Computationally Effective Wideband Worst Case Model of Electromagnetic Wave Penetration between Compartments inside Enclosure

Dzmitry Tsyanenka
EMC R&D Laboratory
Belarusian State University
of Informatics and Radioelectronics
Minsk, Belarus
emc@bsuir.by

Yaraslau Tamashevich
EMC R&D Laboratory
Belarusian State University
of Informatics and Radioelectronics
Minsk, Belarus
emc@bsuir.by

Yauheni Arlou
EMC R&D Laboratory
Belarusian State University
of Informatics and Radioelectronics
Minsk, Belarus
emc@bsuir.by

Eugene Sinkevich
EMC R&D Laboratory
Belarusian State University
of Informatics and Radioelectronics
Minsk, Belarus
emc@bsuir.by

Vladimir Mordachev
EMC R&D Laboratory
Belarusian State University
of Informatics and Radioelectronics
Minsk, Belarus
emc@bsuir.by

Xie Ma
China Electronics Technology
Cyber Security Co., Ltd.,
Chengdu, Taiyuan, China
18081045600@163.com

***Abstract*—A wideband worst case model for estimation of electric and magnetic shielding effectiveness of an enclosure (e.g., an aircraft fuselage, ship hull, or vehicle cabin) divided into compartments by partitions is developed. The model makes it possible to estimate the spatial distribution of electric and magnetic fields in the compartments separated from each other by metallic walls with irregularities (apertures, slots, joints, etc.). The model is based on a combination of analytical solutions describing the penetration of radiation through a wall and the distribution of fields inside cavities. The combination is performed in the framework of the perturbation theory and technique of the multilayer structure calculation. The developed model is validated by comparison of results obtained by the model with known experimental results and with results of numerical simulation in the frequency range from 10 MHz to 3 GHz (that corresponds to the range of wavelengths from very large to quite small as compared with dimensions of the compartments used for the validation).**

***Keywords*—electromagnetic compatibility, electromagnetic shielding, waveguide theory, apertures, Q-factor**

I. INTRODUCTION

For the solving of EMC problems [1]–[4], it is necessary to estimate the amplitudes of electric and magnetic fields in the vicinity of radio & electronic equipment, laying paths of transmission lines, and workplaces of staff [5], [6]. As a rule, the system under consideration has a conductive hull with the complex internal structure, for example, a vehicle cabin divided by partitions, a ship hull consisting of compartments, a building with several rooms, etc. [6], [7]. In the system hull and in conductive walls between the compartments, there are apertures through which the energy of an external electromagnetic (EM) wave penetrates into the compartments [7], [8]. A model of the field distribution inside the compartments, intended for express analysis of EMC, must be applicable in a wide frequency range in order to account for the impact of a complex electromagnetic environment (including ultrawideband pulsed EM disturbances). The model must also have a worst case behavior (i.e., it must eliminate an underestimation of field amplitudes [6]) and a high computational efficiency.

The spatial distribution of EM field in compartments of complex systems can be assessed by methods of computational electromagnetics [8] – [10], but this way requires a high computational burden and leads to the jagged solutions at high frequencies. Experimental methods [3] – [5], [7], [8] are expensive, and their results are valid only for fixed positions of the equipment and personnel inside the compartments. Analytical models based on transmission line theory [11] and its generalization [12] – [15], as well as models based on waveguide and resonator theory [16], do not have the worst case behavior because solutions are jagged at high frequencies as result of resonances.

The objective of this paper is to develop a wideband computationally effective worst case model for estimation of electromagnetic field distribution inside the coupled compartments of the system, the hull and internal walls of which are made of conductive materials and have apertures.

The article is organized as follows. In Section II, a physical model of the enclosure with the complex internal structure is introduced, approximations and simplifications used for the model development are considered. Section III presents an approach for calculation of EM field distribution inside the compartments based on the perturbation theory. In Section IV, a technique of calculation of a multilayer structure is presented. The validation of the model by comparison of results obtained in the framework of developed models with the results of numerical calculations and known experimental result is presented in Section V. In Conclusion, the applicability as well as possible directions of the further refinement of the models are discussed.

II. PHYSICAL MODEL OF COUPLED COMPARTMENTS INSIDE THE ENCLOSURE

The plane electromagnetic wave of frequency *f*, amplitude E_0, and linear polarization irradiates an enclosure having the shape of the rectangular parallelepiped. The partitions (internal walls) between compartments are parallel to the corresponding external walls of the enclosure, so, compartments allocated within the enclosure are the rectangular parallelepipeds, too. The walls have the defined thickness and are made of material with the defined conductivity. There are apertures of arbitrary shapes and dimensions in the walls. The angle between the normal to the front wall of enclosure and wave vector of the irradiating

DOI: 10.1109/EMCEUROPE48519.2020.9245746

plane wave is α (see Fig. 1). The environment is vacuum (relative permittivity and relative permeability are equal to 1, wave impedance of free space is $Z_0 = 120\pi$ Ohm and speed of light is $c = 3 \cdot 10^8$ m/s).

