Microwave Holography for NDT of Dielectric Structures

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***Abstract* — Methods of ultrasonic diagnostics, which are widely applied for non-destructive testing of different constructions, are ineffective for foam insulation, the silicate fiber tiles or honeycomb prepregs due to their high porosity, which leads to high levels of acoustic wave attenuation. Microwave diagnostics using holographic subsurface radars RASCAN-5, which operate in the gigahertz band, could be a good alternative to ultrasonic testing. Experimental results demonstrate the effectiveness of the technology on an example of honeycomb dielectric composite materials.**

***Index Terms* — Dielectric composite materials, holographic subsurface radar, microwave imaging, nondestructive testing, honeycomb prepreg.**

I. Introduction

Composite materials have found widespread application in the aerospace industry all over the world because they have great advantages over traditional metal construction. As a rule, they are lighter, have better resistance to hostile environments, and sometimes cannot be replaced by traditional materials. However, composites demand new methods for control of their quality in the process of their production and in usage.

A few incidents, including the Space Shuttle Columbia disaster which occurred on February 1, 2003 [1], killing all seven crew members, and the partial destruction of the Russian return vehicle Buran [2], were related to imperfections in their heat protection and thermal insulation coverings. These events have driven interest in new NDT methods for dielectric composite structures.

Methods of ultrasonic diagnostics [3], which have found many applications for non-destructive testing of different constructions, are ineffective for foam insulation due to polyurethane's high porosity [4], which leads to high levels of acoustic wave attenuation. Similar considerations apply to the silicate fiber tiles, which shield the outer surfaces of the USA Space Shuttle and Russian Buran [1], [2], as well as to honeycomb prepreg construction materials that also produce incoherent scattering and attenuation of acoustic waves.

In many cases, microwave diagnostics using holographic subsurface radars could be a good alternative to ultrasonic testing. The basic advantage of microwaves in comparison with ultrasonic methods is the fundamental difference in physical properties affecting the propagation of electromagnetic versus acoustic waves in heterogeneous media. Electromagnetic waves reflect from heterogeneities only when their dielectric contrast is sufficiently high, and their dimension is comparable to a quarter of wavelength or greater. Thus, electromagnetic waves propagate practically without loss in foam insulation in which the matrix polyurethane has approximately the same permittivity as the air in the pores, and the pore dimensions are much less than the wavelength of microwaves.

Another advantage of microwave diagnostics is its high sensitivity to humidity because of the extremely high (approximately 80) dielectric constant of water. This provides the opportunity to find places where water invades a composite structure. Since the subsurface radar is a device that can operate with only one-side access to the structure under investigation, this quality makes it possible to perform after-flight inspection of aerospace device components without dismantling them.

However, the main disadvantage of this technology is its inapplicability for inspection of composite materials containing carbon fiber. Carbon fiber has high electrical conductivity which produces high attenuation and prevents propagation of electromagnetic waves. Consequently, our research is restricted to glass fiber composites that have low level of electromagnetic wave attenuation.

II. Holographic Subsurface Radar RASCAN-5

A new NDT method, which uses the holographic subsurface radar of RASCAN type operating in the gigahertz range [5], is discussed in this paper. Fig. 1 represents an overall view of the RASCAN-5 radar that has been produced in lots for the past few years. Various models of the radar have different operating frequency ranges. They are: 1.6–2.0, 3.6–4.0, 6.4–6.8 and 13.8–14.6 GHz [6]. This allows selection of the radar frequency most suitable to the task and conditions. For example, the radar with the lowest frequency band of 1.6–2.0 GHz was designed specially for inspection of concrete floors [7].

For recording holograms, different methods of radar scanning are being used. At present, hand scanning is used for most applications [8]. This scanning method is cheap, reliable, and gives opportunity to scan places that are difficult to access; in the corner of a room for example. For scanning of floors, a special handle has been designed [7]. The use of the handle reduces operator strain, making it possible to scan large spaces in a reasonable time.

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Fig. 1. Overall view of RASCAN-5 holographic subsurface radar: 1 – cables; 2 – antenna attachment for scanning in corners; 3 – radar head; 4 – control block; 5 – power supply unite.

However for using this type of the radar at industrial scale, other more productive methods are needed. These could be robotic or electro-mechanical scanners [9], [10] as well as industrial manipulators.

The latest model of RASCAN radar has a quadrature receiver and specialized software that give the opportunity to reconstruct the recorded complex holograms [11]. Holograms recorded in opaque and dense media have restrictions related to the level of electromagnetic wave attenuation [12], [13]. Recording and restoration of holograms by subsurface radar is possible only for media with low levels of the attenuation. For media with high attenuation such as concrete, holographic subsurface radar may record visually interpretable images, but they have little in common with actual holograms. This effect relates to the radar's inability to record sufficient signal from a subsurface object that is off-axis of the radiation pattern (due to decrease of the antennae gain). However many composite materials have low attenuation, so it is possible to record microwave holograms that can be reconstructed [11].

