Method of Shielding Effectiveness Analysis for an Enclosure with an Aperture

Maxim E. Komnatnov, *Member, IEEE*
Department of Television and Control
Tomsk State University of Control Systems and Radioelectronics, TUSUR
Tomsk, Russia
maxmek@mail.ru

***Abstract*— Analytical expression for the coupling coefficient of an aperture with an enclosure is obtained. This expression permits to realize a fast evaluation of shielding effectiveness by an enclosure with an aperture. Method of shielding effectiveness analysis of communications electronics equipment is developed. Its novelty is the use of an electromagnetic approach and of approach based on the obtained expression. Using the obtained expression the shielding effectiveness in location of the observation point at the beginning and middle of the SNP 339 connector enclosure is calculated in the frequency range from 10 kHz to 1 GHz. Coincidence of frequency dependencies obtained using known analytical and numerical methods with the proposed expression is shown. A study is given for a metal enclosure when there is a metallic object in its aperture without an electrical connection to the enclosure and when there is a dielectric with dielectric permittivity of high value.**

***Keywords*— electromagnetic compatibility, shielding effectiveness, communications electronics equipment**

I. Introduction

Insurance of stable operation of radioelectronic equipment under the influence of electromagnetic interference is actual as the integration of components and the package density of printed circuit boards (PCBs) are increasing. The use of integrated circuits (IC) reduces the mass and dimensions of electronic equipment, but increases the susceptibility to the electromagnetic field (EMF). In addition, the tendency to increase the speed of digital circuits and operating frequencies of analog circuits poses ever more stringent requirements to the electromagnetic compatibility (EMC) of electronic equipment. One of the design tools for ensuring EMC is shielding. When designing electronic equipment, shielding by a plate [1] or by an enclosure [2, 3] is used. In doing so, it often requires an individual design solution with careful simulation and calculation of shielding effectiveness (SE) for each radioelectronic equipment assembly. The SE can be calculated using various known analytical and numerical methods. Among numerical methods, the finite difference time domain (FDTD) [4–6], the method of moments (MoM) [7, 8], the finite element method (FEM) [9], the transmission line matrix (TLM) [10, 11] and the hybrid method are used [12]. These methods make it possible to calculate SE for a wide class of problems: with different arrangement and shape of the aperture in the wall of the enclosure, arrangement of the partitions, taking into account the filling of the case with elements and radioelectronic equipment. Using numerical methods it is possible to obtain the most reliable values of the analysis results. However, these methods are rarely used at the initial stages of design, as the design decisions are not fully worked out and can be changed. In addition, calculations using such methods require experience and a lot of developer time, as well as high computation effort. Therefore, it is reasonable to apply numerical methods at the stage of final design decisions, and at the initial stage –analytical methods for analyzing of the SE. Methods based on the theory of Hans Bethe [15], power balance equations [16] and the equivalent circuit method [17] are known among analytical methods [13, 14]. The latter method is the most universal in relation to the geometric dimensions of the enclosure and the electromagnetic wave length ranges of the source. Using this method, the SE of a rectangular metal enclosure with an aperture (Fig. 1*a*) can be found from the voltages and currents at the point P of the equivalent circuit, at a distance p from the aperture (without taking into account the loss resistance in the metal Z_l) (Fig. 1*b*). The method for calculating the SE reduces to analyzing the circuit using the Tevenin theorem.

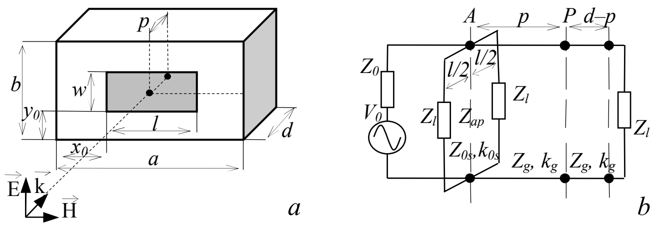

Fig. 1. Geometry of a rectangular enclosure with an aperture (*a*) and its equivalent circuit (*b*)

