PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

ISSN 2081-5891; E-ISSN 2720-5266 **https://promechjournal.pl/**

Research paper

Application of Terahertz Radiation in Non-Destructive Testing of Military-Designated Composite Materials

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Received: July 14, 2022 / Revised: October 31, 2022 / Accepted: November 3, 2022 / Published: December 31, 2023.

2023, 14 (4), 91-102; https://doi.org/10.5604/01.3001.0054.1657

Cite: Chicago Style

Strąg, Martyna, and Waldemar Świderski. 2023. "Application of Terahertz Radiation in Non-Destructive Testing of Military-Designed Composite Materials" *Probl. Mechatronics. Armament Aviat. Saf. Eng.* 14 (4) : 91-102. https://doi.org/10.5604/01.3001.0054.1657

Abstract. The non-destructive testing methods (NDT) are gaining significant attention due to their ability to monitor the objects structure without causing their damage. In recent years, studies focused on NDT have been directed towards imaging with the use of the terahertz (THz) waves. The presented study describes terahertz imaging-based NDT method and testing results on selected military-designated materials with intentionally introduced defects. The main aim of the work was to clearly detect various discontinuities in materials interior and thus, to show the possibilities of the newly developed terahertz-based testing method in transmission mode. The results confirmed high applicability of THz waves for monitoring various materials where each implemented flaw was easily distinguished. Therefore, the presented method looks promising for real applications in everyday practice.

Keywords: non-destructive testing, terahertz radiation, composites, defect detection

1. INTRODUCTION

The development of new materials, elements, or systems used in the military requires the development of tools that will be able to control their proper operation. It is a result of common use of composites that may be weakened by various stresses or defects arising during their manufacturing or lifecycle [1]. Such a state may be very dangerous and can lead to a catastrophic failure of the construction. The most effective prevention tool seems to be the application of non-destructive testing (NDT) methods allowing for a non-invasive assessment of the structure under its working conditions. NDT methods are used to detect and monitor the propagation of surface discontinuities and thickness changes in the material.

So far, the most frequently used NDT methods are based on ultrasound, infrared radiation, X-rays, or eddy current. They allow for detecting discontinuities such as, e.g., delamination, air bubbles, or voids. However, these methods have some limitations which reduce their efficiency. For instance, ultrasounds require direct contact with tested objects, X-rays are harmful for human body, while thermography and optical methods usually are restricted by a very limited penetration depth [2]. Thus, new experimental methods based on the use of terahertz radiation are under development.

Terahertz (THz) radiation is placed between microwaves and infrared radiation, and it corresponds to the frequency range of 0.1 to 10 THz [3, 4] (see Fig. 1). In general, THz technology has been known since the end of the 19th century, however, due to lack of materials suitable for generating and detecting of these waves they did not found application [5]. Nowadays, THz technology is showing rapid growth which relates to access to high-quality THz emitters and detectors.

