

Models for Evaluating the Shielding Properties of Products Made of Composites

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Abstract — A model for evaluating the shielding properties of products (conductive gaskets, shields, absorbing panels, etc.) made of composites is developed. The model allows to calculate the shielding effectiveness of EMI gaskets and flat absorbing panels. Initial data are geometrical parameters of products and general information about the internal structure of the composite material. The validity of the model is confirmed by comparison with the results of experiments in the frequency range from 800 MHz to 16 GHz.

Keywords — electromagnetic compatibility, electromagnetic shielding, EMI gaskets, absorbers, electromagnetic measurements

I. INTRODUCTION

The use of composites for electromagnetic protection of system housings (vehicles, ships, aircrafts, etc.) and electronic equipment cases is determined by the high manufacturability and versatility of these materials [1] – [3]. For example, elastic electrically conductive gaskets, in addition to shielding of electromagnetic (EM) fields, can provide heat dissipation, dust and moisture protection [4]. Composites can provide matching of wave impedances of different media; therefore, they are widely used for the manufacture of EM radiation absorbers [5].

Analysis of the electrical properties of composites and products made of them is carried out by experimental, analytical and numerical methods [2], [6], [7]. These methods have a number of disadvantages. Experimental methods require a significant time resource, since a large number of parameters vary: the substance of the binder and filler, the size and shape of the filler particles, its volume fraction. The application of analytical methods to the analysis of composites is limited by the fact that filler particles have different specific shapes and they are arranged irregularly, that is, composite materials are characterized by parameters with a significant deviation. Numerical methods for composites analysis have computational problems since the sizes of the filler particles are small, their arrangement is irregular. So, the spatial grid for calculations can contain an unacceptably large number of elements [7].

The objective of this work is to develop a model of composites with conductive fillers to analyze their shielding properties due to the reflection and absorption of EM waves. The model must be based on analytical methods ensuring its high computational efficiency. The model must be able to

describe the shielding properties of conductive silicone, rubber, polyurethane foam, and other similar materials.

II. MODEL OF ELECTROMAGNETIC WAVES SHIELDING BY COMPOSITES

The technology for manufacturing of conductive composites is based on the implantation of dispersed conductive particles of metals, graphite, metallized dielectric particles, metal wires (silver, copper, nickel), conductive carbon fibers into a dielectric polymer or ceramics [1]. The particle sizes vary from hundreds of nanometers to tens of micrometers, the radius of the fibers is from 1 μm to 10 μm , and their length is from 10 μm to 10 mm. Conductive particles of filler realize a complex spatial structure, which determines the shielding and absorption properties of composites. In particular, metamaterials and frequency-selective structures are characterized by a certain shape and size of filler particles and their ordered arrangement in the dielectric matrix, so computational electrodynamics can be used for analysis [8].

The object of investigation in this work is conductive composites with a disordered structure. Conductive filler particles (conductivity is σ_2) have a spherical shape and the same diameters d (as a rule, the relative deviation of particle dimensions from the average value in composites is no more than 0.2 [1]). Particles are randomly located in a dielectric matrix. The binder is characterized by the relative permeability ε_1 and electrical loss angle δ_{1e} (δ_{1e} is considered as a frequency-independent quantity, since conductivity of binder is of the order of $10^{-8} \dots 10^{-14}$ S/m). The specified volume fraction of binder is v_1 and of filler is v_2 ($v_1 + v_2 = 1$). The materials are non-magnetic ($\mu = 1$).

The composite products under consideration are plane-parallel plates of the thickness t . The propagation of a plane electromagnetic wave from the first region through the plate (which is the second region) to the third (shielded) region behind the plate is considered (see Fig. 1). The first and the third regions are characterized by the wave impedance $Z_0 = 120\pi$ ohm and by the speed of EM waves propagation $c = 3 \cdot 10^8$ m/s. The field transfer function for the structure under consideration is the ratio of the component of electric E' (magnetic H') field strength in the shielded region to the component of electric E (magnetic H) field strength of the incident EM wave [9]:

$$K_{1,3} = T_{1,2} \cdot \Gamma_2 \cdot T_{2,3} \quad (1)$$

Transmission and reflection of electromagnetic waves across the boundary of homogeneous media i and j is determined by coefficients $T_{i,j}$ and $R_{i,j}$ respectively [10]:

$$T_{i,j} = \frac{2Z_j}{Z_j + Z_i}, \quad R_{i,j} = \frac{Z_i - Z_j}{Z_i + Z_j}, \quad (2)$$

where Z_i , Z_j are the wave impedances of media i and j respectively.

