Computationally Effective Wideband Combined Worst-Case Model of Monopole Antenna Coupling

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***Abstract*—A computationally effective wideband worst-case model of spurious coupling between monopoles placed at line of sight of each other is proposed. The model is constructed by combining analytic solutions of the problem for low-frequency and high-frequency bands by means of weight function determined empirically. The low-frequency solution is used at frequencies below the main resonance frequency of the longer monopole, and it is based on induced emf method. This solution takes into account the mismatch of antennas with a source and a load, and it is validated in three-decade frequency range. The high-frequency solution is based on the equation for free-space transmission of radio waves. The model can be used in the framework of express analysis of EMC to calculate mutual influence of monopoles installed on the fuselage of an aircraft. Validation of the proposed model and determination of its applicability region are performed by comparing results computed by the model with results of numerical modeling by the method of moments (MoM) for the following values of parameters: ratio of the fuselage diameter to the antenna length is varied from 1.75 to 12.5, ratio of a distance between the antennas to the antenna length is varied from 1.00 to 12.5. For additional validation, the comparison of results computed by the proposed model with results of numerical modeling by the finite element method (FEM) for two blade antennas AT-1076 installed at KC-135B airplane is performed.**

Keywords*—*mutual coupling; dipole antennas; electromagnetic interference; analytical models

I. Introduction

Estimation of spurious electromagnetic couplings between on-board antennas is an important problem for electromagnetic compatibility (EMC) analysis [1], [2], [3]. Models intended for express analysis and diagnostics of EMC in complicated systems (e.g., aircraft, ship) [2], [3] must have high computational efficiency and must guarantee a worst-case estimation of antenna coupling in a wide frequency range (at least a decade up and a decade down relative to working frequencies of antennas [4, p.8.2]) both in far- and near-field zones for various matching conditions. Since only the type and in-band far-field characteristics of each antenna are often known in practice of EMC diagnostics, the antenna coupling model must operate even if the detailed data about constructions of antennas are absent.

The worst-case model of antenna coupling developed in the framework of IEMCAP program [2], [5] satisfies the above-mentioned requirements, but at low frequencies (below minimal working frequency of interacting antennas) this model gives in many cases strongly overestimated coefficient of antenna coupling since mismatching of antennas with the source and the load is not taken into account in this model. The model [6], which makes it possible to account for the mismatch, cannot be used at frequencies below 1/5 of the first resonance frequency of the shorter monopole or at distances between monopoles less than wave length [7]. Methods of computational electromagnetics [1], [8] are not fully applicable for express analysis of EMC because they require high computational expenses and exact definition of construction for each antenna.

The objective of this paper is to develop such model of spurious coupling between monopoles that is intended for express analysis of EMC, that satisfies above-mentioned requirements, and that makes it possible to increase the accuracy of antenna coupling estimation at low frequencies (as compared with IEMCAP model) by taking into account the mismatch of the source and load connected to the antennas when the source and load impedances are known.

II. Computation of Coupling Factor between Monopoles by Induced EMF Method

The following assumptions are accepted for calculation: 1) monopoles have a shape of thin cylinders ($r << L$), L is the monopole length, r is the cylinder radius); 2) the line connecting centers of monopoles is perpendicular to the antenna axes (this corresponds to the most of practical cases); 3) in order to provide the worst-case behavior of the model, it is supposed that monopoles have the same length equal to the length of the longer monopole; 4) monopoles are mounted on flat, infinitely large and perfectly conducting metallic surface (the surface dimensions satisfying this assumption are defined in Section VI)); 5) it is supposed that antennas are in line of sight to each other; 6) objects located near to antennas (for example, wings and fin of aircraft) are not taken into account. The following examples show the applicability of assumption 6: a) [9, Fig. 7]; b) measurement results of antenna coupling for antennas AT-1076 mounted on aircraft KC-135 presented in [10] coincide with results of calculation by the finite element method (FEM) when the hull is replaced by a cylinder only (Figure 3).

