Experimental studies of scattering indicatrixes of radar absorbing materials

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Abstract. There is some kind of materials widely used in microwave engineering that known as radar absorbers. Whether it is the aircraft coating, the anechoic chamber interior or waveguide feed load. Anechoic chamber absorbers are typically characterized by reflectivity at normal incidence of electromagnetic wave. The study of the angular dependence of reflectivity for several absorber samples and the appraising of the impact of their combination on the anechoic chamber performance are the main aims of present work. For this purpose the experimental studies were carried out in an antenna measuring and computing complex based on the anechoic chamber. Obtained results may be useful in the anechoic chamber design and construction stages as well as the modernization of existing ones. It can also be used for modeling of the internal electromagnetic field distribution of indoor field test ranges.

1. Introduction
An anechoic chamber (AEC) allows you to reduce or completely eliminate field tests of antenna systems, which leads to significant costs and time savings for development of complex radio equipment. However, high requirements are imposed on the AEC characteristics to ensure small values of the measurement error [1]. Anechoic chambers are characterized by its dimensions, shield performance and reflectivity level.

AEC is a closed electromagnetic shield, the inner surfaces of which has a regular or special shape and is fully or partially covered with a radar absorber material (RAM). The reflectivity level is primarily determined by the properties of the RAM applied as a part of AEC [2]. Absorbers are typically characterized by reflectivity at normal incidence of electromagnetic wave. But in most applications of absorber in indoor ranges, it is important to know bi-static reflectivity for oblique angles of incidence [3].

Many scientific articles discuss the absorbing and scattering properties of various RAMs, where theoretical relations are derived by various approximate methods for representing complex processes occurring in such materials. These are polynomial equations for predicting reflected energy [4, 5], scaling models [6], developing of electrodynamic models of processes in materials [7, 8], and usage of low-frequency models in case of pyramidal arrays [9]. Also are known the experimental studies of absorbers based on novel materials [10, 11].

This paper outlines comparative tests of several types of RAM. All measurements were carried out in free space with suitable equipment in an antenna measuring and computing complex based on the...
anechoic chamber. The purpose of the research is to measure the transmission and reflection characteristics of various absorbers in a wide frequency range.

2. Radar absorber materials

Regarding functionality, the absorber materials are divided into construction materials and absorber coats. Construction absorbers are used as mounted solution with the aim of backscatter reduction. The absorber coatings in its turn are formed on a reflective surface in the form of paint or foam layers. The main difference between construction RAM and coatings is that the last one are formed directly on the object surface, being held on it by adhesion, whereas constructive materials can be used separately.

According to the method of free space matching absorbers can be divided into three groups. There are resonant, gradient and geometrically matched absorbers. Resonant absorbers attenuate reflected radiation due to destructive interference of reflected wave from the material and reflected wave from the metal backing. These materials are pyramidal, tapered, cellular and others. It should be noted that a generalized complete classification of RAM is impossible due to the wide variety of attributes for their classification [1]. All practically significant absorbers are composite with a micro- or macro-structure.

All absorbers can also be divided into two groups by type of influence: materials that scatter radiation and those that absorb it. Structures and coatings based on radar scattering materials provide attenuation of propagating electromagnetic waves due to the effects of reflection, diffraction and refraction. This type of material absorbs radiation energy not by converting it to other forms, but due to its reallocation in the space. Thus, the reflected signal does not reach the working area and does not distort the measurement results. Among such materials one can distinguish groups of shielding, diffusion and polarizing materials. The main distinctive feature of the absorber materials is that the energy of the electromagnetic radiation entering the material is dissipated with the conversion to other types of energy, heat mainly.

Usually the real materials are multilayer structures that combine various types of functioning. Some materials act as both scattering materials and absorbers at once. For example, the matching surface of uniformly gradient pyramidal materials is capable of effectively conversing specular reflection into diffuse scattering along with absorption of electromagnetic field energy.

3. The study of RAM reflectivity

All measurements were carried out in free space with suitable equipment in an antenna measuring and computing complex based on the anechoic chamber (figure 1). Two measurement setups were established. The first one was designed to measure the reflectivity by the NRL arch method (figure 2) [10]. In front of the metal backed RAM sample (material under test, MUT) placed on base 3 there were two wideband measuring antennas 1 and 2 (figure 3a) mounted on tripods. Antennas were in the far field region relative to MUT at a distance $D$. The measuring antennas moved synchronously relative to the normal of RAM surface at an angle $Az$ during the measurements. Using the PNA series vector network analyzer the transmission coefficient was measured over a wide frequency band. A pointwise normalization of measured data to a similar measurement of metal plate only without MUT placing was performed. The result is MUT reflectivity or so-called scattering indicatrix.

The measured samples had an area of about 1 m$^2$ and were of the following types: pyramidal ‘Delta’ (figure 3b), carpet ‘Ternovnik’ (figure 3c) and multilayer flat ‘Isoterm’ RAM, which is the main absorber in the applied research AEC.