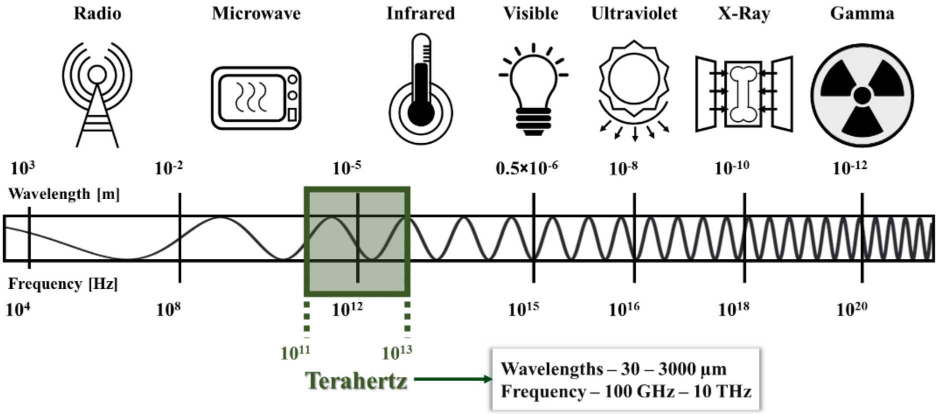


Fig. 1. Electromagnetic spectrum

The THz frequency enables penetrating through non-conductive materials such as ceramics, plastic composites, or polymers [6] and detecting hidden defects. Additionally, THz waves have an advantage over other NDT methods such as, e.g., ultrasounds because it is not required to maintain direct contact with the object under test. Finally, these electromagnetic waves are non-ionising (low photon energy below 4 meV), so they are not harmful to the human body [7]. All these properties make THz potentially useful in many areas such as, e.g., artwork, health, automotive, cosmetics, aerospace, and what is important for us, security. This security refers not only to the ability of THz waves to conceal the detection of prohibited substances or tools but above all to monitor the constructions during their manufacturing and lifecycle. This is especially important in order to protect them from failure being a result of any disturbances appearing in their interior. Such THz waves abilities were presented before [1, 4, 8].

In the frame of this study, the results obtained with the use of terahertz imaging in transmission mode are presented. The investigations were performed on selected specimens that had intentionally introduced defects. A structural inspection was carried out and a potential application was presented.

2. MATERIALS AND METHODS

2.1. Terahertz testing method

In general, the THz testing method is based on simple interaction between the THz wave and the tested object (schematically presented in Fig. 2). To put it simply, the THz wave penetrates through the material. As a result, part of the radiation may be reflected from material or transmitted through it. It is worth noticing here that there is also some part of the radiation which may be absorbed by material, however, in our studies we did not measure a level of the signal loss.

The reflected or transmitted wave is then collected by the proper detectors. Then, the information about internal structure of materials is acquired in a form of the image. Thus, we may consider two configurations of experimental setup using THz waves: reflection in which the THz generator and detector are placed on the same side in reference to the tested object, and transmission in which the THz generator and detector are placed on the opposite sides of the tested object. In our studies, the latter configuration was selected because it provides more information about delaminations, cracks, or water content in the samples interior.

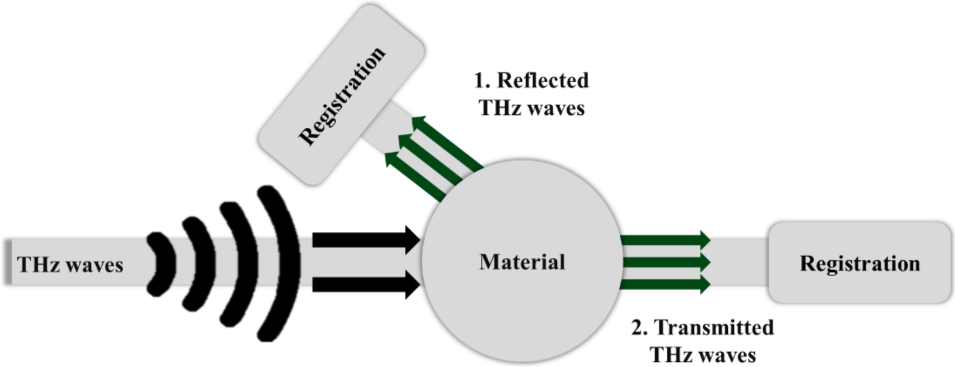


Fig. 2. The idea of terahertz radiation interaction in two configurations (1) reflection, and (2) transmission

The experimental setup was presented in Fig. 3.

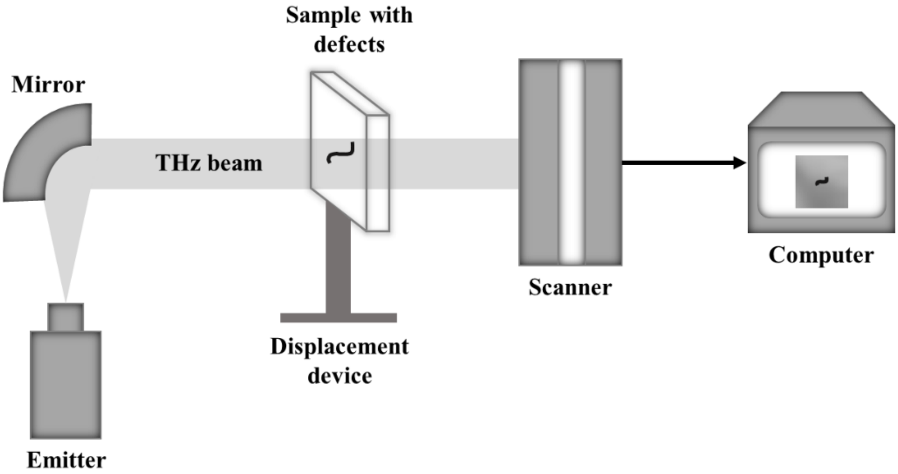


Fig. 3. The schematic representation of the investigation setup in transmission mode

