Imaging System for Non-Destructive Testing of Glass Fibre Reinforced Plastics

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Abstract
A new testing method for composite materials was investigated in this paper. A synthetic aperture radar (SAR) in the W-Band from 75 to 110 GHz served as imaging system. The lateral resolution is around 3.0 mm and the range resolution around 4.3 mm. The system was tested with five glass fibre reinforced plastic (GFRP) samples that have several flat bottom holes to represent defects. The defects were detected with magnitude and phase images. Since the reconstruction returns a 3-D image of the sample also the time-domain data was examined in magnitude and phase. Using the phase and magnitude information together all defects were detected.

Keywords: Electromagnetic Testing, Glass Fibre Reinforced Plastics (GFRP), Millimetre Waves, Non-Destructive Testing, Synthetic Aperture Radar

1. Introduction
Composite materials are widely used in modern aircraft. The non-destructive testing of these materials with conventional test methods is very challenging. This paper presents a new technique based on millimetre-waves. In the frequency region between 30 and 300 GHz glass fibre reinforced plastics (GFRP) are semi-transparent and therefore tomographic imaging can be applied [1] [2]. Defects of interest are delaminations or voids inside the composite material. Both type defects add an additional boundary surface, i.e. an additional reflection of the millimetre-waves that can be detected.

2. Test Setup
The utilised system is based on radar. For conventional radar systems the lateral resolution \(\delta_x\) depends on the size of the antenna aperture \(a\) and the wavelength \(\lambda\):
\[
\delta_x \propto \frac{\lambda}{a}
\] (1)

For small defects a high resolution is necessary therefore a very large aperture or a very small wavelength would be needed. To overcome this problem, a so called synthetic aperture radar (SAR) is used. The coherent radar signal is measured at different positions on a path perpendicular to the image plane. The software reconstruction of the measured signals leads to a 3-D image of the measured scene [3]. The lateral resolution depends on the wavelength \(\lambda\), the length of the synthetic aperture \(L_x\) and the distance between antenna and object \(R\) [4]:
\[
\delta_x \propto \frac{\lambda}{L_x R}
\] (2)

The test setup used for the measurements presented here, has a lateral resolution of approximately 3.0 mm.
The range resolution is given by

\[ \delta_z = \frac{c}{2B} \]  

(3)

where \( c \) is the speed of light in the medium and \( B \) is the used bandwidth. Resulting from a bandwidth in the W-Band (75 to 110 GHz) of 35 GHz the range resolution is approximately 4.3 mm in vacuum.

### 2.1 Samples

For testing the capabilities of the system for defect detection, five planar GFRP samples with flat bottom holes were measured (samples 1 to 5). These holes have different diameters (5, 10, 15 and 20 mm) and different depths from 0.5 to 14.5 mm. With the overall thickness of the composite plates of 15.0 mm, the residual wall thicknesses are between 0.5 and 14.5 mm as can be seen in Table 1. All holes in a row have the same diameter and in a column the same depth. The refraction index between 75 and 110 GHz was approximately 2.15 and the absorption between 1 and 2 cm\(^{-1}\). The resulting depth of penetration is between 1 and 2 cm. Since the range resolution in equation (1) is determined by the speed of light in the medium, the range resolution inside the sample is around 2.0 mm.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Residual wall thicknesses in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>6.0</td>
</tr>
<tr>
<td>4</td>
<td>9.0</td>
</tr>
<tr>
<td>5</td>
<td>12.0</td>
</tr>
</tbody>
</table>

### 3. Results

All samples were measured with the described SAR system. The samples were attached to a metal plate for a fixed reference reflection on the back side. First the average of magnitudes was examined.

#### 3.1 Average of Magnitudes

The magnitude information at one frequency can give deficient results for defect detection. The image has lots of interference patterns and some artefacts from the reconstruction algorithm. To resolve this problem it is best practise to take the average of all measured magnitudes. Due to the reflection on the surface of the samples the signals from the deep defects underneath can hardly be seen in an averaging image of the magnitude. But defects can close to the surface are visible.

