Terahertz ISAR and x-ray imaging of wind turbine blade structures

Robert Martin a, Christopher S. Baird a, Robert H. Giles a, Christopher Niezrecki a

a University of Massachusetts Lowell, 1 University Avenue, Lowell, MA, USA 01854;

ABSTRACT

During the manufacture of wind turbine blades, internal defects can form which negatively affect their structural integrity and may lead to premature failure. The purpose of this research was to conduct preliminary testing of non-destructive evaluation techniques that have the potential to scale up to larger areas. The techniques investigated were: Terahertz frequency fully-polarimetric inverse synthetic aperture radar (ISAR), and x-ray imaging. The terahertz ISAR technique employed standard polarimetric radar cross-section processing, and additionally applied an optimized polarimetry transformation known as the Euler transformation. Also, image back-rotation and compositing algorithms were used to combine multiple ISAR images into a single image to aid in defect detection. ISAR data were collected using a frequency modulated continuous wave 100 GHz radar system. The x-ray technique utilized a commercial airport cargo x-ray scanner. Multiple fiberglass samples with defects representative of manufacturing wind turbine blade defects were investigated using each of the techniques. Out-of-plane defects and resin dry patches were the primary defects of interest in these samples. Images were created of each sample using each of the techniques. Comparing these images with defect diagrams of the samples indicated that these techniques could effectively indicate the presence of certain defects.

Keywords: Terahertz, ISAR, Radar, NDT, X-ray, Wind Turbine, Composite, Fiberglass

1. INTRODUCTION

Wind energy has become an increasingly important energy source in many parts of the world. As wind turbines grow in size and number, it is essential to ensure the structural integrity of all wind turbine blade components. Of particular concern are the blades of wind turbines, which are not only vulnerable to damage but are also subject to manufacturing defects. These manufacturing defects including out-of-plane fiber wave defects and resin dry regions, are believed to cause premature catastrophic failure of wind turbine blades once they have been installed on turbines in the field. These defects are often embedded in the subsurface of the blades and cannot be detected easily via simple visual inspection. As a result, there is a growing need for non-destructive testing (NDT) techniques capable of detecting subsurface defects before the blades leave the manufacturing facility. This manuscript contains the results of an investigation including two techniques: Fully-polarimetric terahertz inverse synthetic aperture radar (ISAR), and x-ray imaging.

Previous investigations into the use of terahertz imaging for fiberglass NDT have indicated that terahertz radiation is capable of detecting fiberglass defects. Material inserts and drilled holes have been shown detectable using terahertz time-domain spectroscopy (TDS) and frequency modulated continuous wave (FMCW) systems. Additionally, benefits of using certain imaging polarizations have been suggested. This work further explores terahertz imaging as an NDT by imaging a number of defect types, using fully-polarimetric analysis, and applying additional image processing, polarimetric transforms, and contrast quantification algorithms.

Additionally, the fiberglass samples were imaged using x-ray radiation. A commercial PX 10.10 MX Non-Palletized Freight X-ray system developed and operated by L3 Communications was used to image the samples for comparison with the terahertz ISAR technique.

2. METHODOLOGY

2.1 Terahertz inverse synthetic aperture radar

The polarization dependent electromagnetic scattering properties of an object can be described using a scattering matrix. The relationship is given by
where $E_{\text{scat}}$ and $E_{\text{inc}}$ represent the scattered and incident electric fields respectively, $R$ is the distance between the radar transceiver and the object, $k$ is a wavenumber, and the $S_{ij}$ are the complex-valued elements of the scattering matrix known as the Sinclair matrix. The H and V subscripts stand for horizontal and vertical linear polarizations, which constitute a commonly-used polarization basis for radar operations. These Sinclair matrix elements are related to the object’s polarimetric Radar Cross Section (RCS) $\sigma$ via

$$\sigma_{ij} = |S_{ij}|^2$$  \hspace{1cm} (2)

The RCS is a measure of the intensity of the scattered radiation and does not contain any information about the phase of the scattered radiation. The phase information contained within the Sinclair matrix elements is often necessary for coherent data processing techniques such as synthetic aperture radar (SAR).

