Full Polarimetric THz Imaging System in Comparison with Infrared Thermography

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Abstract
A synthetic aperture imaging approach is used to detect artificial defects in glass fibre reinforced plastics. To detect anomalies even very close to the backside of the samples a full polarimetric radar system was used. It is shown, that the system is capable to detect all defects even in 14.5 mm depth and only 0.5 mm away from the backside. To compare the results with a conventional test system the samples were also evaluated with pulsed infrared thermography, which was not able to detect all the defects.

Keywords: Electromagnetic Testing (ET), microwave, Terahertz, Infrared Testing (IRT), cross-polarization, synthetic aperture, co-polarization

1. Introduction
The non-destructive testing of glass fibre reinforced plastics (GFRP) and other composite materials is challenging for most of the conventional NDT test methods [1]. Especially very deep buried defects and defects close to the backside surface of the samples are very hard to detect with traditional methods [2], [3]. This paper presents an imaging system for defect detection using millimetre or THz-waves, which enable a three dimensional reconstruction of the sample under test. To enhance defect detection the system uses a full polarimetric radar approach.

2. Test Setup
The system uses a synthetic aperture radar in the W-Band ranging from 75 to 110 GHz and operates at a distance of around 25 cm between the antennas and the sample. To get more information about the sample a full polarimetric measurement is processed. That means that both co-polarization states, linear vertical (VV) and linear horizontal (HH) polarization are measured. Furthermore the cross-polarization (HV) which emits at linear vertical polarization and receives at linear horizontal polarization are measured and evaluated. To generate the different polarizations the rectangular waveguides attached to the conical horn antennas was rotated.

2.1 Resolution
The utilised system is based on a stepped FMCW radar system. For conventional radar systems the lateral resolution $\delta_x$ depends on the size of the antenna aperture $a$ and the wavelength $\lambda$:
For small defects a high resolution is necessary therefore a very large aperture or a very small wavelength would be needed. The first solution becomes very bulky and the second is limited by the increasing absorption and available sources.

To resolve 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 as shown in figure 1. The software reconstruction of the measured signals leads to a 3-D image of the measured scene [4]. To further enhance the signal to noise ratio a so-called quasi monostatic geometry is used, where the transmit and receive antennas are positioned very close to each other.

The lateral resolution depends on the wavelength $\lambda$, the length of the synthetic aperture $L_x$ and the distance between antenna and object $R$ [3]:

$$\delta_x \propto \frac{\lambda}{L_x} R$$

(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 of the system. 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 and increases inside the GFRP, where it reaches around 2.1 mm.
2.2 Cross-polarization

The cross-polarization (HV) receives nearly no signal from surfaces boundaries like the front or the backside of the sample, whereas most defects have a strong response in the cross-polarization signal, especially if they have features at angles that differ from 0° or 90° regarding to the transmitted polarization. This enhances the contrast of defects near the surfaces especially near the backside of the samples, which are very hard to distinguish from the surface reflection in the co-polarization signal. This effect follows the polarimetric scattering matrix $S$ of a dipole which is a coarse approximation for every edge. The scattering matrix describes the behaviour of a radar target for different incoming and outgoing polarizations. For a dipole scatterer the polarimetric scattering matrix $S$ equals to:

$$
S = \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix} = \sqrt{\sigma} \begin{bmatrix}
\cos^2 \gamma & \frac{1}{2} \sin 2\gamma \\
\frac{1}{2} \sin 2\gamma & \sin^2 \gamma
\end{bmatrix}
$$

(4)

With $\sigma$ denoting the radar cross section as a geometrical constant and $\gamma$ the angle between the dipole and the incoming wave. Obviously for angles of 0° and multiples of 90° no signal is scattered in the cross polarization $S_{HV}$ and $S_{VH}$ but it reaches a maximum at angles of 45°, 135°, 225° and 315° respectively.

2.3 Calibration

The calibration for the co-polarization is done with a standard TOSM calibration at the plane of the rectangular waveguide with the vector network analyser. The imaging system is then calibrated by a reflect standard and empty space measurement. For the co-polarization the reflect standard is realized by a metal plate and for the cross-polarization a dihedral at 45° degrees. Since it is very difficult to place the metal plate and the phase centre of the dihedral at the same position, a coherent superposition of the different polarizations was not possible.

