Some approaches to the non-destructive control of composite materials used in the aerospace industry

Valeri Panevski
Bulgarian Academy of Sciences, Institute of Metal Science Equipment and Technologies with Hydro- and Aaerodynamics Centre "Acad. A Balevski", Sofia, Bulgaria
panevski@ims.bas.bg

Abstract: *One of the priority areas for the use of composite materials is the aerospace industry. A number of evaluations have shown that their use in the manufacture of modern aircraft and helicopters lead to a reduction in weight of the respective parts with 20-30% compared to the same manufactured from conventional materials. In this case, an increase in the resistance of the respective part to external influences is usually achieved, and in many cases a decrease in its production cost.*

The increasing use of composite materials in the aerospace industry requires analyzing options for their diagnosis and non-destructive examination of their quality, taking into account their specific features. Because of the enormous diversity and complexity composition for composite materials, various methods of diagnosis have different efficiencies for different types of composites. In many cases, composites contain highly porous or fibrous layers, which results in a strong attenuation of the acoustic waves and render the acoustic method inapplicable to their non-destructive control. In these and other cases, the use of emerging methods for their non-destructive ultra-high frequency (microwave) diagnostics is of interest.

Keywords*: COMPOSITE MATERIALS; NON DESTRUCTIVE CONTROL*

1. Introduction

Composite materials are known to consist of two or more materials with different physical or chemical properties, which together form a composite with properties other than their own. In most cases, composites are created to give them better opportunities for use in various mechanical impacts (friction, shock, vibration, acceleration, loading, etc.), the temperature characteristics of the environment in which they function (extreme or rapidly changing over a wide range of temperatures), chemical and electromagnetic parameters of the environment in which they function (salinity, acidity, radiation, etc.), as well as to achieve certain physicochemical parameters at less weight or with smaller production costs and **[1-4]**.

One of the priority areas for the use of composite materials is the aerospace industry. A number of evaluations have shown that their use in the manufacture of modern aircraft and helicopters lead to a reduction in weight of the respective parts with 20-30% compared to the same manufactured from conventional materials. In this case, an increase in the resistance of the respective part to external influences is usually achieved, and in many cases a decrease in its production cost.

2. Composite materials

In the aerospace industry, composites have been used mainly in the military aircraft industry, but have recently become more widely used in the development of commercial aircraft. The advantages of using composites over traditional aluminum alloys are many, which is why they are more widely used. For the most part, the composite materials used in the aerospace industry are made of two major fiber and matrix components. Fibers or reinforcement provide high strength and hardness, while the matrix is used to bind the fibers together.

Another approach in the construction of composite structures is the layered structures (laminates), which can be made of different types of fiber composites oriented in different directions for optimum strength and rigidity.

An important type of laminated composite is the sandwich composite (a very lightweight but still robust composite laminate), which consists of a lightweight base panel with thin sheets of solid material bonded to the two faces of the core.

The increasing use of composite materials in the aerospace industry imposes the requirement to analyze the possibilities for their diagnosis and non-destructive examination of their quality, taking into account their specific features. Because of the huge variety and complex composition of composite materials, various methods of diagnosis have different efficiencies for different types of composites **[5-7]**.

In many cases, composites contain highly porous or fibrous layers, which results in a strong attenuation of the acoustic waves and render the acoustic method inapplicable to their non-destructive control.

The most famous example of the relevance and significance of this problem is the space shuttle crash of Space Shuttle Columbia in 2003. According to NASA experts, published in the authoritative edition of Aviation Week & Space Technology, one of the reasons that led to the crash were defects in the thermal insulation of the outer fuel container of the spacecraft. This insulation layer is a polyurethane foam with a thickness of 2.5-5.0 cm, applied onto the outer surface of the container to reduce the boiling point of the cryogenic components of the fuel (liquid hydrogen and oxygen) on the launch pad.