II. Experimental Results

To demonstrate this capability, experiments on different materials, which include Space Shuttle heat protection tiles [14], [15] and polyurethane foam insulation of the type used on cryogenic fuel tanks [16], had been performed previously. The honeycomb prepreg composite produced on a base of glass fiber is the next step of research. All these materials have common features: they are heterogeneous, and have a low level of electromagnetic wave attenuation.

Honeycomb prepreg composite materials have found widespread application in the aircraft and space industries [17]. They are used as structural materials as well as for interior finishing of airplanes and helicopters because they have a better strength-to-weight ratio than metals. Such applications demand high reliability including resistance to unfavorable weather conditions.

In this relation, the most dangerous event is water seepage into the honeycomb structure through small cracks. If temperature throughout the day, or during flight goes through zero centigrade, water in the cracks transforms into ice and expands. If this process is repeated a few times, structure can be damaged by this "frost wedging". Northern countries are familiar with this process because drivers see the damage to asphalt roads in spring caused by warm sunny days with frozen nights. The microwave method, based on holographic subsurface radar, is one of the ways to improve diagnostics of honeycomb composite details.

For the current experiments, two samples of honeycomb prepreg composite panels had been used. Sample 1 has an almost rectangular form of 328 by 335 mm, with a fragment of 161 by 75 mm cut from one corner (Fig. 2). Both Samples 1 and 2 have the same design: between two external prepregs the honeycomb strips are placed (Fig. 3). Each sample has an overall thickness of 11 mm.

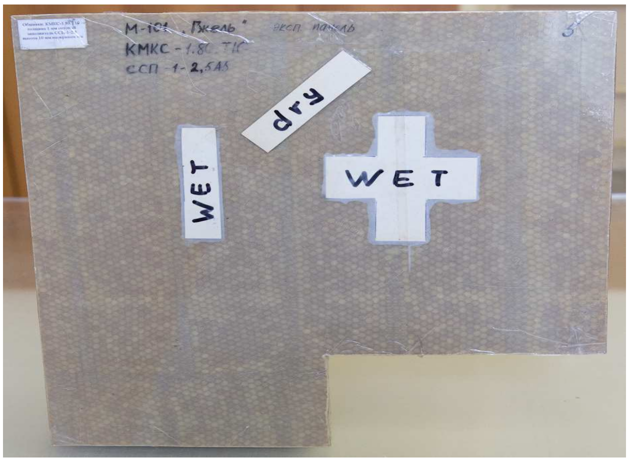


Fig. 2. View of the Sample 1 with the three papers clued to its surface.

For determining sensitivity of the RASCAN radar, two paper strips and one paper cross were affixed using scotch tape on the surface of Sample 1. Two papers were wet and one was dry (Fig. 2). The tape holds the papers on sample surface and prevents wet ones from drying out.

Fig. 3. View of the honeycomb strip from the butt-end of the composite panel.

The Sample was scanned using RASCAN radar as shown in Fig. 4. Hand scanning [8] was used in all of the experiments that are described in this paper. The surface with the wet and dry papers was on the bottom of the Sample 1 during scanning.

Fig. 4. Hand scanning of the Sample 1.

The experimental results at frequencies 6.7 and 14.7 are presented in Fig. 5.