Formulas for mutual resistance and reactance of two dipoles with parallel axes can be obtained by the inducted EMF method [11]:

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$$R_{12d} = (4\Lambda)[\{2\,\mathrm{Ci}(kL\eta) - \mathrm{Ci}(\xi_+) - \mathrm{Ci}(\xi_-)\} +$$
$$+ 2\sin(2kL)\{\mathrm{Si}(2\xi_{0.5+}) - \mathrm{Si}(2\xi_{0.5-}) - 2\,\mathrm{Si}(\xi_+) +$$
$$+ 2\,\mathrm{Si}(\xi_-)\} + 2\cos(2kL)\{\mathrm{Ci}(2\xi_{0.5+}) + \mathrm{Ci}(2\xi_{0.5-}) -$$
$$- 2\,\mathrm{Ci}(\xi_+) - 2\,\mathrm{Ci}(\xi_-) + 2\,\mathrm{Ci}(kL\eta)\}]; \quad (1)$$
$$X_{12d} = R_{12d}[\mathrm{Si} \to \mathrm{Ci}, \mathrm{Ci} \to \mathrm{Si}]; \Lambda = 15/\sin^2(kL)$$
$$\xi_{+,-} = kL\left(\sqrt{1+\eta^2} \pm 1\right), \ \xi_{0.5+,-} = kL\left(\sqrt{1+(\eta/2)^2} \pm 1\right),$$

where $k = 2\pi f / c$ is the wave number; f is the frequency; $c = 3 \cdot 10^8$ m/s is velocity of light in free space; L is the half of dipole length; $\eta = d/L$; d is distance between antennas.

Intrinsic impedance of the dipole can be obtained by equations (1) in special case when the antennas overlap each other [11]. Then the elements of impedance matrix for dipoles $\hat{Z}_d$ takes the form [12]:

$$(Z_d)_{12} = (Z_d)_{21} = R_{12d} + jX_{12d}\,,$$
$$(Z_d)_{11} = (Z_d)_{22} = R_{12d}\big|_{\eta \to 0} + jX_{12d}\big|_{\eta \to r/L}\,. \quad (2)$$

Impedance matrix for monopoles is $\hat{Z} = 0.5\hat{Z}_d$ [11].

If the EMF source is connected to the dipole with number 1 and the load is connected to the dipole with number 2, then one can write in accordance to Kirchhoff law for the equivalent circuit of coupled dipoles [12, p.468]:

$$E - Z_S I_1 = Z_{11} I_1 + Z_{12} I_2;$$
$$0 - Z_L I_2 = Z_{12} I_1 + Z_{22} I_2, \quad (3)$$

where E is the source EMF; Z_S, Z_L are the source and load impedances; I_1, I_2 are the source and load currents.

Taking into account mismatch between monopoles and the source and load, the coupling coefficient can be obtained by the following equations:

$$K_{USUL} = P_2 / P_{1m},$$
$$P_2 = |I_2|^2 \,\mathrm{Re}(Z_L), \quad |I_2|^2 = |Z_{12}/(Z_{22}+Z_L)|^2 |I_1|^2, \quad (4)$$
$$P_{1m} = 0.25|E|^2 / \mathrm{Re}(Z_S) = |I_1|^2 \,\mathrm{Re}(Z_S),$$

where P_2 is active power in the load Z_L, P_{1m} is the maximal active power that the source can deliver to the circuit (value P_{1m} is reached when circuit with impedance $\overline{Z_S}$ is connected to the source; the horizontal line denotes complex conjugation).

The definition (4) is equivalent to definition of coupling coefficient given in [13, p.467] when the system of coupling dipoles is matched with the source and load.

III. Computation of Monopole Coupling Factor by Methods of Computational Electromagnetics

We use the method of moments (MoM) and the finite element method (FEM) [8] to calculate etalon values of the antenna coupling factor. Validation of numerical simulation is performed by comparison of its results with results of experiments in order to confirm applicability of the chosen MoM and FEM implementations for solution of concerned problems class (subject to type of structures, boundary conditions, frequency range, mesh) (Figs. 1, 2, 3).

