Computationally-Effective Worst-Case Model of Coupling between On-Board Antennas That Takes into Account Diffraction by Conducting Hull

Tsyanenka D.A., Sinkevich E.V., Matsveyeu A.A.
EMC R&D Laboratory Belarusian State University of Informatics and Radioelectronics, Minsk, Belarus emc@bsuir.by

Abstract—**A worst-case computationally-effective model for analysis of coupling between on-board antennas mounted on the conducting hull of a system (aircraft, ship, car, etc.) is proposed. Consideration of electromagnetic wave diffraction by the arbitrary-shaped hull is based on combining of the model for calculation of shading by convex surfaces of rotation bodies (cylinder, cone) and the wedge diffraction model obtained in the framework of the Uniform Theory of Diffraction (UTD). The proposed model of antenna coupling is validated by comparison with results of experiments and numerical simulation (by FDTD and GTD-PO methods) in a wide range of parameter values: cases of monopole and dipole antenna mounting in various points of the aircraft hull with several mutual orientations are considered, the frequency is varied from 50 MHz to 7 GHz, the ratio of wavelength to diffraction-path length is varied from 0.001 to 1.**

Keywords—electromagnetic compatibility, mutual coupling, wave diffraction, physical theory of diffraction

I. INTRODUCTION

For analysis of coupling between on-board antennas, it is necessary to take into account the electromagnetic wave interference and diffraction by hull of the system (aircraft, ship car, etc.). Antenna coupling model intended for express-analysis and diagnostics of EMC at the level of complex systems [1], [2] must satisfy the following requirements: physical adequacy, wide range of parameters' variation, worst-case behavior, stability of calculation results against errors in initial data, and high computational efficiency.

Diffraction models [1], [3] which are traditionally used for express-analysis of EMC provide sufficient accuracy only if the hull can be represented as a set of simple geometrical shapes (cylinder, cone, plain tetragons, etc.). However, hulls of modern cars, ships, and aircrafts can not be approximated by the set of these primitives [4].

Up-to-date design tools represent the hull surface of arbitrary shape by a set of triangles (facets) or polygons. Calculation of diffraction by such surfaces is considered in many papers ([5], [6], and others). However, the proposed diffraction models do not satisfy the requirements given above: high-frequency solutions are jagged by the interference and unstable against the changes in parameters (e.g., solutions are changed considerably if the direction of wave propagation is changed to the opposite), and computational burden is high. Therefore, known calculation methods, such as FEM, FDTD, MOM, GO, UTD, PO [7] – [11], as well as hybrid methods [12], [13], can not be directly applied for calculation of antenna coupling in process of EMC diagnostics.

The objective of this work is to develop a computationally-effective worst-case model of electromagnetic wave diffraction by the conducting hull surface defined by a set of facets and (or) polygons for estimation of antenna coupling.

The paper is organized as follows. In Sections II and III, parameters of the problem are defined, approximations and simplifications are introduced. Section IV presents a technique for fast search of diffraction paths. The criteria for selection of calculation method for each part of the diffraction path are introduced in Section V. Combined worst-case model used for calculation of the antenna coupling coefficient is developed in Section VI, and results of the model validation are presented in Section VII. In Conclusion, we discuss the range of the model applicability, its advantages and drawbacks, as well as possible directions of its further development.

II. PHYSICAL MODEL

Antenna coupling coefficient is defined as the relation of power at receiver antenna output P_R to power at transmitter antenna input P_T:

$$X_A = 10\lg(P_R / P_T). \qquad (1)$$

The value of X_A depends on antennas parameters (directivity characteristics, frequency and polarization properties), and on condition of electromagnetic waves propagation from the transmitter to the receiver [1] – [3]. Attenuation of electromagnetic wave intensity provides by propagation in free space and by shading (diffraction) by hull. To develop of antenna coupling worst-case model, it is necessary to take into account the interference for two coherent beams: direct beam propagating from transmitter to receiver and reflected from hull surface beam.

