All-Electronic 3D Terahertz Imaging for the NDT of Composites

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Abstract. We investigate the use of all-electronic Terahertz (THz) / Millimeter wave imaging for the non destructive testing of foam materials and glass fiber composite samples intended for several applications, for instance in the aerospace industry.

Introduction

The increasing use of novel materials and production technologies increase the demand for new non-destructive testing solutions. Terahertz and millimeter-wave imaging (THz imaging) is a novel measurement technique, which can serve both application fields. In the past however, THz imaging was not mature enough to fulfill the numerous industrial and commercial needs. The main limitation was a limited dynamic range leading to a too long image acquisition time. Using all-electronic FMCW technology, we overcome the limitations and present results using a table-top turn-key measurement system which fulfills the needs of scientific and industrial material-testing institutions.

Terahertz and millimeter waves are fully harmless electromagnetic waves (similar to radio waves) in the frequency range from 100 GHz to 10000 GHz (= 10 THz). These waves can penetrate dielectric or non-conducting materials like plastics, ceramics, paper, cardboard, wood, cloth etc. Hence, THz imaging can show the inside of various objects and structures, of hidden or buried interfaces, surfaces or layers. Metallic or conducting surfaces reflect the waves, so that in case of metals and for instance carbon fiber composites (CFRP) only a surface inspection can be performed.

In this paper we concentrate on recent results using FMCW Terahertz imaging for the non-destructive testing of composites and foams.

Figure 1: Photography of a sandwich test sample (left) and 3D visualization of the corresponding THz data (right), clearly showing the whole structure, including the glue layers.
Measurement Setup

The used all-electronic 3D Terahertz (or millimeter wave) imaging system is the commercially available SynViewScan system, which includes the FMCW range profile measurement head SynViewHead. It typically operates in two frequency ranges, 60-110 GHz (SynViewHead 100) and 230-320 GHz (SynViewHead 300). Higher frequencies are available, but most materials are not transparent at higher frequencies. A SynViewHead achieves a uniquely low measurement time of only 100 µs for the full range measurement, i.e. depth profile, with a dynamic range of better than 25 dB. By increasing the measurement time to 100 ms per pixel, a dynamic range of better than 70 dB is achieved. Using the SynViewScan which combines the mechanical translation of the SynViewHead with a powerful software to generate 3D Terahertz images with an extraordinary dynamic range of better than 60 dB. A photograph of the SynViewScan and the SynViewHead is depicted in Figure 2.

The all-electronic SynViewScan 3D Terahertz / Millimeter wave imaging system is a full table-top unit which scans an area of 650 by 650 mm in approximately 15 minutes in which the full 3D tomographic information is acquired. Using the SynViewHead 300, a spatial resolution of 1 mm and a depth resolution of approximately 10 µm for a single interface is achieved. Individual layers or interfaces can be separated if their spacing is larger than approximately 1 to 2 mm. The data acquisition software allows the calculation of both the absolute range information and the signal phase (with respect to the mean frequency).

For industrial application, it is possible to combine several SynViewHeads, e.g. by building a phased array and a synthetic aperture radar approach. In this case, due to the very short acquisition time of the SynViewHead, it is possible to measure larger objects in seconds or even in video rate.

A typical measurement example is shown in Figure 1. To demonstrate the image quality of composite structures, we fabricated a test sample out of various TEFLOX and TPX-plastic plates glued onto a SYRODUR foam plate. As glue we used dark wax. Defects in the foam were simulated by drilling two holes in the side of the foam. A photo of the fabricated sample and the corresponding 3D visualization of the THz data, measured in reflection mode from the bottom side, are shown in Figure 1. The data shows that all interface layers of the sample can be extracted and analyzed separately. Therefore, it is for example possible to study the homogeneity of the glue and to find air gaps at the interfaces or inside the foam.
Other typical examples are the measurement of a coating thickness, package inspection, the evaluation of security applications (body scanners), the non-destructive testing of ceramics, and many more.

NDT OF COMPOSITES AND FOAMS

As mentioned before, the SynViewScan typically operates in two frequency ranges, 65 to 110 GHz or 230 to 320 GHz. In the case of glass fiber composites (GFC), even 300 GHz is fully absorbed within a few millimeters of GFC. Hence, the GFC structures are evaluated using the 65 GHz to 110 GHz range, leading to a penetration depth of about 2 cm and a spatial resolution of about 3 mm. The foam structure is measured in the 230 to 320 GHz range, i.e. using the SynViewHead 300, leading to a spatial resolution of 1 mm.

The first example is a sample consisting of foam material attached to a 5-mm thick aluminum plate and is shown in Figure 3. Two small slits of 1 mm and 2 mm width were artificially introduced in the area of the metal – foam interface. As can be seen in Figure 3, the foam is very transparent for the Terahertz / Millimeter waves, while the metal plate is a strong reflector. Hence, there is a strong reflection from the metal to which the reflected signal of the defects adds. The slits can clearly be seen in the Terahertz image. Due to the range information gained by the SynViewScan system, the height position of the defects can also be identified.

![Figure 3: Top and middle: photograph of a foam sample as potentially used for instance in aerospace environments. Bottom: Terahertz reflectivity image. The incorporated defects can clearly be identified.](image)

One example in the area of non-destructive testing of GFRP samples is the search for a debonding of the individual glass fiber layers. Sometimes in the production process the layers are moved against each other and defects called “bucklings” occur. Such a “buckling”
All defects can be easily detected by finding “the black spot”. Please note that the measurement is performed from the top side of the sample. The defect cannot be seen by eye-inspection from the top side of the sample, because the top layer stays flat, as can also be seen in the photograph of the side view. The GFRP plate with several of these buckling defects has a size of app. 45 cm by 60 cm and a thickness of app. 2 cm. It was characterized in reflection geometry from the top side using the SynViewScan system in about 15 minutes. By evaluation the THz 3D data set layer by layer, it is not only possible to detect defects but also to identify in which layer, i.e. sample height position, the defect occurs. As expected, in the layer of the “buckling” defect, a significant change in the THz image occurs. Probably due to scattering, a dark spot shows in the THz image, as can be seen in

Figure 4: Top row: Terahertz imaging results; bottom row: photographs of glass fiber composite samples with delamination defects. All defects can be easily detected by finding “the black spot”. Please note that the measurement is performed from the top side of the sample.
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SUMMARY

In summary, we have demonstrated the capability of fast all-electronic 3D THz tomographic imaging for non-destructive testing of foams and composite materials. Using FMCW imaging technology, high-quality images are obtained with very short acquisition times. In addition, the flexible implementation options of the used SynViewHead allow a customization for each specific application, e.g. mobile solutions or production line applications.