Additionally, the complex-valued Sinclair matrix can be transformed in order to extract five real meaningful physical parameters. This transform is known as the Euler transform, and the parameters it produces are known as the Euler parameters. Unlike the polarimetric RCS, these Euler parameters do not discard the phase information contained in the Sinclair matrix.

The Euler parameters can be revealed by diagonalizing the Sinclair matrix using a conjugate similarity unitary transform:

$$S_D = U^T S U$$  \hspace{1cm} (3)

$$U = \begin{bmatrix} \cos(\psi)\cos(\tau) - i\sin(\psi)\sin(\tau) & -\sin(\psi)\cos(\tau) + i\cos(\psi)\sin(\tau) \\ \sin(\psi)\cos(\tau) + i\cos(\psi)\sin(\tau) & \cos(\psi)\cos(\tau) + i\sin(\psi)\sin(\tau) \end{bmatrix}$$  \hspace{1cm} (4)

$$S_D = \begin{bmatrix} me^{i2\psi} & 0 \\ 0 & m\tan^2(\gamma)e^{-i2\psi} \end{bmatrix}$$  \hspace{1cm} (5)

where $U$ is the unitary transform matrix and $S_D$ is the diagonalized Sinclair matrix. The five parameters in the elements of these matrices: $m$, $\gamma$, $\tau$, $\psi$, and $\nu$, are the Euler parameters. While equations 3-5 can sufficiently define the Euler parameters, these equations cannot be used to solve for the Euler parameters. Actually solving for the Euler parameters requires a step by step diagonalization of the associated Kennaugh matrix, as shown by Baird.\textsuperscript{12} The Euler parameters presented in this work were determined using Baird’s optimized Euler transform algorithm. This optimized Euler transform resolves certain ambiguities that occur using other Euler transforms.

Each of the five Euler parameters has a phenomenological interpretation that relates to the properties of the scatterer than to the polarization state of the radiation. This is unlike an object’s RCS in the traditional H-V polarization basis, which represent scattering magnitudes for certain transceiver polarization states.

The $m$ parameter corresponds to the maximum reflectivity that would be obtained using the optimum transceiver polarization state. The $\psi$ parameter is the orientation angle of the scattering object for the maximum reflectivity. It can range between -90° to 90° and represents horizontal object orientation at 0° and vertical object orientation at ±90°. The $\tau$ parameter is the object symmetry angle. It can range from -45° to 45° and represents a scatterer that is symmetric about its axis at 0° and nonsymmetric about its axis at ±45°. The $\nu$ parameter is the bounce angle of the object and indicates whether the radiation bounces an even or odd number of times before reaching the detector. It ranges from -45° to 45° and represents an odd bounce at 0° and an even bounce at ±45°. The $\gamma$ parameter is the polarizability angle. It can range from 0° to 45° and indicates a strongly polarizing object at 0° and a nonpolarizing object at 45°.
Several fiberglass samples (discussed in section 2.3) were imaged in one of two frequency modulated continuous wave (FMCW) fully-polarimetric radar ranges. The two ranges operated at 100 GHz and 160 GHz respectively. Figure 2 contains a diagram of these ranges. The samples were mounted on a rotatable stage capable of rotating through a full range of angles in azimuth and tilting to allow measurements for different elevation angles.

![Diagram of 100 GHz compact radar range](image)

Figure 2. A diagram of the 100 GHz compact radar range used to collect scattering measurements.

This sample rotation is used to create a synthetic aperture, and images are generated from the data using inverse synthetic aperture radar (ISAR) techniques. Performing a two dimensional Fourier transform over scattering data that are a function of both frequency and azimuth angle produces data that are a function of both range and crossrange. This grid of data constitutes what is called an ISAR image.