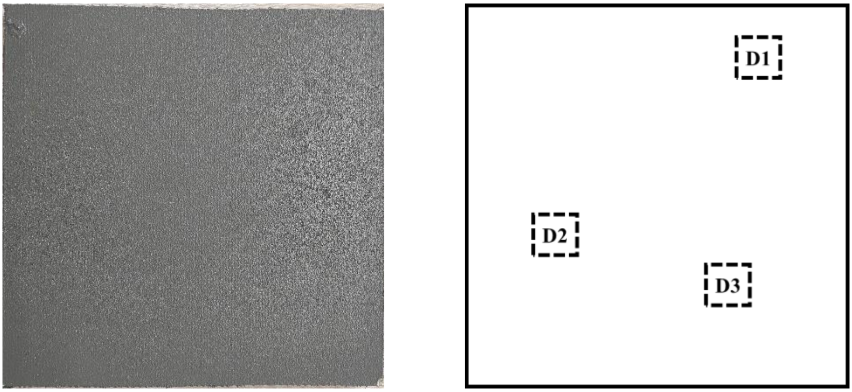
The tests were performed with the use of the instruments from Terasense Development Labs company. The THz source in a form of IMPATT-based THz generator (frequency 292 GHz ±5 GHz and power of ~10 mW) was equipped with novel reflective THz optics based on a specially configured high-gain horn antenna in combination with a metallic mirror. This generator significantly improves the THz imaging capabilities by increasing the amount of power reaching the window of the line scanner called Linear (512 × 1 pixels image resolution with a pixel pitch of 0.5 mm and frequency of ~300 GHz).

The samples were placed on the displacement device which moved along the scanner. The speed of the movement was optimised to ensure the proper shape ratio of samples and to possibly reduce the influence of environment disturbances and it equals 4 cm/s. The data acquired with the use of dedicated software were presented as an image.

2.2. Materials

2.2.1. Aramid fiber-reinforced composite

The first analysed example was aramid fiber-reinforced composite [Fig. 4(a)] which is a material often used for personal protective equipment such as safety helmets [9]. The sample in a form of a flat plate with dimensions 200 × 200 × 10 mm had intentionally introduced defects. The introduced square-shaped defects with dimensions of 10 × 10 mm are marked in Fig. 4(b) as D1, D2, and D3. They had a form of air voids located at different depths below the sample surface. The detailed description is placed in Table 1. It is worth noticing here that the defects had low thickness reaching 3 layers (D1) and 5 layers (D2, D3), thus, each studied defect is thinner than 1 mm.



(a) (b)

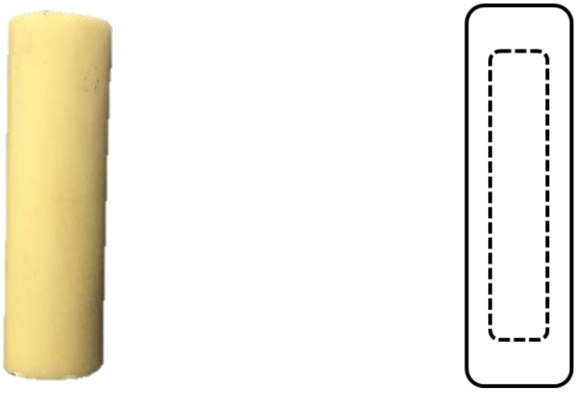
Fig. 4. (a) The outer surface of the tested aramid fiber-reinforced composite, and (b) a diagram showing the distribution of defects D1, D2, and D3

Table 1. The list of locations of defects.