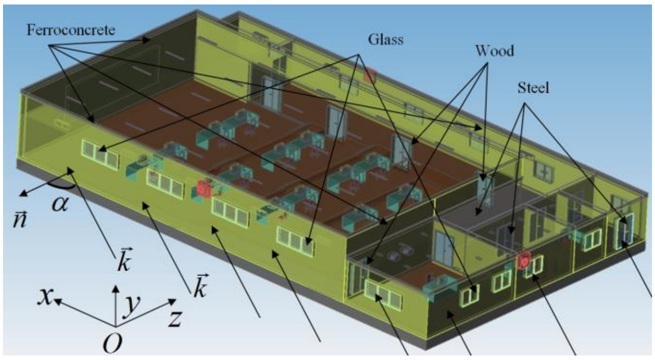

Fig. 1. An example of the system hull divided by internal walls with various shielding effectiveness and irradiated by the plane wave incident at the angle α to normal

The following simplifications and approximations are introduced for the model development:

1) The energy of incident EM wave penetrates inside the enclosure through the external walls and apertures in them. The reverberation component in compartments is excided due to the multiple reflections from the walls [17]. When the wave vector $\vec{k}$ ($|\vec{k}| = 2\pi/\lambda$, $\lambda = c/f$ is the wavelength) of the incident wave is directed along Oz axis, the compartment of the number *i* is considered as a rectangular waveguide of dimension $L_{xi} \times L_{yi}$. Propagation constant γ_{ci} and characteristic impedance Z_{ci} of a waveguide associated with *i*-th compartment are defined by the formulas:

$$\gamma_{ci} = \frac{2\pi f}{c}\sqrt{1-\left(f_{ci}/f\right)^2},\ Z_{ci} = Z_0 \Big/ \sqrt{1-\left(f_{ci}/f\right)^2}, \quad f_{ci} = c/(2L_x) \tag{1}$$

where f_c is the waveguide cutoff frequency (frequency of fundamental mode TE(1,0)) and the waveguide is considered as lossless.

2) A sum of reverberation components and Line of Sight (LOS) fields [18] determines the field distribution inside the compartment in the framework of the worst case model.

3) If the angle of the wave incidence is α , as it is shown in Fig. 1, then the two reverberation components are excided in the compartments: the first corresponds to the propagation of the wave along the axis *Ox* and the second along *Oz*. The calculation of the amplitudes of reverberation components in the framework of the developed model is performed based on the assumption that the external wall, which is parallel to the plane *xOy*, is irradiated by the wave with the amplitude $E_z = E_0 \cos\alpha$ and the external wall parallel to *zOy* plane with the amplitude $E_x = E_0 \sin\alpha$.

4) The model presented in [18] allows calculation of the LOS components. LOS fields are defined for apertures in illuminated external as well as internal walls. Diffraction fields that excide EM waves in compartments by the penetration of radiation through the walls and apertures situated in shadow zone are not considered in the framework of the approach presented in the article.

5) The developed model is linear, i.e. the shielding effectiveness of walls does not depend on the amplitude of EM waves, and the amplitude of the field penetrating to the compartment of number *i* from the compartment of number *j* does not depends on the field penetrating in *i*-th compartment from other compartments.

6) Compartments considered in the framework of the model have high Q-factor. It is supposed that there are no absorbers inside the compartment and its Q-factor is equal to intrinsic Q-factor, which is defined by the shielding effectiveness of the compartment's walls [17].

7) The model developed in [17] allows consideration of compartments filled by absorbers. In this case, the Q-factor of compartment is calculated by formula $Q_{load}^{-1} = Q_0^{-1} + Q_a^{-1}$ where Q_0 is an intrinsic Q and Q_a is defined by absorbers placed into the compartment and defined empirically.

III. THE USE OF PERTURBATION THEORY FOR CALCULATION OF FIELD DISTRIBUTION IN COUPLED COMPARTMENTS

A. Shielding Effectiveness and Reflection Coefficient of Combined Wall

The walls of compartments can consist of regions with various physical characteristics. For example, the first part of the wall of area A_1 can be made of metal (the model of solid metal wall [19] is used for calculation of shielding effectiveness of the region), the second region (with area A_2) is a circle aperture, and the next region (with area A_3) is a wire mesh (shielding effectiveness is calculated by the model presented in [20]). Let us define the region as an area of the wall determined by a single set of parameters: the wall thickness, characteristics of the wall material, aperture dimensions, etc. The combined wall is the wall consisting of regions of various types.

