Technique for Evaluating the Contribution of Protective Means to Shielding Effectiveness of Heterogeneous Wall

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***Abstract*—The model of shielding of electric, magnetic, and electromagnetic fields by a heterogeneous wall is improved, and a technique for applying this model to the description of technical solutions used to improve the shielding effectiveness of buildings, bodies of vehicles and ships, cases of electronic equipment, etc. is developed. An experimental validation of the developed technique is carried out for the case of shielding a magnetic field by metal wire meshes in the frequency range from 100 kHz to 100 MHz and for the case of shielding an electromagnetic field by a wire mesh, metal foil tapes, wire mesh gasket, cloth pad gasket, and finger spring gaskets in the frequency range from 800 MHz to 18 GHz.**

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

I. Introduction

A required shielding effectiveness (SE) of system hull or equipment case can be obtained by using of EMI gaskets [1] – [4] and other types of protective means such as wire meshes, shielding films, metal foil, etc. The choice of technical solutions providing the required SE is based on the analysis of peculiarities of mounting place (dimensions, shape, surface finishing), corrosion resistance [5], ensuring the tightness of the joining, and a number of other technological requirements [1] – [3], [6], [7].

When designing the system hulls and equipment cases, there is a problem of choosing an EM gasket that meets the technological requirements and provides the necessary SE. A technique for evaluating the SE of gaskets installed in a mounting place of a given size and shape (in-situ SE) is proposed in [8]. The technique [8] uses the gasket's SE that must be specified by manufacturer (the standard according to which the SE was measured by manufacturer, e.g. [9]–[12], and the characteristics of the measurement setup are also required) or measured. Unfortunately, the manufacturer's data does not contain this information in most cases.

On the contrary, the material and geometric parameters of protective means are usually available (often specified by the manufacturers, or easily obtainable experimentally). For example, for metal meshes, the type of mesh, the shape and size of the holes, the material of the wire, wire's diameter, and the dimensions of the mesh cell are provided. For finger spring gaskets, the width of the fingers, the distance between them, the metal thickness and conductivity are specified.

The objective of this work is to develop a universal technique that allows evaluating the SE of protective means based on their type, material characteristics and geometric parameters of protective means and their mounting places. The technique for evaluating the SE of protective means must also meet the following requirements specific to EMC analysis: provide an adequate assessment of SE over a wide frequency range, avoiding underestimation by more than 15 dB and overestimation by more than 5 dB; have a high computational efficiency.

II. Model of Shielding of Electric and Magnetic Fields by Combined Wall

A. Problem Formulation and Initial Data

The combined wall is a wall consisting of regions with different SE [13] (Fig. 1). Given geometric and physical parameters of the regions, it is required to calculate the SE of the combined wall by power:

$$S_P = P_0 / P_S, \tag{1}$$

where P_S is the radiation power received by an antenna in the shielded zone and P_0 is the power received by the same antenna in the same point if the wall is absent (see Fig. 1).

Radiation sources can be electric or magnetic dipoles. The source area can be free space, or it can be a volume of a resonator or waveguide, for example, when solving the problem of propagation of EM radiation from one compartment to another. To calculate the SE in the case of a dipole source located in free space, it is necessary to set the distance r_d from antenna phase center to the shield. If the source area is a resonator (waveguide), it is necessary to set parameters of the resonator in order to determine its wave impedance.

The shield is a combined wall (see Fig. 1). To calculate the SE of a combined wall, it is necessary to specify the dimensions of each region belonging to the wall and physical characteristics of the regions. The regions of the combined

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wall can be sheets of solid metal (in particular, the Basic wall in Fig. 1 is a solid metal wall), circular and rectangular apertures, arrays of apertures, insertions made from composite materials, etc.

The shielded area can be a free space or the volume of a resonator (waveguide). In order to calculate the SE in the latter case, it is necessary to obtain the wave impedance of the resonator by using a set of the resonator parameters.