It is possible to calculate the SE by the method of [17], if the rectangular aperture is in the center of the lossless enclosure orthogonally ecxited by plane wave of one polarization, which is the limitation of this method. The model was extended for one or more round holes located in the center of the enclosure wall [18]. Based on the models

Investigation was carried out at the expense of the Ministry of Education and Science of Russian Federation project No. 8.9562.2017/8.9.

described above, a universal analytical model of a rectangular enclosure with a conductive structure or a PCB inside has been obtained [19]. Using this model, the SE can be calculated as a function that depends on the frequency, the size of the enclosure and the aperture. The results of the analytical model were compared with the results of measurements with using log-periodic antennas and with the results of modeling by TLM and showed their usability. Also, based on the analytical model [17–19], combined models for a case with a non-central arrangement of the aperture in the wall [20, 21] and a perforated wall [22], taking into account the conductive properties of the enlosure walls (Fig. 1) were obtained. The results of calculating the SE obtained with the combined model were compared with the measurements obtained with using the log-periodic antenna in the half-anechoic chamber, as well as with the results obtained with FDTD and FEM [23] and modeling in the CST MWS program [24]. The variety of geometric shapes and parameters, as well as the properties of the enclosures, makes the shielding task rather laborious. Due to the complexity of calculating the SE, the developers do not always make the right decisions to ensure EMC of the devices as a whole, which significantly increases the cost of their development at the final design stage. Therefore, it is advisable to analyze the SE at all stages of the design of radio electronic equipment, starting with the initial one. Analytical models have shown their suitability for a rapid analysis of the SE of the enclosure with aperture and applicability at the initial stages of the design of radio electronic equipment. At the initial stages of the design, a structured, sequential approach is needed to perform SE analysis, with successive obtaining of reliable results, which will improve the SE at the final stage of the design of radioelectronic equipment.

The aim of this paper is to develop a technique for analyzing the SE of an enclosure with an aperture for its application at the initial stages of the radioelectronic equipment design.

II. Method of SE Analysis

A method is developed, schematically presented in Fig. 2 and intended for obtaining preliminary (coarse) and final (exact) values of SE for the enclosure of the radioelectronic equipment. The method is based on the experience of carrying out a variety of analyzes of the SE of the units and assemblies of the onboard radioelectronic equipments of a spacecraft, including the results described in [1–3]. To compare the correctness and timing of the calculation of various [17–22] analytical methods, their software implementation in MATLAB is performed.

The method of Fig. 2 is as follows. For selected or given parameters (thickness t, magnetic permeability μ and specific electrical conductivity σ) of the metal enclosure and of the source (receptor), the frequency dependence of the SE *1* [1, 25–27] for a flat uniform metal plate is calculated. The results are SE values in a given frequency range for the selected material, which in case of insufficient shielding can be replaced by another (with increased values of μ and σ or increased thickness t).

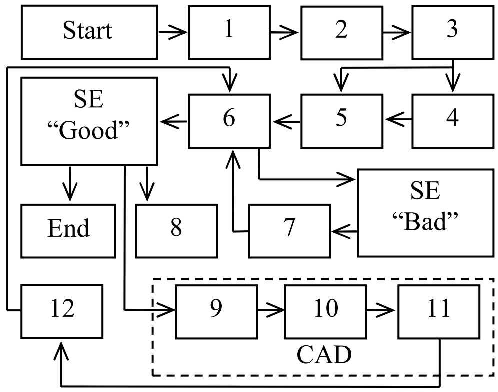

Fig. 2. Method of SE analysis for an enclosure of communications electronics equipment

Next, the analysis *2* of the enclosure design is performed, from which the geometric dimensions of $a\times b\times d$ are derived and the resonance frequencies of the enclosure are calculated according to the expression

$$f_{m,n,p} = \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}} \cdot \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{d}\right)^2} \qquad (1)$$

where m, n, p =0, 1, 2…; c – is the speed of light; a, b, d – the geometric dimensions of the enclosure (m), μ_r, ε_r – the relative permeability and permittivity of the electromagnetic wave propagation medium, respectively.