3. SAR System Results

For testing the capabilities of the system five samples of GFRP with 43 layers of woven fabric with a thickness of 15 mm were measured. From the backside several blind holes were drilled to simulate defects in the samples. The defects have four different diameters of 5, 10, 15 and 20 mm and the depths range from 0.5 to 14.5 mm leading to residual wall thicknesses from 0.5 to 14.5 mm respectively.

3.1 Co-Polarization

For the samples with defects in depth of 0.5 mm to 12 mm (measured from the backside) it is quite easy to detect the defects in the different planes in time-domain images. Figure 2 (a) shows a time slice at 514 ps of sample 3. The residual wall thicknesses are 6.0 mm to 8.5 mm from left to right. Most defects can be identified only the small diameter holes in the top row are hard to detect. Figure 2 (b) shows the corresponding time-domain image at $y = 250$ mm. The defects are clearly visible at 486 ps and 514 ps. The dominating signal is the reflection from the front surface at 343 ps.
Figure 2. (a) Combined co-polarization image (HH+VV) at a time slice at 514 ps of Sample 3 with residual wall thicknesses from 6.0 mm to 8.5 mm from left to right. Most defects are clearly visible.

(b) Time-domain image of sample 3 at y = 250 mm. The strong reflection from the surface of the sample at 343 ps dominates the image. The defects appear at 486 ps and 514 ps close to the backside of the sample at 542 ps.

In figure 3 (a) the time-domain image of the magnitudes of both co-polarizations (HH+VV) is shown at 514 ps. Most defects can be identified, but there large unwanted signals from the backside boundary of the sample. In Figure 3 (b) shows the corresponding time-domain cut at y = 250 mm. The strong reflection from the surface of the sample at 343 ps is dominating the image. The defects are visible mainly because of their shadows from the edge scattering since the range resolution is not high enough to distinguish the backside boundary from the defects.

Figure 3. (a) Time slice at 514 ps of Sample 5 with residual wall thicknesses from 12.0 mm to 14.5 mm from left to right. Most defects are clearly visible, but there is also a lot of signal from the backside of the sample.

(b) Time-domain image of sample 5 at y = 250 mm. The strong reflection from the surface of the sample at 343 ps dominates the image. The defects appear mainly in the same time slice as the backside of the sample at 542 ps.
3.2 Cross-Polarization

The contrast enhancement due to the evaluation of the cross-polarization is shown in figure 4 (a), where the time-domain image at 629 ps in cross-polarization (HV) is depicted. The signal from the backside of the sample nearly vanishes and only the scattering from the edges especially at the angle of 45° and multiples of it are visible. The corresponding time-domain cut is shown in figure 4 (b). The strongest signal comes from the defects at around 629 ps, whereas the signal from the surface of the sample at 429 ps is in the same magnitude range. The reflection from the backside boundary is quite low compared to the defect signals which results in the high contrast of the defects.

![Figure 4. (a) Time slice at 629 ps of Sample 5 with residual wall thicknesses from 12.0 mm to 14.5 mm from left to right. Most defects are clearly visible, especially the corners of the holes.](image)

(b) Time-domain image of sample 5 at y = 250 mm. Strong reflection from the edges of the holes. The signal from the surfaces of the sample at 429 ps and 629 ps are not the dominant part compared to the co-polarization.

4. Infrared Thermography Results

With the infrared pulse thermography the defects close to the surface could be detected very well. But with depth of more than 6 mm is becomes very difficult, because the heat can distribute all over the thick sample, as can be seen in figure 5 (a) in the amplitude image and in figure 5 (b) on the phase image. The defects deeper than 9.0 mm in the samples 4 and 5 could not be detected.

![Figure 5. (a) Thermography amplitude image with 2 Hz of sample 3; with residual wall thicknesses from 6.0 to 8.5 mm from left to right.](image)

(b) Thermography phase image at 2 Hz of sample 3.
5. Conclusion

The presented system using a synthetic aperture imaging approach in the W-Band (75 – 110 GHz) was capable to detect very deep defects in the GFRP samples, in contrary to pulsed thermography. With the full-polarimetric processing it is also capable to detect defects very close to the back surface of the samples. The system was able to detect holes with diameters of only 5 mm in a depth of 14.5 mm of GFRP.

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References


