High Resolution MW Holographic System for NDT of Dielectric Materials and Details

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Abstract — **In recent years, there has been a surge of new applications of composite materials and structures in aerospace industry. The composites have many advantages over traditional metal alloys. They have, as a rule, better strength/weight ratio, withstand to unfavorable weather conditions and aggressive environments. Corrosion also doesn't affect them.**

Traditional methods of ultrasonic diagnostics are ineffective for porous composites such as polyurethane foam insulation, silicate fiber tiles as well as for honeycomb prepreg construction details due to high levels of acoustic wave attenuation in them. In some cases, microwave holographic subsurface radars can be a reasonable alternative to ultrasonic testing.

A specially designed test setup, which uses a vector network analyzer for generating and receiving signals, was created. Operational frequency band of the test setup gives opportunity to carry out experiments in the broad range of 10MHz - 24 GHz. The setup records complex multi-frequency holograms, for the reconstruction of which the software was developed. A sample of polyurethane foam insulation, which is used for shielding of rocket cryogenic fuel tanks, was tested in the setup. The sample had preliminary produced defects. Comparison of the samples testing results and the defects maps showed that they are in a good coincidence.

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

I. Introduction

A few cases, which demonstrate inadequacy of the current methods of non-destructive testing (NDT), are very spectacular. First of all, it is possible to mention the Space Shuttle Columbia disaster, which occurred in 2003, destroying the return vehicle and killing all seven crew members, and secondly, the incident with the Russian space vehicle Buran when the tearing away of the wing heat protection tiles happened that fortunately did not have the same serious consequences [1], [2]. These and other accidents have aroused interest to the new NDT methods for examining dielectric composite details and materials as it was recommended in NASA report related to the Columbia catastrophe [1].

One of these emerging technologies is the microwave (MW) method that is based on holographic subsurface radar of RASCAN type [3]. Electromagnetic waves have advantage over ultrasonic ones because they can penetrate porous and other media that have high level of attenuation of acoustics waves. This is crucial in the case of diagnostics of polyurethane foam that is used for the rocket cryogenic fuel tanks insulation. Defects of polyurethane insulation were the main reason of the Columbia disaster [1], [4], [5].

RASCAN holographic subsurface radar was designed primarily for inspection and diagnostics of buildings construction details [6]. Nowadays, the radars have numerous applications [3] and are produced in lots of different modifications [7] that are differed mainly in operational frequency bands. Applying any RASCAN radar involves manual scanning that sometimes requires a high level of operator's training.

Later the radars were used for diagnostics of space shuttle heat protection tiles [8], [9], polyurethane foam insulation [10] and fiberglass honeycomb prepregs [11]. For diagnostics of dielectric composite materials applied in aerospace industry, the radars operating in frequency ranges of 3.6-4.0, 6.4-6.8, and 13.8-14.6 GHz were used.

The results of these experiments were satisfactory and promising. However, they have shown that there is a need for better resolution and sensitivity, and higher precision when scanning a sample under investigation. This could be achieved by using a higher operational frequency range and an automatic scanning.

It needs to be mentioned that testing samples examined in the foregoing papers [8]–[11] had considerably lower level of MW attenuation than building materials have [12]. For example, the complex permittivity ε of the foam sprayed on the external fuel tanks of the Space Shuttle measured at 10 GHz is equal approximately to (1.05–*j*0.003), its density is also very low and consists only of 4% of water [13]. These characteristics have been taken into account in designing the test setup intended for diagnostics of specimens of rocket tanks insulating materials and other dielectric materials used in the aerospace industry.

It should be noted that there is a significant limitation for the use of microwaves for NDT in the aerospace industry. That is the carbon composites, which have a high level of electrical conductivity and, therefore, a high level of electromagnetic wave attenuation. For their diagnostic ultrasound methods are traditionally used as more suitable.

II. TEST SETUP

For recording high quality MW holograms in broad range of frequencies, a special test setup has been designed, Fig. 1. The setup consists of a vector network analyzer ZVA 24 that generates frequencies in range of 10 MHz to 24 GHz and a two-dimensional electromechanical scanner.