This process can be repeated for each of the four Sinclair matrix elements. Traditionally, the Sinclair matrix elements are then converted to RCS on a dBsm scale, producing four possible ISAR image types. In this work, the Sinclair matrix elements were converted to the Euler parameters, producing a total of 9 types of ISAR images.

Scattering data were collected for a full range of azimuth, allowing for many ISAR images to be created. An algorithm was developed which combines ISAR images at multiple azimuths into a single composite image. This algorithm consists of two steps: Image back rotation, and pixel-by-pixel image composition.

The image back-rotation algorithm applied a simple coordinate rotation of the pixels of the ISAR images by an angle $\theta$,

$$x - x_0 = (x' - x_0) \cos(\theta) + (y' - y_0) \sin(\theta) \quad (6)$$

$$y - y_0 = -(x' - x_0) \sin(\theta) + (y' - y_0) \cos(\theta) \quad (7)$$

Where the primed coordinates are the new coordinates, and the naught coordinates are the coordinates of the center of rotation of the sample in the image. The rotation algorithm creates a new image one pixel at a time. Equations (6) and (7) are used to determine the value of a pixel located at $(x', y')$ with respect to the original coordinates $(x, y)$ and the azimuth angle $\theta$.

After the ISAR images have been properly back-rotated, all of the pixels in the images that represent the same range/crossrange cell are averaged together. This produces a single composite ISAR image where each pixel is an average value of multiple pixels from different images. The pixels were composited by calculating the mean of all of the pixels in a given range/crossrange cell with some basic thresholding applied. For the magnitude parameters, the thresholding involved excluding from the averaging any pixels with values of less than -80 dBsm. For the angular Euler parameters, only pixels whose $m$ parameter value were above -80 dBsm were included in the averaging.

These composite images offer several benefits that aid defect detection. Fluctuations caused by diffuse scattering, which may make defect detection in a single-azimuth ISAR image very difficult, are averaged away in the composite image.
Defects that stand out against this diffuse scattering, even for a small sub-range of angles in azimuth, stand out against this diffuse scattering in the final composite ISAR images. Additionally, artifacts of the imaging process, such as the DC bias line, are averaged out. Figure 3 contains a single-azimuth ISAR image and two composite ISAR images of a fiberglass sample. The two composite images were created using 8 and 360 single-azimuth ISAR images. The images used to form each composite image were uniformly distributed in the full range of azimuth angles, i.e. 0° to 360°. In the traditional ISAR image it is difficult to distinguish between the fiberglass sample and the mounting apparatus. As more images are added to the composite, the sample and its features begin to stand out.

![Figure 3. Single ISAR image of a sample (left), composite ISAR images of a sample created by compositing 8 images (middle) and 360 images (right).](image)

While the composite ISAR images show a qualitative contrast between regions with and without defects, there is a need for a way to evaluate quantitatively the effectiveness of the compositing algorithm, the polarization channels, and of the terahertz NDT technique in general.

A contrast quantification algorithm has been developed which allows a user to draw a box on the composite image specifying the known location of a material defect. The user can also set the dimensions of a larger box drawn around the smaller box. The software then compares the pixels inside the smaller box to the pixels that are exclusive to the larger box.

The purpose of this calculation is to establish a numerical score for how well a material defect shows up for a specific imaging approach. If the defect shows up well in the image where a defect is known to be, then the pixels in the inner box will produce a different value than the pixels in just the outer box (i.e. there will be high contrast between defect pixels and surrounding background pixels).

The method involves plotting two histograms of the values of the pixels in the two regions. A cubic spline function is applied to the two histograms, and the area under each spline curve is calculated using the Bode rule (also known as Boole’s rule) and is normalized to one. The area of overlap of the two histograms is then determined and used as a measure of the contrast, called a defect imaging score. A defect imaging score of one indicates that the two histograms lie completely on top of each other and there is no contrast between the two pixel regions. A defect imaging score of zero indicates that the two histograms have no overlap and there is significant contrast between the two pixel regions. This scoring method has the advantage that it produces a defect imaging score that is unitless, independent of the size and magnitude of the defect, and always between zero and one.