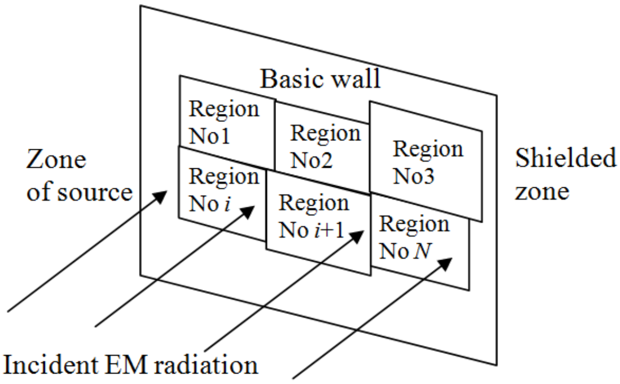

Fig. 1. Selection of the source area and the shielded area when solving the problem of EM radiation shielding by a combined wall, which is a set of regions with different shielding properties

B. *Transfer Functions of Homogeneous Regions of Shield*

A solid metal wall or a single aperture is considered as homogeneous region of the combined wall. The field transfer function for a homogeneous region is the ratio of the component of electric (magnetic) field strength in the shielded area to the component of electric (magnetic) field strength of the incident EM wave [14]:

$$K_{(e,m,r1,fs,r2)} = T_{1,2(e,m,r1)} \Gamma_{2(e,m,r1,fs,r2)} T_{2,3(fs,r2)} \quad , \qquad (2)$$

where indexes correspond to a source in form of electric (e) or magnetic (m) dipole, or resonator ($r1$). Index (fs) corresponds to the penetration of EM radiation into free space and index ($r2$) – into the resonator. Quantity $T_{1,2}$ is the transmission coefficient (by a field) from the source area (medium 1) to the homogeneous region of the combined wall (medium 2); function Γ_2 determines the propagation of EM wave through medium 2 from the boundary of medium 1 to the boundary of medium 3; $T_{2,3}$ is the transmission coefficient from the medium 2 to the shielded area (medium 3). For conditions ensuring the worst-case behavior of the model (see [13]), the transmission coefficients are calculated by using the wave impedances of the corresponding media:

$$T_{i,j} = 2Z_j / \left(Z_j + Z_i \right) . \qquad (3)$$

Function Γ_2 is expressed by formula:

$$\Gamma_2 = \frac{\exp(-i\gamma_2 t_2)}{1 - R_{12} R_{23} \exp(-2i\gamma_2 t_2)}, \qquad (4)$$

where γ_2 is the propagation constant in medium 2, t_2 is the thickness of region, and reflection coefficients are:

$$R_{i,j} = \left(Z_i - Z_j \right) / \left(Z_i + Z_j \right) . \qquad (5)$$

So, for calculation of the transfer function, it is necessary to determine the wave impedances of corresponding media.

If a homogeneous region is a solid wall, then its thickness t and material properties (conductivity σ, relative permeability μ, and relative permittivity ε) are set. These parameters allow determining the wave impedance depending on frequency f:

$$Z_{sw} = Z_0 \sqrt{\frac{\mu}{\varepsilon - \left(j\sigma / 2\pi f \varepsilon_0 \right)}}, \qquad (6)$$

where Z_0=120π ohm is the wave impedance of free space, ε_0 is electrical constant of SI system.

When analyzing a single aperture, a waveguide is assigned to it [15]. In this case, the wall thickness, the shape of the aperture, its geometric dimensions, permittivity, and permeability of the aperture filling are specified. The wave impedance of such region is determined by the formula:

$$Z_a = \frac{Z_0 \sqrt{\mu}}{\sqrt{\varepsilon} \sqrt{1 - \left(f_c / f \right)^2}} A(Q_a), \qquad (7)$$

where f_c is the critical frequency of waveguide, $f_{cr} = c/(2\max(a,b))$ for rectangular waveguide, c is speed of EM wave in free space, and a, b are length of rectangular aperture sides. For circular waveguide: $f_{cc}=c\cdot\eta_{11}/(\pi d))$, where η_{11}=1.8412 is the first zero of the derivative of the 1-st order Bessel function and d is the aperture diameter. Dimensionless function $A(Q)$ of Q-factor of waveguide, associated with aperture, determines the EM energy dissipation in aperture [13]. In developed model $A(Q_a)$=1.

