Applicability of microwave non destructive diagnostics for composite materials used in the aerospace industry

Nikolay L Gueorguiev 1, Atanas Nachev 2, Sergey Ivashov 3

1 BAS - Institute of Metal Science, Equipment and Technologies with Hydro- and Aerodynamics Centre “Acad. A. Balevski” – 67, Shipchenskiprohod St., 1574 Sofia;
2 Technical University of Sofia, Branch Plovdiv, 25, Tsanko Diustabanov St., 4000 Plovdiv, Bulgaria;
3 Bauman Moscow State Technical University, 2-nd Baumanskaya, 5, 105005, Moscow, Russia.
niki0611@abv.bg

Abstract. The paper offers an analysis of some of the peculiarities associated with the application of the microwaves (MW) for non-destructive testing (NDT) of composite materials used in the aerospace industry. Special attention is paid to the influence of the compound of the materials of which are made composites, their shape and structure on reflection, refraction and attenuation of electromagnetic waves.

1. Introduction
It is well-known that composites (composite materials) have increased resistance to various mechanical, temperature, chemical, electromagnetic and other effects and oftenweight less or have lower manufacturing costs than ordinary materials[1-5]. Therefore, one of the priority areas for composites use is in the aerospace industry. A number of evaluations show that over the last decade, their use in the production of modern aircraft, helicopters, rockets, and spacecraft has grown exponentially. This, together with the high requirements for the reliability of aerospace assets, requires the analysis of various possibilities for composites diagnosis and for the non-destructive control of their quality, taking into account their specific features. The paper offers analysis of some of the peculiarities associated with the application of the microwave diagnostics methods for composite materials used in the aerospace industry. Special attention is paid to the impact of the composition of materials of which the composites are made, their shape and structure, and the system or the device in which it is used to reflect refract and attenuate MW transmissions.

2. General approach
It is known that microwave oscillations are reflected, refracted and damped depending on the electromagnetic characteristics, geometric shape and physical-mechanical structure of the composite materials being diagnosed. The capabilities of the microwave diagnostics, in turn, depend on the particular device in which the composite material is used, its accessibility and the conditions for its
operation[6-9]. It is, therefore, appropriate to evaluate the influence of reflection, refraction and attenuation of the ultra-high frequency radiation used for the diagnosis of composite materials, taking into account the composition of materials from which the composites are constructed, as well as their shape and structure.

2.1. Influence of the composition of composite materials used in the aerospace industry on the possibilities for their diagnosis through ultra-high frequency methods.

It is known that the propagation of electromagnetic waves in an medium could be described with the help of the Maxwell equations, which are a function of the dielectric permittivity $\varepsilon$ and magnetic permeability $\mu$ of the medium in which they propagate. If the medium is homogeneous, these parameters are constant, but in the real medium, they could change.

There are three main types of interconnected energy interactions of microwaves with the composite material – reflection, refraction and attenuation. These interactions depend mainly on the nature of the materials from which the composites are made. As well as the frequency and type of ultra-high frequency radiation[6,8,9]. The reflection and refraction of the microwave oscillations occur from the surfaces between two materials with different dielectric properties and depend on the size and electromagnetic characteristics of these surfaces. Thus, by reflecting on the one hand, it is possible to record the heterogeneities in the composite materials, and on the other hand, the energy of that part of the electromagnetic waves, which continues to propagate in the composite material, is reduced. The refraction does alter the wavefront, which continues to propagate into the composite material. The reflection of the microwave is described upon the basis of unevenness of the surface between the two materials having different dielectric characteristics. In some cases, this surface can be regarded as smooth, in which the reflection is mirror-like; or not smooth, in which case the reflection is diffuse and is determined by the reflections of the individual sections of the surface.

According to the Rayleigh criterion, the reflecting surface can be considered smooth, i.e. reflection is mirror if, in the case of perpendicular irradiation with a plane wave (i.e. at a 90° incidence angle), the surface irregularities are less than one sixteenth of the electromagnetic wavelength. This means that in microwave diagnostic methods at frequency of 24 GHz (wavelength is about 1.25 centimeters), the conditions for the reflectance of reflection are border irregularities less than 0.78 millimeters. When the angle of incidence is changed, these irregularities must be smaller (they decrease with the value of the sine of the slip angle of the microwave oscillation).