IV. Account for Mismatch When Computing the Monopole Coupling Factor

A. Monopole Coupling Factor in Case of Perfect Match

Coupling factor K_{MSML} of the system of monopoles perfectly matched with the source and load (subject to reflected input impedances of antennas) can be found in the

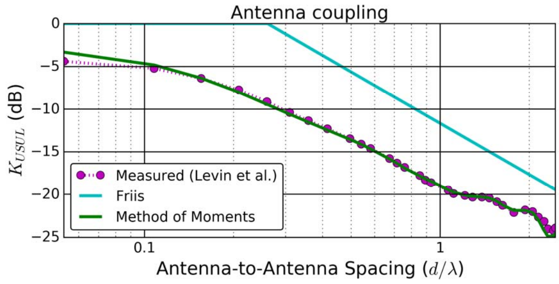

Fig. 1. Coupling factor between vertical monopoles installed at a common metallic sheet: comparison of measurement results [14, Fig. 4] with results of calculation by the method of moments. Parameters of the problem: f=506 MHz, length of monopoles is 0.25 λ, radius of monopoles is 1 mm, dimensions of the sheet are 4λ x 2λ, Z_S=Z_L=50 Ohm.

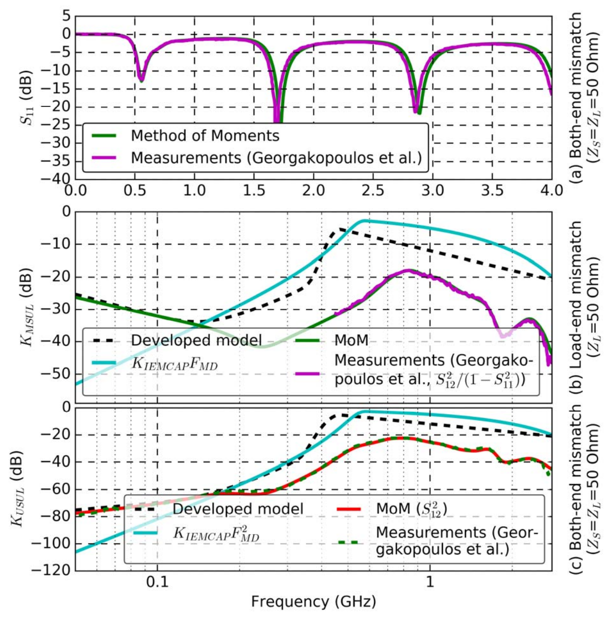

Fig. 2. Analysis of vertical monopoles installed at a common metallic sheet: comparison of measurement results [9, Figs. 2 and 3] with results of computations. Parameters of the problem: length of the first monopole is 12.8 cm, length of the second monopole is 7.65 cm, r=0.787 mm, d=32.3 cm, dimensions of the sheet are 40.8 cm x 61.2 cm.

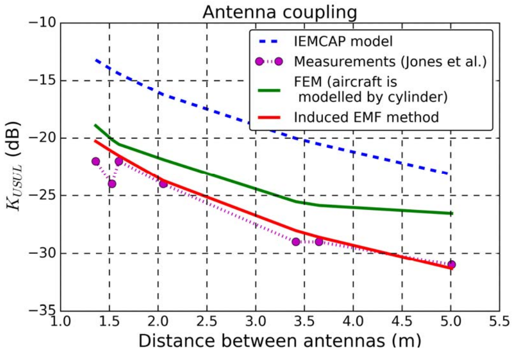

Fig. 3. Coupling factor of two antennas AT-1076 [15] installed on KC-135B aircraft [10, Table 2]. The analysis frequency f=225 MHz. The following values of parameters are used for calculation by induced emf method: L=0.33 m, r=0.053 m (according to [12, p. 514]). For modeling by the FEM, the aircraft body is replaced by a cylinder of height H=8.0 m and diameter W=4.2 m. Distances are restored from the aircraft photo. Z_S =Z_L=50 Ohm.

