STUDY OF ELECTROMAGNETIC WAVES REFLECTION FROM FOAM SAMPLES AND DETERMINATION OF THEIR DIELECTRIC PERMEATIVITY

O. O. Drobakhin, L. A. Filins'kyy*

Oles Honchar Dnipro National University, Dnipro, Ukraine
**e-mail: leonidfil2016@gmail.com*

Reflectivity and dielectric permeativity of liquid foam structures with an initial foaming ratio of 55 units in the form of flat-layered foam samples with fixed thicknesses of 40 and 80 mm are under measurement. A multi-frequency technique for studying the foam samples is used. The measuring and computing complex operates in the microwave range from 38 to 52 GHz. It is shown that the foam structure reduces the reflection of electromagnetic waves from metal surfaces significantly. The obtained value of the dielectric permeativity of the foam samples is in the range from 1.08 to 1.26. The results are useful for studying the reflection characteristics of foams and help to determine their dielectric permeativity.

Keywords: millimeter waves, multi-frequency measurements, reflection, foam, foam structure, liquid foam.

Received 15.10.2023; Received in revised form 07.11.2023; Accepted 15.11.2023

1. Introduction

In 1955 G.F. Williams [1] found an extraordinary effect. On the surface of the sea, covered with foam formations, there was a large emissivity in an ultra-wide range of frequencies compared to a clean water surface. This effect was of great interest to specialists in radiophysics, because it opened new studies of an unusual dielectric in the form of a mixture of liquid and gas. Eventually, people have learned to convert liquid foam formations into a solid state and widely use them in various fields of science, technology, and production of a wide range of consumer goods due to the extraordinary properties of such materials.

Active studies of electromagnetic wave propagation in foam structures began after the tragedy of the space shuttle Columbia where a protective foam coating was used. There was an urgent need to investigate the quality of this coating by means of non-destructive testing, and to identify the defects that led to the tragedy. Considerable human, technical and financial resources were allocated by NASA for the research. For example, S. Kharkovsky, F. Hepburn, J. Walker, R. Zoughi, J.T. Case, and M.A. Abou-Khousa worked effectively in one of the scientific groups, which managed to solve many problems with foam coatings for space shuttles using millimeter waves [2, 3].

Over time, publications appear both concerning flaw detection of shuttle foam coatings (especially, quality control of the connection between the tiles of the thermal protection foam system and the aluminum substrate) using an on-ground radar and several other radiophysical problems related to methods and means of non-destructive testing of materials [4-6].

One of the effective areas of radiophysical research of foam structures, both in the millimeter and centimeter range, is the development of equipment and methods for measuring the reflection characteristics of electromagnetic waves from foams [7, 8]. Such measurements showed very high absorption and very small reflection of electromagnetic waves, that is extremely important for tasks of masking important objects from radar detection [9, 10].

A. Chithra, P. Wilson, and S. Vijayan devoted a lot of time to the issue of the propagation of electromagnetic waves in foam structures like carbon foams with low thermal conductivity and high electromagnetic interference (EMI) shielding [11]. V. Nyagu paid great attention to studying the dependence of wave propagation on the foam layer thickness at frequencies 6 and 26 GHz in a wide range of foam parameters [12]. In papers [13, 14] the authors use millimeter radars to investigate foam structures in cryogenic and industrial chemical plants. By means of remote non-destructive sensing, they find methods of analyzing the parameters of foam coatings.

The phenomenon known as "foam caps" [15] manifests itself in the generation of various foam structures on the ocean surface when wind speeds exceed 7 meters per second. A critical task is to research the interaction of electromagnetic waves of different spectra with these oceanic foam formations. This inquiry is significant because it makes it easier to observe and predict the movement of foam caps, offering important information for weather forecasting and maritime traffic management. This is especially pertinent for vessels such as boats, ships, and submarines, which leave visible traces of foam during their passage. Such distinct foam signatures are effectively detectable both through aerial observations from aircrafts and through remote sensing from space-based platforms.

The work [16] showed several important technical problems and ways to achieve the necessary cloaking characteristics by reducing the reflection of electromagnetic waves of the millimeter range from metal objects using dynamic foam structures. Within the microwave frequency range spanning from 8 to 12 GHz, the study was detailed in reference [17] with an analysis of electromagnetic wave reflection and attenuation. The analysis was predicated on experimental data. The experimental setup used model samples of foam consisting of seven distinct layers characterized by different dielectric properties and thicknesses. In [18], the reflection characteristics of foam samples were studied in the frequency range from 1 to 1250 MHz. The samples were studied in a wide range of multiplicity from 10 to 55 units, and with salt additives of 1%, 4% and 6%. The measurements results showed that the studied foam structures can significantly reduce the reflection of electromagnetic waves in the range under consideration.