The refraction of the electromagnetic wave, when passing through medium with variable electromagnetic parameters, is characterized by their refractive indexes (which are the square root of their relative permittivity $\varepsilon$). According to Huygens' principle, each point on the boundary of the two media is a source of secondary spherical electromagnetic waves. It turns out that the front of the microwave oscillation in them is different, taking into account the different coefficients of refraction of the media. The ratio of the sinuses at the edges of the microwave oscillations in the two media is inversely proportional to the ratio of their refractive indexes, i.e. per square root of the ratio of their relative dielectric constant. If the $\varepsilon$ of the second medium is smaller than that of the first medium, then the refraction angle is greater than the incidence angle. Therefore, there is a critical value of the incidence angle at which the broken wave angle becomes 90°. This critical value is equal to the square root of the relation between the relative dielectric permittances of the second and first media. In this case, obviously, if the incidence angle is greater than the critical value, then the electromagnetic wave will be reflected completely from the boundary surface without penetrating the second medium. The later proves that in assessing the possibilities of using microwave radiation, methods for the diagnosis of composite materials must take into account their reflecting and refractive capacities, as well as the arrangement of the installation determining the angles of incidence of the drilling radiation[16,17]. Reflection is the
dominant effect of the interaction between ultra-high frequency oscillations and conductive materials – metallic and some non-metallic. For non-conductive materials, the reflection is less pronounced, and the refraction and absorption, as well as the associated damping, are dominant.

The absorption of ultra-high frequency oscillation reduces its energy and is determined by the electromagnetic properties of the materials that make up the composites. In general, for non-conducting materials, the absorption is proportional to the attenuation of the ultra-high frequency oscillations and depends mainly on the dielectric constant of the materials in which it propagates. In practice, the so-called "relative dielectric constant" is usually used for convenience. The relative dielectric constant of the material \( \varepsilon_r \) representing the relationship between its dielectric constant and the dielectric constant of the vacuum.

If the absorbent material is a dielectric, then the damping of the microwave oscillations therein is determined by the dielectric losses, which represent the active electrical power released by the dielectric. Specific dielectric losses have two components. The first one is due to the conductivity of the material and is the same at constant and alternating voltage. The second one is manifested only by the action of variable fields in polar dielectrics and is related to the friction between the particles in their continuous reorientation (it is insignificant in non-polar dielectrics). The second component of the specific dielectric loss is usually much larger than the first and is determined by the tangent of the so-called dielectric loss angle. For some types of dielectrics, the tangent of the dielectric loss angle is very small, in the order of 4 to 10, and they are practically invariant to the frequencies of electromagnetic oscillations.

When analyzing the absorption of microwave oscillations by dielectrics, should be considered that it has a certain maximum value. The maximum density of absorbed power depends on the properties of the material, such as for materials based on rubber or foam polystyrene this power is \( 0.155 \div 0.465 \, \text{W/cm}^2 \), for foam ceramics, it is \( 7.75 \, \text{W/cm}^2 \) and for polyurethane, it is \( 1.3 \, \text{W/cm}^2 \).

The absorption of microwave radiation from composite materials is uniquely related to their penetration into them. It is obvious, the energy of the microwave oscillation penetrated into the nearest part of the surface of the material is the difference between the oscillation which has fallen on the surface and the reflected oscillation. For its part, the energy of the microwave oscillation at its propagation in a homogeneous isotropic medium at a certain distance from the surface is equal to this distance, multiplied by the absorption (loss) coefficient of the material concerned. Thus, for a material of infinite thickness at some distance from its surface, the energy of the microwave oscillation will become negligible. This distance is called the depth of penetration of the microwave oscillation, and for non-conducting materials it is considerable.

In the case of conductive materials, there is also penetration of ultra-high frequency radiation, but it is limited to a certain critical depth, also called skin depth. This depth is in the order of units to parts of a millimeter and is inversely proportional to the square root of the product of the frequency of oscillation, the electrical conductivity of the material and its magnetic permeability.

The studies conducted to determine the possibility of ultra-high frequency flaw detection of a composite material composed of carbon fibers, show that it is possible that the depth of penetration of some ultra-high frequency oscillations in it may exceed a separate layer of material. As a non-magnet, the magnetic permeability of carbon is equal to that of free space \( (4\pi \times 10^{-7} \, \text{H.m}^{-1}) \), whereby the depth of penetration of ultra-high frequency oscillations at it at a frequency of 100 megahertz is about 1 mm and at a frequency of 300 megahertz reaches twice the thickness of one standard layer of 0.25 mm. is on the order of several millimeters.

