Fast Discrete Diagnostics of EMC of Complex Co-Located Radio Systems by Using Worst-Case Models of Electromagnetic Spurious Couplings

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***Abstract*—A technique of high computational efficiency for EMC diagnostics of complex co-located set of radio systems is presented. The technique is based on the following: the use of worst-case models of electromagnetic spurious couplings between antennas (in order to eliminate the second-type errors in detection of dangerous couplings), iterative refinement of these models for the potentially dangerous couplings in the process of solving an EMC problem, and the extra efficient discrete technique for nonlinear behavior simulation of radio receiver operation in complex electromagnetic environment.**

***Keywords*— EMC diagnostics, co-located system, worst-case models, electromagnetic coupling, intermodulation**

I. Introduction

EMC defines the operability of radio equipment of complex co-located radio-electronic systems (CLRS). Fast diagnostics of intra-system and inter-system EMC is a critical part of designing and ensuring normal operation of CLRS because it allows early detection and identification of all potentially dangerous electromagnetic (EM) spurious couplings (SC) between antennas of radio transmitters and receivers, as well as early detection and identification of undesired impact of external sources of EM fields (EMFs) on the receivers of CLRS.

As a rule, the performance of such EMC diagnostics of CLRS requires multi-variant analysis of danger of EM SC between CLRS antennas, i.e., analysis of different location variants and operation modes of CLRS equipment with different variants of protective solutions, different external EME, etc. In practice, it is required to analyze dozens or even hundreds of variants of CLRS implementation and operation, therefore the decrease in time of EMC analysis for each variant is particularly important.

When detecting and identifying EM SC between CLRS elements, as well as linear and nonlinear interferences in CLRS radio receivers (RRs), it is reasonable to focus on worst-case EMC estimations that tolerate errors of the first kind ("false alarm") and exclude errors of the second kind ("erroneous undetection"), because the cost of the second-kind errors is much higher.

The most complicated problems of fast computer-based EMC diagnostics of CLRS are as follows:

1) The absence of complete and reliable information concerned characteristics of CLRS equipment, e.g., radiation spectra of radio transmitters (RTs) and susceptibility characteristics of RRs in a wide frequency range, design features of antennas and feeder circuits, etc.,

2) A large quantity of EM SCs (10^2–10^4 and more) and external EMFs (10^2–10^4 and more) to be analyzed, and

3) A large number of variants of CLRS realization and operation.

An effective way to overcome these problems is the use of the following:

1) Analytical worst-case models describing EM SC between CLRS elements, e.g., the IEMCAP models [1],

2) System-level EMC criteria and procedures of discrete linear analysis (DLA) of EMC in the frequency domain, and

3) Efficient technique of discrete nonlinear analysis (DNA) of EMC in the time domain [2-5].

The objective of this paper is to summarize a technique for fast discrete computer-based diagnostics of EMC of CLRS radio equipment operating in severe external electromagnetic environment (EME). The technique is based on IEMCAP ideas; it involves specialized methods and approaches proposed by the authors, which provide its high efficiency and practical importance.

II. Discrete Analysis of CLRS EMC by Using Worst-Case Models of Electromagnetic Spurious Couplings

The technique of the fast discrete CLRS EMC diagnostics based on multi-variant EMC DNA & DLA of CLRS equipment in severe EME with the help of worst-case models includes the following main stages:

1) Development of CLRS 3D geometric models with initial variant of allocation of RT and RR antennas and definition of all CLRS characteristics that affect on EM SC between them (geometry and material of hull, characteristics

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of antenna placement, etc.). Examples of such CLRS 3D models are presented in Fig. 1, 2, 3.