The purpose of this study is to measure reflection coefficients of a flat layer of foam with a fixed thickness and an initial multiplicity of 55 units, which constantly decays [19], wherein to use a multi-frequency method with the implementation of the Fourier holographic principle [20].

2. The main features of the foam samples

To obtain foam samples, a dispersion method was used, the essence of which is that when a jet of gas (air) passes through a foam generator with a grid irrigated with a foam-forming liquid, foam will be formed at its exit. In the foam generator, several mesh partitions with different hole diameters were used, installed in such a sequence in the direction of gas and liquid movement that the last mesh had the minimum cell size and corresponded to the required average bubble diameter.

The foaming liquid, which passed alternately through all the grids with the help of a gas jet, creates foam of the required dispersion at the output of the foam generator. The foaming ratio is the value that represents the ratio of the volume of the foam to the volume of the liquid from which it is prepared, depends on the set values of gas and liquid consumption. The foaming ratio of 55 units was used, with an average foam dispersion of 0.1-1 mm. Before starting the measurements, the foam generator was calibrated according to the multiplicity of the obtained foam. Foam sample structures were prepared from a 6% aqueous solution of foaming agent PO-05-P at room temperature.

The samples were prepared in the form of flat layers of the required thickness in a foam plastic tray with a base size (270×290) mm, on the bottom of which a metal plate was placed. Samples with a height of 4 and 8 cm were produced.

3. Computing complex for foam research

A measuring device (Fig.1) was used for the research. In it, the ratio value of the "reflected signal" to "incident" was fixed in decibels and converted into dimensionless values of the reflection coefficient. The reflection from the short-circuited plate was taken as the "zero" value, the level of complete absorption was fixed as the reflection from the matched load of -35 dB. The studied foam sample was placed on a metal sheet and its reflection was measured in the frequency range from 38 to 52 GHz. Thus, the frequency characteristic of the reflection of the samples was obtained. Measurements were made with an antenna length of 120 mm and a horn opening (46×46) mm.

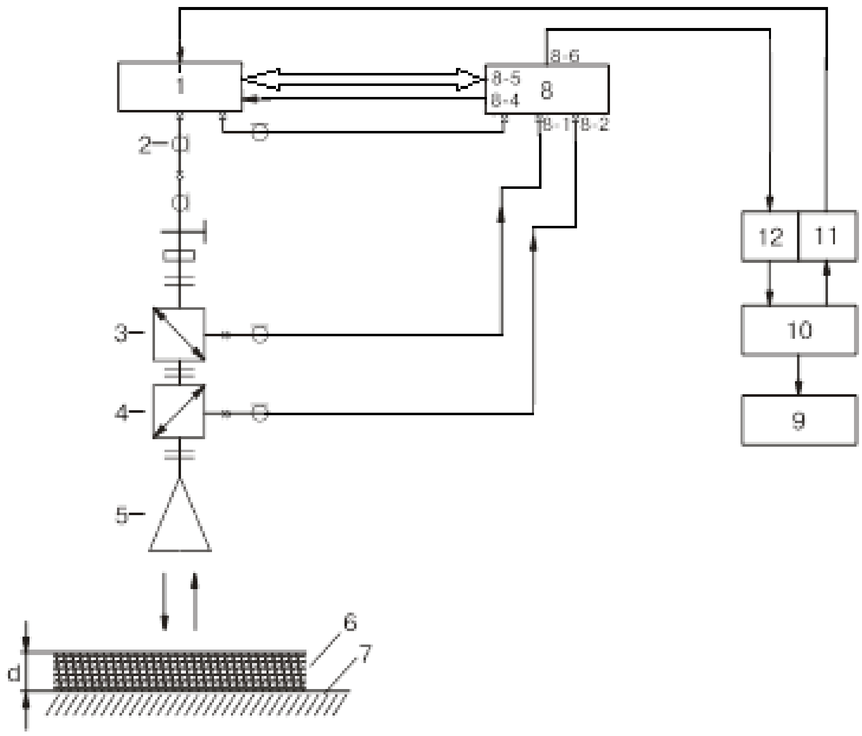

Fig. 1. Computing complex for measuring and determining the foam samples:
sweep generator from the R2-68 1, microwave cable 2, reflectometer from directional coupler 3 and 4, horn antenna 5, a sample of the foam 6, metal substrate 7, an indicator 8, computer 9, a digital-to-analog and analog-to-digital converter interface block 10, 11, 12.
Here: d is the foam sample thickness.