When calculating the SE of an enclosure with an aperture, in the frequency range above the first resonant frequency, it is difficult to predict the shielding properties of the enclosure. The values of SE at resonance frequencies can vary significantly depending on a variety of factors that are difficult to predict and take into account in the calculation. For this reason, the useful operating frequency of the radioelectronic equipment device for which shielding analysis is performed should at best be below the frequency of the first resonance, and at worst between the resonance frequencies. Its coincidence with resonance frequencies is inadmissible: it is necessary to change the dimensions of the enclosure. In the selection *3* of wall with an aperture in the enclosure, which is affected by the plane wave the largest side of the wall is used. If a group of apertures exists in the enclosure wall, the area of apertures is recalculated into a single aperture *4*. Further, for a geometric model of an enclosure with aperture the frequency dependence of SE is calculated *5* using models [19–22], depending on the type of enclosure being analyzed *6*. An analysis of the obtained frequency dependences of the SE is completed. If the SE value is insufficient, additional measures *7* can be applied to increase it (reducing the area or number of apertures) and the SE is recalculated. When the necessary SE values are obtained for a particular enclosure with an aperture, the analysis is completed or more accurate estimates of the SE *8* are obtained using the model [20–22], taking into account the formula (3) described in the next section. In order to obtain the most accurate results of SE, a model of the device as a whole is built in the CAD system, for example in Solid Works, and internal elements of the construction *9* are added. A change in the geometric dimensions of the aperture *10* is performed, if it is obtained with uncontrolled parameters, due to rolling, cutting or other inaccuracies that occur during metal processing. The models of sealing elements and other dielectric materials that can be placed in the aperture of the enclosure *11* are added. The device model is imported from CAD system into the program, which allows performing the electromagnetic analysis of the structure as a whole *12*. In this program, the properties of metal and dielectric are taken into account in the program of electromagnetic simulation, as well as elements of the component base, the models of which are replaced by conductive structures. After the completed electromagnetic analysis of the SE, it can be completed or, with insufficient SE values, repeated using measures to increase the SE. The results of the SE analysis method application are: the SE values in a given frequency range for the selected material, which, in the enclosure of low SE, can be replaced by another; recommendations on the choice of the dimensions of the enclosure and apertures in its walls, taking into account the operating frequencies of the device located in the analyzed case; increase the values of SE with the use of additional measures *7* to improve the overall SE of the enclosure.

III. The Rectangular Enclosure with an Aperture

This chapter describes a simplified expression, through which fast, refined SE estimates are performed (as provided for Item *8* of the analysis method). Also, we show changes of SE frequency dependence for an enclosure with an aperture, within which the sealing elements and other dielectric materials are placed (as provided for Item *11* of the analysis method).

A. Coefficient of aperture coupling with enclosure

The unique feature of the combined method described in [21] consists in the coefficient (2) for taking into account higher-order modes and the aperture coupling at its different positions in the enclosure wall, which makes it possible to obtain the frequency dependence of the SE with an arbitrary arrangement of the aperture in the wall of the enclosure from the side of the plane wave. The value obtained in calculating the expression (2) in [21] is taken into account in calculating the characteristic impedance of the aperture Z_{ap} of the enclosure (Fig. 1*b*).

For a combined method that allows one to obtain the SE frequency dependence with an arbitrary arrangement of the aperture in the wall of the enclosure from the side of the incidence of a plane wave, an expression of the aperture coupling coefficient (3) for its different positions in the shell wall, under condition of the TE_{10} wave propagation mode enclosure is obtained. In expression (3), the variables X, Y are the coordinates of the center of the aperture; a is width of the shell wall; l, w are the width and height of the aperture in the shell wall; The coefficient $\beta=(X-Y)/l-0.5$. The values of the origin of the aperture x_0 and y_0 are expressed in terms of $X-l/2$ and $Y-w/2$, respectively.