To test the histogram scoring method, test images were created by directly assigning pixel values to an inner and outer region of a small image. The pixel values were determined by assigning to each region a base pixel value and then applying Gaussian noise to each region. Figure 4 contains an example image where the inner region of pixels is clearly more intense than the outer region. Figure 5 also shows the histogram cubic spline fits for the inner and outer regions used to determine the score. Similarly, Figure 5 contains the same information for an image where there is little difference between the pixels in the inner and outer regions.
The bins of the histogram plots were kept constant throughout the investigation. The magnitude parameters (HH, HV, VH, VV, and $m$) were all investigated using a histogram with 500 evenly spaced bins spanning a range from -80 to 20 dBsm. The bins for the angle Euler parameter histograms were all 0.25° in width and spanned the full range of each Euler parameter.

2.2 X-ray imaging

Fiberglass samples were imaged using a PX 10.10 Non-Palletized Freight commercial x-ray system, developed by L3 Communications, shown in figure 6. Each sample was placed on the system’s conveyor belt such that the inspection surface was facing the 160 kVp x-ray source. The system measured the transmission of x-rays though the sample, and produced images using the transmission data.
2.3 Fiberglass samples

Four fiberglass samples were included in this study. These fiberglass samples each contained several defects that are representative of defects that would be found in wind turbine blades.

Sample number 1 was provided by Sandia National Labs and contains multiple resin dry patches and out-of-plane material wave defects of various sizes and located at various depths. Figure 7 contains a photograph and schematic of sample 1.

Sample number 2 was provided by TPI Composites Inc. and contains multiple out-of-plane material wave defects. Some of these wave defects have fibers bending out of the body of the sample, and these are designated “convex” material wave defects. Other material wave defects have fibers bending into the body of the sample and these are designated “concave” wave defects. There is also a discontinuity in sample thickness between the defect region and a thin region in sample 2. This thickness discontinuity should show up clearly in the images. Figure 8 contains a photograph and a defect schematic of sample 2.
Sample 3 was also provided by TPI Composites and contains three out-of-plane wave defects. These three defects are smaller than those in sample 2 and are each convex material wave defects. Figure 9 contains a photograph and a schematic of sample 3.
The fourth sample was provided by Sandia National Labs. It contains four out-of-plane wave defects and six resin-dry regions of various sizes. It is a sibling of sample 1, as both samples 1 and 4 were created using the same schematic. Despite sharing the same original schematic, the two samples still differ physically. Of particular note is a large surface defect on sample 4. Figure 10 contains a photograph and a schematic of sample 4.

![Figure 10. Photograph and schematic of sample 4. The green objects along the top of the schematic are resin dry patches, increasing defect thickness from left to right. The grey objects are wave defects of various depths. The green objects along the top of the schematic are resin dry patches, increasing defect thickness from left to right. The grey objects are wave defects of various depths. See Sandia National Labs’ report for more information.](image)

### 3. RESULTS AND DISCUSSIONS

#### 3.1 Terahertz ISAR

Generally, the single-azimuth ISAR images do not reveal any defects by themselves. The composite ISAR images are more effective at producing contrast between defect and defect-free regions and therefore composite ISAR images will be the focus of this manuscript.

All of the composite ISAR images included in this section were created using 360 traditional ISAR images. The azimuthal angles for these traditional ISAR images ranged from 0° to 359° in steps of 1°. A dashed brown box indicates the locations of the fiberglass samples within each composite ISAR image. The rest of the image content located outside of the brown box is part of the sample mounting apparatus. A defect schematic of the sample present in the ISAR image is included alongside the ISAR images.