For express analysis of antenna coupling, the diffraction path which has a minimal length (i.e., the shortest path) is selected. The path is defined on the hull surface represented by a set of facets or polygons. The path consists of sections. Here and bellow the sections are the segments connecting of

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transmitter, diffraction points, and receiver. Two sections located in consecutive order are called the part of path.

The computation of X_A coefficient is carried out by various methods for near-field, intermediate, and far-field zones in dependence of the diffraction path length D between antennas. The boundary of near-field zone is equal to the maximal size for two (transmitter and receiver) antennas D_A. In near-field zone coefficient X_A is supposed to be equal of 1. The boundary of far-field zone is defined by formula:

$$D_F = \max[3\lambda,\ 2D_A^2/\lambda], \quad (2)$$

where λ is the wavelength: $\lambda = c/f$, $c = 3\cdot 10^8$ m/s, f is the frequency.

If the receiver is located in far-field zone, the basic losses due to propagation in free space are calculated by formula $T_{FS} = (\lambda/4\pi D)^2$ and for description of intensity change by interference and diffraction, the coefficient S_f is introduced.

For antenna coupling description in intermediate zone $D\in(D_A, D_F)$ the function $X_A = (D/D_A)^{\frac{X_A(D_F)}{10\lg[(D_F/D_A)]}}$ is introduced, that takes the value of 1 and $X_A(D_F)$ at the ends of interval.

The diffraction path contains more than one section when antennas are not in line of sight. In this case, the path is divided to parts and the method of calculation the shading coefficient $S_{S\,i}$ is associated to each part of path in accordance with criteria defined in Section IV (i is the number of part of path coinciding with the number of diffraction point). Two types of diffraction are considered: diffraction by wedge and diffraction associated with creeping wave propagation on convex surfaces of rotation bodies.

Figure 1 presents the geometry corresponding to physical model of high-frequency diffraction by edge of wedge.

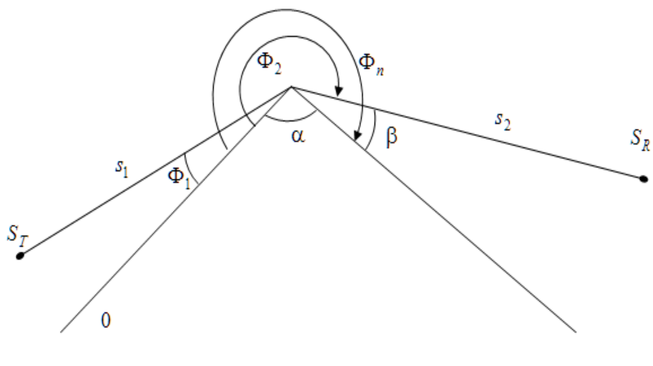

Figure 1. Geometry that corresponds to the diffraction by wedge. Notations: Φ_1 is the incidence angle relative to illuminated side "0" of the wedge, α is the angle between wedge sides in the plane of incidence, Φ_n=2π – α, β is the diffraction angle, Φ_2 is the subsidiary diffraction angle (measured from the illuminated side $\Phi_2 = \Phi_n - \beta$), s_1 is the distance from wave source to the edge, s_2 is the distance from the edge to observation point

Calculation of diffraction by wedge is carried out in UTD approximation according to technique proposed in [10]. Calculation of diffraction by convex surface of cylinder is carried out in accordance to technique developed in [1], [3].

III. Approximations and Simplifications

The following simplifications and approximations are made for development of antenna coupling model.

1. For each element of hull surface (polygon or facet), the parameter of radio-transparency is defined. Consideration of material properties in framework of UTD method is based on definition of complex permittivity. For metallic surfaces with a great value of conductivity, the model of Perfect Electric Conductor (PEC) is used. Environment of system is vacuum (or air). Dielectrics considering in framework of model are homogeneous and isotropic. Permittivity does not depend on frequency and amplitude of electromagnetic wave. Magnetic materials are not considered ($\mu = 1$).

2. Antenna patterns are defined for free space (monopoles are considered with regard to mounting on infinite conducting plane). Correction of antenna patterns as a result of surface curvature is not introduced, and influence of objects located near to antennas is not taken into account. Antennas placed in far field zone are considered as points. Antenna phase centers play the role of their coordinates.