By means of two flexible phase-stable feeders, a transmitter-receiver antenna is connected to the network analyzer. The antenna is mounted on a tripod with adjustable height that allows changing the distance between the antenna and the probed sample. It is possible to place various types of antennas in the setup.

To avoid influence of antenna movement on the results of an experiment, antenna is placed on the tripod motionlessly. Meanwhile, a tested sample is placed on a support mounted on the two-dimensional electromechanical scanner. The scanner consists of two linear units and moves the sample under the antenna line-by-line [14].

Every linear unit uses stepper motors as a driver that provides the required positioning accuracy at scanning multiple cycles of lines. Stepper motors linear actuators are steered by a microcontroller (MC). The test setup is adaptive and has broad possibilities for adjusting scanning parameters to the tasks under consideration.

At initializing MC installs the number of pulses required for moving per unit length along each of the directions. The size of the scanning area along each of the directions and sampling intervals are also defined. The vector network analyzer initialization creates a grid of frequencies, specifies the format of the transmitted data, and installs synchronization of the measuring cycle by the external clock signal.

After determining the desired parameters, scanning is started, and the antenna is moved relative to the sample according to the trajectory presented in Fig. 2.

It is possible to select two scan modes. At the first mode, the registration is performed when the hologram parameters are recorded only in one direction of the scanner movement. The second mode gives opportunity to record in both directions.