The shielding effectiveness for electric and magnetic components is defined as the ratio of electromagnetic field energy transferred into the compartment to the energy of incident plane wave. For the plane wave, the radiation power transferred by the electric and magnetic components of the electromagnetic field is proportional to the square of the corresponding strength amplitude. So, the shielding effectiveness of the wall can be calculated by the ratio of the power $P_{tr(E,H)}$ of the radiation penetrating through the wall to the power of the incident radiation $P_{0(E,H)}$ [16]:

$$\begin{aligned} S_E &= -10\lg(P_{tr\,E}/P_{0E}) = -20\log(|E'|/|E_0|)\,, \\ S_H &= -10\lg(P_{tr\,H}/P_{0H}) = -20\log(|H'|/|H_0|)\,. \end{aligned} \tag{2}$$

where $|E'|$ is the electric field amplitude in the shielded zone; $|E_0|$ is the amplitude of electric field of incident wave; $|H'|$ and $|H_0|$ are the corresponding amplitudes of the magnetic fields.

Let's consider wall consisting of N regions with different shielding effectiveness. According to the model of combined wall, the power penetrating through the region with a number μ does not depend on the power penetrating through the other regions. So, the shielding effectiveness of the combined wall $S_{G(E,H)}$ is calculated by summation of the power ratios defined for each region [17]:

$$S_{G(E,H)} = -10\lg\left(\sum_{\mu=1}^{N} 10^{-S_{\mu(E,H)}/10} A_\mu / A_0\right), \qquad (3)$$

where $S_{\mu(E,H)} = -10\lg(p_{tr\,\mu(E,H)} / p_{0(E,H)})$, $p_{tr\,\mu(E,H)}$ is a radiation flux density penetrating through the region with the number μ of the area A_μ, $p_{0(E,H)}$ is a flux density of incident radiation (indexes (*E, H*) denotes the type of the component), $A_0 = A_1 + A_2 + \ldots + A_N$ is total area of the wall.

One can obtain the reflection coefficient of combined wall by analogy to (3):

$$R_G = \sqrt{\sum_{\mu=1}^{N}\left(R_\mu{}^2 A_\mu\right)/A_0}\,, \qquad (4)$$

where the reflection coefficient R_μ of the μ-th region is defined as follows (the angle of incidence is 0):

$$R_\mu = \left(Z_\mu - Z_e\right)/\left(Z_\mu + Z_e\right), \qquad (5)$$

where Z_μ is the wave impedance of the μ-th region of combined wall and a wave impedance of the environment Z_e can be the wave impedance of free space Z_0 or the characteristic impedance of the compartment Z_{ci} (1) depending on the direction of the wave propagation (from the compartment to free space through the wall or from compartment to compartment).

B. *Estimation of Field Distribution in Coupled Compartments Based on Perturbation Theory*

In order to develop the worst case model of spatial field distribution inside the coupled compartments and to define the worst case amplitude-frequency characteristic (AFC) of field amplitudes in compartments, the perturbation theory can be used.

In zero order of the perturbation theory, compartments are considered as uncoupled, even if they have common walls. It is supposed that, if the EM energy of the reverberation component leaves the compartment volume through the walls, then it does not come back. Based on the model proposed in [17], the amplitude of the reverberation component in compartments having external walls irradiated by incident electromagnetic wave is calculated. The field strength in the compartments, which do not have walls irradiated directly, is equal to zero. The reverberation component distribution corresponding to mode TE(1,0) in the rectangular compartment is defined by formulas

$$\begin{aligned} E_{y10}(x,y,z,f) &= -jE(z,f)\cos\left(\pi x/L_x\right),\\ H_{x10}(x,y,z,f) &= jH(z,f)\cos\left(\pi x/L_x\right), \qquad (6)\\ H_{z10}(x,y,z,f) &= H(z,f)\sin\left(\pi x/L_x\right). \end{aligned}$$

where amplitudes of the reverberation components are:

$$\begin{aligned} E(z,f) &= \left|E'\right|\left[e^{(-j\gamma' z)} + R_b e^{(-j\gamma'(2L_z - z))}\right]G(f)\\ H(z,f) &= \left|H'\right|\left[e^{(-j\gamma' z)} - R_b e^{(-j\gamma'(2L_z - z))}\right]G(f) \qquad (7)\\ E' &= E_0 10^{-S_{fE}/20},\ \ H = H_0 10^{-S_{fH}/20}, \end{aligned}$$

and taking into account only the intrinsic Q, one can write:

