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Research Article

# Application of microwave holographic subsurface technology for non-destructive testing of reinforced polyurethane foam

**Vladimir Razevig, Andrey Zhuravlev and Sergey Ivashov***

Remote Sensing Laboratory, Bauman Moscow State Technical University, 5, 2nd Baumanskaya str., Moscow, 105005, Russia

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***Corresponding author:** Sergey Ivashov, Remote Sensing Laboratory, Bauman Moscow State Technical University, 5, 2nd Baumanskaya str., Moscow, 105005, Russia, Tel: +7 903 687-2291;
E-mail: sivashov@rslab.ru

**ORCiD:** https://orcid.org/0000-0002-3605-5623

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## Abstract

Glass fiber Reinforced Polyurethane Foam (RPUF) has found wide application primarily in the aerospace and construction industry due to its outstanding properties. Unlike pure non-reinforced Polyurethane Foam (PUF), it has increased strength characteristics and at the same time retains unique heat and sound insulation properties. The paper considers the features of reinforced polyurethane foam examination in the Microwave (MW) range. It is shown that there is a significant difference in the recorded MW images compared to pure polyurethane foam. This is expressed primarily in the fact that the reinforcing fibers have a dielectric constant that is different from enclosing polyurethane foam, which leads to scattering and reflection of the incident electromagnetic wave on them. Experimental studies have shown that for RPUF, in contrast to PUF, there is an optimal wavelength range in which the contrast of defects against the background of glass fiber reflections is of the greatest value. An experimental comparison of two methods of examination back-scattering and forward-scattering methods was also carried out for RPUF. It is shown that the forward-scattering technology of measurements, if it can be implemented, has certain advantages since allows reducing the contrast of background reflections from the reinforcing fibers.

## Introduction

The Space Shuttle Columbia catastrophe in 2003 [1,2], which resulted in the death of its entire crew of seven people, was the result of a detached chunk of the heat-insulating polyurethane foam, which covering the liquid hydrogen tank, pierced the wing leading edge of the vehicle during its launch. Later when Columbia returned to Earth after completing his mission in orbit, the plasma resulting from air deceleration in the upper stratosphere penetrated the wing structure, which led to its destruction, and subsequently the entire spacecraft and the death of the crew. This disaster, as well as the accident with the Space Shuttle Challenger in 1986 caused by a burst gasket in a solid propellant booster, showed that the cause of the accident could not be the most complex and technically advanced structural element, but a lack of attention to simple details and their consequences. These events gave rise to a number of studies in the field of non-destructive testing of dielectric heat-insulating materials, carried out both in the millimeter [3,4] and microwave [5,6] ranges of the electromagnetic spectrum.

PUF-based materials have found wide application not only in the aerospace industry but also in construction and many branches of engineering. This is due to their outstanding properties such as low thermal conductivity, high soundproofing, low specific gravity, and ease of machining [7]. To this should be added the relatively low cost of polyurethane foam products. By the combination of these properties, PUF is undoubtedly the leader among other structural and insulating materials. The same advantages of polyurethane foam make the use of ultrasound unsuitable for diagnostics due to the high

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level of attenuation, and X-ray due to the low level of defects contrast [8].

The main disadvantage of PUF materials and coatings is their low strength and load-bearing capacity, which led in particular to the Columbia disaster. The most obvious means of increasing the strength of such materials is their reinforcement, for example with glass fiber [9]. This circumstance, as experimental studies have shown, qualitatively changes the approach to choosing the optimal frequency range of the electromagnetic spectrum when examining reinforced polyurethane foam. Pure PUF without fillers hardly absorbs electromagnetic waves [4], which facilitates the use of higher frequencies for increasing the spatial resolution and contrast of detected defects [10,11]. The presence of glass fiber makes this dependence non-linear since the contrast of filler fibers also increases with increasing frequency, which can mask the revealing defects of the material. The main goal of the described study was to elucidate the differences in the diagnosis of PUF and RPUF and related effects.