During the preparation for the start, which lasted several days, the moisture from the air penetrated the crevices of the coating and due to the difference in temperatures condensed therein. According to one hypothesis, as the shuttle took off, as the flight altitude increased, the external pressure decreased rapidly, causing the water to boil explosively, creating increased pressure. This resulted in the removal of a layer of thermal insulation coating which was rejected from the air stream and caused damage to the leading part of the wing of the space vehicle. Upon landing, at the stage of entering the Earth's atmosphere, plasma penetrates the openings, causing complete destruction of the apparatus and causing the death of the entire crew. Several other similar incidents have been reported, both in the aerospace and energy fields, which fortunately did not lead to such distressful consequences.

Therefore, the non-destructive diagnostics of composite materials of this type requires the development of new technologies, one of which could be the proposed technology of radar ultra-high frequency radiation in the GHz range. In these and other cases, the use of emerging methods for their non-destructive ultra-high frequency (microwave) diagnostics is of interest.

In general, the objectives of microwave diagnostics can be classified as superficial diagnosis - for the presence of superficial heterogeneities and / or defects, sub superficial diagnostics - for heterogeneities and / or defects within the composite material itself, and superficial diagnostics and for non-uniform defects. material behind the composite material or behind a certain layer of composite material.

3. Diagnosis methods

Depending on the method of diagnosis, it is appropriate that it be classified as a diagnosis on the basis of reflection (reflective diagnosis) or diagnosis on the basis of transition in the material (transient diagnosis).

Reflective diagnosis is more commonly used and is performed with the ultra-high frequency transmitter and receiver located on the same side of the material. In this case, the heterogeneity and / or the defect are recorded on the basis of the change in the signal received by it. Basically reflective surface diagnosis is applicable to all types of composite materials.

In the *transient diagnosis*, the transmitter and the receiver of the ultra-high frequency oscillation are located on both sides of the composite material, and inhomogeneities and / or defects are recorded based on the change of the signal passed through them.

In the case of composite materials whose surfaces are electrically conductive, a basic reflective ultra-high-frequency diagnosis is possible for the presence of surface inhomogeneities and / or defects. In some cases, when the electrically conductive surface layer is twice less than the penetration depth, a reflective diagnosis of the interior of the material is possible, and when this layer is less than the penetration depth, a transient diagnosis is also possible.

For matrix composite materials whose matrices are of electrically conductive material, but their reinforcement is of non-electrically conductive material, the possibilities for subsurface and subsurface ultra-high frequency diagnostics depend on the size and density of the matrix components. If the dimensions of the matrix component are significantly smaller than the depth of penetration of radiation into it, or if the distance between the individual individual components exceeds 0.25 - 0.5 of the length of radiation, it may be possible to perform sub-surface and even sub-surface reflective or transient diagnostics.

If the matrix and its reinforcement are not composed of conductive material, then it is possible to perform sub-surface and sub-surface ultra-high frequency reflective and transient diagnostics.

If the matrix is not composed of electrically conductive material but its reinforcement is of electrically conductive material, then in principle the possibilities of performing sub-surface and sub-surface ultra-high frequency diagnostics are extremely limited.

If the composite material is multilayered and the individual layers are not composed of conductive material, then there are possibilities for under-surface and sub-surface reflection and transient high-frequency diagnostics. If the composite material is multilayer, but only part of the individual layers (including the surface material) are not composed of conductive material, then there is a possibility to perform sub-surface ultra-high-frequency reflective diagnostics only up to the first layer, made of conductive material.

For multilayer composite materials and the use of the reflection diagnostic method, the effect of the summation of the direct ultra-high frequency signal and its reflection from surfaces with different electromagnetic characteristics should be taken into account. If the reflected and direct signals are dephased by about 90 degrees (due to the distance between the sheets in proportion to about 0.5 of the wavelength of the signal), they will compensate for each other. This effect can be avoided both by selecting the appropriate frequency of radiation for the particular type of composite material and by displacing the transmitter and receiver and providing a definite angle between the transmitted and the received signal.

4. Non-destructive testing of composite materials by holographic subsurface radar

Non-destructive testing - Definition

Non-destructive testing (NDT) is a testing and analysis technique used by industry to evaluate the properties of a material, component, structure or system for characteristic differences or welding defects and discontinuities without causing damage to the original part. ***[8]***

NDT also known as non-destructive examination (NDE), non-destructive inspection (NDI) and non-destructive evaluation (NDE).

