Space Terahertz Instrumentation for Integrity Inspection of Non-Conducting Composites

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Abstract. In this article we describe the results of reusing THz and MWW instrumentation initially developed by NOVA Netherlands Research School for Astronomy for ground-based mission, such as ALMA (Atacama Large Millimetre Array) for non-destructive inspection goals. Several pilot projects have been defined together with industry to study the advantages and limitations of applying Terahertz radiation for non-destructive testing of non-conducting composite materials, such as glass fibre, ceramics, insulation foam as well as for identification of areas rich of resin, integrity testing of adhesive layers, etc.. To generate THz radiation, a quasi-optical single port vector network analyser is built covering the frequency range from 100 GHz till 600 GHz with signal to noise ratio of about 60 dB and spatial resolution of about 3 mm. The described set-up allows us to obtain phase, amplitude, time-of-flights, group delay 2D and 3D THz images that provide us the comprehensive information about the size(s) and depth(s) of the defects under investigation. The obtained results indicate that, indeed, THz radiation is a very promising inspection technique that opens a discussion about introducing a new THz standard along with other existing NDT standards, defined for ultrasonic inspection, acoustic emission, X-ray and IR.

Introduction

There is an established trend in aerospace and marine industry that metallic parts are replaced by composite structures, such as solid laminates of glass fibre and aramid fibre in epoxy resin, or sandwich structures using a core in honeycomb or Rohacell. It implies that instead of identifying corrosion in metallic construction, there is a need to detect new types of defects, such as porosity, delamination, etc., in modern materials, such as composites. To do so, novel non-destructive (NDT) methods are required. Terahertz (THz) inspection is one of them.

Terahertz instrumentation is originally designed to deal with cosmic radiation with a very high frequency from 100 GHz till 3 THz and was initially developed for space missions, such as Herschel Space Observatory launched by ESA in 2009 and international ground based missions, such as ALMA Atacama Large Millimeter Array. These missions
are designated to investigate for, example, the birth and death of stars, research physics of the cold Universe and directly image the formation of planets.

Besides astronomical research, Terahertz instrumentation has also great potential in inspection of composite materials. Such for example, Terahertz non-destructive testing method was born on the technological arena after NASA Columbia Shuttle Catastrophe in 2003. The fatal accident was caused by the detached foam from fuel tank. Apparently, the conventional NDT techniques at that time were unable to detect the integrity of the insulation foam [1]. As has been shown in multiple research [1-5], some classes of composite materials, namely non-conducting composites, such as glass fiber reinforced plastic, foam, epoxy, ceramics, balsa wood, Kevlar, etc. that are often used in aerospace and marine industry are transparent in THz frequency range, that makes them perfect for THz inspection. In contrast, the carbon fiber based composites are conductive and highly reflective in THz frequency range. Their reflectivity will depends on fiber orientation and polarization of the incident THz radiation, i.e. on angle between the electrical field vector and fiber direction. Such for example, if the electrical field vector of the incident radiation is parallel to the fiber, then the higher reflectivity is observed. Otherwise, if electrical field is perpendicular to the grid, the lower reflectivity and higher penetration occur. This property of THz radiation behaviour is used to assess various heat damage levels in CFRP materials [1-3]. Terahertz radiation is also used to trace defects in bonded layers, such as the inclusion of air or pollution and the incorrect bonding of the materials (i.e. two materials are attached to each other but not bonded) [6-7].

There are mainly two modalities of Terahertz radiation, namely terahertz pulses in the time domain spectroscopy (TDS) and continuous wave (CW). The behaviour of THz TD waves is similar to ultrasonic waves, with only fundamental difference that THz radiation propagates via composite specimen as an electromagnetic wave and ultrasound as a mechanical wave. It implies that phenomena, such as diffraction, reflection and refraction are valid both for ultrasonic and THz waves. However, it is interesting to note that at higher THz frequencies - on the border with IR - under certain conditions the quantum phenomena, such as entangled photons, might be observed. That opens a revolutionary way of developing quantum images based completely on a new principle, i.e. where one photon interacts with a specimen under test, and another photon - which does not interact with a substance at all - is used to construct the image [8]. To conclude, Terahertz frequency remains the most intriguing and unknown range in the electromagnetic spectrum, where classical and quantum worlds are able to coexist with each other.

In our research we investigate the advantages and disadvantages of re-applying CW THz radiation for detecting internal defects in composites and adhesive layers within a frequency range from 100 GHz till 600 GHz. For this purpose multiple study cases in cooperation with aerospace and marine industrial partners were conducted. In this paper we describe the pilot project particular dedicated to Terahertz inspection of marine composite assemblies.