Expression (3) is obtained on the basis of the integral expression (2), under the condition of the propagation mode of the main type wave (TE_{10}) in the waveguide and can be realized together with the known analytical expressions [17–22]. The simplicity of the resulting expression makes it easy to implement its software implementation. In this case, the peculiarity of the combined method is accounting for higher-order modes, when calculating a group of several frequency dependences, leads to an increase in computation effort. Thus, in obtaining the frequency dependences of SE for a rectangular connector shell or shielding casing for a PCB whose geometric dimensions are smaller than the wavelength, and the first resonance frequency is much further than the upper operating frequency, expression (3) can be applied.

B. Connector shell

The calculation of resonant frequencies and SE is performed using a software module with the resulting expression (3). The frequency dependences of the SE of the SNP 339 connector shell, with full and reduced aperture openings on the cable side, in the frequency bands f_1 (10 kHz–1 MHz) and f_2 (1 MHz–1 GHz), for the observation point at the beginning, center and end of the connector shell are presented [3] (Fig. 3). It is shown that the dependencies obtained with the CST MWS program and the implemented software module are consistent. At the innermost observation point, the SE values differ by 10 dB in the frequency range up to 1 MHz (Fig. 3*a*) and by 6 dB – in the frequency range up to 1 GHz (Fig. 3*b*).

Also, the frequency dependences of SE in the frequency range 1–20 GHz are calculated. Behavior of SE is preserved, but at resonance frequencies the SE values differ up to 20 dB.

$$C_{ma}=\frac{\int_{x_0}^{x_0+l}\int_{y_0}^{y_0+w}\cos\left(\frac{n\cdot\pi\cdot y}{b}\right)\cdot\cos\left(\frac{n\cdot\pi\cdot(y-y_0)}{w}\right)\cdot\sin\left(\frac{m\cdot\pi\cdot x}{a}\right)\cdot\sin\left(\frac{m\cdot\pi\cdot(x-x_0)}{l}\right)dxdy}{X\cdot Y} \tag{2}$$

$$C_{ma}=\left[\frac{\cos\left(\pi\cdot\left(\frac{Y}{\alpha}+\beta\right)\right)}{\alpha-l}-\frac{\sqrt{\cos^2\left(\pi\cdot\left(\frac{Y}{\alpha}-\beta\right)\right)}}{\alpha+l}\right]\cdot\frac{\alpha\cdot l^2}{\pi\cdot X\cdot Y}\cdot\sqrt{\sin^2\left(\frac{\pi\cdot w\cdot(\alpha-l)}{2\cdot\alpha\cdot l}\right)} \tag{3}$$

The average calculation time for each frequency dependence of SE of the connector shell, in two frequency bands with the number of 1000 points, was 4 s in the developed module, and 1864 s in CST MWS , therefore acceleration of 466 times is obtained. Thus, on the basis of the realized modules, fast estimates of SE for radioelectronic equipment were obtained.

As a result of comparison of the frequency dependencies of SE obtained by different methods (Table 1), it is evident that in the frequency bands f_1 and f_2, when calculating using (3), the difference in SE values in comparison with the CST MWS program does not exceed 3 dB for all observation points except the furthest, on which the difference is 11.8 dB. The difference in the values obtained with the software implementation of the model [17], in comparison with the CST MWS program in the frequency range f_1, does not exceed 14 dB, and in the range f_2 it is 22.5 dB, which is much higher (about 12 dB) than when using the proposed model [17]. In the frequency range f_3 (1 GHz–20 GHz), the difference in the SE values obtained by the developed module and CST MWS remains about 10–15 dB up to the frequency of the first resonance, but at resonance frequencies it increases to 20 dB. The difference in the SE values in the frequency range f_3 for the model [17] and CST MWS increases to 35 dB.