$$\begin{aligned} &G(f) = (1 - R_f R_b e^{(-j\gamma' 2L_z)})^{-1},\ \gamma' = \gamma A(Q),\\ &Z' = Z\,A(Q),\ \ A(Q) = 1 + \xi(Q) - j\xi(Q),\\ &\xi(Q) = \sqrt{1 - \left(4\pi/\ln(1 - 2\pi/Q)\right)^2}, \qquad (8)\\ &Q_{(E,H)} = 2\pi \cdot 10^{(S_{f(E,H)} + S_{b(E,H)})/20}. \end{aligned}$$

where $S_{f(E,H)}$ and $S_{b(E,H)}$ are the shielding effectiveness of the front and back walls for electric and magnetic components, respectively. Note that index *i* numbering the compartments is not written in (6) – (8).

In the first order of perturbation approach, solutions obtained in zero order based on equations (6) – (8) for the reverberation component in each compartment *i* are considered as the fields exciting the neighboring compartments by penetration of EM fields through the walls. Components E_{1i} and H_{1i} of the reverberation waves that propagate to the partitions between compartments are considered as exciding wave. For calculation of fields excited by the penetration of energy through the partitions between compartments, EM field amplitudes E_{1i}, H_{1i} (and corresponding parameters of internal walls) are substituted in formulas (6) – (8) instead of E_0 and H_0. Note, that the consideration of the reverberation components is performed for each of three directions (*Ox, Oy, Oz*) independently from each other in the framework of the developed model.

The calculation in the second order is performed as follows. The components of reverberation waves propagating in the directions of the internal walls E_{2i} and H_{2i} calculated in the first order are considered as the fields, which additionally (to the incident wave) excites the neighboring compartments due to the penetration of radiation through internal walls in the corresponding direction. Correction obtained in the second order is added to the values of the field strengths calculated in the previous order. At the next step, the total fields $E_{1i} + E_{3i}$ and $H_{1i} + H_{3i}$, where E_{3i}, H_{3i} are solutions obtained at the second order, are considered as exciting fields instead of E_{1i}, H_{1i}, etc.

The worst case generalization of the obtained solution is performed by the technique proposed in [17]: the resonance frequencies of compartment are calculated taking into account the value of Q, and the amplitude of reverberation component is defined for this frequencies. Segments of straight lines connect the obtained points of AFC to prevent the underestimation of the field amplitude. Accounting for the LOS fields is performed by the same approach as in [17], and the amplitude of the field incident on aperture in internal wall is the sum of the LOS component and the reverberation component in the compartment, which is considered as exciting one. Let us consider an example given in Fig. 2.

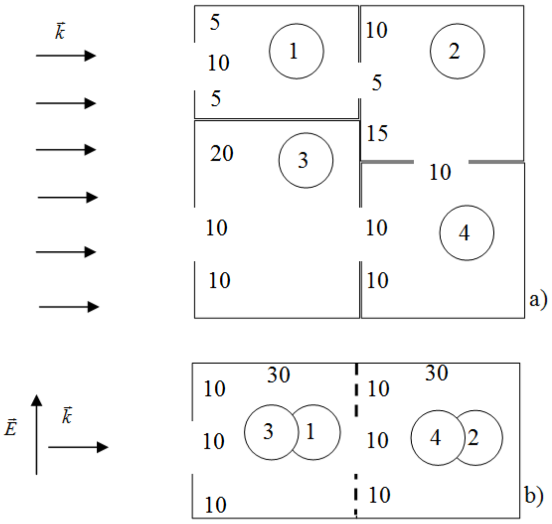

Fig. 2. Example of coupled compartments that could be considered as a scaled model: a) top view, b) side view. Dimensions are given in cm, numbers of the compartments are depicted in circles. The walls are made of aluminum. The thickness of external walls is 0.5 mm and of internal walls is 1 mm. The amplitude of the incident electric field is 1 V/m.

In the framework of approach based on perturbation theory, AFC of the worst case model of field strength in the coupled compartments is obtained for the example presented in Fig. 2. Firstly, the reverberation components corresponding to TE(1,0) mode is obtained in compartments with numbers 1 and 3, which are excited by the plane wave incident to the front side. Then, the waves propagating in direction of compartments 2 and 4 penetrates though the internal walls: from compartment 1 to compartment 2 through combined wall consisting of the two regions in form of solid metal and rectangular aperture of dimension 5×10 cm; from compartment 3 to compartment 2 through the solid metal region and to compartment 4 through the aperture of dimension 10×10 cm and two solid metal regions. At the following step, the reverberation waves excited in compartments 2 and 4 and propagating towards to walls between compartments, penetrates through the corresponding regions of the walls. The correction, which is the result of this step, is added to the strengths values obtained at the first step. The result of calculation is presented in Figs. 3 – 6.