The high-frequency signal from the high-frequency transducer enters the reflectometer, where part of the signal is branched off, detected, and enters the connector of the indicator as an incident wave signal. Further, from the microwave reflectometer, the signal passes in a direct direction through the splitter to the antenna, radiates in the direction of the sample placed on the metal substrate.

The microwave signal is reflected from the metal substrate, the front face of the sample, and the inhomogeneities of the antenna (in the plane of the aperture and throat), passes to the splitter, is detected, and arrives at the connector of the indicator as a reflected wave signal. From the indicator, a signal proportional to the ratio of the reflected and incident wave signals is removed and fed through the analog-to-digital converter (the interface unit) to the personal computer as data of the amplitude-frequency characteristic.

In this way, the installation provides a qualitative study of foam samples by measuring the reflection coefficient value on a grid of discrete frequencies, followed by the transformation of the obtained characteristic into the spatial domain (fast Fourier transformation is used). On the PC monitor, it is possible to observe the placement of inhomogeneities on the path of electromagnetic wave propagation from the reflectometer to the metal substrate with the foam sample.

The PC uses a digital-to-analog converter to set the frequency in the generator. The antenna serves to irradiate the investigated structure and receive the reflected signal. The signals of the incident and reflected waves are separated by a reflectometric circuit and are sent from the detectors to the indicator, where their ratio is calculated, i.e., the reflection characteristic is entered.

The voltage proportional to the logarithm of the reflection characteristic module is measured and sent to the PC through the analog-to-digital converter. Such measurements were carried out in the selected frequency range. A specially developed program was used for measurements.

4. Experimental results

Before measuring the reflection characteristics of foam samples, it is necessary to calibrate the measuring device in open space or on a special radio-absorbing material that has reflection characteristics (in the given frequency range) no more than the reflection in free space.

Fig. 2 shows the reflection characteristic curve in the tract for the case of measuring the foam structure. In Fig. 2, the graph has the peaks corresponding to the cross-correlation reflectance function. Thus, peak 1 characterizes the cross-correlation function of the reflection from inhomogeneities in the neck and aperture, peak 2 corresponds to the cross-correlation function of the reflection of the front face of the foam sample and the reference inhomogeneity in the neck and is located at a distance of 197 mm from it, peak 3 corresponds to the cross-correlation function of the reflection from the rear face foam sample and support inhomogeneity in the neck and is located at a distance of 280 mm from it.

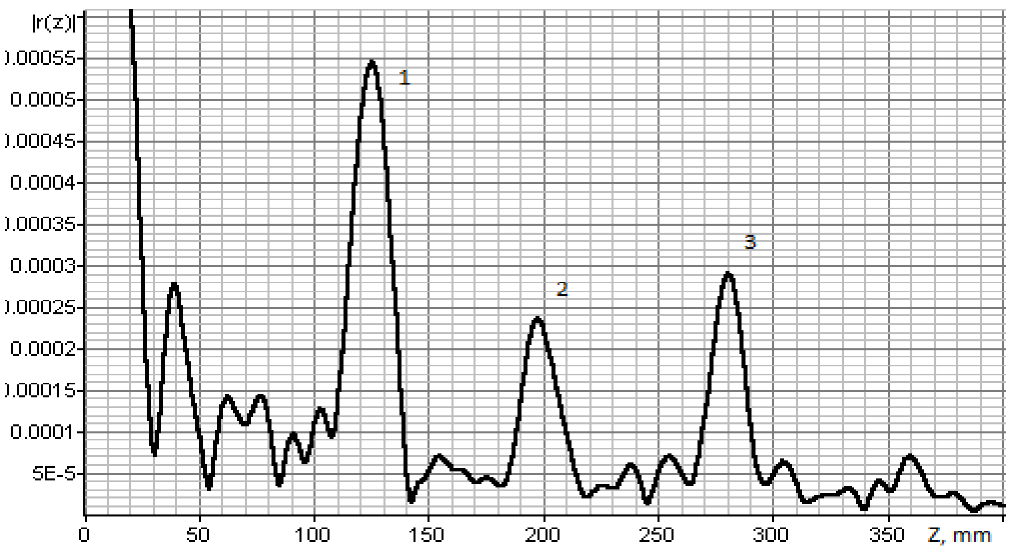

Fig. 2 The peaks of reflection from the front (2) and the back (3) for the sample zh20-80-16.