3. The reason for application of UTD and creeping wave methods is the fulfillment of condition [9] – [11]:

$$k\rho >> 1, \text{ or } \rho/\lambda >> 1, \quad (3)$$

where $k = 2\pi/\lambda$ is wave number and ρ is surface curvature radius or characteristic dimension of obstacle (for calculation of diffraction by wedge). For development of model, the condition (3) is replaced by the following condition: the distance from transmitter to diffraction point (s_1) and from diffraction point to receiver (s_2) (see Figure 1) must be greater than wavelength λ.

4. Calculation of coefficient (1) is carried out along the shortest path. Sections of shortest path belong to the one plane. Starting point and final point of shortest path coincides with phase centers of transmitter and receiver. Value of antenna coupling coefficient X_A depends on diffraction path characteristics and antennas characteristics therefore it should not change by permutation of transmitter and receiver.

In the limit when the diffraction path tends to smooth curve, the AFC of antenna coupling coefficient obtained in framework of model must tend to envelope of AFC calculated by accurate methods.

5. Two possible polarization states are considered: electric field vector belong to plane of incidence (parallel polarization) and electric vector is perpendicular to plane of incidence (perpendicular polarization). The maximal value of coefficient S_f obtained for both polarization states is the result that provides the worst-case behavior of model.

IV. SEARCH OF SHORTEST PATH BETWEEN ANTENNAS

For hull represented as a set of facets or polygons, the discretization of geometrical model (mesh generation on hull surface) is carried out for the definition of diffraction path with the minimal length [14]. The number of points under consideration increases sufficiently by discretization and that leads to increasing of computation time.

Simplification of the task of shortest path definition may be associated with consideration of hull cross-sections by set of planes. Secant planes pass through the line connecting of antenna phase centers. Intersection points of secant plane with facet or polygon edges are obtained.

Obtained intersection points uniquely determine the shortest path in the plane by using Dijksra's algorithm [14]. Transition to a new secant plane rotated relative to the initial plane at angle $\Delta\varphi$ around the straight line passing through the antenna phase centers is carried out. The shortest path in the plane is determined for new cross-section. The result is a set of shortest paths in each cross-section. The path with a minimum length from resulting set of the shortest paths in the planes is selected to solve the problem of definition the shortest path in space with certain accuracy. The described method reduces the number of points in the implementation of Dijkstra's algorithm because it is realized only in the secant plane, but not in the three-dimensional space, that eliminates the necessity of model discretization. However, the accuracy of proposed method is lower than in known approaches (e.g. tree-dimensional algorithms and multipath propagation technique). For improvement of the shortest path definition, described above operations are carried out for angles range $[\varphi_m - \Delta\varphi, \varphi_m + \Delta\varphi]$ near to plane containing the shortest path (characterized by angle φ_m and obtained by rotation step $\Delta\varphi$) with decreased step $\Delta\varphi_n = 0.1\Delta\varphi$.

The following characteristics are defined for shortest path: number of diffractions points in path N, coordinates of diffraction points (x_i, y_i, z_i), $i = 1 \ldots N$, set of angles corresponding to diffraction points $(\alpha_i, \Phi_{1\,i}, \beta_i)$. Where (see Figure 1) α_i is the angle between wedge sides for diffraction point with number i ; Φ_{1i} is the incident angle of beam relative to illuminated side of dihedral angle; β_i is the diffraction angle.

V. CALCULATION OF ATTENUATION BY DIFFRACTION

Two types of diffraction are associated to parts of diffraction path: diffraction by wedge and propagation of creeping waves on hull surface. Empirically established criteria define the choice of calculation method for diffraction based on the following algorithm.

1. Carry out the following verification for every diffraction point of the shortest path:

1.1) if the angle between sides of wedge $\alpha_i = 180$ deg in given point, diffraction is not considered ($S_{Si} = 1$);

1.2) if $\alpha_i \le 120$ deg, then go to position 2) of present algorithm;

1.3) if $120 < \alpha_i < 180$ deg, then analyze the incident angle Φ_{1i} and diffraction angle β_i;

1.3.1) if $\Phi_{1i} > 0.2$ deg and $\beta_i > 0.2$ deg, then go to position 2) of present algorithm;

1.3.2) else go to position 3) of present algorithm.