Holographic subsurface radars (HSR) are not often used, probably due to the fact that high attenuation of electromagnetic waves will not allow sufficient depth of penetration. It is true that the fundamental physics of HSR prevents the possibility of changing the receiver gain over time (i.e. depth) to adapt to a lost environment (as possible with impulsive subsurface radar (ISR)).

However, the use of HSR to investigate shallow subsurface objects, defects or inhomogeneity is an increasingly proven field of application.

In this case, HSR can record higher resolution images than is possible for ISR images.

Holographic subsurface radar is characterized by the requirement for routine surface scanning to record holograms. In this sense, HSR is an analogue of the optical hologram technology proposed and implemented by D. Gabor in 1948 **[9]**. The method proposed by Gabor can simply be illustrated with an example of recording a hologram in a point object. Axially symmetric hologram of an object point can be recorded on a flat plate such as an interference pattern between a coherent plane wave with constant phase perpendicular to the plate, and the waves that are scattered from a point object. A schematic representation of the Gabor optical hologram method for a point object is shown in fig. 1**[10].**

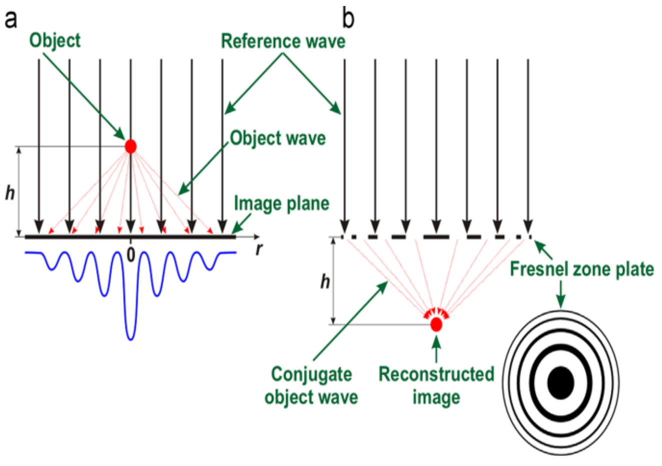

Fig. 1: *Optical hologram recording (a) and reconstruction (b)* ***[10]***

The plate that records the interference pattern of waves is called a hologram. Unlike optical imaging, a microwave hologram could record not only the intensity of the waves scattered by the object, but also information about the phase of these waves. When the optical hologram is illuminated by coherent light of the same wavelength used for recording, a virtual three-dimensional image of the object is projected across the screen. In the case of a point object, the hologram is a Fresnel lens and the projected or reconstructed object is simply the point itself **[9].**

The Gabor method for recording holograms has many drawbacks in terms of the quality of the hologram and the convenience of its application. A new step in the development of holography was made by E.N. Leith and J. Upatnieks after the invention of the laser **[9]**.

A method using a coherent beam of light at an angle to the recording plate is proposed. A diagram of this type of holography is presented in fig. 2. Subsequent innovations in optical holography include the use of various combinations of mirrors and light. Nevertheless, holographic technology is of great use in radar. For example, holographic radars were designed to detect weapons concealed on human bodies at airports.

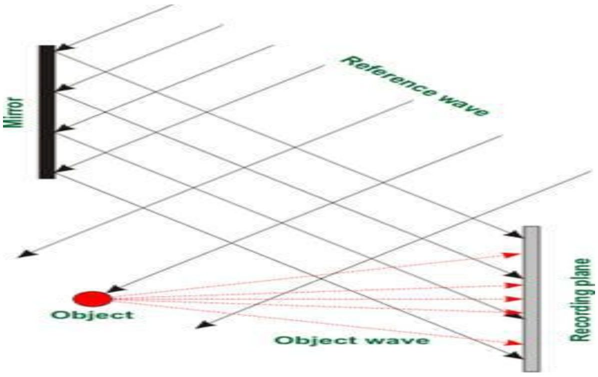

Fig. 2: Optical hologram with inclined light beam **[9]**

Radar holography in the atmosphere or outer space also has many features in common with optical holography, due to the lack or very low level of attenuation and dispersion of electromagnetic waves in these environments.

Holographic subsurface radars are designed to investigate heterogeneous environments with relatively high attenuation rates and sometimes high dispersion. This property can have a great influence on the recording of multifaceted holograms.