The wave impedance of the source area Z_1 is calculated for electric and magnetic dipoles by formulas [16]:

$$Z_{1e} = E_{\theta e} / H_{\varphi e}\,, \;\; Z_{1m} = H_{\theta m} / E_{\varphi m}\,, \qquad (8)$$

where $E_{\theta e}$ $H_{\varphi e}$ are the components of electric and magnetic fields radiated by electric dipole, $E_{\theta m}$ $H_{\varphi m}$ are the components of fields radiated by magnetic dipole. Only components that determine the energy transmission by EM waves are taken into account in formulas (8). Note that for frequencies $f > f_d = c/(2\pi r_d)$ the wave impedances (8) tends to Z_0.

In the case when the first or third medium is the resonator volume, its wave impedance is calculated by formula (7) by substituting the resonator parameters into it instead of the aperture parameters (the method for estimating the value of $A(Q_r)$ for this case is presented in [13]). Free space can be the third medium (note that the wave impedance of resonator for TE_{10} mode tends to Z_0 for $f > f_c$ [17]).

The field transfer function (2) for each homogeneous region is expressed from power-based SE (1) as follows:

$$K^2 = 1 / S_P \,. \qquad (9)$$

C. Method for Calculation of Shielding Effectiveness of Combined Wall

For the combined wall, the value of the SE defined by (1) is evaluated by formula [13], [14]:

$$S_{Pc\,wall} = \left(\sum_{i=1}^{N} K_i^2 A_i / A_0 \right)^{-1}, \ K_i^2 = 1/S_{Pi}, \qquad (10)$$

where A_i is the area of i-th region with SE of S_{Pi} and $A_0 = \sum A_i$ is the total area of a wall consisting of N regions.

Formula (10) solves the stated problem of calculating the SE of a combined wall, given geometric and physical parameters of its regions.

D. Method for Calculation of Shielding Effectiveness of Periodic Structures by using the Combined Wall Model

The structures under consideration are periodically arranged identical apertures separated by metal partitions of the same width and thickness. Similar structures were analyzed in [18] by using an equivalent sheet impedance operator.

The initial data for the calculation are data characterizing one aperture (see subsection *B*) and the dimensions of the partitions between the apertures in two perpendicular directions: Δ_x and Δ_y. The full dimensions of the considered structure L_x, L_y, and the parameters of the partition's material (σ, μ ε) are also set.

The SE of periodic structure is calculated by the following algorithm:

- The number of cells in directions x and y is obtained:
  $N_x = (L_x + \Delta_x)/(a + \Delta_x)$, $N_y = (L_y + \Delta_y)/(b + \Delta_y)$
  $N_x = (L_x + \Delta_x)/(d + \Delta_x)$, $N_y = (L_y + \Delta_y)/(d + \Delta_y)$
  for rectangular and circular apertures respectively. The full number of cells in structure is: $N_{xy} = N_x \cdot N_y$.
- According to formula (2), using (3) – (5), (7) and (8) (depending on the conditions of using the model), the transfer function of one aperture is calculated with respect to the field radiated by an electric or magnetic dipole, or to the field, incident from the volume of the resonator.
- The contribution of all apertures of periodic structure is calculated by the model of combined wall (10) (A_{a1} is the area of one aperture):

$$G_{Na} = N_{xy} A_{a1} K_{1a}^2 . \qquad (11)$$

- The contribution of all metal partitions of the periodic structure is calculated using the formulas (3)–(6), (8) and (10):

$$G_{Nsw} = (A_0 - N_{xy} A_{1a}) K_{1sw}^2 , \qquad (12)$$

where $A_0 = L_x \cdot L_y$ is the full area of the structure.

