformation can be applied here, producing:

\[ F_{x',y'} = \frac{1}{N_n N_m} \sum_{n=0}^{N_n-1} \sum_{m=0}^{N_m-1} f_{n,m} e^{-i2\pi \left(\frac{(x'-x_0)\cos(\theta)+(y'-y_0)\sin(\theta)+x_0}{N_n}\right)n} \times e^{-i2\pi \left(-\frac{(x'-x_0)\sin(\theta)+(y'-y_0)\cos(\theta)+y_0}{N_m}\right)m} \]
After back-rotation, the pixels from different ISAR images can be averaged to produce a single composite ISAR image.
Quantitative Evaluation

- Pixels within each user defined region are compared to quantify contrast.
Histogram Scoring Method

Defect imaging score = 0.184

Defect imaging score = 0.928
Fiberglass Sample 1

- Sample 1 contains out-of-plane wave defects and resin-dry patches.
Sample 2 contains microballoons, mold and grease inserts, and voids in an adhesive layer.
Sample 3 contains two kinds of out-of-plane wave defects and a thickness variation.
Fiberglass Sample 4

- Sample 4 contains three out-of-plane wave defects
Sample 5 contains an uneven layer of adhesive material with embedded Kapton tape inserts.
Sample 6 (similar to sample 1) contains out-of-plane wave defects and resin dry patches.

The sample also contains an unintentional surface defect.
Ranges operate at 100 GHz and 160 GHz

Results
Single Azimuth ISAR Images

Single Azimuth HH ISAR Image of Sample 1

- 0° azimuth, 25° elevation, 160 GHz
Composite ISAR Images

Composite HH ISAR Image of Sample 1

- 360 images composited, 25° elevation, 160 GHz
Composite ISAR Images

Composite HH ISAR Image of Sample 2

- 360 images composited, 25° elevation, 160 GHz
Composite ISAR Images

Composite HH ISAR Image of Sample 3

- 360 images composited, 30° elevation, 100 GHz
Composite ISAR Images

Composite $m$ parameter ISAR image of Sample 3

- 360 images composited, 30° elevation, 100 GHz
Composite ISAR Images

Composite angular Euler parameter ISAR images

\[ \gamma \] parameter

\[ \psi \] parameter

\[ \nu \] parameter

\[ \tau \] parameter
Composite ISAR Images

Composite $m$ parameter ISAR images at other elevations

- 360 images composited, 100 GHz

45° elevation  
60° elevation
Back-Rotation Algorithm Analysis

Composite $m$ parameter ISAR image using Fourier space back-rotation

- 360 images composited, 100 GHz
Composite ISAR Images

Sample 4 composite $m$ parameter ISAR image

- 360 images composited, 30° elevation, 100 GHz

Learning with Purpose
Composite ISAR Images

Sample 5 composite $m$ parameter ISAR image

- 360 images composited, 30° elevation, 100 GHz
Composite ISAR Images

Sample 6 composite $m$ parameter ISAR image

- 360 images composited, 30° elevation, 100 GHz
Quantitative Evaluation

Defect Imaging Scores for a defect in Sample 3

<table>
<thead>
<tr>
<th>ISAR image type</th>
<th>defect imaging score</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH polarization RCS</td>
<td>0.715</td>
</tr>
<tr>
<td>HV polarization RCS</td>
<td>0.619</td>
</tr>
<tr>
<td>VH polarization RCS</td>
<td>0.640</td>
</tr>
<tr>
<td>VV polarization RCS</td>
<td>0.635</td>
</tr>
<tr>
<td>$m$ Euler parameter</td>
<td>0.532</td>
</tr>
<tr>
<td>$\gamma$ Euler parameter</td>
<td>0.864</td>
</tr>
<tr>
<td>$\tau$ Euler parameter</td>
<td>0.910</td>
</tr>
<tr>
<td>$\psi$ Euler parameter</td>
<td>0.828</td>
</tr>
<tr>
<td>$\upsilon$ Euler parameter</td>
<td>0.636</td>
</tr>
</tbody>
</table>
The scores for this defect were determined using different numbers of ISAR images in the composite.
Parameter Optimization

Multiple defects averaged together

- This process was repeated for multiple defects
- The defect imaging scores for each of these defects were averaged together
Parameter Optimization