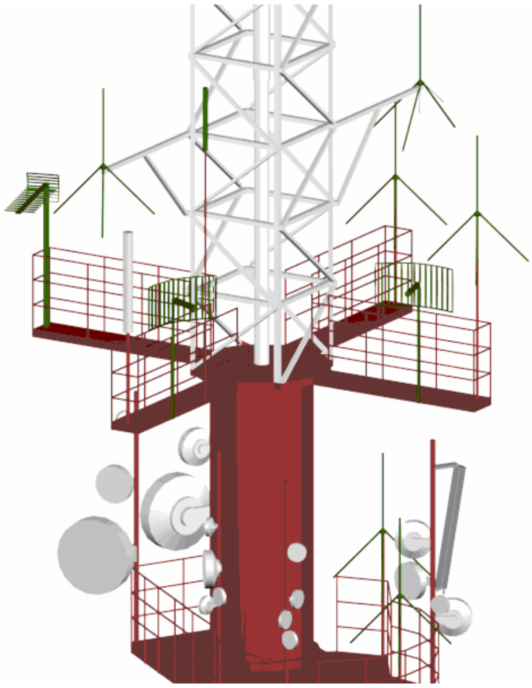

Fig. 1. 3D model of CLRS created by the set of VHF, UHF, and SHF radio equipment allocated on the high-rise antenna mast [2].

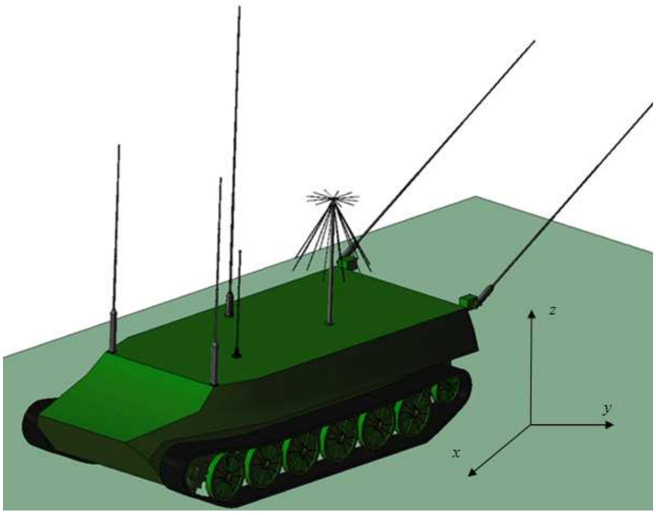

Fig. 2. 3D model of CLRS created by the set of HF, VHF, and UHF radio stations allocated on vehicle [4].

2) Development of EM SC worst-case models for different variants of CLRS implementation including models of EM SC between antennas, models of antenna patterns (AP) to analyze external EME impact; models of main and spurious emission spectra for each RT in a wide frequency range (ten times exceeding the maximum working frequency); models of frequency selectivity characteristics of each RR via the main, adjacent and spurious reception channels in a wide frequency range (ten times exceeding the peak adjustment frequency of RR); models of frequency selectivity of input/output filters of RT and RR (preselectors, combiners, etc.).

3) Development of external EME model (in the form of an ensemble of external EMFs with predefined power characteristics, frequency spectra, direction of arrival and polarization) based on data on allocation and operation of external RT (ground-based, RT of other CLRSs, of aircrafts, ships, etc.), as well as using radiomonitoring data.

4) Implementation of EMC DLA with the use of worst-case models [1] of EM SC and taking into account external EME for each variant of CLRS antennas placement and elevation. Results of this analysis are used for detection the set of possible potentially dangerous EM SC that can cause high-power input exposures and radio interferences in each RR within CLRS.

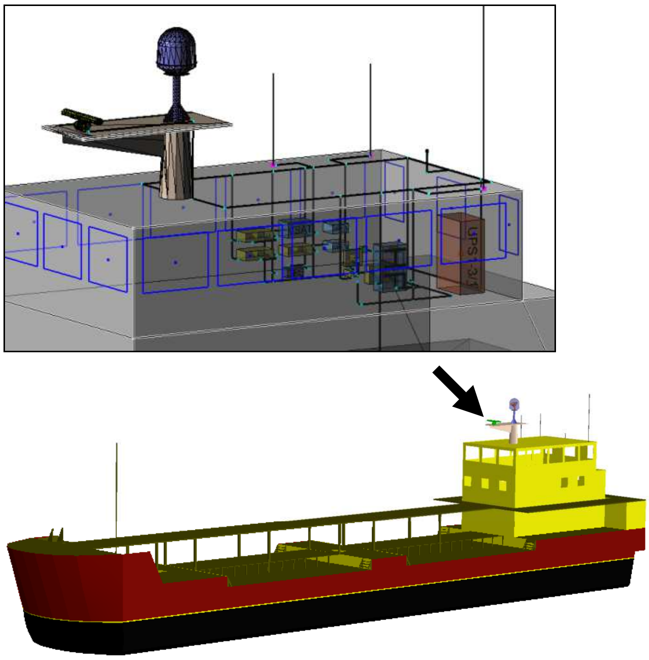

Fig. 3. 3D model of CLRS created by the set of HF, VHF, UHF, and SHF radio stations allocated on ship [5].