- The total contribution of apertures and partitions to the transfer of EM radiation power through the periodic structure is obtained:

$$G_{ps} = G_{Na} + G_{Nsw}. \qquad (13)$$

- The SE is calculated for the periodic structure in accordance with (10):

$$S_{P\,ps} = (G_{ps} / A_0)^{-1} . \qquad (14)$$

It has been empirically established that when analyzing the shielding of a magnetic field by a thin-wire structure, it should be taken into account that induction currents flow not in a solid metal, but through wires. This is realized by multiplying the wire metal conductivity in (6) by correction factor depending on the structure of the wire mesh:

$$\sigma_w = (\sigma\pi \cdot \min(r_w, \delta)) / (8 \cdot l_{ms}) , \qquad (15)$$

where r_w is a wire radius, $\delta = \sqrt{1/(\pi f \mu\mu_0 \sigma)}$ is the skin depth and l_{ms} is the dimension of mesh cell.

The obtained value of the SE of the periodic structure (14) can be used as the SE S_{Pi} of a certain region in formula (10), e.g., if the region is a homogeneous mesh or lattice.

III. Technique for Application of Developed Model to Analysis of Protective Means

A. Test Site for Experimental Validation

Except for Fig. 5, the validation of the developed technique is carried out by comparison of results obtained by the calculation in framework of the technique with the results of measurements performed by procedure presented in [8], which corresponds to the measurement procedures described in standards [9] – [12].

The SE measurement technique proposed in [8] uses the multipurpose measuring cabin (herein and after it is called Cabin). The Cabin has instrumental window of dimension 30×20 cm. The Cabin is well shielded to provide required dynamic range [8] for frequencies under consideration. The transmitting test antenna is installed outside the Cabin. The radiation axis of this antenna coincides with the normal to the center of the instrumental window. The receiving test antenna of the same type as transmitting one is mounted inside the Cabin in close proximity to instrumental window. Working polarizations of antennas coincide (it is vertical).

Measuring horn antennas with aperture dimension of 30×20 cm are used in the frequency range from 800 MHz to 18 GHz [8]. These frequencies are more than the cut-off frequency of waveguide associated with instrumental window of Cabin and the wave propagating through the open instrumental window can be considered as plane wave [10].

The measurement of the SE of a protective mean is performed by the following procedure. At the first step, the calibration is performed: the received power P_0 is measured when the generator produces the predefined power and instrumental window of cabin is open. Then the window is closed by the protective mean under test and the power P_S penetrating through the instrumental window is measured. The SE S_P of protective mean is calculated relative the open window by formula (1).

B. Validation of Combined Wall Model in Cases of Single Apertures and Unidimensional Periodic Structure

For the experimental validation of the combined wall model, an aluminum sheet with two holes was placed in the instrumental window of the Cabin. Aluminum sheet of 0.5 mm thickness has one square aperture with a side of 100 mm and one circle aperture with a diameter of 12 mm. The sheet was fixed in the instrument window with a frame that is bolted to the cabin body. The slot along the perimeter of contact between the metal sheet and the frame was reinforced by an EM gasket and aluminum foil. The SE of the aluminum sheet with two holes was measured in accordance with the procedure given in [8] and calculated by formula (10) using a combined wall model for three regions: two apertures and solid metal wall. Then the circular aperture was glued up by aluminum foil and the experimental results and calculated SE for the square hole were obtained in a similar way as in previous case. The results of calculations and measurements are shown in Fig. 2.