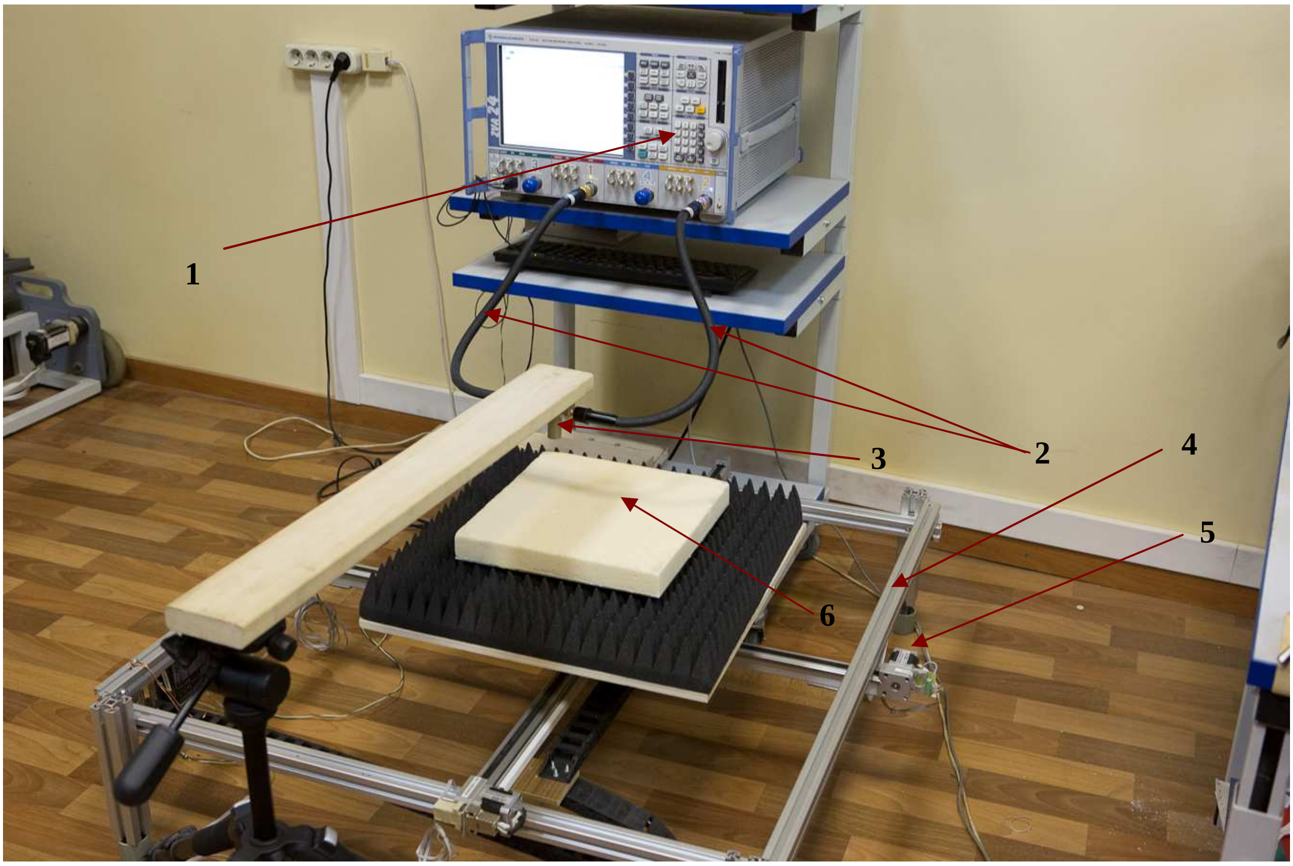


Fig. 1. Photo of the test setup

1. Vector network analyzer ZVA 24
2. Two flexible phase-stable feeders
3. Antenna
4. Scanner frame
5. Stepper motor
6. Sample

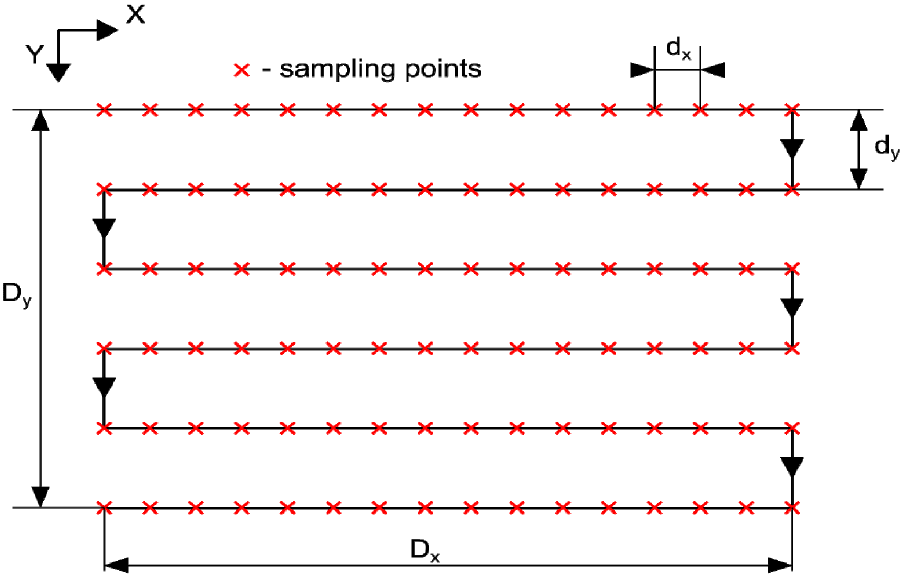


Fig. 2. Diagram of a sample scanning

d_x – sampling interval along axis X
d_y – sampling interval along axis Y
D_x – dimension of scanning area along axis X
D_y – dimension of scanning area along axis Y

III. Experimental Results

Creating the test setup described above greatly expanded the possibilities for experiments with samples of dielectric structures. The advantages of bench tests include:

- the ability to use the entire operating frequency range of the vector network analyzer up to 24 GHz
- a more accurate positioning of the holographic radar antenna relative to the sample in comparison with the manual scanning at using the RASCAN radar
- the ability to conduct experiments at any antenna height above the surface of the sample
- reducing the load on the operator at automatic scanning of the samples.

To test capabilities of the new setup, a sample of heat insulation with preliminary produced defects was used. The draft of the sample is presented in Fig. 3.

The dimensions of the sample were 500 by 400 mm. The thickness of the polyurethane insulation is equal to 4 cm. Insulation was glued on a metal substrate of aluminium alloy of 5 mm thickness. The sample was prepared in two stages. Initially, the central circle with a diameter of 270 mm was sprayed with adhesive, and three round cuts with a diameter of 50 mm and a height of 1 mm were done on the bottom surface of the foam.