## Experimental setups

To carry out experiments on the RPUF diagnostics, two types of installations were used, in which the principles of sounding were implemented by back-scattering and forward-scattering methods. In the first case, the receiving and transmitting antennas are located on the same side of the test sample, and in the second case on different sides, i.e., the projection technology is implemented that is usually used in X-ray machines. Both types of installations were designed on the basis of a vector network analyzer (VNA ZVA24, Rohde & Schwarz) as a generator and receiver of signals.

Previously, the back-scattering technology was implemented in the study of samples of rocket tanks' polyurethane foam coatings that were provided by SPA Tekhnomash, Russia, and Vikram Sarabhai Space Centre, India [10,12]. A photograph of this experimental setup is shown in Figure 1. It consists of VNA ZVA24, which is used for the generation and receiving of MW signals in a wide range from 6 GHz to 24 GHz, and a three-coordinate electromechanical scanner for moving the test sample line by line under a transmit-receive antenna connected to the port of the vector network analyzer with flexible armored phase-stable cables. Such a scheme avoids the influence of cable bending on the phase of the recorded signal. The detachable transmit-receive antenna is mounted on a tripod and located above the probed sample. By adjusting the tripod height, which can move along the vertical axis, the distance from the antenna opening to the surface of the sample placed on the scanner is set. When probing the sample at forward-scattering mode, the scanning scheme is the same, but two antennas located at opposite sides of the test sample and oriented towards each other are used, Figure 2.

As raw data in the experiments, the signal scattering parameters (S-parameters) recorded by the VNA ZVA24 on a uniform frequency grid in the scanning plane with given sampling steps along the X and Y axes are used. As a result of applying this method, an array of complex numbers is recorded and specified on a two-dimensional grid in the region of space occupied by the sample.

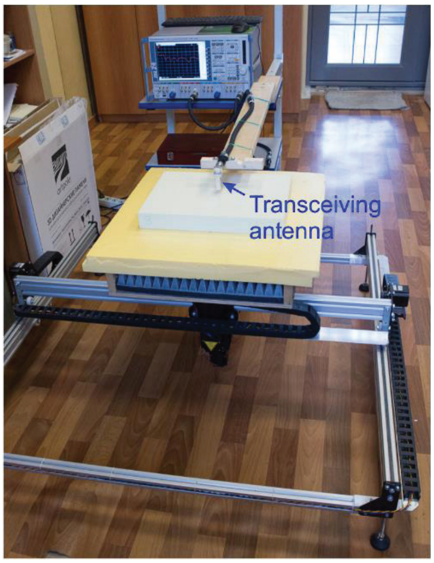

**Figure 1:** Photo of the experimental setup with the VNA ZVA24 on the background and a three-coordinate electromechanical scanner for the implementation of the back-scattering technology.

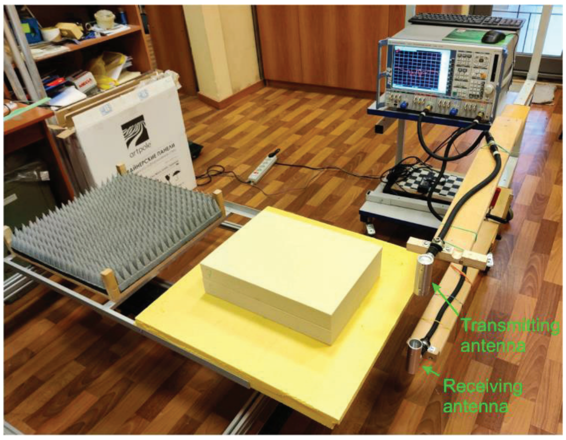

**Figure 2:** Photo of the setup, in which the coordinate scanner is modified for forward-scattering study.

The signal set obtained in this way is also called a MW hologram because of the direct analogy with an optical hologram [13,14]. To reconstruct an MW image from a registered multi-frequency radar hologram, the numerical method of wavefront back-propagation is used, which was described in detail in [15,16]. The method is sufficiently resistant to minor reflections from glass fiber filaments. This allows it to be used in the case of RPUF.