Function Γ_2 , describing the propagation in medium 2, (which is the composite plate in this case), is determined by the multiple reflections from the boundaries of the plate. Function Γ_2 is expressed by the formula [11]:

$$\Gamma_2 = \frac{e^{-j\gamma_2 t_2}}{1 - R_{1,2} R_{2,3} e^{-2j\gamma_2 t_2}}, \quad j = \sqrt{-1}, \quad (3)$$

where γ_2 is the propagation constant in medium 2, t_2 is the thickness of the plate.

To determine the wave impedance of a composite, it is needed to consider the dependence of electrical properties on the concentration of conductive filler particles. In the case of a small volume fraction of filler $v_2 \ll 1$, there is no electrical contact between filler particles. In this case, the scattering of EM waves of the radiofrequency (RF) range by these particles is insignificant, since at $d/\lambda \ll 1$, (d is the average diameter of filler's particles) the intensity of the scattered component is small $I \sim (d/\lambda)^4$ according to Rayleigh's law. Consequently, in the limit $v_2 \ll 1$, the composite can be considered as homogeneous dielectric with losses. For this case, the characteristic impedance Z_2 and the propagation constant γ_2 are calculated using the formulas [11] ($\mu=1$):

$$Z_2 = Z_0 \sqrt{1/\epsilon_c}, \quad \gamma_2 = \frac{2\pi f}{c} \sqrt{\epsilon_c}, \quad (4)$$

where f is the frequency and ϵ_c is the complex permittivity of composite, ϵ_c can be determined by the Nielsen equation by the use of characteristics of a binder and a filler [1], [12]:

$$\epsilon_c = \epsilon_1 \frac{1 + A \cdot B}{1 - B \cdot \psi \cdot v_2}, \quad A = k_E - 1, \quad (5)$$

$$B = \frac{\epsilon_2 / \epsilon_1 - 1}{\epsilon_2 / \epsilon_1 + A}, \quad \psi = 1 + \left(\frac{1 - v_{2\max}}{v_{2\max}^2} \right) \cdot v_2,$$

where $v_{2\max}$ is the maximum volume fraction of the filler for the given packaging of particles (it is equal to 0.524 for cubic densely packed structure of spherical particles and $v_{2\max}=0.79$ for the densely packed structure of filaments), k_E is the coefficient for taking into account the shape of filler particles ($k_{ES}=2.5$ for spherical particles and $k_{EF}=4$ for filaments).

The complex relative permittivity for the binder ϵ_1 and complex relative permittivity for the filler ϵ_2 are respectively:

$$\epsilon_1 = \epsilon_1 (1 - j \tan \delta_{1e}), \quad \epsilon_2 = 1 - (j\sigma_2 / (2\pi\epsilon_0 f)). \quad (6)$$

where ϵ_0 is absolute permittivity and σ_2 is per-unit conductivity of the clusters formed by the filler particles.

When the volume fraction of conductive filler particles increases, the probability of electrical contacts occurring between them increases. It leads to an increase in the average size of conductive clusters, and, consequently, to more intense scattering of EM waves by these inhomogeneities. To develop the model, we assume that the conducting clusters are cells of an irregular three-dimensional grid (see. Fig. 1), [13].

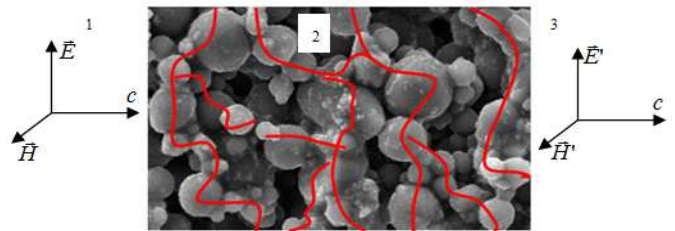


Fig 1. Geometrical model of shielding by composite plate and structure of composite with the filler in the form of the conductive spherical particles. The conductive channels (depicted by the red color) arising due to the contact between surfaces of filler particles determine the conductive clusters.