2) Calculate the coefficient by shading S_{Si} by using UTD method for diffraction by wedge [10]. The initial point of part is considered as the source of spherical wave, the diffraction point is associated to infinitely long edge of wedge, the final point of part is considered as observation point.

3) Calculate the coefficient by shading S_{Si} in framework of empirical approach proposed in [3] describing of creeping wave propagation on hull surface. The part of path is associated to circular arc. For developed model, the diffraction path is defined in the plane only; therefore, criteria for consideration of diffraction path parts located in consecutive order as elements of cylindrical or conical spiral are not defined.

4) Repeat position 1), 2), 3) for all diffraction points of shortest path. Calculate the full coefficient of shading by formula

$$S_S = \prod_{i=1}^{N} S_{S\,i}, \tag{4}$$

where N is number of diffraction points in shortest path.

VI. WORST-CASE MODEL OF ANTENNA COUPLING

A. *Account for Wave Interference of Line-Of-Sight Antennas*

Electromagnetic oscillation energy increases in point of interference maxima as result of direct ray and reflected ray interference. Therefore, in order to take into account the case of the line of sight between transmitter and receiver, expression for coefficient S_f takes the form:

$$S_f = \begin{cases} 4 & N = 0; \\ S_S & N > 0, \end{cases} \tag{5}$$

where for coefficient of shading S_S formula (4) is used.

B. *Calculation of Shading Coefficient Based on UTD*

The following formula is used for coefficient $S_{S\,i}$, when the part of path is associated with diffraction by wedge (in accordance to criteria defined in Section IV) and calculation based on UTD:

$$S_{Si} = S_{Wi} = \min\left(1, \left|\frac{s_0}{s_{1i}} \max\left(\left|D_i^{||}\right|, \left|D_i^{\perp}\right|\right) \sqrt{\frac{s_{1i}}{s_{2i}(s_{1i} + s_{2i})}}\right|^2\right), \quad (6)$$

where s_0 is the distance between transmitter and receiver calculated along the line connected of antennas phase centers, s_{1i} and s_{2i} are distances defined in Figure 1 for *i*-th diffraction point.

The choice of distance s_0 for normalization of coefficient by shading (6) provides a worst-case behavior of model and correctness of calculation result for S_{Wi} in cases when $s_{1i} \le \lambda$ and (or) $s_{2i} \le \lambda$ ($S_{Wi} = 1$ for this case) and the coincidence of results obtained in framework of model with well-known result [10], [11] for diffraction paths presented by one part. Factors $D_i^{||}$, $D_i^{\perp}$ are the diffraction coefficients in UTD depending on polarization of incident wave [10].

To provide a high computational efficiency of model, Fresnel integral determining of diffraction coefficients $D_i^{||}$, $D_i^{\perp}$ is supposed to be equal to 1 in deep shadow region.

To provide a worst-case behavior of model, the angle between incident ray and edge of wedge is chosen equal to $\pi/2$. In the case of metallic hull, (conductivity of material is infinity) coefficient of reflection $R^{\perp} = -1$ and $R^{||} = 1$ for waves of parallel and perpendicular polarization correspondently. Values of electric field amplitude calculated in observation point for wedge with infinitely long edge in framework of UTD are large than practical values. In case of diffraction by an infinitely long wedge, the diffracted wave is a cylindrical wave, therefore its attenuation by free-space propagation is less than attenuation of the wave scattered by a finite-length edge.

C. *Calculation of Shading Coefficient in Case of Wave Creeping along Hull Surface*

When the part of path is associated with creeping waves propagation, the following formula for S_{Si} is used [1], [3] for calculation of coefficient by shading:

$$S_{Si} = S_{Ci} = 10^{-A_i/(\eta_i A_i + \xi_i)}, \quad (7)$$

where S_{Ci} corresponds to shading by cylinder surface and parameters η_i and ξ_i are defined in [1], and for A_i ones can write:

$$A_i = \theta_{Ci}\sqrt{k(s_{1i} + s_{2i})}, \quad (8)$$

where θ_{Ci} is the angle corresponding to circular arc, which is associated to the part of shortest path with number i. This angle is equal $\theta_{Ci} = \pi - \alpha_i$ in framework of model.