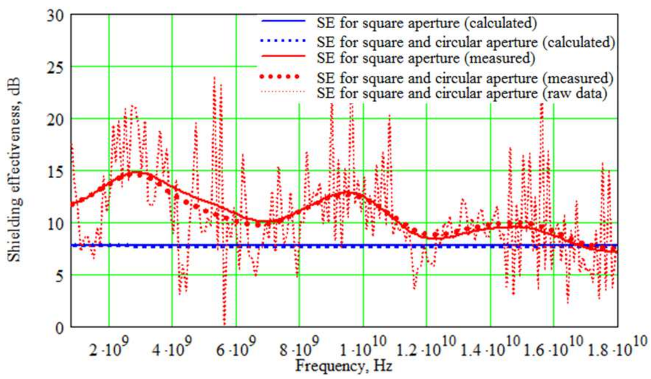

Fig. 2. Measured and calculated SE of metall sheet with two apertures (dotted lines) and with only one aperture (solid lines)

The raw data (i.e., the measurement results obtained at frequency grid with the step of 100 MHz) are smoothed by computing local weighted averages with the use of the Gaussian window (see Fig. 2). The bandwidth of the window is 2.5 GHz. The graphs of raw data will not be shown further.

Then only the circular aperture was left, and the square one was glued up by foil. The measured and calculated SE in case of the circular aperture is shown in Fig. 3.

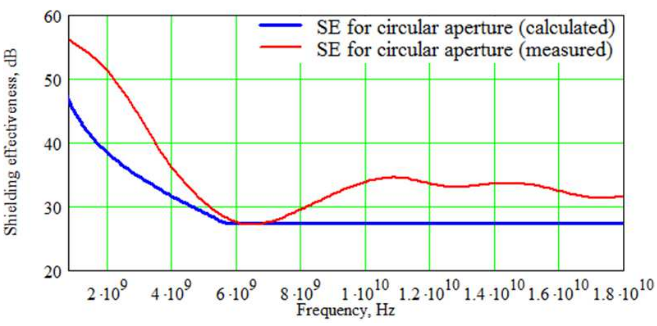

Fig. 3. Measured and calculated SE of aluminum sheet with circular aperture

The SE of the periodic structure was analyzed using the example of a slot that appears between the solid sheet of metal (aluminum of 0.5 mm thickness) and the cabin body, when a sheet of cardboard of 0.5 mm thickness is inserted between the metal sheet and the fastening frame. Since the frame is bolted to the cabin body by steel bolts with a diameter of 3 mm, and the distance between the centers of the bolt holes is 45 mm, the periodic structure with the corresponding parameters arises. The measured and calculated SE for the periodic structure formed by the frame fastening bolts is shown in Fig. 4.

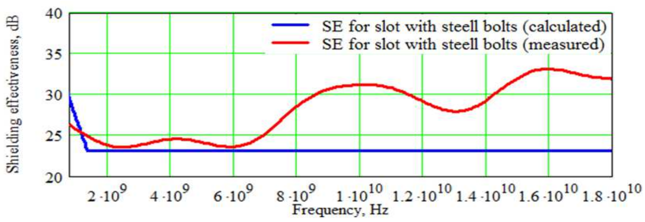

Fig. 4. Measured and calculated SE of slot with steel bolts periodically located along perimeter of instrumental window

C. Shielding Effectiveness of Magnetic and Electromagnetic Fields by Wire Mesh

The measurement results from [15] were analyzed for validation of correctness of the SE for the magnetic field calculation using the combined wall model. In [15], two loops located coaxially in two parallel planes and having diameter of 3 inches were used as transmitting and receiving antennas. The distance between the antennas is 3.5 inches. A shield in the form of a copper wire mesh was located in the middle of distance between the antennas [15].

Meshes are characterized by the diameter of the copper wire (d_wire) and by the number of cells per inch. The calculation results using (14), (15) in comparison with the measurement results from [15] are shown in Figure 5.

Comparison of the EM-field SE measured by the procedure described in subsection III.A and calculated by the combined wall model for a brass mesh is shown in Figure 6. Parameters of the brass mesh (semi-packed brass mesh 01 N GOST 6613-86, model L80, normal precision) are as follows: diameter of wire is 0.06 mm, dimension of square apertures of mesh is 0.1 mm.