Figure 1 shows the average of magnitudes of 201 frequencies of the sample 1 with the deepest holes (12.5 – 14.5 mm) and therefore with the smallest residual wall thickness (0.5 – 2.5 mm). The defects with the large diameters (20 mm) in the lowest row can be clearly identified. The smaller holes in the upper row (5 mm) vanish in the averaged image. Sample 2 behaves the same as Sample 1. Sample 3 is shown in figure 2 with residual wall thicknesses between 6.0 and 8.5 mm. The defects in the first row and some in the second row cannot be seen and also the defects in the
5th and 6th columns disappear. This is caused by the destructive interference between the reflections of the surface and the defect and the multiple reflections of the defect itself. There is also some fringe pattern present in all images resulting from the reconstruction algorithm. The signals of the defects in sample 4 and 5 are too weak to be clearly detected.

3.2 Phase Information
Another way of identifying the defects is evaluating the phase information. Since there are 201 measured frequencies one could look at every of these phase images. But most information can be seen around the middle frequency of the used bandwidth; here 92.5 GHz. Figure 3 shows the phase of the sample 1 with the deepest holes. The edges of nearly all defects can be identified due to the edge diffraction. The flat part of the holes can only be seen for some defects. One reason is the interference of the reflected signal with the surface signal. This can be resolved by looking at another frequency, where the interference occurs at other path lengths. Sample 2 is shown in Figure 4. The upper row is not visible anymore, because the reflected signal is too small to change the phase information of the main reflection from the surface. At the Samples 3 to 5 the defects can no longer be detected because the reflected signal from the defects is too weak.

3.3 Time-Domain
Since the reconstruction algorithm returns a full 3-D image. It is possible to take a look inside the samples. Figure 5 shows a slide through sample 1 at y = 240 mm directly through the large defects. The surface reflection at around 175 ps is clearly visible. Also all six defects can be seen and the multiple reflections underneath the defects. At around 275 ps is the
reflection of the metal plate on the back side of the sample. The Samples 2 and 3 show quite similar results to Sample 1. Sample 4 is shown in figure 6. The defects can be seen but the detection becomes difficult. At Sample 5 the range resolution becomes too small to separate all defect reflections from the reflection of the metal plate at the back side of the sample.

Figure 7 shows a cut through a time slide at 243 ps at sample 2. The defects in the first two columns nearly disappear because they are located earlier in time. The defects in the first row appear later in time because their signals get more diffracted by the edges of the small hole. Therefore their electrical path length is longer.

Sample 5 with the thickest residual wall thicknesses between 12.0 and 14.5 mm is shown in figure 8. It is the same time-slide as the reflection of the metal plate on the back side at 300 ps. The defects in the first four columns are only visible as shadows because most of the signal was reflected already in the defect in a time slide before. The last two columns also show the reflection of the flat surface of the hole. All defects can be identified because of the edge refraction that can be seen as shadow around each hole.

3.4 Phase and Time-Domain
To improve the defect detection it is possible to combine the time-domain information with the phase information. The brightness of the image is defined by the magnitude and the colour is defined by the phase. With this method even the smallest and most shallow defects in
sample 5 of row one can be identified as can be seen in figure 9. The different depths of the holes are represented by different colours. The edges of the defects are marked by a dark ring around the hole due to the edge diffraction.

4. Conclusion
The presented synthetic aperture imaging system in the W-Band (75 to 110 GHz) is capable of detecting flat bottom holes in glass fibre reinforced plastics. The magnitude and phase information enabled the detection of holes with residual wall thicknesses up to 7.5 mm. By using the phase and time-domain information it was possible to detect all hidden defects with residual wall thicknesses up to 14.5 mm. The lateral resolution enabled the detection of defects with diameters of down to 5 mm. The next step is extending the system capabilities for detecting cracks in the material.

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References