TABLE I. COMPARING THE SE VALUES FOR CONNECTOR SHELL

***f*, MHz**	**1**			**1000**		
***p*, mm**	***1***	***10***	***20***	***1***	***10***	***20***
[17]	–4.6	56.5	23.9	47.5	4.2	76.2
CST MWS	9.8	78.2	37	70	17.8	97.8
(3)	12	77.8	30.5	69.9	21	86

The SE values at the beginning and middle of the connector shell are calculated when the aperture is opened in range 2–8 mm in steps of 1 mm. It is shown that at frequencies up to 1 GHz with the aperture opening of 2 mm, the SE value increases, in comparison with the full opening, by about 20 dB, and in the intervals between the resonant frequencies by 10 dB, whereas at the resonance frequencies of the shell the shielding can deteriorate. Thus, the SE of the connector shell can be increased by 20 dB, in the frequency range up to 1 GHz.

C. Metal and dielectric plates inside the enclosure aperture

The additional SE analysis of the enclosure with aperture was performed. In this case, we placed the metal plate with the dielectric between faces of the aperture (Fig. 4). The value of its relative permittivity (ε_r) was varied from 1 to 140. The distance x (the width of the dielectric) between the edges of the metal plate (with a thickness equal to the thickness of enclosure) assumed values of 0.1; 0.5; 1; 1.5 mm. In CST MWS, a geometric model was constructed and the SE (Fig. 5) was calculated at the center (p=150 мм) of the enclosure, when a plane wave was irradiated from the side of the wall with the aperture. The enclosure model was chosen with geometrical parameters a=d=300 mm, b=120 mm, w=80×80 mm.

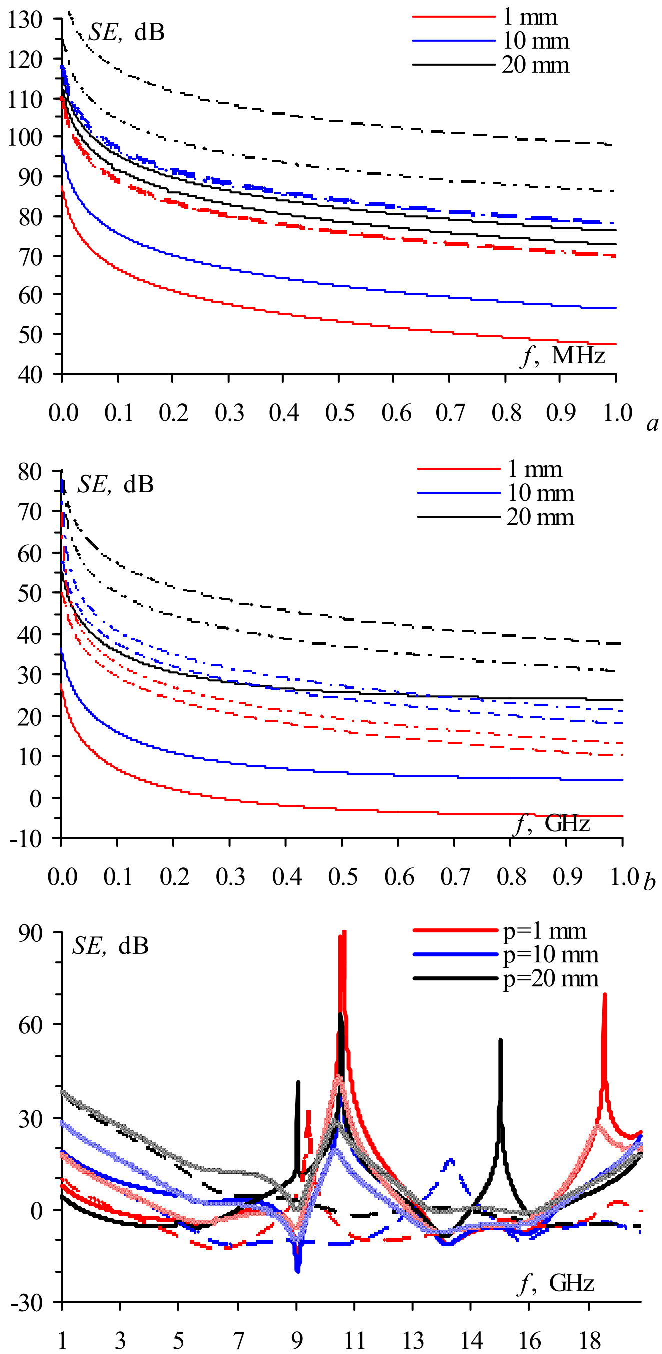

Fig. 3. Frequency dependencies of the SE of the connector shell in the frequency bands f_1 (*a*) and f_2 (*b*), with a change in the distance p (— Robinson M.P., – – – CST MWS, – · – · – our)