Calculation based on formula (7) provides a worst-case estimation of shading coefficient (4) by two reasons. Firstly, cylindrical (or conical) spiral is replaced by circular arc that leads to increasing of coefficient by shading (4) and coefficient of antenna coupling (1). This overestimation is sufficient for antennas displaced along cylinder axis relative to each other. Secondly, in case of several parts located in consecutive order, the use of formula (7) for each part and multiplication of results in accordance with (4) leads to larger values of the shading coefficient (4) than the result of calculation by (7) for the path obtained by joining of these parts.

D. *Correction for Taking intoAaccount the Polarization Properties of Dipole Antennas*

The correction factor M taking into account the mismatch of working polarization for emitter antenna and receptor antenna is introduced in [15] by generalization of experimental data ($M = -16$ dB for linearly polarized antennas). As it is shown by practice (see Section VII), it is useful to improve the estimation of antenna decoupling due to polarization mismatch by accounting for dependence of factor M on the angle γ between directions of emitter-antenna and receptor-antenna polarization. The dependence of M on distance between the antennas is also introduced (since the polarization is not determined in the near-field zone $s_0 \le \lambda/2\pi$ of antenna radiation), and the depolarization due to wave diffraction by the hull is taken into account. Therefore, in this paper, factor M is calculated by the following semi-empirical formula:

$$M = \max\{-16, 10\lg(\cos^2\gamma)\}\frac{2\pi f s_0}{2\pi f s_0 + c}\left(1 - e^{-1/(N+1)}\right), \text{ dB.} \quad (9)$$

The introduction of dependence on the angle γ in (9) is based on polarization loss factor [16]. The second multiplier in (9) takes into account the distance between antennas and tends to zero in the near-field zone. The third multiplier describes the wave depolarization and tends to zero with increasing of the number N of diffraction points which belong to diffraction path. The dependences on distance and number of diffraction points in (9) are selected empirically with accounting for the requirement of the worst-case behavior of the model.

So, the coefficient of antenna coupling takes the form:

$$X_A = 10\ \lg(S_f \cdot G_T(\theta_R, \varphi_R) \cdot G_R(\theta_T, \varphi_T) \cdot T_{FS}) + M, \quad (10)$$

where S_f is calculated by (5), M is computed by (9), $G_T(\theta_R, \varphi_R)$ is the gain of transmitter antenna in direction to receiver antenna, $G_R(\theta_T, \varphi_T)$ is the gain of receiver antenna in direction to transmitter antenna. Direction (observation angles θ_R, φ_R) from transmitter antenna to receiver antenna is calculated for the diffraction path section adjacent to transmitter antenna (angles θ_T, φ_T are computed similarly).

VII. Validation of Developed Model

Validation of model is carried out by comparison of antenna coupling AFC calculation result (10) with result of experiments [17] (Figures 2, 3) and results of numerical simulation performed by FDTD method in frequency range from 50 MHz to 0.6 GHz (Figure 5) and GTD-PO method in frequency range from 50 MHz to 7 GHz (Figure 6) which are considered as etalons.

In order to perform the comparison with experimental results for antennas mounted on side surface of the cylinder, the cylinder is approximated by straight regular prism with 12, 24, and 48 flat sides. Comparison results (Figures 2 and 3) show that the worst-case model overestimate of antenna coupling coefficient by 10-15 dB. Cases of underestimation of antenna coupling coefficient by the model are not established. The overestimation increases with increasing of the angle θ_C between transmitter and receiver. Reasons of overestimation are considered in subsection VI.C.