As it seen in Figs. 3 and 5, the comparison with results of FDTD calculation shows that the second order of perturbation theory provides the sufficient value of the field strength for the worst case model formulation in considered case.

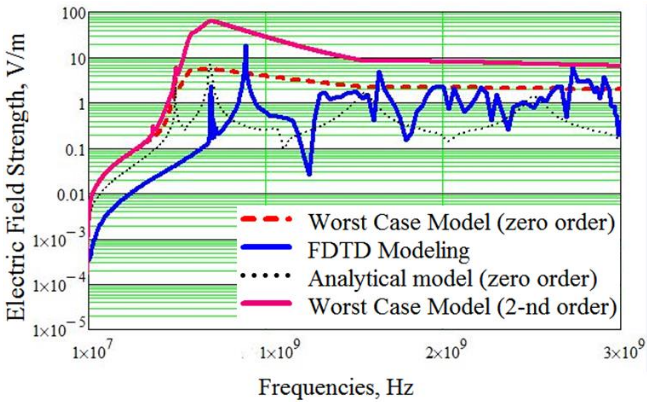

Fig. 3. AFC of the electric field strength in the geometrical center of the first compartment

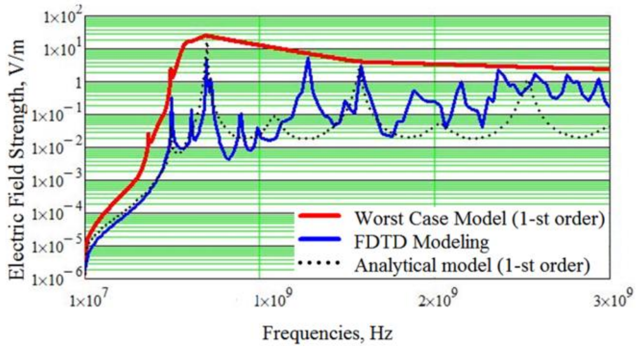

Fig. 4. AFC of the electric field strength in the geometrical center of the second compartment (ref Fig. 2)

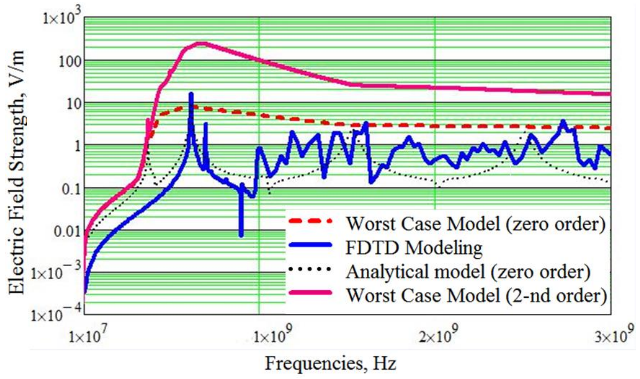

Fig. 5. AFC of the electric field strength in the geometrical center of the third compartment (ref Fig. 2)

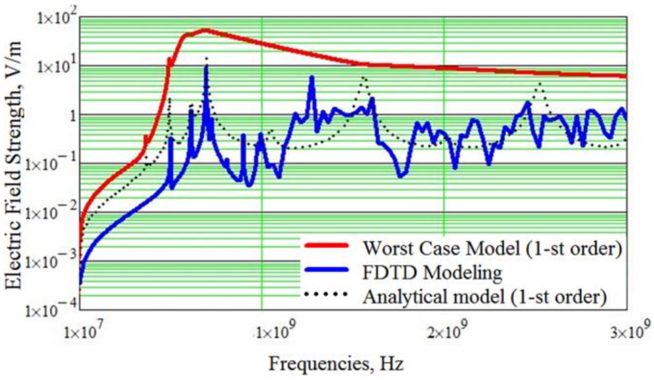

Fig. 6. AFC of the electric field strength in the geometrical center of the fourth compartment (ref Fig. 2)

The following conclusions can be made from the comparison of the solutions obtained in the framework of the developed model and results of numerical simulation performed by FDTD method.

1) The worst case model based on the perturbation theory provides the adequate results in description of the field strength inside the compartments already in the second order for the given case.

2) The presence of the aperture in the wall between the compartments of numbers 2 and 4 does not influence to the field of the resonance mode TE(1,0) distribution when the propagation of waves is realized in the perpendicular direction to the normal to aperture that confirms the assumption made above in Section III.

3) The approach based on the perturbation theory is useful for analysis of the systems consisting of relatively small number of compartments and when the shielding effectiveness of the internal walls is quite significant.