The test results are presented in the form of scattering indicatrixes in the figure 4. Horizontal axis of the graphs shows the deviation angle $Az$ of the each measuring antennas position in the range from 10° to 60°. Antennas transmission coefficient (red line – reflectivity from metal plate and blue one – MUT reflectivity) is plotted along the left vertical axis. Attenuation of the signal in the material is shown on the right vertical axis (black line). The graphs are shown for only two frequencies from the measured range: 3.0 GHz and 7.5 GHz.
For example in figure 4a it can be seen that the pyramidal MUT at a given frequency has an absorption of 34 dB at small incident wave angles and it almost uniformly decreases to 6 dB value at higher angles. The other measured materials behave differently but are similar to each other. At small angles the attenuation for both materials is only 20 dB as shown in figure 4c and figure 4e which is worse relative to pyramidal RAM. However, the maximum attenuation occurs at approx. 35° angle and it takes a value of 25 dB for carpet MUT and 37 dB for multilayer flat one respectively.
Figure 4. Measured indicatrixes: (a) – ‘Delta’ at 3.0 GHz; (b) – ‘Delta’ at 7.5 GHz; (c) – ‘Ternovnic’ at 3.0 GHz; (d) – ‘Ternovnic’ at 7.5 GHz; (e) – ‘Isoterm’ at 3.0 GHz; (f) – ‘Isoterm’ at 7.5 GHz.

At a frequency of 7.5 GHz the picture is changing. As shown in figure 4f the indicatrix of multilayer flat MUT becomes more uniform, and the maximum attenuation with a value of 35 dB is reached at small incident angles. In turn the indicatrix of carpet RAM becomes less uniform at higher frequency as shown in figure 4d. With a frequency increasing the pyramidal MUT indicatrix does not substantially change its character except its slope as shown in figure 4b.

In this experiment the absorption of the pyramidal MUT does not appear at high frequency so clearly while the reflection from the absorber boundary increases. So it can be assumed that pyramidal MUT is an absorbing material designed for relatively lower frequencies. The other two are materials of scattering type and in a wide frequency band they both demonstrate an improvement in their properties.
The disadvantage of this study is that it does not allow measuring the attenuation of an electromagnetic wave in case of normal wave incidence on material. This is not allowed by the experimental setup and continuous-wave type of measurement.

4. Measurements of RAM attenuation

The second measuring setup (figure 5) was designed to measure the absorber attenuation for normal incidence of wave. The measurement was also carried out in the AEC. Two measuring antennas 1 and 2 mounted on tripods were located opposite each other in the far field region. Then using network analyser the transmission coefficient between antennas was measured. Next, MUT was placed between antennas and transmission coefficient was measured again. Thus, the substitution method was applied to study the MUT properties and free space transmission (without installed MUT) was used as the reference measurement. A comparative analysis of obtained data was carried out.

![Figure 5. The diagram of MUT attenuation measurement setup.](image)

For a mathematical description of the measurement process, let us write the transmission equation in a logarithmic representation:

\[ S_{21} = G_a + G_b + CL_{THRU} + TL_{free} + TL_{MUT} \] (1)

where \( S_{21} \) – measured transmission coefficient; \( G_a, G_b \) – antennas gain; \( CL_{THRU} \) – uncorrected cable loss from antennas to the plane of calibration; \( TL_{free}, TL_{MUT} \) – free space transmission loss and MUT attenuation respectively.

In the second experiment the absorbing properties of measured materials were studied depending on the thickness of MUT as well as their combination. Measurements were made with single and double thickness of carpet material and multilayer flat one. Figure 6 show various stages of measurements.

The measurements were carried out in the frequency range 1.0 GHz to 18.0 GHz. The experiment carried out according to the specified scheme allows estimating the MUT absorbing properties in a wide frequency band. In addition to the previous studies of this article, the results allow to reveal the properties of materials more fully.

Figure 7a shows the attenuation of each of three RAMs as a function of the frequency in the case of normal incidence of an electromagnetic wave. The pink line shows the dependence for the ‘Ternovnik’ (RAM 2), brown for ‘Isoterm’ (RAM 3) and blue one for ‘Delta’ (RAM 1). The results of measurements in the frequency sub-bands are combined on one graph with data overlapping; the vertical marker lines show the boundaries of used antennas: 1.0 to 12.0 GHz and 4.0 to 18.0 GHz.
The attenuation curves for several MUTs are presented on figure 7b over frequency band: the blue line for one layer of ‘Ternovnic’ MUT, the brown line for ‘Isoterm’ and the pink one for double layer of ‘Ternovnic’. As can be seen, the doubling of carpet MUT gives a gain in attenuation of up two times at frequencies below 13.0 GHz in comparison with more expensive and broadband multilayer flat material. But for higher frequencies it is inferior in parameters.

Figure 7c shows a comparison of results for compositions of two different material types. Linear interpolation is used to behavior trend tracing of these structures and to evaluate repeatability by differentiate the sub-bands measurements. The pink line shows the frequency response of absorption by a combination of carpet material and multilayer flat MUT. A blue line shows similar characteristic for pyramidal material covered with carpet one. It can be seen that the average attenuation in each of studied MUTs are improved as a result of their combination, reaching values of 50-60 dB at some frequencies. Moreover, the addition of the pyramidal material absorbing properties to the dispersive one carpet seems even more significant than in the case of multilayer flat material. The combination of those materials scattering properties introduces some instability over frequency. However, one can recommend using a RAMs combining to improve their absorbing properties and AEC performance in general.

5. Conclusions
The transmission and reflection characteristics of various RAMs were measured over wide frequency range. The materials under test belonged to the pyramidal, multilayer flat and carpet types. The properties of single materials and their combinations were investigated. If there is necessity to reduce backscatter, for example, in terms of improving the reflectivity level within working area, a technique for combining various types of RAMs should be considered.

The obtained results can be of scientific interest and also used for modelling the internal AEC electromagnetic field distribution.
Figure 7. Measured attenuation: (a) – single MUTs; (b) – carpet RAM thickness doubling; (c) – compositions of different types of materials.
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