As already noted, one of the main characteristics of the materials determining the reflection, refraction, and attenuation of the microwave oscillations in them is their relative dielectric constant. It depends on
the chemical composition of the materials, their density, shape, temperature, etc. The relative dielectric permittivity values of some materials used in the composites are shown in Table 1.

Table 1. Relative dielectric permittivity values ($\varepsilon_r$) of some materials used in composites at 18 °C (unless otherwise stated) and frequency 50 Hz

| material                  | $\varepsilon_r$ | material                  | $\varepsilon_r$ |
|---------------------------|-----------------|---------------------------|-----------------|
| vacuum                    | 1,0             | porcelain                 | 2–6             |
| air                       | 1,0005          | epoxy resins              | 4,3–5,4         |
| styrofoam                 | 1,03            | mica                      | 5,4             |
| benzene                   | 2,28            | aluminum oxide            | 7               |
| PTFE and Teflon           | 2               | glass                     | 6–8             |
| polyethylene (PE) (90 °C) | 2,4             | ceramics                  | 3-11            |
| polypropylene (PP) (90 °C) | 2,1             | silicon                   | 11,8            |
| rubber                    | 2,5–3           | alloyed barium strontium ceramics | 100 - 600 |
| quartz                    | 3,8             | barium titanate           | $10^3$–$10^4$   |
| acrylonitrile butadiene styrene (30 °C) | 4,3 | special ceramics | $10^3$–$10^6$ |

The value of the relative dielectric constant in a vacuum is equal to one, and the increase of the relative dielectric constant of the material through which the electromagnetic oscillation propagates causes its attenuation to increase.

The data shown in Table 1 are for low frequencies of electromagnetic oscillations and can only be used for comparative estimations, and apparently, with increasing frequency of radiation, the relative dielectric capacity will increase significantly. However, it is apparent that a number of materials used for composites for the aerospace industry have relatively good opportunities for transmitting ultra-high frequency oscillations. This makes it possible to use ultra-high frequency diagnostics both to control the uniformity of their structure and to control the quality of the materials beneath them. Of particular interest in this direction is the holographic subsurface radar created by the Moscow Technical University. The later is intended for the study of the zones of stable adhesion, the presence of deformations or inhomogeneities of metal housings under thermal insulation coatings up to 50 cm thick.

2.2. Influence of the structure of composite materials used in the aerospace industry on the possibilities for their diagnosis through ultra-high frequency methods.

The structure of the material plays an important role in determining the possibilities for their diagnosis through ultra-high frequency methods. As already indicated, the reflection, refraction, and attenuation of the microwave oscillations depend on the electromagnetic characteristics of the composite materials. If they consist of several elements (eg successive layers, fill matrices with different materials, etc.) with
different relative dielectric permissions, then no complex and repeated internal reflections and refractions can be expected. If the construction of the composite material contains elements spaced multiple of one-quarter of the microwave wavelength, the internal reflected wave will be in counter-phase with that propagating. This would lead to an additional "constructive" attenuation of the propagating microwave oscillation, which, depending on the reflection coefficient, could be significant. Overcoming this effect can be achieved by varying the frequency of the microwave oscillation, for example by modulating it in frequency, insisting in the diagnostic process, using multiple frequency microwave means, etc.

If the relative dimensions of the objects are significantly smaller than the wavelength of the microwave oscillation (e.g. in nanocomposites), the concept of geometric optics is not applicable. Then, the principles of wave optics, and in particular those related to diffraction, must be used to evaluate electromagnetic processes. When a flat electromagnetic wave interacts with a finite-size object, two types of non-planar electromagnetic fields emerge – an internal diffraction field within the object boundary and an external diffraction field. The essence of the diffraction wave process is that the object excited by the incident electromagnetic wave is an emitter of an additional wave field.

The consideration of the stated effects of the construction of composite materials on the possibilities of their diagnosis by microwave methods is appropriate to be carried out on the basis of the aims and methods of its use.