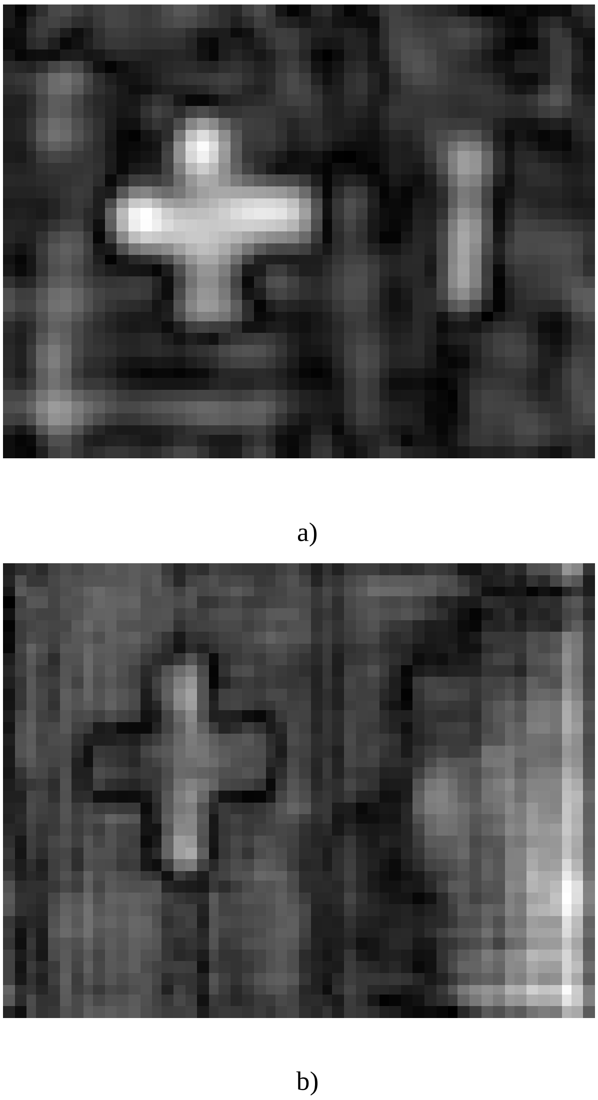


Fig. 5. The experimental results at frequencies of 6.7 GHz (a) and 14.7 GHz (b).

On the microwave images recorded particularly at a frequency of 6.7 GHz, one can clearly observe the wet paper figures, while the dry paper rectangle is invisible. The contrast of the moist paper figures is explained primarily by the high dielectric constant of water. On the images presented in Fig. 5 a) and b) the seams between the honeycomb strips are also observed.

The next series of experiments was carried out with the Sample 2 that has a smaller size of 173 by 273 mm as shown in Fig. 6. Unlike the Sample 1, in Sample 2 a portion of the honeycomb interior was filled with polymer paste. These areas are visible as light strips in Fig. 6.

The aim of the experiments with Sample 2 was determining the RASCAN capability to find water inside the honeycomb strips and its sensitivity to small quantity of water. For intrusion of water into the cells a syringe was used to perforate the sample surface and inject a small amount of water.

In one case, only one cell has been pierced and in the other case a group of 9 cells in the form of an oblique cross has been filled with water (Fig. 6).

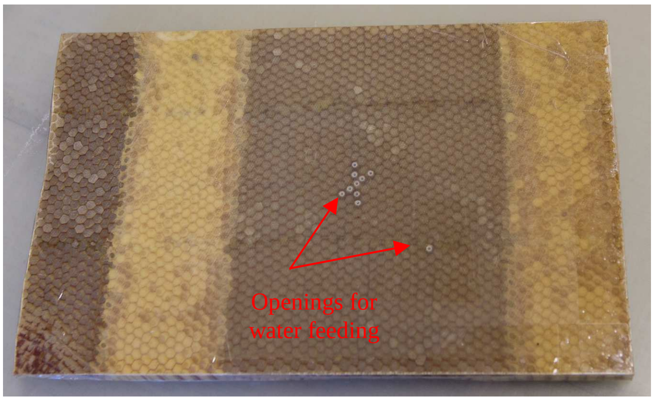
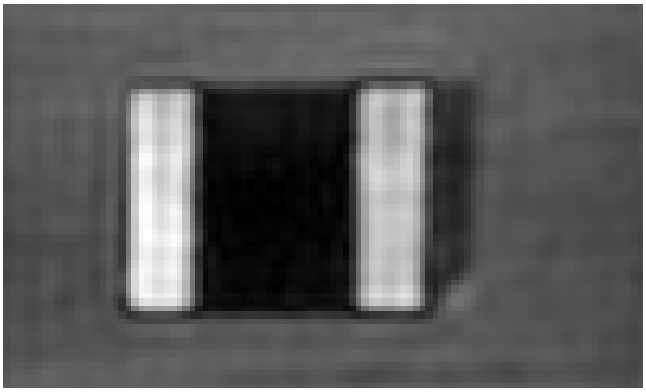
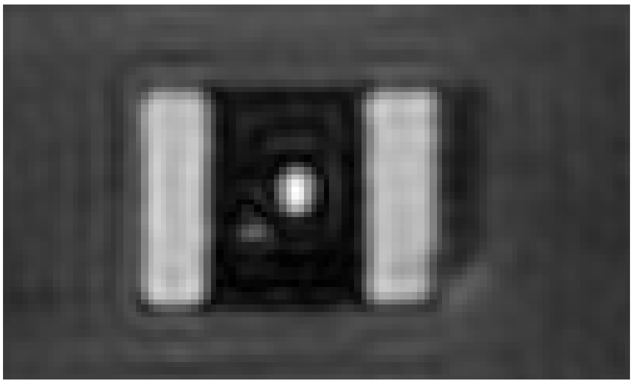


Fig. 6. View of the Sample 2. Two bright strips are cells that filled with polymer paste. Openings for water injection are indicated by arrows.