A closed cell formed perpendicular to the direction of plane EM wave propagation represents a short waveguide. If EM wave frequency is less than the cutoff frequency of the waveguide associated with the cell, then the reflection of waves from the surface of the composite and the propagation of waves inside it are determined by the wave resistance and propagation constant given by the formulas:

$$Z_2 = \frac{Z_0 f}{\sqrt{\epsilon_1 \cdot (f^2 - (f_c)^2)}}, \quad \gamma_2 = \frac{2\pi}{c} \sqrt{\epsilon_1 (f^2 - (f_c)^2)}, \quad (7)$$

where f_c is the cutoff (critical) frequency of waveguide associated with the closed cell. The conducting clusters have different shapes and sizes, and they are randomly distributed throughout the volume of the composite material, so f_c will be different for different clusters.

A model for evaluating the EM wave shielding effectiveness of products made of composites can be obtained by generalizing the combined wall model proposed in papers [11], [14]. For the composite regions occupied by the closed clusters, the model of shielding by the wire mesh, and for other regions, the model of EM wave propagation in lossy dielectrics should be used. The shielding effectiveness (SE) of a product made of composite is determined by a combination of transfer functions K_i (1) applied to regions (i -is the region's number). Some of regions are parts of the wire mesh and other regions are dielectric with losses. The SE S_{Pc} (in dB) of combined wall is as follows [11], [14]:

$$S_{Pc} = 10 \log \left(\sum_{i=1}^N \left(|K_i|^2 A_i \right) / A_0 \right)^{-1}, \quad (8)$$

where A_i is the area of i -th homogeneous region and $A_0 = \sum A_i$ is the total area of all N regions in the wall.

Since there is no exact information about the area A_i of each region and regions structure is unknown (in the general case, ϵ_{ci} and f_{ci} , used for calculations in (4) and (7) are different for each region), we rewrite (8) in the following form:

$$S_{Pc} = 10 \log \left(\frac{|K_{M1}|^2 A_1 + |K_{M2}|^2 (A_0 - A_1)}{A_0} \right)^{-1}, \quad (9)$$

where K_{M1} is the transfer function calculated by (1) for the model of EM wave propagation in lossy dielectric, when (4) is substituted in (2) and (3). K_{M2} is transfer function (1), obtained by the use of model of EM wave propagation in the waveguide, i.e. by the substitution of (7) in (2) and (3). Quantity A_1 is the full area occupied by the regions in which there are no closed conductive clusters and $A_2 = A_0 - A_1$ is the remaining area, which is occupied by the conductive clusters considered as the three-dimensional conductive wire mesh.

Calculation of parameters ϵ_{ci} and f_{ci} , which are present in (4) and (7), can be realized using data given by the manufacturer of products, or on the measurement results. The assessment of these parameters can be performed based on percolation threshold analysis p_c [13]. For example, it is noted in paper [15] that the percolation threshold p_c is achieved when the volume fraction of filler (particles of copper covered by silver) is equal to 0.18–0.25. Data of paper [12] shows that for the filler particles in the form of finely dispersed graphite, the percolation threshold p_c is achieved for volume fraction of filler of 0.20–0.23. As it follows from the given data and formula $p_c = 1/(1 - k_z)$, the composites with the filler particles having the shape, which can be approximated by the sphere, the coordination number k_z of the Bethe greed [13], associated with the structure of composite, is equal to 5. Therefore, we assume that the filler particles in the corresponding close-packed structure are located at the vertices of a cube with a side equal to the diameter of the sphere that approximates the particle. So, the value of maximum volume fraction of the filler in (5) is $v_{2 \max} = \pi/6 = 0.524$.

If the volume fraction of the filler is insufficient for the achievement of percolation threshold p_c , then the composite can be used as the material for manufacturing of EM radiation absorbing panels, because the reflection of EM waves from its surface is small and the most part of EM radiation power penetrates into the volume and is absorbed into it. When the percolation threshold is achieved, the reflection coefficient is sharply increased for EM waves having frequencies less than the cutoff frequency of the waveguide associated with the conductive mesh that represent the structure of composite. That material can be used for manufacturing of EMI gaskets.