Fig. 5 shows, that for ε_r>1 there are additional resonances in the low-frequency region. The SE values at resonant frequencies increase with increasing number of aperture resonances. Fig. 6 shows the dependence of the resonant frequencies on ε_r for different values of x.

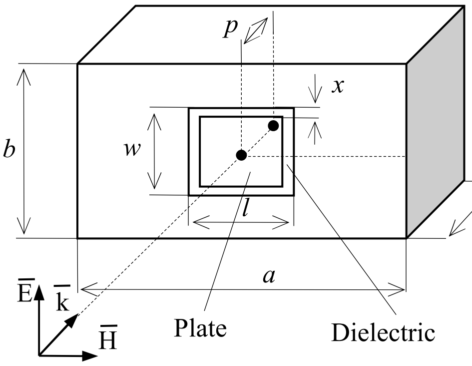

Fig. 4. Geometry of the rectangular enclosure with a metal plate and a dielectric inside the aperture

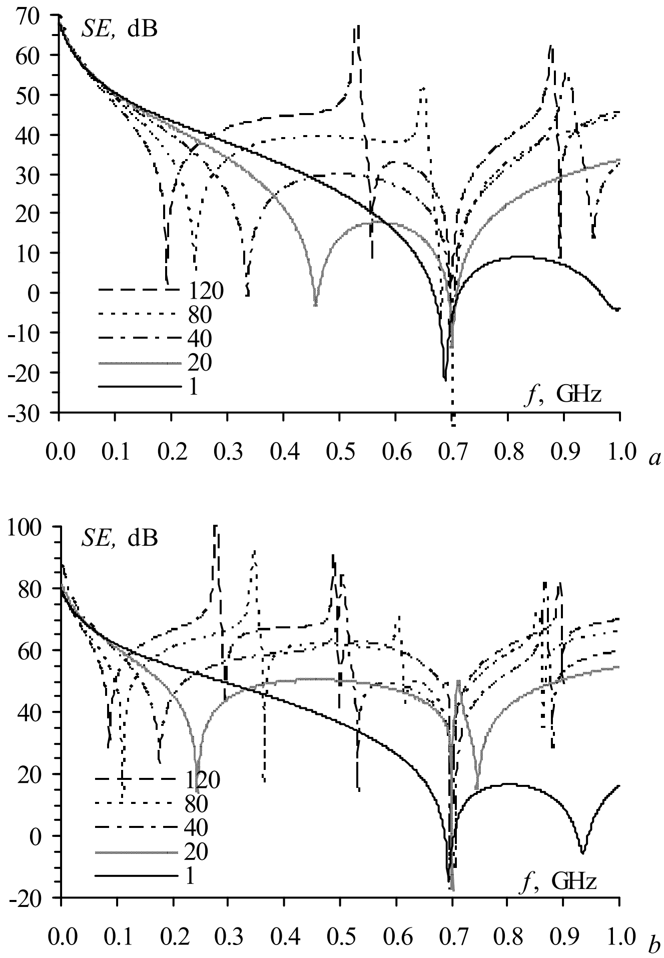

Fig. 5. The frequency dependences of SE in the center of the shell, with a dielectric width x=0.1 mm (a) and 1.5 mm (b) for different ε_r

It is seen from Fig. 6 that with increasing ε_r of the material the resonance frequency of the aperture decreases. With decreasing x, this decrease is stronger.