following ways: 1) by (4), fitting their impedances Z_S and Z_L numerically; 2) analytically by known Y-parameters of the system for given Z_S and Z_L [12, Eq. (8-74)]:

$$K^{Y}_{MSML} = [1-\sqrt{1-L^2}\,]/L;$$
$$L = \left|Y_{12}Y_{21}\right| / \left(2\,\mathrm{Re}(Y_{11})\,\mathrm{Re}(Y_{22}) - \mathrm{Re}(Y_{12}Y_{21})\right); \quad (5)$$

The coupling factor computation by the MoM was performed by both fitting impedances using optimization methods and on basis of expressions (5) and

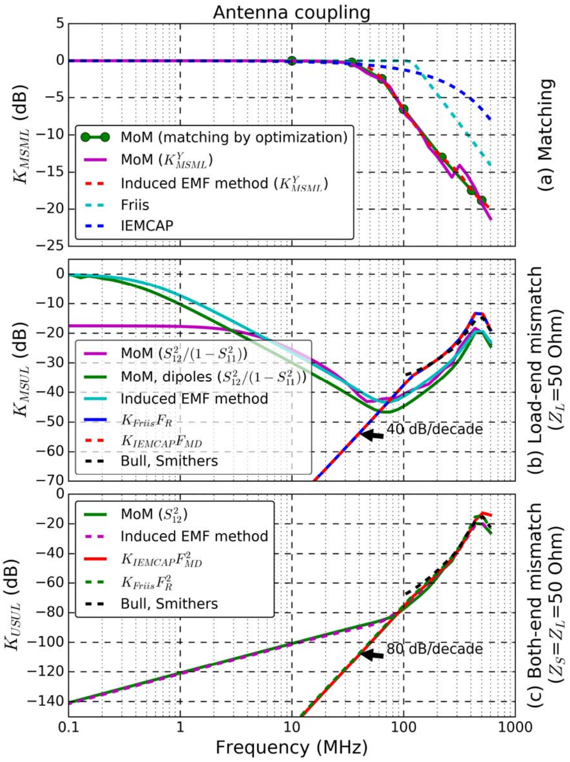

Fig. 4. Coupling factor of two monopoles. Parameters are: d=0.659 m, L=0.148 m, r=1 mm (one of configurations for [14, test 1]), values of the remaining parameters are given in caption of Fig. 1.

$\hat{Y} = \hat{y}(\hat{S}+\hat{I})^{-1}(\hat{S}-\hat{I})\hat{y}$, where $\hat{y} = [[1/\sqrt{Z_S},\ 0],\ [0,\ 1/\sqrt{Z_L}\,]]$ is matrix of port admittances, $\hat{S}$ is matrix of S-parameters computed by the MoM, $\hat{I}$ is identity matrix [16]. Calculation by the induced emf method was performed on basis of expressions (5) and $\hat{Y} = \hat{Z}^{-1}$ [17] (for computation of $\hat{Z}$, see Section II).

Example of computation results is shown in Fig. 4 (a): the IEMCAP model with linear interpolation [5] provides absence of the antenna coupling underestimation, but a model based on Friis equation [13, p.467] and on energy conservation law $K_{Friis} = \min(1, G_1 G_2 (\lambda/(4\pi d))^2)$ (gain factors used for monopoles are $G_1 = G_2 = 3.28$) gives lower overestimation (8.2 dB versus 12.4 dB). [18, fig. 5] is also confirms effectiveness of the use K_{Friis} in the near-field zone at low frequencies for perfect match cases.

B. *Monopole Coupling Factor in Case of Load Mismatch*

The coupling factor of monopoles in case of the load mismatch can be obtained by substituting value $Z_S = \overline{Z_{11} - Z_{12}{}^2/(Z_{22}+Z_L)}$ to the expression (4) (the load impedance Z_L can take arbitrary value in opposition to the case of perfect match (5)):

$$K_{MSUL} = \frac{\left|Z_{12}/(Z_{22}+Z_L)\right|^2 \mathrm{Re}(Z_L)}{\mathrm{Re}(Z_{11} - Z_{12}{}^2/(Z_{22}+Z_L))} \quad (6)$$

Z_L in (6) can be replaced by Z_S in order to take into account the source mismatch in case of the load match.