1. Marine Composite Assembly

A marine composite assembly under test has the following composition (see Fig. 1). The upper layer consists of monolithic glass fiber reinforced plastic (GFRP), followed by a foam as a core material with resin as epoxy, polyester and vinyl ester. The bottom layer is monolithic carbon fiber reinforced plastic (CRFP).
Fig. 1. A marine composite assembly under test, where the upper layer is GFRP, followed by foam attached by epoxy resin to monolithic CFRP hull.

The described marine assembly is scanned by a THz beam as shown in Fig. 2. As a result, reflected THz signals in time and frequency domains are collected and the corresponding amplitude and phase THz images are constructed.

Fig. 2. Terahertz inspection of a marine assembly.

In the described assembly based on the obtained THz data the following defects need to be identified: porosity (voids are trapped between the layers), delamination (two plies are split apart), crack, voids (pores between two plies) and weak bounds (poor quality of the interface between the adhesive and the adhered foam).

2. Terahertz Instrumentation

To generate THz radiation, various CW THz set-up can be built. In our paper we present CW THz set-up operating in a frequency range from 90 till 600 GHz and based on a single port quasi-optical vector network analyzers (VNA), which resembles the set-up built by NOVA to measure the frequency and spatially resolved reflection response of a SiC/Stycast absorption coating for ALMA ground based mission.

For this task we deal with two types of reflectometers, namely Michelson reflectometer operating within frequency range of 610-712 GHz and reflectometer based on directional coupler within frequency range of 90-140 GHz have been used. A detailed
design of a single port reflectometer based on a classical Michelson arrangement - where one arm forms the test port and the other arm provides a beam dump is discussed in [9-10]. Here we briefly recall that as a signal source, e.g. ALMA band 9 x6 warm multiplier assembly - that has 610-712 GHz frequency coverage and 40 microwatt of peak output power - can be chosen and as a detector a Schottky diode (for a frequency range of 420-1100 GHz) or a sub-harmonically pumped superlattice device (for a frequency range of 420-1980 GHz) can be used.

The reflectometer based on directional coupler within frequency range of 90-140 GHz is shown in Fig. 3. A test signal is generated by a Schottky diode multiplier. After passing the waveguide elements it is radiated by means of the horn and focused by quasi-optical lens set-up to the specimen under test. The signal - reflected from the specimen - passes back through the same lens and horn set-up, deviated by a directional coupler and directed to a Schottky diode detector operating as a harmonic mixer. This particular reflectometer enables to achieve a dynamic range of 80 dB without using a cryogenic detector and spatial resolution of about 3 mm. The described THz set-up - that is compact and light - is mounted on a XY scanner to provide 2D images.

![Fig. 3. A single port quasi-optical VNA used in our experiments. Green dashed lines indicate the signal path towards the object, while purple one shows the reflected signal from the object, which is going to the detector through the directional coupler. Diagonal horn and quasi-optical lens focus the signal to sample under test with a spatial resolution of 3 mm.](image)

3. Terahertz Images

The proposed configuration set-up allows us to construct two types of images, amplitude and phase, that provides us the information about the size(s) and depth(s) of the defects under investigation. Amplitude image gives information about the intensity of reflected THz radiation. Phase image provides information about the delay of THz radiation via specimens, and allows us to detect the dielectric properties of the material under investigation. For example, changes in the amplitude and the phase of the THz radiation transmitted via a sample, allow us to characterize its material properties, such as refractive index, absorption coefficient, and thickness.

Below we discuss the obtained THz images which are shown in Fig. 4 and Fig. 5..
Fig. 4. THz signal reflected from marine composite assembly under test at depth of a few millimetres. Lower reflections (depicted as dark blue areas) indicate the presence of the defects and higher reflections (depicted as yellow areas) indicate the ‘0’ defect zone. Reflective tape markers used as reference points are clearly visible at coordinates (230,250) and (370,250) as well.

Fig. 5. RGB image of marine assembly under test with a transparent overlay of THz image in reflection mode. Dashed red line indicates the damage area detected by ultrasonic inspection.
4. Conclusion

In this paper the obtained results confirm again and again that THz radiation can be successfully applied for non-destructive inspection of marine non-conductive composite parts and assemblies. The constructed THz images provide the comprehensive information about the sizes, depths and locations of the defects. Despite the fact that Terahertz technology is accepted in space industry as a certified non-destructive testing method, in marine sector Terahertz remains an emerging technique. This state-of-art opens a discussion about introducing Terahertz inspection standards in marine world as well.

References