Average defect imaging scores for multiple defects

<table>
<thead>
<tr>
<th>ISAR image type</th>
<th>defect imaging score</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH polarization RCS</td>
<td>0.706</td>
</tr>
<tr>
<td>HV polarization RCS</td>
<td>0.679</td>
</tr>
<tr>
<td>VH polarization RCS</td>
<td>0.683</td>
</tr>
<tr>
<td>VV polarization RCS</td>
<td>0.595</td>
</tr>
<tr>
<td>$m$ Euler parameter</td>
<td>0.562</td>
</tr>
<tr>
<td>$\gamma$ Euler parameter</td>
<td>0.850</td>
</tr>
<tr>
<td>$\tau$ Euler parameter</td>
<td>0.804</td>
</tr>
<tr>
<td>$\psi$ Euler parameter</td>
<td>0.748</td>
</tr>
<tr>
<td>$\upsilon$ Euler parameter</td>
<td>0.722</td>
</tr>
</tbody>
</table>
Parameter Optimization

Effect of Balance Parameter on defect region
Parameter Optimization

Effect of balance parameter in non-defect region
Parameter Optimization

Difference between balance parameter plots
Different Compositing Methods

<table>
<thead>
<tr>
<th>compositing method</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH polarization RCS</td>
<td>0.706</td>
<td>0.648</td>
<td>0.689</td>
<td>0.737</td>
<td>0.729</td>
<td>0.649</td>
<td>0.642</td>
<td>0.647</td>
</tr>
<tr>
<td>HV polarization RCS</td>
<td>0.679</td>
<td>0.631</td>
<td>0.631</td>
<td>0.665</td>
<td>0.686</td>
<td>0.617</td>
<td>0.619</td>
<td>0.608</td>
</tr>
<tr>
<td>VH polarization RCS</td>
<td>0.683</td>
<td>0.643</td>
<td>0.637</td>
<td>0.663</td>
<td>0.681</td>
<td>0.632</td>
<td>0.635</td>
<td>0.619</td>
</tr>
<tr>
<td>VV polarization RCS</td>
<td>0.595</td>
<td>0.604</td>
<td>0.586</td>
<td>0.632</td>
<td>0.675</td>
<td>0.598</td>
<td>0.605</td>
<td>0.591</td>
</tr>
<tr>
<td>$m$ Euler parameter</td>
<td>0.562</td>
<td>0.527</td>
<td>0.580</td>
<td>0.632</td>
<td>0.684</td>
<td>0.529</td>
<td>0.530</td>
<td>0.526</td>
</tr>
<tr>
<td>$\gamma$ Euler parameter</td>
<td>0.850</td>
<td>0.882</td>
<td>0.842</td>
<td>0.809</td>
<td>0.798</td>
<td>0.857</td>
<td>0.856</td>
<td>0.874</td>
</tr>
<tr>
<td>$\tau$ Euler parameter</td>
<td>0.804</td>
<td>0.748</td>
<td>0.788</td>
<td>0.785</td>
<td>0.804</td>
<td>0.797</td>
<td>0.790</td>
<td>0.808</td>
</tr>
<tr>
<td>$\psi$ Euler parameter</td>
<td>0.748</td>
<td>0.704</td>
<td>0.690</td>
<td>0.673</td>
<td>0.605</td>
<td>0.780</td>
<td>0.740</td>
<td>0.742</td>
</tr>
<tr>
<td>$\nu$ Euler parameter</td>
<td>0.722</td>
<td>0.687</td>
<td>0.724</td>
<td>0.739</td>
<td>0.721</td>
<td>0.702</td>
<td>0.696</td>
<td>0.697</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>mean of all pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>B</td>
<td>median of all pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>C</td>
<td>include brightest 50% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>D</td>
<td>include brightest 25% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>E</td>
<td>include brightest 10% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>F</td>
<td>exclude brightest 10% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>G</td>
<td>exclude brightest 20% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>H</td>
<td>exclude brightest and dimmest 10% of pixels above the threshold for each range/crossrange cell</td>
</tr>
</tbody>
</table>
Combining the Optimum Parameters

Composite $m$ parameter ISAR image of Sample 3

- 360 images composited, median image composition method
Future Work

- Continue to apply the technique to different fiberglass defects and other wind turbine blade structures
- Investigate the benefits of other SAR techniques, such as interferometric ISAR (IFISAR), az-el scans, and full 3D ISAR
- Take full advantage of the electromagnetic characteristics of the sample materials
- Investigate other polarimetric transformations
Terahertz radiation has been proven capable of detection subsurface defects in fiberglass materials.

The image compositing algorithm offers significant improvements in defect detection over traditional single-azimuth ISAR images.

The Euler $m$ parameter has been shown to produce the best contrast between defect and defect free-regions.
Literature Cited


Acknowledgments

- Dr. Christopher Baird
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  - Dr. Robert Giles, Jason Dickinson, Dr. Tom Goyette, and Michael Coulombe
Questions?