Figure 4 (b) presents calculation results of antenna coupling factor amplitude-frequency characteristic (AFC). AFC calculated by inducted EMF method (on basis of (6) and results of Section II) tends to 1 with decreasing of frequency. AFC of monopole coupling factor obtained by the MoM tends to the value K_0 independent on frequency but depending on the mesh density (the more detailed mesh, the closer K_0 to 1). Value $K_0 = 1$ was obtained by the MoM when monopoles were replaced by dipoles in accordance with the image principle (see Fig. 4 (b)). We assume that the value of K_0 must tend to 1 for monopoles too (see also Fig. 5). It is connected with high level of mutual coupling [19], [20].

If mismatch of the load connected to the second monopole is taken into account by multiplying antenna coupling factor K_{IEMCAP} defined in IEMCAP [5] by coefficient F_{MD} defined in the model of mismatch “Matched dipole” [21], then the MoM, (6), and $K_{IEMCAP}F_{MD}$ lead to similar values in frequency range 70…600 MHz (see Figure 4 (b)). But at frequencies less than 70 MHz $K_{IEMCAP}F_{MD}$ tends to zero with decreasing of frequency. Thus, if monopoles are located in the far-field (induction) zone relative to each other, then it is necessary to use more general methods (for example, induced

EMF method) in order to account mismatch in low frequency band.

Note that $K_{IEMCAP}F_{MD}$ coincides with $K_{Friis}F_R$, where $F_R = 1 - \left|(Z_{22} - Z_L)/(Z_{22} + Z_L)\right|^2$ is the power transfer factor through the junction of the source and the first monopole [21, p. 2-4]) (Figure 4, b).

C. Monopole Coupling Factor in Case of Source and Load Mismatch

In this case, the results of calculation of the coupling factor AFC (Fig. 4 (c)) make it possible to draw the following conclusions (analogous to conclusions from Section IV.B): 1) the induced emf method is in perfect agreement (difference less than 2.4 dB) with the MoM; 2) the coupling factor is strongly underestimated by $K_{IEMCAP}F_{MD}^2$ at low frequencies.

Both perfect electric conductor (PEC) and copper are used during computations by the MoM. Divergence of results was negligible (less than 4.2 dB for all matching modes).

V. Combined Model of Monopole Coupling Factor

The model (4) becomes instable at frequencies more than the first resonance frequency of monopoles $f_{res} = 0.25c/L$: small errors in initial data can lead to shift of resonance frequencies (including dips in the AFC of spurious coupling) and, as result, to underestimation of the spurious coupling. Consequently, it is reasonable to use known worst-case model K_{HF} of the antenna coupling (the Friis model K_{Friis} or the IEMCAP model K_{IEMCAP}) at $f > f_{res}$. Therefore, we combine the models (4) and K_{HF} by the following rule:

$$K_C = \begin{cases} K_{USUL}, & f \le f_{res}/2; \\ K_{USUL}[1 - w(2f/f_{res} - 1)] + & \\ \quad + K_{HF}\,w(2f/f_{res} - 1), & f_{res}/2 < f < f_{res}; \\ K_{HF}, & f \ge f_{res}; \end{cases} \tag{7}$$

where $w(x) = \left(3x^2 - 2x^3\right)^{10}, x \in [0,1]$ is a weight function providing absence of discontinuities of the AFC and its derivative for transition from the model (4) to the model K_{HF}.

Comparison of the model with measurement results for $K_{HF} = K_{Friis}$ is presented in Fig. 2.

Computational efficiency of the model (7) was estimated by calculation of the antenna coupling AFC in range [1 MHz, 150 MHz] on logarithmic frequency grid consisting of $5{\cdot}10^6$ samples: mean duration of calculation for single frequency was $\Delta t = 1.4$ μs. For comparison, the coupling factor between two monopoles installed at a cylinder having length H and diameter W was computed by methods of computational electromagnetics. The following results were obtained: 1) the MoM, thin monopoles ($H = 8.5$ m, $W = 4.4$ m, $d = 2.8$ m, $f = 14$ MHz): $\Delta t = 0.6$ s; 2) the MoM, two antennas AT-1076 ($H = 8.0$ m, $W = 4.2$ m, $d = 1.4$ m, $f = 20$ MHz): $\Delta t = 228$ s; 3) the FEM, two antennas AT-1076 ($H = 8.0$ m, $W = 4.2$ m, d =1.4 m, $f = 20$ MHz): $\Delta t = 250$ s. Therefore, computation by the combined model (7) is performed 10^5...10^8 times faster than by method of computational electromagnetics.