## Samples

For the experiments, several samples of a polyurethane foam coating reinforced with glass fiber were used. All samples have the shape of a rectangular parallelepiped with dimensions of 390 ± 5 mm long, 290 ± 3 mm wide, and 50 mm high. The samples were provided by TECHNONICOL, Russia, which produces a wide range of materials for the construction industry [17].

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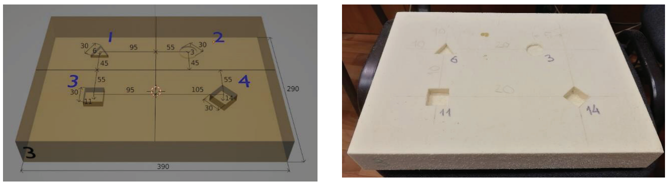
In Sample 1, four cavities of simple geometric shapes with a depth of 3 to 14 mm with a characteristic size of 30 mm were cut out by milling. The defect map of Sample 1 is shown in Figure 3 along with its photograph, in which the cavity depths are indicated with a marker near each hole.

This sample was studied on the setup shown in Figure 1, in two frequency bands from 6 GHz to 12 GHz and from 15 GHz to 24 GHz. Each band used its own transceiver antenna with the appropriate bandwidth. The obtained MW images of defects in Sample 1 located with the defects up are shown in Figure 4. In these experiments, the observation was carried out for the reflected signal, i.e. the transmitting and receiving antennas were located on the same side of the sample above it.

Another Sample 2 was made using an engraving tool with a ball nose cutter. Five cavities were made in it with a hemispherical surface 20, 25, and 30 mm in diameter, compressed or stretched in a direction perpendicular to the surface. The Sample 2 defect map is shown in Figure 5 along with its photograph. Defect No. 2 in this panel was made in the place of the existing production cavity, which continued deep into the sample beyond the border of a hemispherical artificially created defect.

Similar experiments were carried out on Sample 2, the results of which are shown in Figure 6. These experiments show that the addition of glass fiber filler, which has a dielectric constant different from the polyurethane foam containing it, qualitatively changes the situation, because the filler creates background reflections that mask defects in the RPUF, see Figures 4 and 6. In this regard, the 6 GHz - 12 GHz sounding range is preferred over the 15 GHz - 24 GHz range, because in the first case, the contrast of background reflections from glass fiber is lower compared to the contrast of defects. This differs from that for pure PUF, where the observed effects showed that the contrast of defects only improved with increasing frequency [10].

Inspection of heat-insulating coatings in back-scattering mode has undoubted technological advantages in the examination of ready-to-use products, such as cryogenic fuel rocket tanks [3,5]. In this case, forward-scattering technology is not applicable because the metal shell of the tank would completely absorb electromagnetic emission. But when it comes to technological lines for the production of PUF or RPUF, it becomes possible to use forward-scattering technology. This possibility was implemented by modifying the experimental setup with the location of the transmitting and receiving antennas on different sides of the sample under study, Figure 2. Features of registration and reconstruction of MW images in the implementation of the forward-scattering method, as well as its comparison with the back-scattering method were studied in detail in [18].



a) b)