As in the previous experiments, scanning of Sample 2 was carried out in two ranges: 6.5 GHz and 14 GHz. The scan results are shown in Figs. 7 and 8.



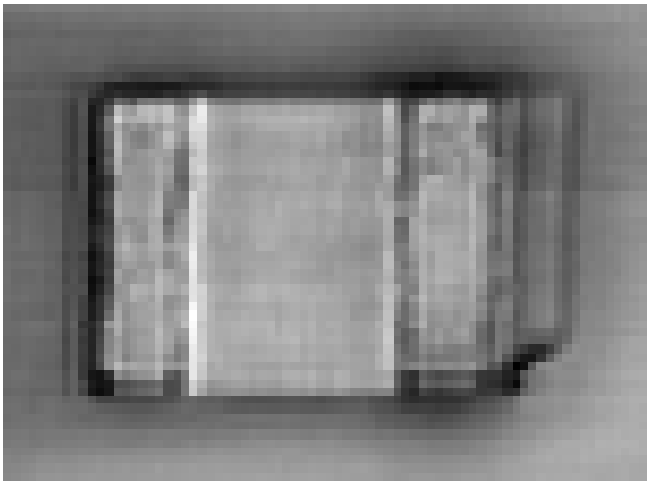
a)



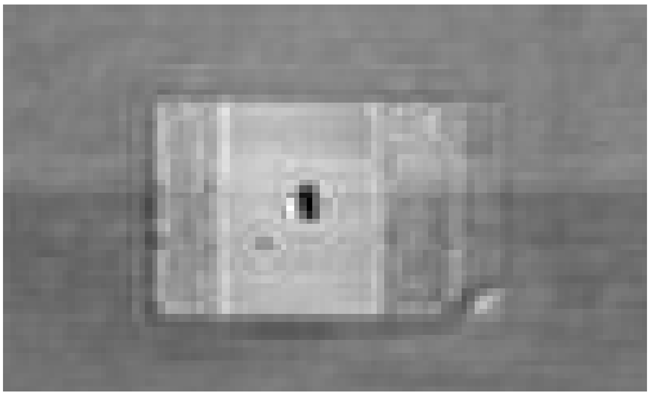
b)

Fig. 7. Microwave image of the Sample 2 at frequency of 6.5 GHz: a) the image before water injection; b) the image after water injection.

Given that Sample 2 was smaller than the Sample 1, the scan area was greater than the sample limits. Scanning of Sample 2 was carried out from the back side on which there were no holes for water injection. This explains the mirroring of the recorded contrast details on the microwave images in Figs. 7 and 8 with respect to the photo image of Sample 2 in Fig. 6. Note that the same is true with regard to experiments with Samples 1.



a)



b)

Fig. 8. Microwave image of the Sample 2 at frequency of 14 GHz: a) the image before water injection; b) the image after water injection.

The scan results at different frequencies presented in Figs. 7 and 8 show that subsurface radar RASCAN-5 can detect the presence of water not only in the group of cells but in a single cell whose cross dimension of 4 mm is about 10 times lesser than the wavelength corresponding to frequency of 6.5 GHz ($\lambda \approx 4.6$ cm). Such high sensitivity to the small object is very unusual, and can be explained by high water contrast in gigahertz range.

At the higher frequency of 14 GHz even smaller irregularities (which are absent at the frequency of 6.5 GHz) are visible on the image. In this regard, it can be concluded that the selected frequency range should correspond to the task under consideration, so that small heterogeneities do not obscure the objects that are the intended targets of the inspection. It should be noted that Sample 2 has a defect in the form of a slice in the lower right-hand corner (see Fig. 6). This defect is visible on the recorded microwave images in Figs. 7 and 8.

One of the advantages of holographic subsurface radars of RASCAN type is the relatively simple possibility of adapting their designs to work in a new frequency band. Currently a radar that will operate in the 20–24 GHz frequency range is under development. This will increase the sensitivity and resolution of the method in cases where it is required by conditions of the target or material under inspection.

III. Conclusion

Though subsurface radar technology has not yet found widespread use as a tool for NDT diagnostics of dielectric aerospace materials and details, the latest research gives us quite successful examples of its application. Holographic subsurface radars have some advantages over impulse radar. They are cheaper and more adaptive to the task conditions in comparison with impulse radar. Subsurface radar technology also has superiority over traditional ultrasound devices because this technology provides the opportunity to survey porous material such as polyurethane foam, silicate fiber tiles (which shielded the USA Space Shuttle and Russian Buran), and silicate composites that have honeycomb design. Further investigations are needed for improving the resolution and sensitivity of proposed technology.

Acknowledgement

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