VI. Relationship Between Characteristic Dimensions of Monopoles and Ground Plane

Quantitative analysis of influence of an object served as ground plane on coupling factor seems to be possible only experimentally or by means of computational electromagnetics.

A set of numeric computations for various dimensions of the ground plane was performed in order to validate possibility of using the developed model for calculation of the coupling between monopoles installed at top of a car. Two identical monopoles with length $L = 1$ m and radius $r = 1$ mm were symmetrically installed on a rectangular perfectly-conducting metallic sheet at a distance d from each other. Dimension of the sheet along a line connecting monopoles was $2L_1 + d$, another dimension of the plane was $2L_2$. Modeling was performed in a frequency range 10 kHz…100 MHz for the following values of parameters: L_1=[0.1, 0.2, 0.5, 1,2] m, L_2=[0.1, 0.2, 0.5, 1, 2] m, d=[0.1, 0.25, 0.6, 1.5, 4] m. Example of results calculated for the case of perfect matching of the source with the system of coupled monopoles is shown in Fig. 5. The model (7) is considered to be unsatisfactory (due to considerable underestimation of the antenna coupling factor), if condition $10\log\{\max[K_{MoM}(f)/K_C(f)]\} \ge 3$ dB, where $K_{MoM}(f)$ is AFC of the coupling factor retrieved by the MoM, is hold for defined values of parameters. Using of the model (7) brought to underestimation of the antenna coupling for the most of parameters combinations. Underestimation is decreased with decreasing of d and with increasing of L_1 and particularly L_2.

Therefore, the model (7) is inapplicable if the dimensions of metallic object used as the ground plane are comparable with lengths of antennas.

In order to check if the model (7) can be used for computation of the coupling between monopoles installed on an aircraft, two sets on numeric computations were performed.

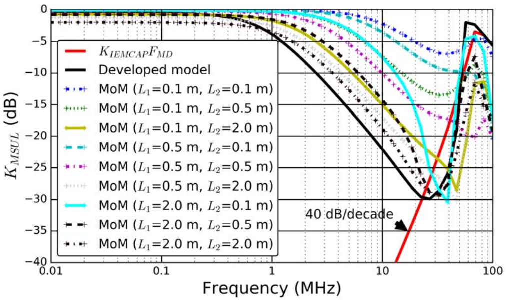

Fig. 5. AFC of coupling factor between monopoles for various ground planes (a flat rectangle sheet of dimensions ($2L_1+d$) x $2L_2$)) in case of matched source and mismatched load (Z_L=50 Ohm). Distance between monopoles is d = 1.5 m, length of monopoles is 1 m, radius of monopoles is 1 mm.

For the first set, aircraft body is modeled by a cylinder. Two identical monopoles of length 0.4 m and radius 2.5 mm, located at distance d from each other, are installed on cylinder along one of its generatrices. One of monopoles is placed at distance p from the cylinder end. The modeling is performed in frequency range 100 kHz...188 MHz (188 MHz is the first resonance frequency of monopoles) for the following values of parameters: (H, W)=[(8.0 m, 2.0 m), (48 m, 4.2 m)], d=[0.40 m, 1.6 m, $2/3\,H$], p=[0.40 m, $0.20\text{ m} + (H-d)/4$, $(H-d)/2$]. Results of the modeling show that the coupling underestimation is absent for small distances between antennas (about 1.6 m). The most important result obtained for this set of computations: increase of p tends to growth of the coupling between antennas. This makes it possible to exclude parameters p and H from consideration (by maximizing them) and perform more detailed examination in order to establish restrictions on parameters d and W.