Sample 1 was imaged in the 160 GHz radar range. Data were collected for a full range of azimuths and across a bandwidth greater than 10 GHz centered on 100 GHz, and used to generate ISAR images. Figure 11 is a composite ISAR image for sample 1 for HH polarization and at 25° elevation. This image is representative of all composite ISAR images created for sample 1.
In figure 11 there is a noticeable region of brighter pixels near one of the wave defects. This defect is one of the larger wave defects in this sample. This defect is also the defect closest to the inspection surface. This suggests that the 160 GHz radiation is not achieving deep penetration through the fiberglass material, and is only reaching surface defects.

Samples 2-4 were each tested in the 100 GHz radar range. Each sample was imaged at elevation angles of 30°, 45°, and 60°. Data were collected for a full range of azimuths and across a 16 GHz bandwidth centered on 100 GHz, and used to generate ISAR images.

Several of the wave defects in sample 3 are visible in the composite HH polarization ISAR image, as shown in figure 12. All composite images in this section were created using 360 single-azimuth ISAR images. The concave wave defects in particular are quite visible in this image.
Composite ISAR images were also created using the Euler parameters. Figure 13 contains a $m$ parameter ISAR image of sample 2. In general, the composite ISAR images for the angular Euler parameters are not as revealing as the traditional polarimetric ISAR images, while the $m$ parameter is typically better at producing contrast between defect and defect-free regions than the traditional polarization images.

Composite ISAR images were also generated at 45° and 60° elevation. Figure 14 contains $m$ parameter ISAR images for sample 3 at 45° and 60° elevation.
Many types of ISAR images were created for sample 3. Samples 4 through 6 received the same treatment, with multiple types of images being created. The $m$ parameter composite ISAR image consistently produced the best defect/defect-free region contrast for all samples. Figures 15 and 16 contain $m$ parameter composite ISAR images for samples 3 and 4 at 30° elevation.
The three wave defects in sample 3 are not easily visible in figure 15. There is a diagonal region of contrast in the approximate area of a wave defect in the schematic, but there is not very strong contrast by eye.

Several of sample 4’s defects are visible in figure 16. The large vertical line of bright pixels is not a subsurface defect, but is an unintended surface defect. To the left of that line is a region of bright pixels that correspond to the same wave defect that was visible on sample 1 in figure 11. There is also a region of brighter pixels corresponding to the second resin defect from the right. The two rightmost resin defects in the schematic diagram are the thickest resin defects in the sample, and therefore the closest resin defects to the surface. This suggests that the 100 GHz radiation penetrates the fiberglass better than the 160 GHz radiation, but is still not reaching the deeper defects.

While these images appear to be able to qualitatively indicate defects, there is a need to quantitatively evaluate the contrast in these images between defect-free and defect-positive regions. Using the histogram scoring algorithm described in section 2.1, the contrast can be quantified. Figure 17 is a composite ISAR image for sample 3 created using 360 ISAR images. The image contains a white box indicating the boundaries of the inner region used to score the defect imaging algorithm, with the outer box (not shown) extending an extra two pixels in each direction. Table 1 contains the results of the score for this particular image and box boundaries. A lower defect imaging score indicates better contrast.
Table 1. Defect imaging scores for a defect in sample 2 using the composite ISAR image created by compositing 360 images. A lower defect imaging score indicates better contrast.

<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>

Figure 17. Sample 2 composite image showing the inner box used to calculate the scores shown in Table 1.

Table 1 indicates that of the 9 different types of ISAR images created, the $m$ parameter image produces the best contrast (lowest score value) between defect pixels and defect-free pixels.

For all of the composite images above, 360 separate ISAR images created at different azimuth angles were composited into a single image. To quantify the improvements offered by the compositing algorithm, different composite images were created using a different number of ISAR images. Figure 18 is a plot of the defect-imaging-score vs number-of-images for the defect box shown in figure 17. The four traditional polarizations and the 5 Euler parameters are included in this plot.
Figure 18. Defect-imaging-score vs number-of-images for the sample 3 defect shown in Fig. 31. A lower defect imaging score indicates better contrast.