IV. TECHNIQUE OF COUPLED COMPARTMENTS' ANALYSIS BASED ON MULTILAYER STRUCTURE CONSIDERATION

The technique of the calculation of the shielding effectiveness of multilayer structure is presented in [21]. Let us consider the multilayer structure (see Fig. 7).

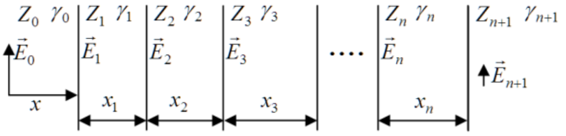

Fig. 7. Parameters of the multilayer structure: Z_i is the characteristic impedance; γ_i is the propagation constant; x_i is the thickness of i-th layer along the direction of wave propagation; E_i is the absolute value of the electric field vector in i-th layer

$R_{(i,i+1)}$ is reflection coefficient for boundary between i-th and $(i+1)$-th layers and is calculated by (5) when the layer is an uniform structure (for example, the solid metal wall, aperture, mesh, or compartment) or by (4) and (5) in case when the layer is an combined wall. The recurrent algorithm is:

1) The reflection coefficient R_{i-1} accounting reflections for boundaries of all layers between free space and $(i-1)$-th layer is given (it is equal to $R_{(0,1)}$ when $i=0$ or calculated by (11) for previous layers);

2) Define the transfer coefficient T_{i-1} by formula

$$T_{i-1} = \sqrt{1 - \left|R_{i-1}\right|^2}. \tag{9}$$

3) Calculate $R_{(i,i+1)}$, $T_{(i,i+1)} = \sqrt{1 - R_{(i,i+1)}{}^2}$ for the boundary between i-th and $(i+1)$-th layers.

4) Calculate the field strength of the wave incident to the boundary $(i, i+1)$ (the field strength transferring the boundary $(i-1, i)$ is equal to $E_0|T_{i-1}|$) by formula (7) in which the term $R_b \exp(-j\gamma'(2L_z - z))$ is removed, and $z = x_i$, $R_f = R_{i-1}$, $R_b = R_{(i,i+1)}$, $\gamma' = \gamma_i$.

5) Obtain the transfer function accounting of all boundaries between free space and $(i+1)$-th layer i-th layer:

$$\begin{aligned} T_{i+1E} &= T_{i-1} \cdot E_i(S_E,\, R_{i-1},\, R_{(i,i+1)},\, \gamma_i, x_i) \cdot T_{(i,i+1)}, \\ T_{i+1H} &= T_{i-1} \cdot H_i(S_H,\, R_{i-1},\, R_{(i,i+1)},\, \gamma_i, x_i).T_{(i,i+1)} \end{aligned} \tag{10}$$

By repeating the steps described above iteratively, one can obtain the reflection and transition coefficients of the multilayer structure consisting of n layers

$$\begin{aligned} &E_{n+1} = E_0 T_n,\ T_1 = \frac{\exp(-i\gamma_1 x_1) T_{01} T_{12}}{1 - R_{01} R_{12} \exp(-2i\gamma_1 x_1)}, \\ &T_i = \frac{T_{i-1} \exp(-i\gamma_i x_i) T_{i,i+1}}{1 - R_{i-1} R_{i,i+1} \exp(-2i\gamma_i x_i))}, R_{i-1} = \sqrt{1 - T_{i-1}{}^2}. \end{aligned} \tag{11}$$

Obtained solution for the multilayer structure (11) automatically takes into account all of the waves reflected from all of boundaries presented in the multilayer structure.

Let us apply the proposed approach to the analysis of the example shown in Fig. 2. The field in each compartment can be calculated when its walls are considered as a multilayer structures. For compartment of number 1, the front wall is the combined wall consisting of the aperture and one region of the type "solid metal wall" and the back wall is the multilayer structure consisting of the set of objects. They are as follows: a) combined wall between compartments 1 and 2; b) the volume of 2-nd compartment; c) back wall of compartment 2; d) the wall of dimension 15×30 cm between compartments 2 and 3; e) the volume of 3-th compartment and front wall of compartment 3; f) walls and volume of compartment 4. Items d)-f) are accounted for taking into account their area according to the model of combined wall. Compartment 2 has the front wall in the form of multilayer structure: front wall of compartment 1, the volume of compartment 1, the back wall of compartment 1 (wall between compartments 1 and 2); front wall of compartment 3; volume of compartment 3 and wall between compartments 2 and 3. The back wall of compartment 2 is simple solid metal wall. Compartment 3 has combined front wall and multilayer structure as a back wall. This structure consist of the following layers: the combined wall between compartments 3 and 4; the volume of compartment 4; back wall of compartment 4, the wall between compartments 3 and 2, volume of compartment 2; its back wall; wall between compartments 2 and 1, volume of compartment 1 and its front wall. And a similar consideration can be performed for compartment 4.