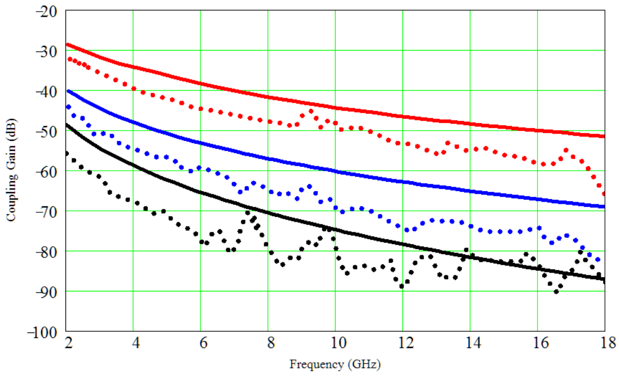

Figure 2. Comparison of antenna coupling coefficients computed by the worst-case model (solid lines) with experimental results (dotted lines). Transmitting and receiving antennas are isotropic; they are mounted in the plane which is perpendicular to the cylinder axis. Parameters of modeling: radius of the cylinder is 1.91 ft, angular coordinate of the transmitting antenna is θ_0 =0 deg, angular coordinates of the receiving antennas are θ_1 =30 deg (red lines), θ_2 =60 deg (blue lines), and θ_3 =90 deg (black lines). The cylinder is approximated by a prism with 24 flat sides

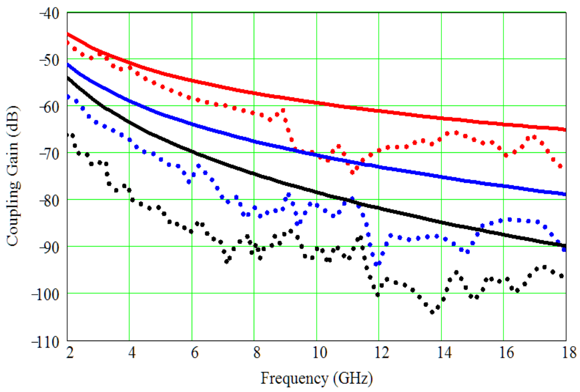

Figure 3. Comparison of antenna coupling coefficients computed by the worst-case model (solid lines) with experimental results (dotted lines). Parameters of modeling: the transmitting antenna is displaced from the receiving antennas to the distance of 8 ft along the cylinder axis, angular coordinates of the receiving antennas are θ_1 =30 deg (red lines), θ_2 =90 deg (blue lines), and θ_3 =120 deg (black lines). All other parameters are the same as for the case presented in Figure 2

For comparison of calculation results by worst-case model with result of numerical simulation, the test CAD-model of F-4 aircraft (Figure 4) is used: in various points of fuselage (the surface is considered as perfectly conducting), monopole- and dipole antennas are mounted. For validation of corrections (9) the orientation of monopoles is varied. Some results of comparison are presented in Figures 5 and 6.

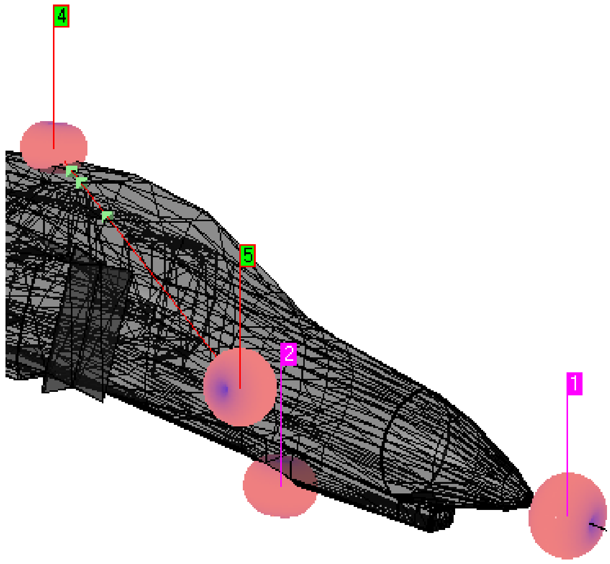

Figure 4. CAD-model of F-4 aircraft fuselage with mounted antennas. The fuselage surface is defined as a set of facets. The antenna patterns are depicted schematically near to the points of antenna mounting. The shortest path between antennas 4 and 5 is shown by red line, and the diffraction points are marked by green color