All these factors impair the quality of microwave holograms and, in many cases, make the recording of holograms impossible. The theoretical explanations for the influence of the properties of the sources on the quality of the subsurface holograms were discussed recently by N. Chubinski **[11]**. Surface attenuation and surface heterogeneities limit the maximum effective penetration depth for HSR. It is important to emphasize that the ISR has a clear advantage over the HSR in terms of effective penetration depth because of the possibility of applying a variable time gain to a strobe beam for selectively amplifying deeper reflections that have a longer “time-of-flight” (a method of measuring the distance between a sensor and an object based on the time difference between the signal being transmitted and returning to the sensor after being reflected by an object). Since time-of-flight is irrelevant to HSR, the main application of HSR is related to shallow depths.

At shallow depths, where applicable, the main advantage of HSR is the ability to record higher resolution images in the search plane than the ISR. High resolution at shallow depths is crucial for many applications, including the diagnosis of composite materials.

The catastrophic loss of the US space shuttle Columbia has forced researchers to find new possible methods and devices for non-destructive testing and evaluation of the space shuttle's thermal protection system, as well as the insulation foam of an external fuel tank. Such diagnostic methods can be useful not only for current spacecraft, but also for promising spacecraft such as the Orion manned spacecraft **[10]**.

The basic problem with non-destructive testing of space vehicles thermal protection systems is that the task requires examination of a layer of dielectric material, applied directly on the metal support shell. If such composite structures were investigated by means of pulsed subsurface radar, the absorption of a radiated pulse between the metal surface and the radar antenna would significantly complicate the detection of heterogeneities and defects in the dielectric heat-shielding material. Holographic subsurface radars do not contain this disadvantage since the signal reflected by the metal surface parallel to the surface of the radiation shielding material has a constant phase and does not affect the quality of the recorded radar images.

5. Status of research on the problem

New ultra-high-frequency non-destructive testing technologies can be based on the technology used to create so-called holographic subsurface radars, developed at Bauman Moscow State Technical University and found widely application in the diagnosis of building structures.

Preliminary experiments conducted jointly with State Space Corporation ROSCOSMOS and Vikram Sarabhai Space Center, Indian Space Research Organization, Kerala, India on presented specimens of various composite materials containing porous and elastic components, including specimens of thermal insulation coatings for space new generation rocket launchers have shown the promise of this direction.

The analysis of the reports presented at the International Conference on Non-Destructive Control in the Aerospace Industry **[9,10]** shows that the methods of ultra-high frequency diagnostics were presented only in the report of the Bauman Moscow State Technical University **[10]**. It is known that NASA, USA, a few years studies have been conducted on ultra-high frequency diagnosis of insulating coatings of rocket containers, but probably due to the use of other methods of information processing are not achieved good results and these studies have not received development in the US **[10,11]**.

The holographic subsurface radars **[7]** developed at the Bauman Moscow State Technical University have a working frequency range of 1.6 to 6.8 GHz and are commercially available and are used for the diagnosis of building structures both in Russia and in other countries. The authors of the project have received a government award in science and technology for their development. At the same time, it is necessary to continue the studies related to the reflection of electromagnetic waves from the internal structure of the given materials, as well as to carry out a number of studies in order to develop new technologies for ultra-high frequency diagnostics, including in other frequency ranges. Due to the use in the aerospace industry of a number of low-attenuation dielectric coatings, such as fiberglass, polyurethane, quartz, ceramics, non-metallic nanoclusters, etc., one direction in this direction is related to the use of a 24 GHz frequency band leading to quality improvement the image and the possibility of recording minor defects in the components manufactured. To evaluate this possibility, it is necessary to evaluate the specific vibration damping at a frequency of 24 GHz for some composite materials using them.

6. *Conclusion*

A summary of the theory, technology and applications of holographic subsurface radar is presented in this paper. The main advantages and limitations of commonly used pulse radars are also considered. In many practically important cases the depth of penetration is insufficient and the quality of recorded images does not allow reliable identification of detected objects. However, the proper choice of the type of sounding signal and its frequency range can lead to useful results that cannot be achieved by other non-destructive diagnostic methods. A typical area of application for holographic subsurface radar is the study of opaque shallow-depth objects where high resolution is desired. In these cases, it is possible to define the shape and dimensions of the targets and elementary objects with sufficient accuracy and to formulate reasonable assumptions about their nature for developing image-based classification pictures.