In Fig. 3, peak 2 corresponds to the cross-correlation function of the front face reflection of the foam sample and the support inhomogeneity in the neck and is at the distance of 196 mm from it, peak 3 corresponds to the cross-correlation function of the reflection from the back face of the foam sample and the support inhomogeneity in the neck and is at the distance of 280 mm.

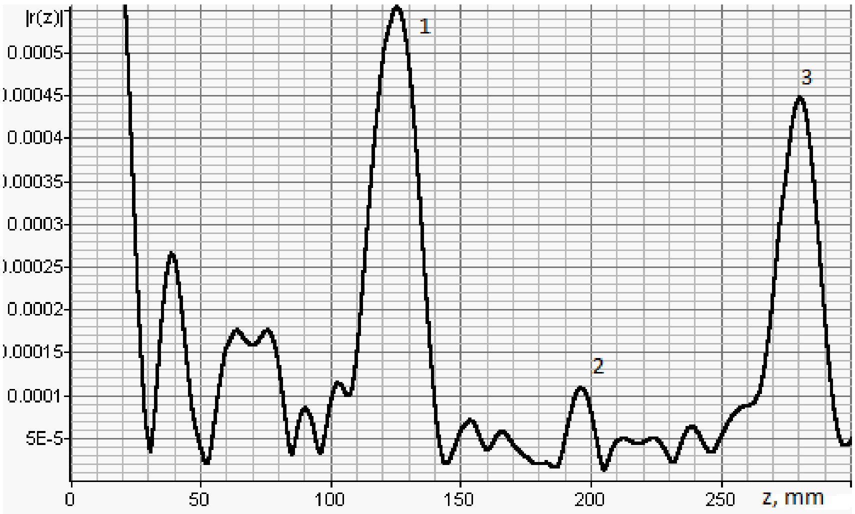

Fig. 3. The peaks of reflection from the front (2) and the back border (3) for the sample zh20-80-19.

In Fig. 4, peak 2 corresponds to the cross-correlation function of the front face reflection of the foam sample and the support inhomogeneity in the neck and is at the distance of 247 mm from it, peak 3 corresponds to the cross-correlation function of the reflection from the back face of the foam sample and the support inhomogeneity in the neck and is at the distance of 288 mm from it.

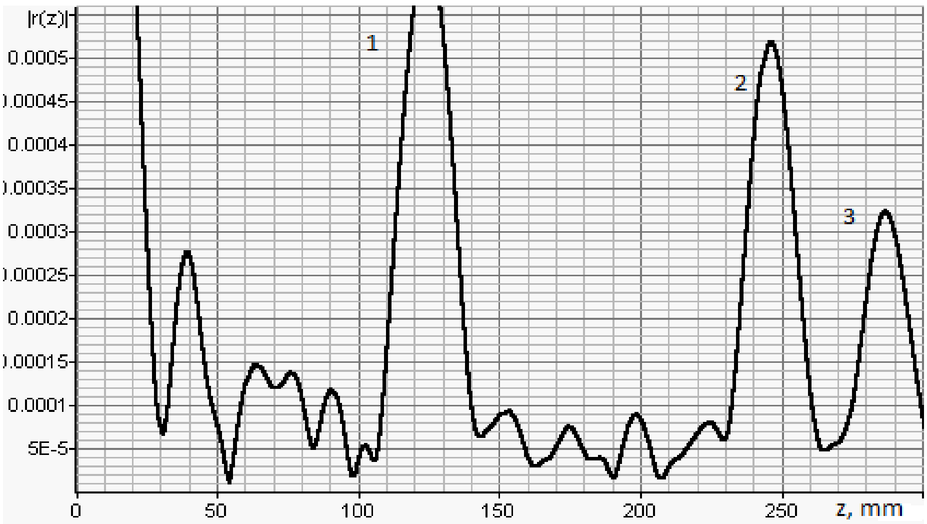

Fig. 4. The peaks of reflection from the front (2) and the back border (3) for the sample zh40-40-1.