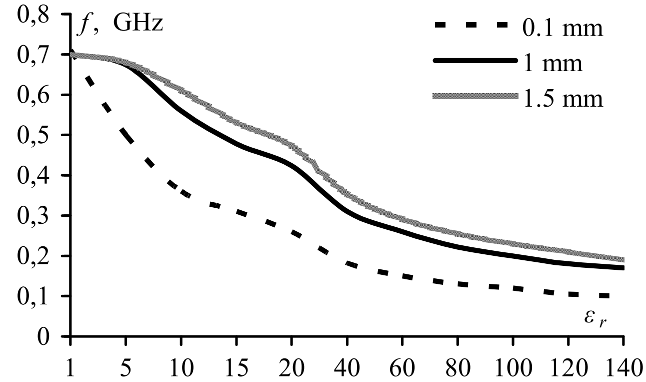

Fig. 6. Dependence of resonant frequencies on ε_r for different x

This study can be useful for the enclosure where the metal object is without electrical connection to the enclosure, and there is a dielectric with a high value of ε_r between the object and the enclosure. Examples are a rubber gasket (ε_r=5) or ice (ε_r=57.8 at a frequency f=100 Hz) formed, for instance, due to changes in climatic conditions.

D. 3-D visualization of SE frequency dependencies

Designed MATLAB program implements analytical expressions from known methods [17–22] and draws a 3-D vizualization of the SE for the enclosure with the aperture. A visual representation of the SE values along the displacement of the point p (Fig. 1), with a step of 1 mm, can be obtained by 3-D visualization of the SE frequency dependences (Fig. 7).

This software implementation allows to analyze the worst SE values and make a preliminary placement of electromagnetic field sensitive elements and assemblies of radioelectronic equipment.

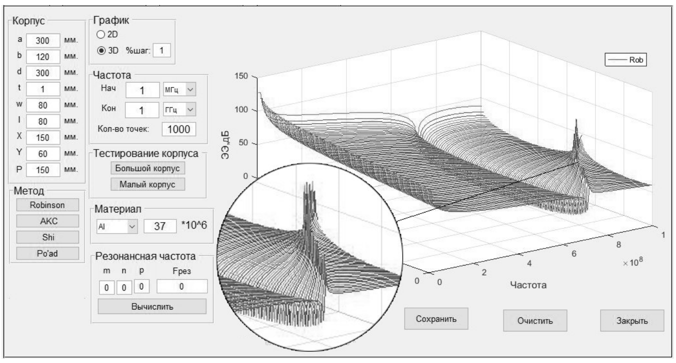

Fig. 7. 3-D visualization of the SE frequency dependencies for the enclosure with the aperture when the distance p is changed (in increments of 1 mm)

It is also possible to observe the displacement of the resonance frequencies and their amplitudes when the observation point p moves deep into the enclosure. For example, Fig. 7 shows, that the amplitude of the first resonance (707 MHz) has a maximum in the center of the enclosure, whereas at the beginning and end of the enclosure the amplitude of the resonance decays. The second resonance of the enclosure shifts from 707 MHz (near the aperture p=1 mm) to 1 GHz (at p=125 mm). Over 125 mm SE is not less than 20 dB and has a smooth character without the presence of resonances.

IV. Conclusion

The results of improving the SE analysis are presented. The method for analyzing the SE of radioelectronic equipment is developed, which is distinguished by the use of analytical and electromagnetic approaches. The expression for the coupling coefficient of the aperture with the enclosure is obtained in a closed form, which makes it possible to realize a fast evaluation of SE by an enclosure with an aperture in the frequency range from 10 kHz to 1 GHz. The software implementation of the presented models in the form of modules allowing to perform a fast evaluation of the SE of a rectangular metal case with an aperture is carried out. It is shown that the dependences obtained by means of electromagnetic analysis and the implemented module using the obtained expression are consistent. The SE for an enclosure with a plate and a dielectric inside the aperture is calculated. The frequency dependences of the SE are given, from which it is seen that for ε_r>1 additional resonances appear in the low-frequency region. Thus, on the basis of the developed methodology and implemented modules, useful estimates of SE can be obtained at the initial stages of the design of the enclosures for radioelectronic equipment.

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