III. EMPIRICAL MODEL OF SHIELDING EFFECTIVENESS OF GASKETS MADE OF COMPOSITES

Empirical model of the shielding by gaskets made of composite can be used for the design of system EM protection in the case when the exact information about the internal structure of the composite is absent. The main idea of the empirical model for assessing the shielding effectiveness of a gasket made of a composite is to represent the composite material as an equivalent wire mesh.

To develop the model, it is assumed that the dependence of SE on frequency for the equivalent wire mesh must be the same as the dependence of composite's SE obtained by measurements. This dependence determines the characteristics of the equivalent mesh, which is associated to the composite. Based on the obtained characteristics of the equivalent mesh, the shielding effectiveness of the gasket made of the composite can be calculated. In the general case, the gasket can have an arbitrary shape and can be mounted in arbitrary place of the system under protection.

Parameters of the equivalent mesh, which is a periodically located conductive filaments in a dielectric matrix with a given complex permittivity ϵ_1 , are considered as parameters of the conductive structure averaged over the volume of the composite. Metal wires, carbon fibers, and chains of contacting spherical particles (see Fig. 1) play the role of conductive filaments in the equivalent mesh. The calculation of composite SE is performed by the use of the wire mesh model with the rectangular cells [14].

For the calculation of the shielding effectiveness of the gasket made of composite (conductive silicone, rubber, plastic), the following parameters must be specified: diameter of filaments d and the distance between the neighboring filaments Δd . So, the period T of the equivalent mesh is $T = d + \Delta d$. The relative conductivity σ_r of the filament material (relative to copper conductivity $\sigma_{Cu} = 5.5 \cdot 10^7$ (ohm·m)⁻¹) must be specified too. Based on the given parameters, the following quantities are defined:

- the average number of equivalent mesh layers in the direction of the EM energy transfer: $N = t / T$, where t is the thickness of the gasket,
- the thickness h of region in form of the wire mesh corresponding to the gasket. It is obtained as the product of the filament's diameter to the number of the layers: $h = N \cdot d$,
- the averaged relative conductivity of the composite with filaments: $\sigma_{av} = \sigma_r \cdot N_{pu} \cdot \pi d^2 / 4$, where N_{pu} is the filament's number per unit area.

It has been empirically established (see Section V) that the volume-averaged internal structure of samples, made of conductive composites with a dielectric binder (rubber, silicone or other type of plastic) and conductive fillers in form of spherical particles with diameter of 5 μm or filaments with diameter of 2 μm and the length of 50 μm , can be considered as an equivalent wire mesh with the following parameters: the conductive filaments diameter is 2 μm , mesh cell is 200 μm , complex permittivity of matrix is $2.5(1 - j \cdot 10^{-3})$, conductivity of filaments is σ_{Cu} .

IV. MODEL OF ABSORBERS MADE OF COMPOSITES

Absorbers are used for a decreasing of the amplitude of electric and/or magnetic fields in the shielded zone due to the absorbing the energy of EM waves. As a rule, absorbers are the panels made of the conductive material having the wave impedance matched with the wave impedance of environment to suppress the reflections from its surface. Absorbing panels are mounted on the reflecting (metal) walls of the compartment.

The electric field strength at the output of the absorber plate of thickness t_2 is described by formula:

$$E_3 = E_1 \cdot K_{1,3}, \quad (10)$$

where E_1 is the strength of the electric field of the EM wave impinging the surface of the absorber, $K_{1,3}$ is the transfer function (1) for the E-field component.

When the wave impedances of the 1-st and 3-rd media are equal to each other, the shielding effectiveness of EM wave by the absorber plate is defined similarly to (8): $S_{ab}=K^2$. The reflection and transmission coefficients (2) are used to calculate K_{13} by the substitution the wave impedance (4) with the complex permittivity determined by (5) and (6) for the composite.