For the second set of numeric computations, parameters correspond to parameters of computations for the first series except $p=(H-d)/2$ (the maximum value). Values of computation parameters are: W=[0.70, 1.29, 2.4, 4.4, 8.0] m, d=[0.40, 1.1, 2.8, 7.5, 20] m, $H=\min(\max(3d, 8\text{ m}), 40\text{ m})$. Frequency range is 100 kHz...188 MHz. Antenna coupling at high frequencies did not calculated for some combinations of parameters because of high computational complexity. Example of computation results is shown in Fig. 6.

Computed underestimation of the coupling factor by the developed model for various combinations of cylinder parameters in case of the load mismatch is shown in Fig. 7. Set of values of parameters W/L and d/L for which it is acceptable to use the model (in cases of the load mismatch and of both the source and load mismatch) can be estimated by the following inequality:

$$W/L \geq 0.65(d/L - 2.5)\,; \qquad (8)$$

VII. Realistic Case: Two Antennas AT-1076 on Fuselage of Aircraft KC-135B

In order to demonstrate validity of the model (7), it is important to show its applicability to real-world situations (i.e., to antennas used in practice and installed in real places on existing objects). Let us consider two antennas AT-1076 installed on KC-135B aircraft [10] as an example of such case. This situation is chosen by the following reasons: 1) there are results of measurements (at working frequencies) [10]; 2) construction of antennas is known [15]; 3) antennas are in line of sight of each other along one fuselage generatrix (this minimizes influence of diffraction).

All models predict value of the coupling factor at working frequency of AT-1076 antenna with reasonable accuracy (see Fig. 3). But values of the coupling factor by the model (7) are significantly more than values computed by the FEM for frequencies lower than working band (225…400 MHz for

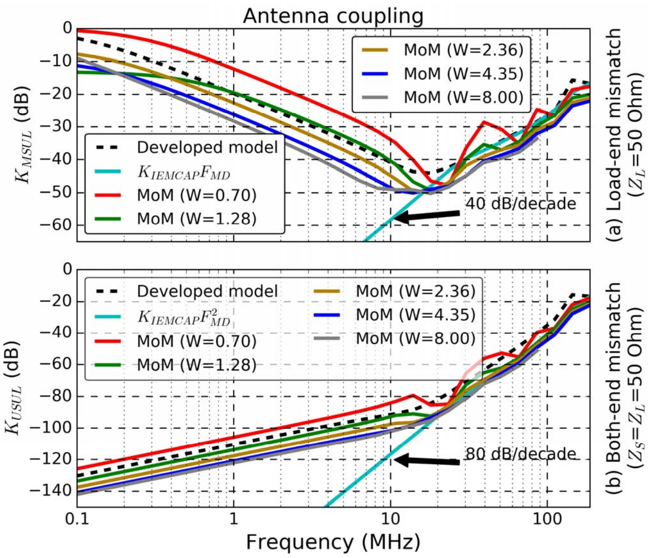

Fig. 6. AFC of coupling factor between monopoles installed on cylinder for various values of the cylinder diameter W. Length of the cylinder is H=8.4 m, distance between monopoles is d=2.8 m

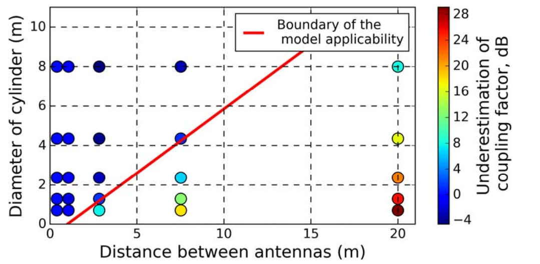

Fig. 7. Maximum (in frequency range of the analysis) underestimation of antena coupling by the developed model for monopoles installed on the cylinder versus d and W. Red line represents estimation (8) of the model applicability range. Length af antennas is 0.4 m, the load is mismatched (Z_L=50 Ohm)

AT-1076 antenna) (Fig. 8). This effect can be explained by presence of a shunt stub in AT-1076 antenna [15]. Modeling results for antennas without stub confirm this (see Fig. 8 (b)).Given example shows the importance of account for lightning protection of aviation antennas when coupling between the antennas is computed at low frequencies, but detailed information about construction of the antennas is required for such account. There are aeronautical antennas for which the lightning protection is made not as a high-pass filter (e.g., as a shunt stub, like for AT-1076) but as an arrester triggered when the field amplitude exceeds a threshold [22]. The model (7) gives upper bound of the antenna coupling AFC, therefore it can be used when information about construction of antennas is absent.