While the scores are very inconsistent for a lower number of images, they level out after about 120 images or so. The plot indicates that the $m$ parameter scores the best contrast of the 9 ISAR image types, and offers significant improvement in contrast over the traditional polarizations.

Next, defect-imaging-score vs number-of-images data were generated for multiple defects within samples 2, 3, and 4. Figure 19 shows the inner scoring boxes of all of the visible defects included in the defect-imaging-score vs number-of-images plots. Only the defects that produced noticeable contrast are included in figure 19. The included defects consist of 7 out of the 11 wave defects in sample 2, 1 out of the 3 wave defects in Sample 3, 1 out of the 4 wave defects in sample 4, and 1 out of the 6 resin-dry regions in sample 4.

![Figure 19. Defect scoring boxes for samples 2 (left), 3 (middle), and 4 (right) used to create defect-imaging-score vs number-of-images plots.](image)

To study the overall performance of the technique and the scoring algorithm, the results for each of these defect boxes were averaged together. This is possible because the score for each defect is unitless, independent of the absolute values of the pixels, and only depends on the relationship between the pixels in the inner and outer regions. The normalization of the histogram curves to 1 also makes the scores independent of the sizes of the scoring boxes. For these reasons, the
scores can be averaged together within the 9 separate types of ISAR images. Figure 20 is the resulting defect-imaging-score vs number-of-images plot for the averages of all the scores of the defects shown in figure 19.

Figure 20. Defect imaging score, averaged over all defects shown in Figure 19, vs the number of images composited for each of the 9 types of ISAR images. A lower defect imaging score indicates better contrast. These results add quantitative evidence to the observation that the $m$ parameter composite ISAR images consistently produce the best contrast, and therefore the best imaging of defects. Interestingly, the VV polarization composite ISAR images score better than the other 3 traditional polarizations. Figure 20 also demonstrates quantitatively that the compositing algorithm significantly improves defect detection.

3.2 X-ray Imaging

Fiberglass samples 2 through 4 were imaged a PX 10.10 MX Non-Palletized Freight x-ray system developed and operated by L3 Communications. Figures 21 through 23 contain the respective x-ray images alongside defect schematics for each of the fiberglass samples.
Figure 21. X-ray image, defect schematic, and photograph of sample 2.

Figure 22. X-ray image, defect schematic, and photograph of sample 3.
Nearly every defect in all three of the samples using the x-ray system is visible in these images.

4. CONCLUSIONS

Both terahertz and x-ray radiation has been proven capable of detecting several subsurface defects in fiberglass materials. The 100 GHz frequency system appeared to be more successful at indicating subsurface defects than the 160 GHz frequency system. The x-ray system was able to produce clear contrast between defect and defect free regions. Although unable to detect every defect, out-of-plane fiber wave defects and resin dry regions have been shown to be detectable via terahertz ISAR data collection.

Traditional ISAR data processing alone was not sufficient to produce terahertz ISAR images with enough contrast for defect detection. The single-azimuth ISAR images rarely produce any images where defect contrast is present, and even then the contrast is minimal. The image compositing algorithm developed in this study offers significant improvements in defect detection over traditional single-azimuth ISAR images. This claim is supported qualitatively from the images themselves, and quantitatively from the defect imaging score data.

Additionally, the Euler m parameter has been shown to produce the best contrast between defect and defect-free regions in the images generated in this study. The m parameter consistently outperformed the traditional polarizations used in the radar field, as well as the other four Euler parameters. This significant improvement over any of the traditional polarizations reveals the benefit of not only utilizing a fully polarimetric system for nondestructive evaluation, but also using the optimized Euler transform on the polarimetric scattering data.

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