In Fig. 5, peak 2 corresponds to the cross-correlation function of the front face reflection of the foam sample and the support inhomogeneity in the neck and is at the distance of 245 mm from it, peak 3 corresponds to the cross-correlation function of the reflection from the back face of the foam sample and the support inhomogeneity in the neck and is at the distance of 288 mm from it.

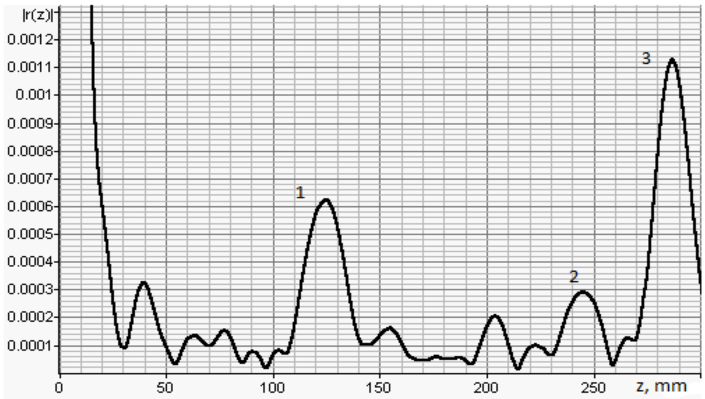

Fig. 5. The peaks of reflection from the front (2) and the back border (3) for the sample zh40-40-16.

In Fig. 6, peak 2 corresponds to the cross-correlation function of the front face reflection of the foam sample and the support inhomogeneity in the neck and is at the distance of 243 mm from it, peak 3 corresponds to the cross-correlation function of the reflection from the back face of the foam sample and the support inhomogeneity in the neck and is at the distance of 288 mm from it.

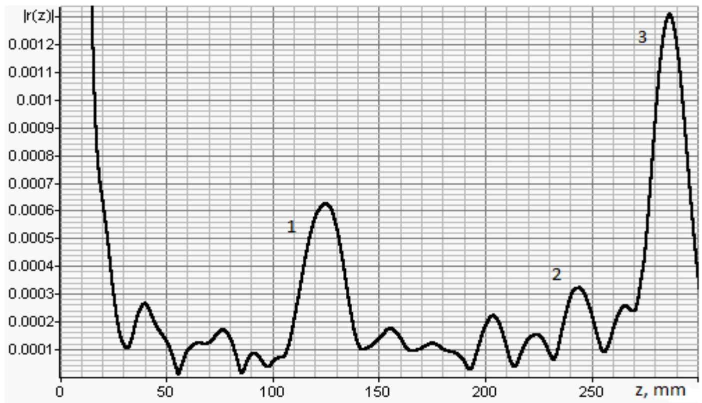

Fig.6. The peaks of reflection from the front (2) and the back border (3) for the sample zh40-40-18.

Figs. 2 and 3 present studies of samples with a thickness of 8 cm, and Figs. 4 – 6 present the results of the studied samples with a thickness of 4 cm.

They make it possible to clearly identify the characteristic peaks that correspond to the cross-correlation function of the reflection from the front and back faces of the foam samples and the reference inhomogeneities in the neck of the antenna. Based on these data, the values of the effective dielectric constant of the foam sample were calculated.

So, in Fig. 2 peak responsible for reflection from the front face is localized within 197 mm, and from the rear face within 280 mm.

The difference of these data will give us the electrical thickness of the sample of 83 mm. Since the geometric thickness of this sample is 80 mm, we calculate the value of the effective dielectric constant of this foam sample as $(83/80)^2 = 1.08$. Similarly, the calculated values for the specified samples are presented in Table 1.

Table 1

Dielectric permeativity of foam samples

Electrical thickness of the sample (mm)	Geometrical thickness of the sample (mm)	Effective dielectric permittivity of the sample	Sample designation
83	80	1.08	zh20-80-16
84	80	1.10	zh20-80-19
41	40	1.05	zh40-40-1
43	40	1.15	zh40-40-16
45	40	1.26	zh40-40-18

Thus, the noted values of the dielectric permittivity of the foam samples are in the range from 1.05 to 1.26 for the conducted research.

Conclusions

Dielectric permeability of foam structures, as can be seen from the research, can have values close to unity. This fact can prove to be an important argument for the creation of low-reflective materials based on foam structures. Indeed, it was experimentally shown, in the obtained results, the reflection value was in the range of 0.0001 - 0.0012. The technique [21] was used for obtaining the estimate.

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