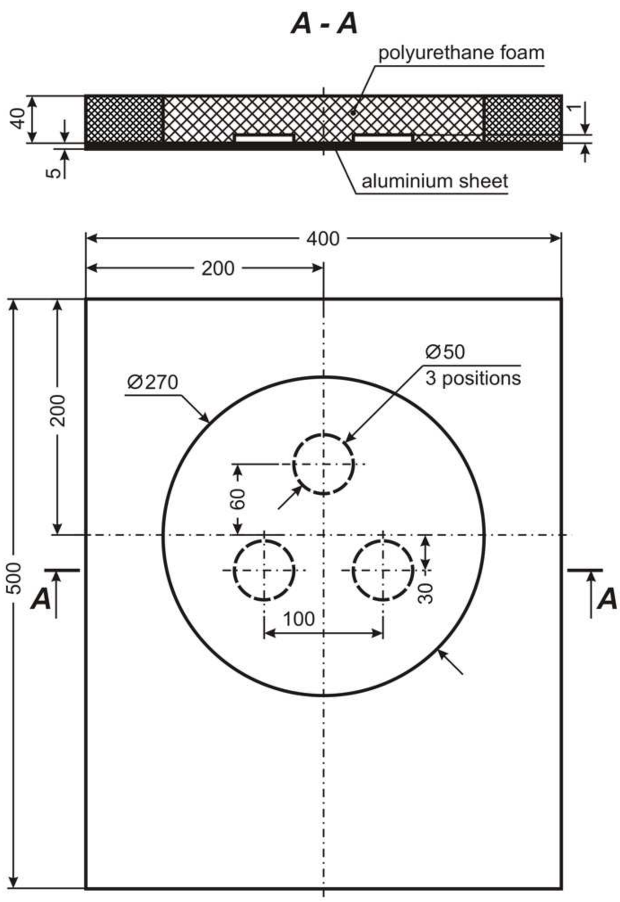
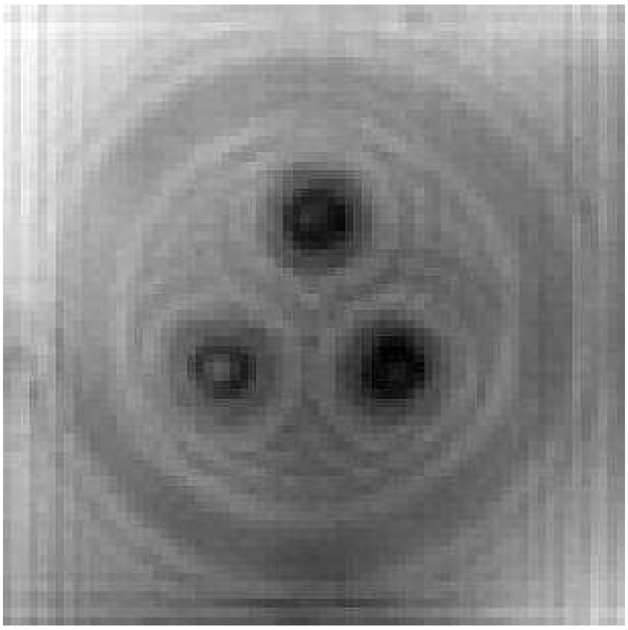
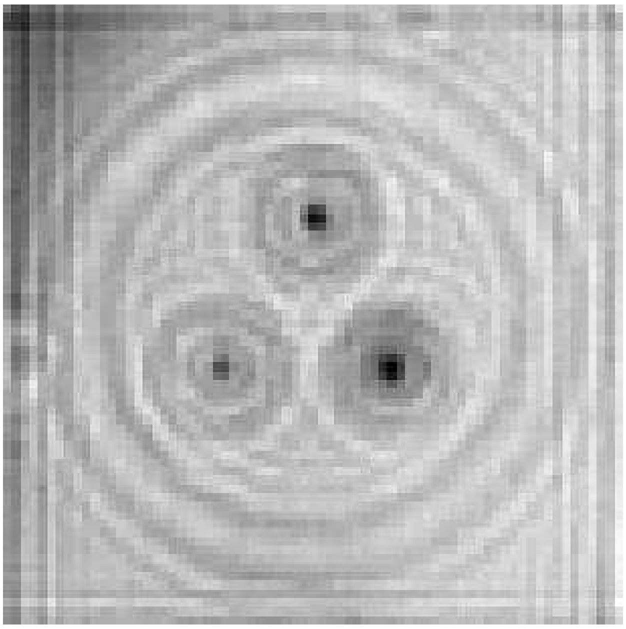