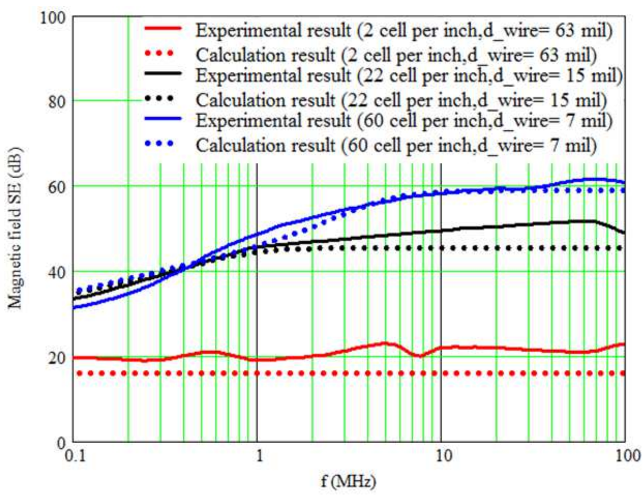

Fig. 5. Measured and calculated magnetic-field SE of copper wire meshes with various parameters

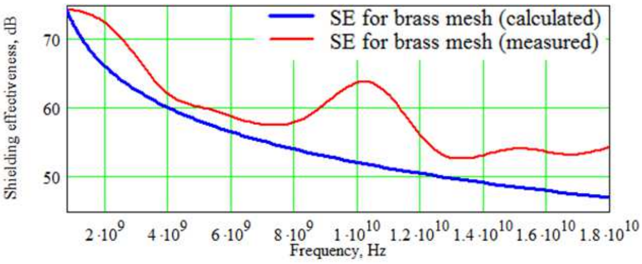

Fig. 6. Measured and calculated EM-field SE of brass wire mesh (wire diameter is 0.06 mm, distance berween wire edges is 0.1 mm)

D. *Shielding Effectiveness of Aluminum Foil Strips Glued on Dielectric Basis*

The structure, which is a dielectric base glued over by strips of aluminum foil, is analyzed. We used foil on a non-conductive adhesive basis in the form of tapes having 50 mm width and 50 µm thickness. Foil strips were glued on top of each other overlapping by half the width. Cases of single-layer foil strips (horizontal and vertical), as well as two-layer structure (horizontal strips over vertical ones) were analyzed.

To calculate the SE of the structure, which is a set of horizontal strips of foil, the following parameters were set within the framework of the combined wall model. The length of the horizontal slots can be chosen from 7.5 cm to 30 cm (it does not significantly affect the result of the calculation if the range of considered frequencies lies above the critical frequency of the waveguide associated with the slot). In the calculation formulas, the value of the slot length is 10 cm, the width is 2 µm (it is the thickness of the adhesive base) and the depth is 25 mm (because the strips are overlapped). The horizontal distance between the slots was chosen to be 20 µm (which corresponds to the average size of the contact spot that occurs along the edge of the foil strip when it is tightly glued to the adjacent strip), and vertical distance is equal to 25 mm (half the width of the strip).

When calculating the SE of a two-layer structure of horizontal and vertical stripes, the following values of the parameters for the combined wall model calculation were empirically selected: the slot length is 25 mm, the width is 2 µm, the slot depth is 25 mm, the distance between the slots is 25 mm in horizontal and 20 µm in vertical directions. The measured SE of a system of vertical strips is close to the SE of a two-layer structure (see the measurement results in Figure 7) and therefore can be adequately described by a combined wall model with the same parameter values.

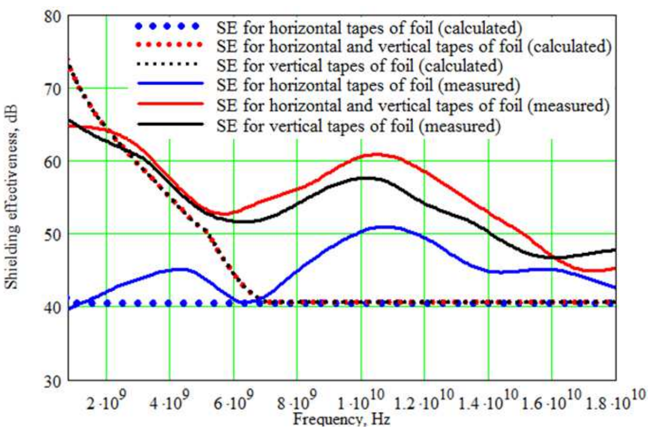

Fig. 7. Measured and calculated SE of foil tapes glued on the cardboard in different ways