From the analysis of the structure under consideration given above, the following conclusions can be made:

1) When the plane wave illuminates the front walls of compartments 1 and 3, these compartments are coupled by the energy penetration though compartment 2 and both of considered compartments.

2) Compartment 1 does not have common walls with the compartment 4. As for compartment 2, its coupling with compartment 4 is not realized by the penetration of energy through common wall as result of the difference between the direction of the propagation of waves of TE(1.0) mode and normal of common wall in this example. Compartments 1 and 2 are coupled with the compartment 4 through the field in volume of compartment 3. The field distribution in compartment 3 is the function $E_3(S_{E3f}, S_{E34b}, S_{E32b}\, R_{03},\, R_{32},\, R_{34}\, \gamma_3, L_3)$ of the shielding effectiveness and reflecting coefficient of the wall between compartments 3 and 4. So, the proposed approach based on the multilayer structure takes into account the dependence of field distribution in compartments 1 and 2 on properties of compartment 4 (that corresponds to the third order of perturbation theory).

A worst case model is implemented by connecting values at resonance frequencies. When calculation is performed at frequencies below first resonance, calculation according to (11) is performed.

The comparison of results obtained by both approaches applied to the example in Fig. 2 shows that the difference between worst case AFCs is negligible small in low frequency range (below the cut-of frequency of waveguide associated with compartment 1). For the high frequency range difference of solutions does not overcome 2 dB for electric field and 3 dB for the magnetic field.

The proposed approach can be used for the calculation of fields distribution in the compartments of complex systems, because it do not require definition the field values in the intermediate compartments, which are considered as layers of the multilayer structure describing any wall of compartment under consideration. The technique is valid when the walls between compartments have a low shielding effectiveness.

V. VALIDATION OF DEVELOPED MODELS

The developed models are validated by comparison of results obtained by the use of the models with the results of experiment presented in [15]. A rectangular metallic double enclosure has the dimensions 80×30×20 cm and consists of two 40-cm-long compartments located one after another on the axis of radiation. There is a slot of dimensions 2×8 cm in the front wall of the outer compartment, and there is another slot (at the same position and of the same dimensions) in the wall between the compartments. The outer compartment is excited immediately by the plane wave radiated by an antenna mounted at the distance of 6 m (in the far field zone). The EM field in the inner compartment is excited by the penetration of the radiation through the aperture in the partition between the compartments. The comparison shows good agreement between the simulated and measured results for both worst case models (Fig. 8).

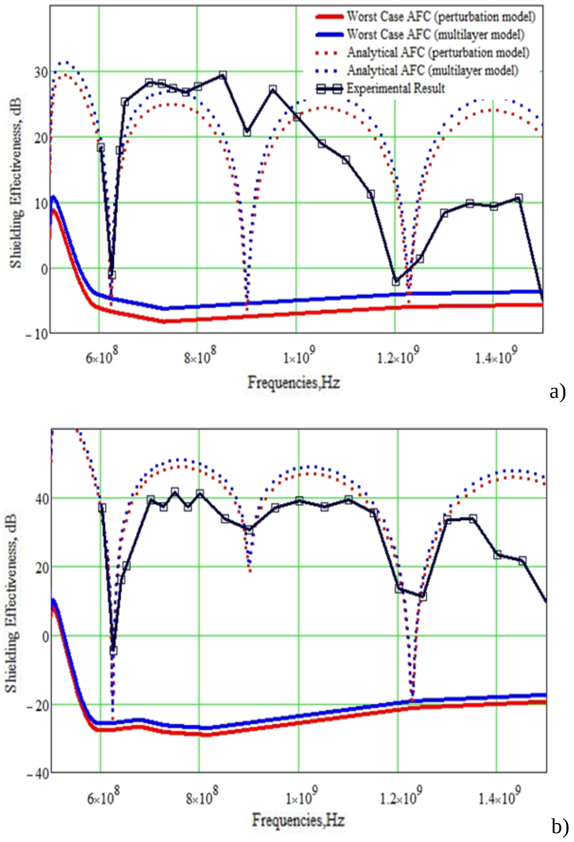

Fig. 8. AFC of the shielding effectiveness for electric field in the center of the outer compartment (a) and of the inner compartment (b)

VI. CONCLUSION

The developed models can be used for analysis of shielding effectiveness of the enclosures divided by internal partitions and estimation of the EM field distribution within coupled compartments. Examples of such systems may be compartments of a ship, aircraft cabin, rooms of a building etc.

The possible future development of the models is connected with more accurate analysis of LOS fields and consideration of compartments with low Q-factor. Proposed calculation technique will be implemented in EMC-Analyzer software [6].