Since the exact data for determining the complex permittivity are usually not specified by the manufacturer, the reflectivity specified by the manufacturer in the specification can be used to evaluate the shielding effectiveness of the absorber panel. The reflectivity M_r is defined as the ratio of the power flux density (PFD) of EM radiation reflected from the absorbing cover mounted on the metal wall to PFD of EM radiation that incident on the cover surface $M_r = (|E_{1r}|/|E_1|)^2$. For the normal incidence of EM radiation on the flat surface of the absorber, the E-field strength of the reflected wave is determined by the formula:

$$E_{1r} = E_1 \left(R_{1,2} + \frac{R_{2,me} \cdot e^{-2j\gamma_2 t_2}}{1 - R_{1,2} R_{2,me} \cdot e^{-2j\gamma_2 t_2}} \right), \quad (11)$$

where $R_{2,me}$ is the reflection coefficient for the boundary between the absorber and metal. The wave impedance of absorber is higher than the wave impedance of free space or compartment, but it must not differ from them sufficiently for matching of media wave impedances. Since absorber's wave impedance is sufficiently less than the wave impedance of the metal, and it is possible to assume that $|R_{2,me}|=1$ for assessment of SE. In this case, the phase shift of the wave reflected from the absorber is of about to the phase shift of the wave reflected from the metal. As the result, the shielding effectiveness of absorber panel for the case of free space propagation of EM radiation is expressed from M_r and $R_{1,2}$ by the formula:

$$S_{1,3} = \left(\frac{1 - a^2 R_{1,2}}{a \cdot (1 - R_{1,2}^2)} \right)^2, \quad a = \sqrt{\frac{R_{1,2} - \sqrt{M_r}}{R_{1,2} (\sqrt{M_r} + 1) - 1}}. \quad (12)$$

Note that for the partial covering of the area of metal wall by the absorber with the given reflectivity, the reflectivity of corresponding combined wall is determined by the formula, which is similar to (8):

$$M_{rcwall} = \frac{M_r \cdot A_{abs}(1 - A_{abs}) + A_0}{A_0}, \quad (13)$$

where A_0 is the total area of the metal wall and A_{abs} is the area covered by the absorber with the given value of M_r .

It is known [9], [16], that the using of absorbers with the multilayer structure improves the shielding effectiveness due to the multi-reflections from the boundaries of layers.

V. EXPERIMENTAL VALIDATION OF DEVELOPED MODELS

A. Validation of Model for Calculation of Shielding Effectiveness of EMI Gasket Made of Composite

The developed model for calculation of composite material SE has been validated for the gasket made of silicone with the conductive filler by the comparison of calculation results with the results of measurement carried out in accordance with the technique described in [17] for frequencies from 800 MHz to 16 GHz. During the measurements, the gasket was installed in the slot of the instrument window of the Measuring cabin [17] and fixed by a frame (the instrument window was covered with a metal plate). The frame was mounted to the cabin wall along the contour of the window using steel bolts spaced at 45 mm intervals. The power received by the antenna located directly behind the instrument window inside the cabin was measured for two cases: when the slot was open and when the gasket under study was installed in the slot. Based on these measurements, the shielding effectiveness of the gasket is obtained as the difference of the measured powers (in dBm). Smoothing of experimental data was carried out by using the least mean squares method with an adaptive choice of the number of nearest neighbors.

For the rectangular gasket Laird 8861-0175-93 [18], which have the width $B=0.8$ mm (equal to the width of the slot at the perimeter of instrumental window) and the thickness $A=6.4$ mm (equal to the depth of the slot), in accordance with the model described in Section III, we obtain that the number of equivalent mesh layers is 32 and the total thickness of equivalent mesh is 64 μ m. Using for the calculations the model proposed in [14] for the shielding effectiveness of wire mesh, we obtain results depicted in Fig. 2 by the black dashed line. Improved result obtained by the taking into account the presence of the composite with the average relative conductivity of $5.9 \cdot 10^{-5}$ inside the mesh cells is shown by the blue solid line in Fig. 2 (filler volume fraction is 0.46, spherical particles are considered, $k_E=2.5$ in (6)).