Defect	Location
D1	Between 16th and 18th layer
D2	Between 1st and 5th layer
D3	Between 8th and 12th layer

2.2.2. Imitator of gas generator

Next, the sample manufactured in such a way to imitate a gas generator used in real military applications was taken into consideration. It was assumed to prepare a sample with a geometry similar to a real object and to introduce some commonly observed defects in its interior. The sample had a cylindrical shape with a diameter of 25 mm and a height of 85 mm. Figure 5(a) presents the real sample while Fig. 5(b) indicates the area in which the defects were introduced. Small discontinuities had various sizes and density and they were distributed irregularly in the sample volume. The used fillers were PMMA, talc, and zinc oxide.



(a) (b)

Fig. 5. (a) The outer surface of the tested imitator of gas generator, and (b) a diagram showing the area of defects occurrence

2.2.3. Soft ballistic insert of bulletproof vest

The last investigated case was the sample imitating a soft ballistic insert of a bulletproof vest. The image presenting the smooth surface of the sample is presented in Fig. 6(a). It had dimensions of 200 × 200 ×~8 mm and was covered by black textile. The defect was placed in the central part of the analysed object [see Fig. 6(b)]. It consisted of three aramid layers soaked with water and next foiled to protect the water from evaporation and spilling over.

The chosen foil was transparent for THz radiation. It had dimensions of 50 × 50 mm and was placed below the sample surface at approximately 1/3 of its thickness.

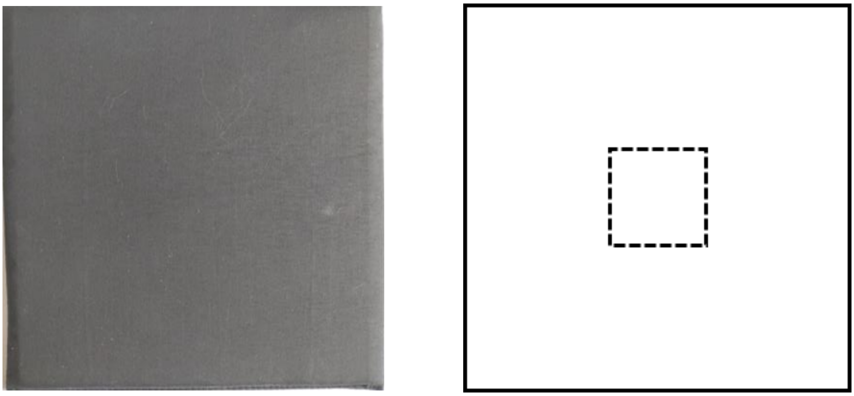

(a) (b)

Fig. 6. (a) The outer surface of the tested soft ballistic insert of bulletproof vest, and (b) a diagram showing the distribution of defect