REFERENCES

[1] Paul C. R. Introduction to Electromagnetic Compatibility, 2nd ed., Wiley, Hoboken, NJ, 2006, 983 p.

[2] Violette J.L.N., White D.R.J., Violette M.F.A., Electromagnetic Compatibility Handbook, Springer Sc+Busines Media, NY, 1987 .

[3] MIL-STD-464C. Electromagnetic Environmental Effects Requirements for Systems. U.S. Government Printing, Washington, 2010.

[4] IEC 61000-4-21 International Standard. Electromagnetic Compability (EMC) – Part 4-12. Testing and measurement techniques – Reverberation chamber test methods. Edition 2.0, 2011-01,

[5] Marvin A.C., at al. “A Proposed New Definition and Measurement of the Shielding Effect of Equipment Enclosures,” IEEE Trans. on EMC Vol. 47, No. 3, 2005, pp. 589-601.

[6] EMC-Analyzer. Mathematical models and algorithms of electromagnetic compatibility analysis and prediction software complex. Minsk, 2020.

[7] Andersen J.B., et al. “Reverberation and Absorption in an Aircraft Cabin with the impact of Passengers.” IEEE Trans. of antennas and propagation, Vol. 60, No 5, Oct. 2016, pp. 1456 – 1464.

[8] Goergakopoulos S.V., Bricher C.R., Balanis C.A “HIRF Penetration Through Apertures: FDTD Versus Measuremants,” IEEE Trans. on EMC, Vol 43, No. 3, 2001, pp. 282-294

[9] Davidson D.B., Computational electromagnetics for RF and microwave engineering,” 2-nd ed., Cambridge University Press, 2011.

[10] Chen Ke, at al. “An Impruved MOM Approach to Determine the Shielding Properties of a Rectangular Enclosure With a Double Periodic Array of Apertures” IEEE Trans. on EMC Vol. 58 No. 5, 2011, pp. 589-601.

[11] Robinson M.P., et al. “Analytical Formulation for the Shielding Effectiveness of Enclosures with Apertures” IEEE Trans. on EMC, Vol. 40, No. 3, 1998, pp. 240-248.

[12] Konefal T., Dawson J. F., Marvin A. C., Robinson M. P. et al. “A Fast Multiple Mode Intermediate Level Circuit Model for the Prediction of Shielding Effectiveness of a Rectangular Box Containing a Rectangular Aperture,” IEEE Trans. on EMC, vol. 47, No. 4, 2005, pp. 678–691.

[13] Jenu M. Z. M., Po’ad F. A., “Electric and Magentic Shielding Effectiveness of Metallic Enclosures with Apertures,” in Proc. Asia-Pacific Microwave Conference (APMC), Dec. 2006, pp. 536-539.

[14] Po’ad F.A., “Analytical and Experimantal Study of the Shielding Effictiveness of a Metall Enclosure with Off-Centered Appertures,” 17th Int. Symp. on EMC, 2006, pp. 618-621.

[15] Liping Yan at al., “A Fast Prediction for Shielding Effectiveness of Double Enclosures,” 2015 Int. Symp. on EMC – EMC EUROPE, Dresden, Germany, 2015, pp. 959-962.

[16] Klinkenbusch L. “On the Shielding Effectiveness of Enclosures,” IEEE Trans. on EMC, Vol. 47, No. 3, 2005, pp. 589-601.

[17] Tsyanenka D., Sinkevich E.; Arlou Y., “Wideband Worst-Case Model of Electromagnetic Field Shielding by Metallic Enclosure with Apertures,” 2017 Int. Symp. on EMC – EMC EUROPE, Angers, France, 2017, pp. 371-377.

[18] Tsionenko D., et al. “Computationally-Effective Ultra-Wideband Worst-Case Model of Electromagnetic Wave Diffraction by Aperture in Conducting Screen,” 2014 Int. Symp. on EMC – EMC EUROPE, Gothenburg, Sweden, 2014, pp.1287-1292.

[19] Cowdell R.B. “Simplified shielding,” IEEE Int. Symp. on EMC, 1967, pp. 399-412.

[20] Jarva W. “Shielding efficiency calculation methods for screening, waveguide ventilation panels, and other perforated electromagnetic shields,” Proc 7-th Conf. on RIR and EMC, 1961, pp. 478-498.

[21] Tsyanenka D., Arlou Y., Sinkevich E., “Worst-Case Model for Considering Gaskets in Calculation of Shielding Effectiveness of Metallic Enclosures,” 2018 Int. Symp. on EMC– EMC EUROPE", Amsterdam, The Netherlands, 2018, p.178-183.