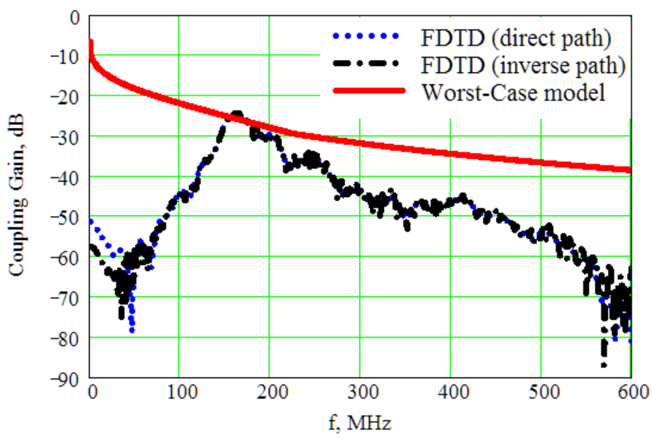

Figure 5. Comparison of antenna coupling coefficients computed by the worst-case model (solid lines) and by FDTD method (dashed and dotted lines). Parameters of modeling: antennas are mounted in points 4 and 5 (see Figure 4), each antenna is a 40-cm-long monopole, the straight-line distance between the antennas is 3.99 m, and the length of the shortest path is 4.02 m

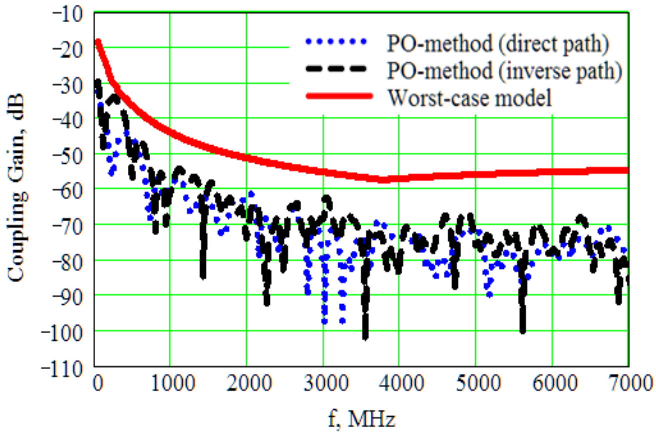

Figure 6. Comparison of antenna coupling coefficients computed by the worst-case model (solid lines) and by GTD-PO method (dashed and dotted lines). Parameters of modeling are the same as in Figure 5

Among of 35 considered cases (which differs by places of antenna mounting on hull, antenna types, dimensions and orientations of antennas), one case of underestimation of the antenna coupling coefficient by the developed model is established (the value of underestimation is of 2.8 dB). The maximal overestimation of the high-frequency etalons (obtained by GTD-PO method) by the worst-case model is of 23 dB; the overestimation is caused by the transition from far-field zone to intermediate zone in accordance to condition (2). The overestimation of the low-frequency etalons obtained by FDTD method is caused by the use the high-frequency methods for calculation of shading coefficients S_{Si} by (6) and (7) (see condition (3)).

VIII. Conclusion

Developed model of antenna coupling may be applied for diagnostics of EMC between the equipment of complex systems. The model is implemented in software "EMC-Analyzer" [2] except for correction (9).

The advantages of the model are worst-case behavior, wide band of considered frequencies, stability against errors in initial data, and high computational efficiency. The last is achieved by consideration of the shortest diffraction path belonging to a certain plane only. In particular, the AFC of coupling coefficient for antennas mounted in points 4 and 5 (ref Figures 4, 5, and 6) is computed by the developed model in 17 seconds, by FDTD – in 1 hour 24 minutes, and by GTD-PO – in 49 minutes.

Possible generalizations and future development of the model are associated with refinement of the conditions of transition from intermediate to far-field zone, improvement of the model at low frequencies, rigorous physical substantiation of correction (9).

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