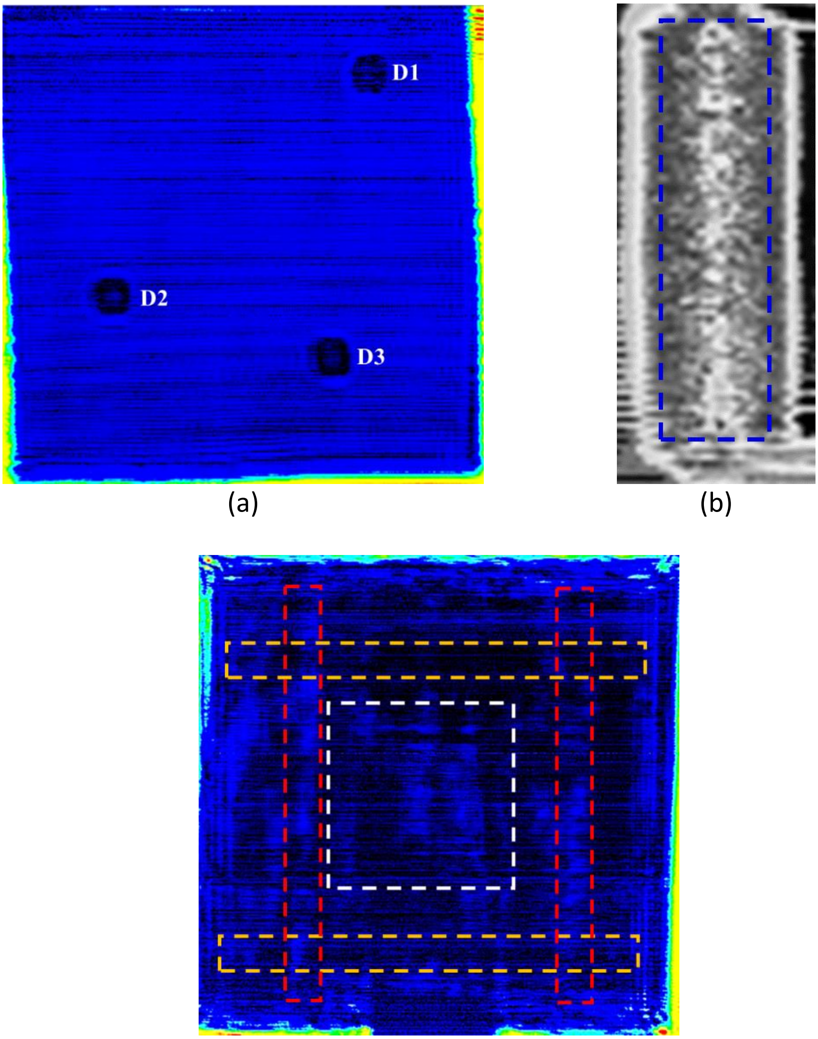
3. RESULTS AND DISCUSSION

Figure 7(a-c) presents the THz images acquired in transmission mode operated at the frequency of 300 GHz. Each image contains flaws in a form of horizontal, parallel lines which correspond to the detectors in the scanner.

Figure 7(a) presents the THz image obtained for the aramid fiber-reinforced composite sample. As it is presented, each defect is easily visible regardless of its depth below the sample surface. These defects in a form of air voids are characterised by dark contours with the lighter interiors. It corresponds to the scattering and interference at sharp edges of the object and enhanced transmission connected with a lack of material in the middle area [6]. Moreover, the edges are rounded which is also connected with interactions between terahertz electromagnetic waves with the defect acting different from the surrounding material. One may notice that the defects are slightly lighter with increasing depth below the sample surface and thus, D1 is lighter than D2. It results from partial absorption of radiation by the investigated material. As a result, less amount of radiation reaches the lower lying layers of material and the received signal is weaker. This may be also connected with the thickness of D1 which is lower than D2 and D3.

Monitoring of the aramid fiber-reinforced composites was previously investigated with the use of active thermography. In doing so, there is a need to use external heating or cooling source which, using different thermal properties of the defect and material, leads to exposure of defects in the material interior.

The results of investigations with the use of ultrasounds [10] and lamps with thermal excitation systems [11] showed that it is possible to non-destructively monitor interiors of objects and to detect hidden flaws. However, in comparison to active thermography, the THz testing method is much faster, contactless, and it does not affect the sample in any way thus, the investigations may be performed one by one. On the other hand, ultrasounds allow for inspection of bigger objects, also those made of metals. The image presenting internal structure of the imitator of the gas generator is presented in Fig. 7(b).



(a) (b)

(c)

Fig. 7. THz images acquired in transmission mode for (a) aramid fiber-reinforced composite, (b) imitator of gas generator, and (c) soft ballistic insert of bulletproof vest

As it was predicted, internal structure revealed many particles whose diameter ranges from very small (strictly below 1 mm) to relatively big having more than 1 mm. Surprisingly, our method allowed us to clearly see small points (air voids or inclusions introduced during the manufacturing). The disturbances are also visible as dark and white points which correspond to different chemical compositions of the observed elements what results in various absorption of THz radiation. In order to present small points, we needed to change the speed of the device movement to 1.5 cm/s. For that purpose, the observed elements were stretched out in a vertical direction. On the other hand, one may observe the white background which corresponds to the cloud of points that could not be resolved due to the limited method resolution.