VIII. Conclusion

Physical adequacy of the IEMCAP model [5] at low frequencies was demonstrated by example of mutual coupling between monopoles: the antenna coupling factor reaches the value of 1 (see Section IV.A) in the worst case (for perfect match of interacting antennas with the source and load). The account for antenna mismatch by means of the developed model makes it possible to improve the IEMCAP-model estimation of the coupling by 20…40 dB in case of mismatched load and by 60…120 dB in case of mismatch of both source and load (in considered frequency range)

The developed worst-case model of monopole antenna coupling can be used for diagnostics (express analysis) of EMC between on-board radio-electronic equipment of big systems [3]. The model does not account for diffraction phenomena at low frequencies for the purpose of providing worst-case behavior of antenna coupling estimation. The developed model can be used together with model [23] in order to account the diffraction at high frequencies.

Limited range of applicability (see Section VI) is a drawback of the model; this makes impossible to use the model for computation of coupling between antennas installed on automobiles. Besides this, the model does not account for possibility of resonances at $f < f_{res}$. These resonances result from unintended matching of antennas with the source and/or the load at certain frequencies due to frequency dependence of out-of-band impedances for the transmitter, receiver, and antennas (including the antenna matching devices) and due to transformation of these impedances by feeders [24]. Antenna coupling level can increase by 10-20 dB [25, p. 34] at frequencies of the resonances. At frequencies $f \geq f_{res}$, these resonances are taken into account by the worst-case model K_{HF} which postulates perfect match of antennas [12, 13]. Possible improvements in the model are associated with account for the influence 1) of dimensions and shape of the ground plane, 2) of difference in dimensions of the interacting monopoles, and 3) of the resonances in the system “transmitter (receiver) – feeder – antenna” at frequencies $f < f_{res}$.

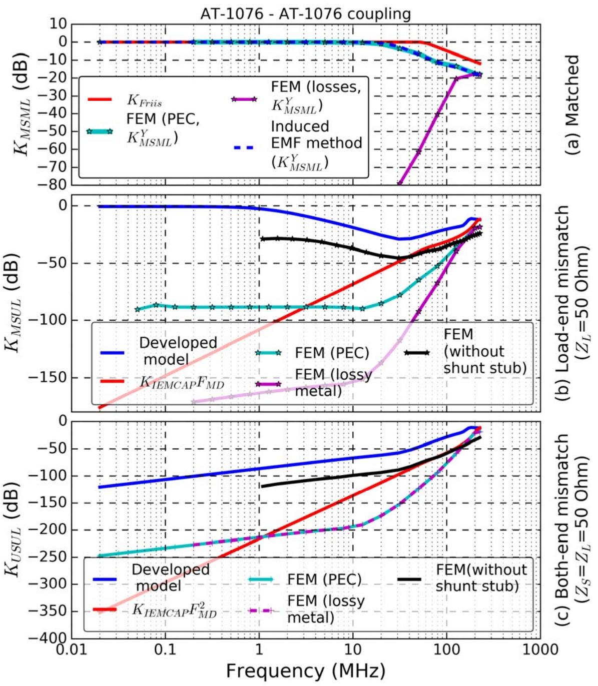

Fig. 8. AFC of coupling factor between two antennas AT-1076 installed symmetrically on cylinder of length 8.0 m and diameter 4.2 m; d=1.4 m. Parameters of calculation by the model (7) are L=0.33 m, r=0.053 m (in accordance with [12, p. 514]). Importance of account for losses for this case is clearly seen.

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