ACKNOWLEDGEMENT

The results of this development have been achieved in accordance with Contract № KP-06-RUSSIA /22 dated September 28, 2019 between IMSTCHA-BAS and the National Science Fund of Bulgaria (NSFB) for the implementation of the Project "New technologies for nondestructive testing of composite materials in aerospace industry", funded by NSFB as a result of the "Bilateral Cooperation Program Competition 2018 - Bulgaria - Russia 2018-2019".

Bibliography:

[1] Yavor Boichev, N. Dyulgerov, "Metalphysical Investigations of Composite Aluminum Alloy with Microcrystalline Structure", "Metal Science, Hydro and Aerodynamics, National Security", 2013, ISSN:1313-8308, p.p. 219-221;

[2] Boychev Y., "Investigation of plasticity of composites based on aluminum alloys with microcrystalline structure at different test temperatures", Proceedings NDT Days' 2014, 2014, ISSN:1310-3946, p.p. 214-216

[3] Yavor Boichev, G. Stefanov, N. Dyulgerov, S. Gyurov. "Structural features of compact composites with a microcrystalline structure based on aluminum alloys", Proceedings - Fifth National Conference with International Participation, " Metal Science, Hydro and Aerodynamics, National Security'2015 ", 2015, ISSN:1313-8308, 200-203

[4] Dyulgerov N., Boychev Ya. Preparation and properties of real-size composites and microcrystalline structure based on aluminum alloy with TiC addition. XXVI International Conference "NDT days '11" Proceedings, 2011, p.p. 234-235

[5] Genov BG, "Possibilities for Using Non-Destructive Control Methods in Ballistic Protection Systems Assessment", International Conference "Non-Destructive Control Days" 2011, Sozopol, 11-14.06 2011, ISSN 1310-3946, p. 107-110 Genov B., The Need for the Implementation of Non-Destructive Control Methods in the Stages of the Lifecycle of Defense Products, International Conference "Days of Non-Destructive Control" 2012, Sozopol,11-14.06 2012, ISSN 1310-3946, стр. 363-365

[6] Borislav G. Genov, "Model for evaluation of the technical state of rocket propulsion engines based on the results of non-destructive testing" International Conference "Days of Non-destructive Control" 2018, Sozopol, June 2018, published in NDT Days, Volume I / Issue 4 (2018), ISSN: 2603-4018 (print), 2603-4646 (online), p.p. 484-493

[7] Borislav G. Genov, "Criteria for Choosing Non-Destructive Control Methods in the Ammunition Lifecycle", International Conference "Days of Non-Destructive Control" 2018, Sozopol, June 2018, published in NDT Days, Volume I / Issue 4 (2018), ISSN: 2603-4018 (print), 2603-4646 (online), p.p. 494-503;

[8] https://www.twi-global.com/technical-knowledge/faqs/what-is-non-destructive-testing;

[9] Sergey I. Ivashov, Vladimir V. Razevig, Igor A. Vasiliev, Andrey V. Zhuravlev, Timothy D. Bechtel, Lorenzo Capineri, "Holographic subsurface radar: TECHNOLOGY AND APPLICATION", JOURNAL OF RADIO ELECTRONICS, N 10, 2010, electronic journal, ISSN 1684-1719;

[10] S. Ivashov, V.Razevig, I.Vasiliev, T.Bechtel, L.Capineri, „Holographic subsurface radar for diagnostics of cryogenic fuel tank thermal insulation of spacevehicles", NDT&E International 69 (2015), pp. 48–54, ISSN: 0963-8695;

[11] N. P. Chubinsky, "Possibilities of holographic methods at sounding of lossy media", Proceedings of 4th Russian conference RadioPhysics Methods in Remote Sensing, Murom, 30 June – 3 July 2009, pp. 47-60,(in Russian).

Available: http://www.mivlgu.ru/conf/murom2009/img/doclad/lecture/3.pdf.