E. *Shielding Effectiveness of Finger Spring Gaskets*

The finger spring gasket is considered as a one-dimensional periodic structure consisting of metal partitions and periodically spaced apertures. The length of the partitions is equal to the width of the fingers, and the length of the apertures is the distance between the edges of the neighboring fingers. The width of the apertures is chosen to be 4 times larger than the thickness of the gasket metal. The depth of the apertures (i.e., the thickness of the partitions) is chosen equal to twice the thickness of the gasket metal.

When testing, finger spring gaskets are installed around the perimeter of the aluminum plate that closes the instrumental window of the Cabin, and they are pressed by the frame to the cabin body by bolts. When calculating by the combined wall model, the parameters of the periodic structure are set in accordance with the parameters of the gaskets (see Table I), and the aluminum sheet is considered as a basic wall (see Fig. 1). The calculated and measured SE versus frequency is shown in Fig. 8.

TABLE I. PARAMETERS OF FINGER SPRING GASKETS

Name	Metal thickness, mm	Finger width, mm	Distance between fingers, mm
JOVI-1538-01	0.127	8.52	1
JOVI-1605-01	0.127	5.35	1
JOVI-1656-01	0.1	5.59	0.76

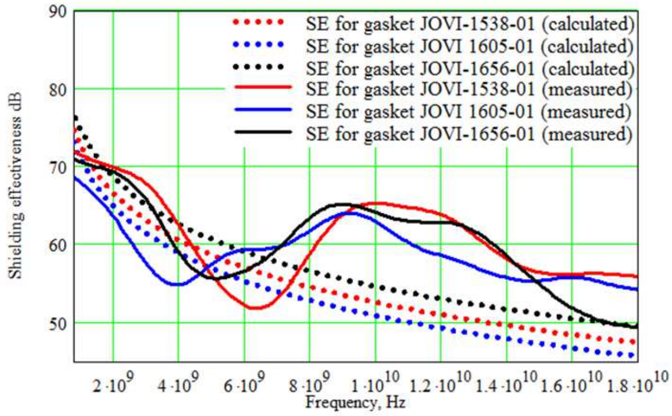

Fig. 8. Measured and calculated SE of aluminum plate with finger spring gaskets mounted along its perimeter

F. *Shielding Effectiveness of Wire Mesh Gasket and Cloth-pad Gasket*

When analyzing a gasket made of wire mesh, the wire diameter plays the role of the distance between the edges of the holes in horizontal and vertical directions. The thickness of the partitions t between the holes is chosen equal to the product of the wire diameter d_w and the number of mesh layers: $t = N \cdot d_w$. Cell dimensions in the uncompressed state of gasket are determined by direct measurements using a ruler, caliper or micrometer. For the compressed gasket, the dimensions of the cell decrease depending on the force compressing the gasket. For a fully compressed gasket, the width of the slots is taken equal to twice the thickness of the partitions $b_{\min} = 2 \cdot t$, and the length is taken to be a half of the cell length in the uncompressed state: $a_{\min} = 0.5 \cdot a_0$. For example, to analyze the ES6X4-6AC4-5M gasket (see [6]), the wire diameter is chosen to be $d_w = 0.1$ mm, the mesh cell size in the uncompressed state is $a_0 = 1$ mm, the wire material is monel (the conductivity is 0.04 relative the copper conductivity), the number of mesh layers is 2.