For D-shape gasket Laird 8861-0160-93 [18] having the width in the pressed state $C=1$ mm (C is thickness of gasket walls) and thickness $A=2.5$ mm, we obtain that the number of equivalent mesh layers is 12 and mesh thickness is 25 μ m. Using the model proposed in [14] and the model of composite with parameters noted above, we obtain result shown in Fig. 3.

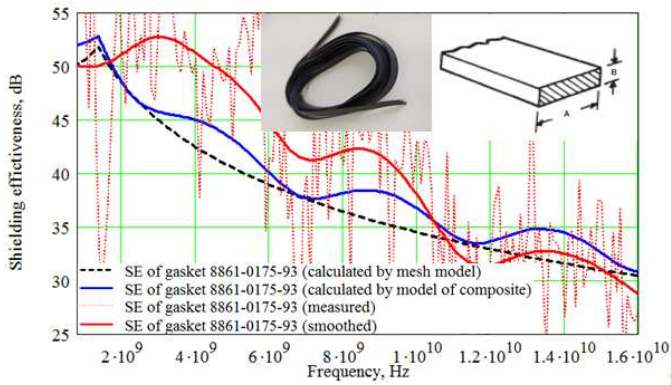


Fig 2. Shielding effectiveness of rectangular gasket Laird 8861-0175-93 made of the conductive silicon

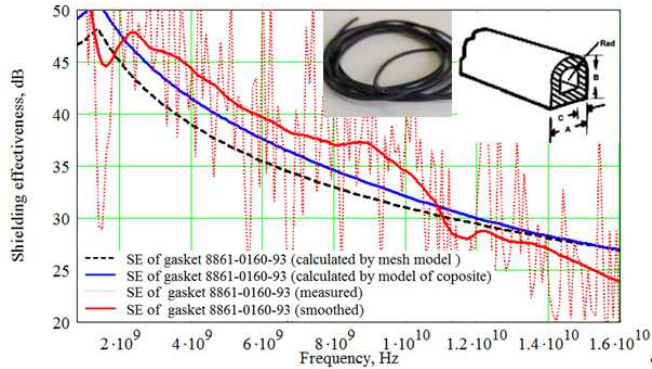


Fig 3. Shielding effectiveness of D-shape gasket Laird 8861-0160-93 made of the conductive silicon

B. Validation of Calculation Model for Shielding Effectiveness of Multilayer Structure

The calculation model for SE of multilayer structure in application to the composites have been validated by the comparison of calculation result with the results of SE measurements for the thin plate of material MECF-020P-210x310. In accordance with the information given by the manufacturer [19], the material under test is the multilayer structure with the total thickness of 2 mm. The layers are the foamed polyurethane with the conductive filler, conductive adhesive, and wire mesh. During the measurements, the panel is installed in the instrumental window of the Measuring cabin. The shielding effectiveness of the multilayer plate is obtained using values of power received by the antenna installed inside the cabin for the case when the instrumental window is open and for the case when it is closed by sample under test (see [14]).

For the modeling the plate made of the material under test, we introduce the equivalent wire mesh with the parameters given in Section III (diameter of wire is 2 μm , mesh cell is 0.2 mm, relative conductivity is 1). Relative permittivity is 2.5, tangent of losses in dielectric is $5 \cdot 10^{-3}$. The thickness of layer in the form of the mesh is 1 mm, number of mesh layers is 5 and the thickness of mesh is 10 μm . The conductive layer of the foamed polyurethane is determined by the implantation of spherical particles ($k_E=2.5$, $v_{2 \max}=0.524$) with volume fraction $v_2=0.3$. The comparison of results is shown in Fig. 4.

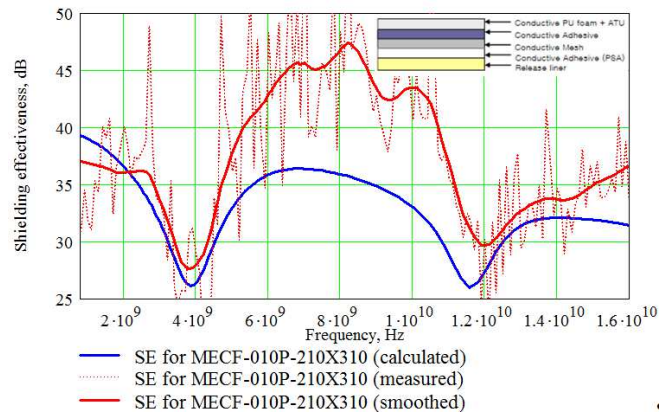


Fig 4. Shielding effectiveness of plate MECF-020P-210x310 made of the layers of wire mesh and conductive foamed polyurethane