The pyrotechnic materials had been already studied with the use of the THz testing method [8] operating at a frequency of 100 GHz. The results revealed the presence of various discontinuities in samples interiors. In comparison to the data presented within this study, they were characterised by lower quality with higher number of noises visible in THz images. Moreover, the presence of disturbances on the THz images was observed. Such disturbances are a result of high sensitivity of the experimental setup to any vibrations coming from the environment such as, e.g., movement of the devices. In our case, the influence of such factors was minimised by optimising the test conditions and speed of the displacive equipment. It is worth mentioning here that these referenced investigations were performed on flat samples whereas here the results for the cylindrical object are presented. This presents increasing opportunities for THz waves and the development in this field.

The last analysed case was the soft ballistic insert of a bulletproof vest, presented in Fig. 7(c). The square-shaped defect (marked in the figure with white square) is localised in the central part of the sample. One may notice that it is darker which relates to high absorption of THz waves by water which was introduced in this area [12]. The dark area is also visible in the top-left corner however, here a metallic holder, which strongly reflects THz radiation, is visualised. Moreover, in Fig. 7(c), the stitches in the aramid fabrics are visible. They were marked by red and yellow rectangle for horizontal and vertical stitches, respectively. They are partially covered by periodic horizontal lines which come from detectors. Because of that we may not see the lines running through the whole thickness of the sample or its length.

4. CONCLUSIONS

In the frame of this work, the examples of effective use of terahertz radiation as a non-destructive testing method and potential application for monitoring of military-designated materials were presented. The results proved that the THz testing method is able to detect flaws hidden in aramid fiber-reinforced composites, gas generator, and soft ballistic insert of the bulletproof vests.

Moreover, this method allows monitoring and controlling of the objects during their lifecycle without causing any damage to those objects. Besides, the presented advantages of implemented NDT setup like short experiment time, contactless and affectless inspection, it is worth noticing here that it has some limitations. They include relatively low penetration depth, small area of investigations (limited by the size of the scanner) and setup vibrations leading to disturbances in THz images. While the latter two may be somehow controlled by us, the depth of penetration is the main stumbling block. It is related to a lack of commercial higher power sources of THz radiation. As long as they will not be developed, it will be impossible to ripple through thicker objects made from the presented materials.

However, it is believed that the terahertz monitoring system in transmission mode may find real application for monitoring military-designated objects. It may not only analyse the hidden sub-structure but above all it may increase the safety of military parts being in use. This aspect is highly important not only from a security point of view but also it is economically efficient.

FUNDING

The research was financed by the Polish National Center for Research and Development (Project no. DOB-SZAFIR/02/A/001/01/2020).

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Zastosowanie promieniowania terahercowego w nieniszczących badaniach materiałów kompozytowych o przeznaczeniu militarnym

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Streszczenie. W prezentowanej pracy opisano zastosowanie metody obrazowania nieniszczącego przy wykorzystaniu promieniowania terahercowego. Badaniom poddano wybrane grupy materiałów kompozytowych znajdujących zastosowanie w wojsku, które miały celowo wprowadzone defekty. Głównym celem pracy było wyraźne wykrycie różnych nieciągłości we wnętrzu materiałów kompozytowych, a tym samym pokazanie możliwości nowo opracowanej metody testowania opartej na zastosowaniu promieniowania terahercowego w trybie transmisyjnym. Metoda terahercowa w trybie transmisyjnym, gdzie generator promieniowania i detektor znajdowały się po przeciwnej stronie próbki. W wyniku badań wykryte zostały wszystkie defekty celowo wprowadzone do analizowanych materiałów kompozytowych, wśród których wyróżniono: kompozyty wzmocnione włóknem aramidowym, gazogenerator, wkład do kamizelki kuloodpornej. W ramach tej pracy przedstawiono przykłady efektywnego wykorzystania promieniowania terahercowego jako metody badań nieniszczących oraz potencjalne zastosowanie w monitorowaniu materiałów o przeznaczeniu wojskowym. Wyniki dowiodły, że metoda terahercowa jest w stanie wykryć wady ukryte w kompozytach wzmocnionych włóknami aramidowymi, gazogeneratorze i wkładzie do kamizelki kuloodpornej. Wyniki przedstawione w postaci zdjęć cechowała wyższa jakość w odniesieniu do danych literaturowych.

Słowa kluczowe: materiały kompozytowe, badania nieniszczące, promieniowanie terahercowe, detekcja defektów