For measurements, the gasket is glued (conductive adhesive base) around the perimeter of the aluminum plate, which plays the role of the basic wall and is pressed by the instrument window frame to the cabin body with the help of bolts. As a result of consideration of the ES6X4-6AC4-5M gasket, it was empirically established that with a torque on the bolts equal to 2 N•m, the cell dimensions can be chosen equal to the original ones, and with a torque of 10 N•m the gasket will be completely compressed. The calculated and measured SE of the wire mesh gasket is shown in Fig. 9.

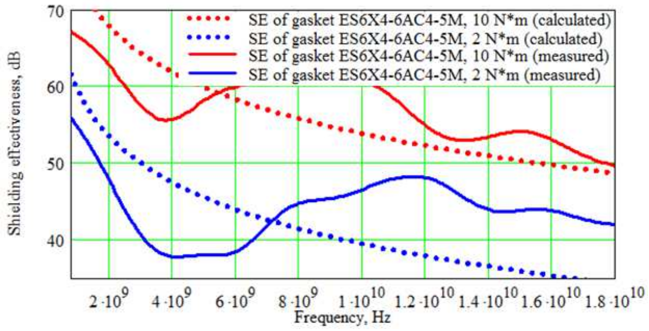

Fig. 9. Measured and calculated SE of aluminum plate with wire mesh gasket installed along its perimeter (for different values of torques of bolt clamping forces)

Cloth-pad gaskets are considered similarly to wire mesh gaskets, but the cells of the mesh associated with the fabric are considered as independent on the compression force applied to the gasket. For example, in order to calculate the SE of the cloth-pad gasket 3020503 WE-LT [7], the following parameters were chosen: the thickness of the conductive filaments is $d_w = 20$ µm, the cell dimensions of the corresponding mesh is $a_0 = 0.2$ mm, two layers of the mesh are taken into account, the conductivity is chosen to be 0.1 of the conductivity of copper (the effect of this parameter on the calculation result is insignificant). For measurements, the gasket under test is glued (conductive adhesive base) around the perimeter of the aluminum plate covering the instrumental window. The comparison of the calculation results and results of measurements in accordance with rules of standards [12] and [11] is shown in Fig. 10. Note that the SE measured (calculated) in accordance with [11] is SE obtained relative open window (according to [12]) minus SE shown in Fig. 4 for the slot in the instrumental window.

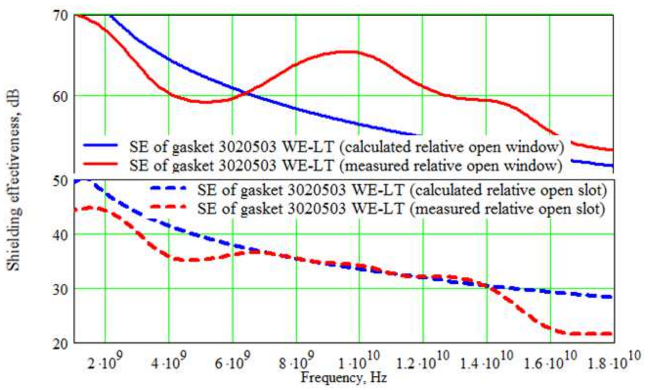

Fig. 10. Measured and calculated SE of aluminum plate with cloth-pad gasket "3020503 WE-LT" installed along its perimeter.

IV. Conclusion

The proposed technique makes it possible to estimate the in-situ SE of a protective mean by using its material and geometrical parameters. Therefore, the proposed technique of SE calculation can be used for assessing the contribution of protective means to the SE of equipment cases, vehicle bodies, ship hulls, etc. [14]. The fast estimation of the SE provided by analytical calculations is important, since a tight schedule for the development of new products hardly ever allows organizing measurements of the in-situ SE.

Developed analytical method for calculating the SE of periodical structures (see Subsection II.D) generalizes the method proposed in [15] to the case of high frequencies (up to tens of gigahertz).

Further development of the technique for express-assessment of SE of protective means is associated with the development of models that describe the shielding properties of composite materials (conductive plastics, rubber, silicone, sealant, etc.) and products made from these materials.

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