By the same manner, the SE of a needle-punched material containing carbon fibers [20] have been measured. It is used for shielding the EM radiation of cellular communication systems. Basic structure of this material is polyester, polypropylene, and wool fibers with linear mass densities of 3.3×10^{-7} , 4.4×10^{-7} , and 7.6×10^{-7} kg/m respectively. Carbon additives in a form of 6.5 mm long carbon cellulose-hydrate filaments are used as conductive fillers. Diameter of filaments is from 7 to 10 μm , linear electrical resistance is less than 20 ohm per cm, and volume electrical resistance of 1 cm^3 sample is less than 24 mohm [20]. The number of layers of material under test is 1, 2, 3, 4 and 8. The parameters of each composite layer are as follows: the thickness of layer is 2.5 mm; length of mesh cell is 8 mm; diameter of wire is 7 μm ; relative conductivity of wires is 0.24; the area that corresponds to the mesh region is $0.1A_0$. The composite area is $0.9A_0$, it has the equivalent relative conductivity 10^{-8} , conducting filaments ($k_E=4$) volume fraction is 0.04 and maximum volume fraction is $v_{2 \max}=0.79$. The model of multilayer structure [9] was used for calculation. The comparison of calculation and measurement results is given in Fig. 5.

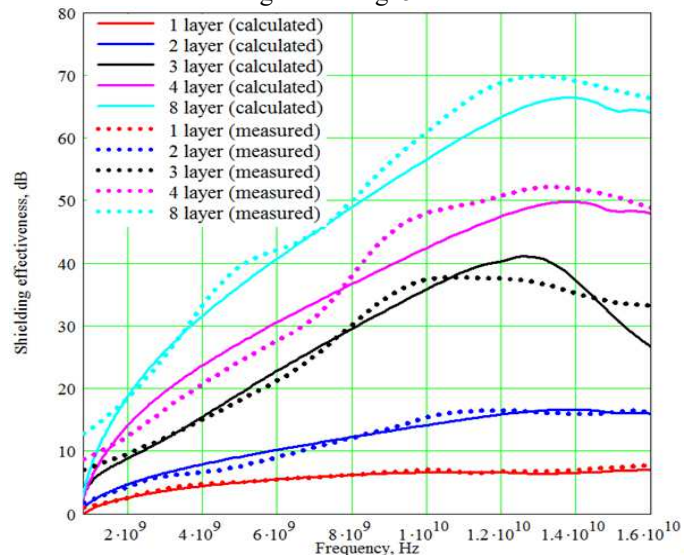


Fig 5. Shielding effectiveness of layers of needle-punched material containing carbon fibers

VI. CONCLUSION

The developed model for the analysis of composite's conductivity makes it possible to evaluate the shielding effectiveness of a wide class of products: silicone and rubber conductive gaskets, conductive adhesives, paints, and sealants. It is established that, independently on the manufacturing method, all noted types of products can be approximated by the equivalent mesh with the parameters determined only by the percolation threshold arising in composites under consideration when the volume fraction of the filler tends to the defined limit. The developed model allows to evaluate the shielding properties of the flat panels of the absorbers of EM radiation in the wide frequency range, too. The model tends to underestimate the SE value because it is based on the worst-case models of wire mesh, solid wall, and multilayer structures [9], [14], [17]. Results of SE obtained by calculation in the framework of the developed model do not overestimate the measurement results by more than 5 dB in some limited frequency ranges.

The proposed approach is based on the consideration of the power of EM wave penetrating through the combined wall, so the model is valid for high frequencies and for the far-field zone. Further development of the model could be associated with determining the shielding effectiveness of gaskets made of composites for the case of low frequencies and in the near field zone of the EM wave source, as well as for angles of incidence different from normal. An actual direction in the development of the model is also the consideration of ordered periodical structures.

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