Fig. 3. Draft of the polyurethane insulation sample

Prime coating and glue are missing under the round cuts on the metal surface. Instead, they were placed on the inner surface of the cuts. This procedure imitates the effect of delamination on the border between the foam and the metal surface. Usual total thickness of the prime coating and glue is about 200 microns. On the second stage, the rest of the sample was filled with foam. The sample was scanned on the test setup at the frequency of 21.8 GHz. The recorded microwave complex hologram is presented in Fig. 4, and the result of its reconstruction is in Fig. 5.



(a)



(b)

Fig. 4. Microwave complex hologram:

a) *I*-quadrature
b) *Q*-quadrature

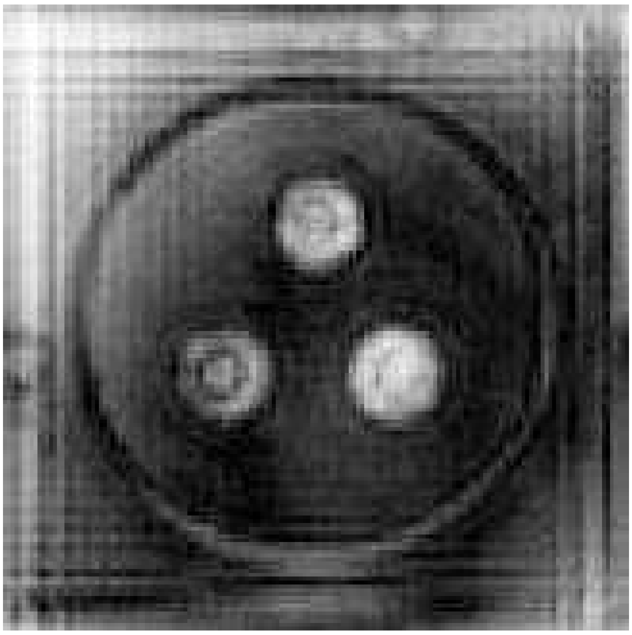


Fig. 5. Reconstruction of the hologram presented in Fig. 4

The scanned surface was smaller than the sample area, it was 35 by 35 cm and covered all heterogeneities and defects of the sample.

Reconstruction of the complex holograms was performed by using an algorithm that was described in [15], [16]. The same sample was used in experiments with the RASCAN radar at the frequency of 14.6 GHz by using manual scanning [10]. Comparison of these results gives ground to assert that using the test setup greatly improves quality of the reconstructed holograms, their resolution and sensitivity to the defects of the sample.

IV. Conclusion

Although subsurface holographic radar technology has not yet found a broad application as a tool in the field of non-destructive testing of dielectric materials and components, recent researches provide us with a sufficient number of successful examples of its application, including the ones that involve aerospace industry. Holographic subsurface radars have certain advantages over pulse radars, since they are cheaper and more adaptive to the task conditions. The developed technology has also advantage over the traditional ultrasound devices in certain areas, as it provides an opportunity to examine the porous materials with high attenuation of acoustic waves such as polyurethane foam, thermal protection tiles made of sintered quartz fibers, and multilayer composite materials based on glass fibers having a honeycomb structure. Further studies are necessary to improve the resolution and increase the sensitivity of the developed holographic subsurface radar technology and to adapt it for applying under the industrial conditions.

Acknowledgment

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