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

In addition, depending on the method of diagnosis, it is appropriate to classify it as a reflection-based (reflective) diagnosis or material-based (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 is recorded on the basis of the change in the signal received by it. In general, reflective surface diagnostics 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 on the basis of the change of the signal passed through them.

In the case of composite materials whose surfaces are of an electrically conductive layer, a basic reflective ultrahigh-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 components exceeds $0.25 \div 0.5$ 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 reflection and transient diagnostics.

If the matrix is composed of not 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 sheets are composed of conductive material, then there are opportunities to perform sub-surface and sub-surface reflective and transient high-frequency diagnostics. If the composite material is multilayer, but only part of the individual sheets (including the surface) of the composite material is composed of electrically conductive material, then there is a possibility to perform sub-surface ultra-high-frequency reflective diagnostics only up to the first sheet, which is composed of electrically conductive material. If the latter is less than the depth of penetration, it can be assumed that reflective and transient diagnostics could also be made for the layers behind this sheet.

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 defaced with a window of 90 degrees (due to the distance between the sheets in proportion to about 0.5 of the wavelength of the signal), then they will offset 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 broadcasts and the received signal.

2.3. Influence of systems using composite materials on the possibilities for their diagnosis through ultra-high frequency methods.

In general, systems and devices using composite materials predetermine the possibilities of physical access to the technical means for performing ultra-high frequency diagnostics and at the angles at which it is possible to perform microwave radiation. That determines both the limitations associated with the reflection and refraction processes described above, as well as the possibilities of using a particular type of diagnosis.

![Sketch of the sample N1. View in the top of the sample N1.](image)

In the process of operation, composite materials located on the surface of individual systems and devices are available for various types of reflective ultra-high frequency diagnostics. Some of these could be available for transient microwave diagnostics, such as antenna components, helicopter propellers, etc.
In the course of the various types of repairs, composite materials may be available for one or more types of ultra-high frequency diagnostics, depending on the degree of their dismantling. Due to the wide variety of possibilities, it is appropriate in the technical, technological and operational documents of the individual aerospace vehicle to determine the composite component and the conditions under which their condition can be investigated and controlled by a method. What is more, including ultra-high frequency diagnostics. Of course, the particularities of the various flaw detectors must be taken into account and the most appropriate cases used. In particular, given the material presented in the presented material, ultra-high-frequency subsurface and subsurface diagnostics is extremely suitable for composites using materials having low acoustic and thermal permeability (e.g., thermal insulation coatings of polyurethane foam), in which acoustic and thermal methods.

One of typical subjects of investigation by the Holographic subsurface radar is the polyurethane foam, used as the thermal insulation. The dielectric permittivity of polyurethane foam that was used as Shuttle tank insulation is essentially close to the same parameters of air, and has very low level of attenuation in microwave range.

The multiple investigations were conducted with the sample N1, made by the polyurethane foam, provided by SPA Tekhnomash, Russia. The Sketch and view of the sample N1 and result of the investigation (figure 1). In the sample are made three circular voids which are subject to registration by the holographic subsurface radar. It is evident that the use of a higher frequency significantly improves the quality of the registration.

It is very interesting to make any comparison of different NDT&E technologies and holographic subsurface radar. Comparative tests were carried out using Thermal (infrared) imager Testo 885 (with high sensitivity of 30 mK at 30°C), X-ray microscope XD75000NT and holographic subsurface radar (HSR). The results are shown in the figure 2.

![Visual view](image1.png) ![HSR image](image2.png) ![Infrared image](image3.png)

(a) Comparison of HSR and Infrared images

![Visual view](image4.png) ![HSR image](image5.png) ![X-ray image](image6.png)

(b) Comparison of HSR and X-ray images

**Figure 2.** Results of the HSR, Infrared and X-ray images.
3. Conclusions
The above paper has offered an approach for analyzing the effect of a composition of the materials of which composite are made, their shape and structure. As well as the system or device in which the composite is used on the basic parameters of the microwave radiations used for their diagnosis. Particular attention has been paid to the analysis of the influence of the indicated characteristics of composite materials on the reflection, refraction, and attenuation of ultra-high-frequency radiation.

The analyzes made can be used in planning and organizing the performance of microwave diagnostics and non-destructive testing, as well as in the preparation of operational and repair documentation of the parts and devices of aerospace vehicles using composite materials.

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