**Figure 3:** Sample 1: a) Defect map b) Photo.

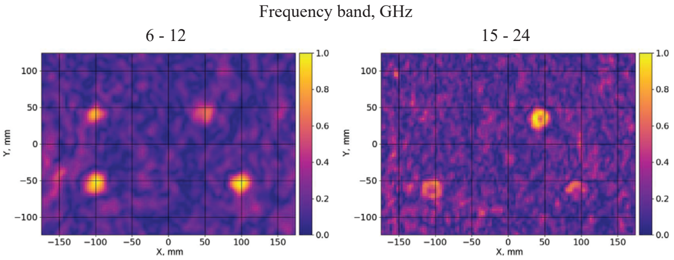
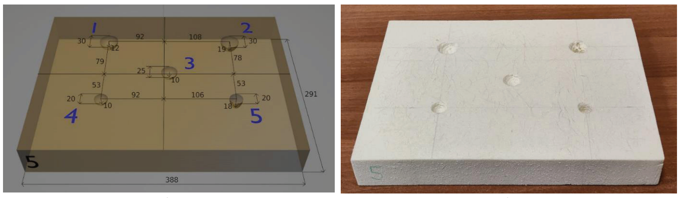


**Figure 4:** MW images of Sample 1 in two frequency bands.



a) b)

**Figure 5:** Sample 2: a) Defect map b) Photo.

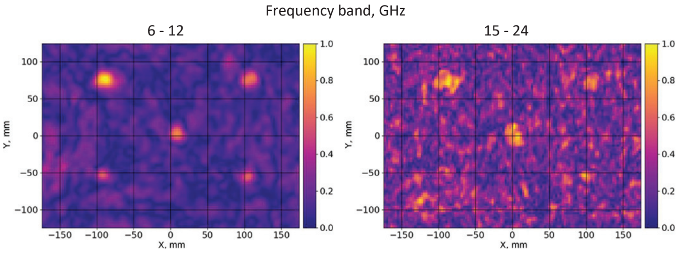


**Figure 6:** MW images of Sample 2 in two frequency bands.

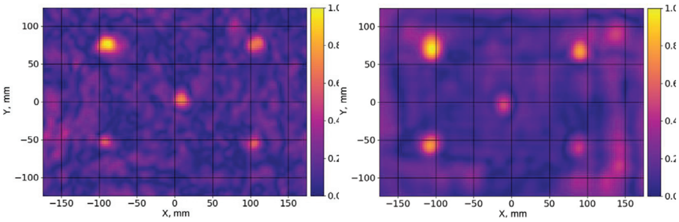


**Figure 7:** MW images of Sample 2 in the range of 6 to 12 GHz
a) Back-scattering and b) Forward-scattering modes.

Figure 7 compares the MW images obtained by both methods on Sample 2. The forward-scattering image is noticeably better than the back-scattering image. Perhaps this is due to the summation of the signal from the randomly located reinforcing fibers of the filler as it propagates through the thickness of the sample under study, which leads to background equalization. This opens up additional possibilities due to the use of the polarization properties of the recorded signals obtained in crossed polarizations.

The use of microwaves in recent years has been increasingly used in various fields of nondestructive testing of composite materials and can be used both independently and

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in conjunction with other methods [8,19,20]. Considering that RPUF, due to their improved mechanical properties compared to PUF, will find wider application, the features of using microwave diagnostics to study their properties are of interest both for the production and operation of finished products. This short article presents preliminary results that will be refined in further studies.

## Conclusion

In this work, using the samples of reinforced polyurethane foam panels, it was studied the influence of the frequency range on the quality of recorded radar images of artificially created defects in the RPUF material. It has been experimentally shown that an increase in the probing frequency above certain values can lead to a decrease in the contrast of defects due to an increase in background reflections from reinforcing fibers. This observation is qualitatively different from the case of non-reinforced polyurethane foam, where an increase in frequency over the entire range of microwave and mm waves leads to an improvement in the resolution of radar images, since to some extent, PUF can be considered transparent for electromagnetic waves in these ranges.

Another result of the study was a comparison of the performance of the back-scattering and forward-scattering methods. It was shown that the technology of forward-scattering measurements, in the event that it can be implemented according to the conditions of production, has certain advantages because it allows for the reduction of the contrast of background reflections from the reinforcing fibers.

As a further direction of research, it should be proposed to study the polarization properties of the signals reflected from the sample and transmitted through the sample for the most effective detection and classification of defects and reducing the contrast of background reflections from reinforcing fibers.

## Funding

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