5) After detection of all potentially dangerous EM SC "antenna-to-antenna" that can cause interferences to CLRS RR, these couplings are analyzed using the numerical methods (FDTD, MoM, etc.); this analysis is performed in the following order: models of amplitude-frequency characteristic (AFC) of S-matrix elements which characterize SC in predefined frequency ranges are dveloped and refined by variation of values of antennas parameters; worst-case envelope of AFC of "antenna-to-antenna" SC is constructed; models of AP taking into account antennas' design features, orientation to the elements of CLRS hull structure and underlying surface taking into account conductivity thereof are refined (for more detailed analysis of external EME impact); discrete models of RT radiation spectra and of RR susceptibility characteristics are refined.

After that, the EMC DLA for each variant of antennas location in CLRS space using refined models of potentially dangerous EM SC and refined RR susceptibility characteristics, is performed; it refines the danger of detected EM SC and the levels of interferences at different tuning frequencies of CLRS RR with estimation of Integrated Interference Margin (IIM) for each RR as the interference receptor. For antennas with SC defined as potentially dangerous, variations of parameters for determination of these SC are carried out.

6) Selection of one or several of the most promising variants of CLRS realization (with absence of exposure via the main reception channels and the least possible levels of out-of-band input disturbances) for further detailed analysis. Then for each of the selected variants of antennas location in CLRS space a set of measures to eliminate linear interferences between corresponding RR and RT is worked out and EMC DLA of CLRS is performed taking into account implementation of these measures (if necessary).

7) Implementation of EMC DNA of CLRS for the situations remaining potentially dangerous in terms of nonlinear interferences by methodology [6] including determination of nonlinearity and selectivity characteristics of RR through the antenna input taking into account features of structure, components and conversion of frequencies in RR. The best result can be achieved based on the results of testing RR by the DFT technique [7] allowing detection, identification and measurement of parameters of all real linear and nonlinear paths of probable RR damage by interferences through the antenna input, as well as rather accurate measurement of RR input nonlinearity. Examples of 3D plot of double-frequency characteristic (DFC) of ship RR and of the cross-section of this plot - the double-frequency diagram (DFD) of this RR at the level –95 dBm, obtained with the use of DFT technique, are presented in Fig. 4 and Fig. 5.

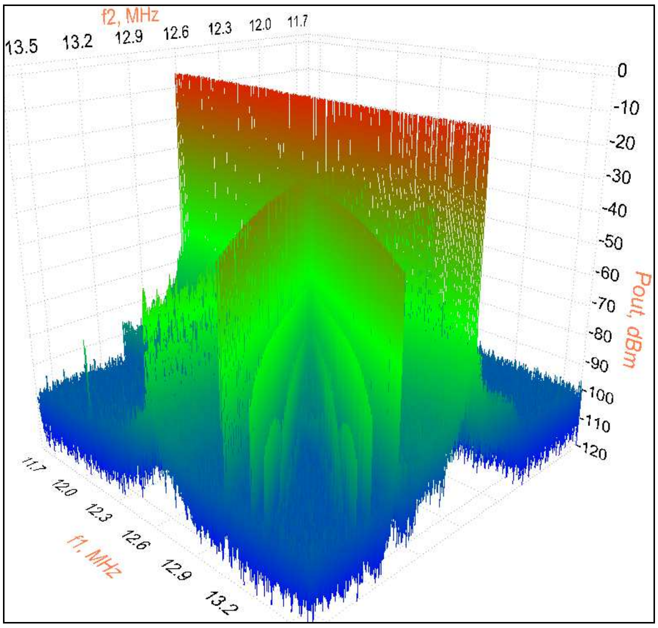

Fig. 4. 3D plot of DFC of ship HF RR: images of 3-, 5-, 7-, 9-, 11-order intermodulation paths are observed [5]. The desired response at RR tuning frequency is colored in red. Image of RR noise is colored in blue.

Such analysis is carried out for each variant of antennas location in CLRS which is recognized as the most promising one by the results of refining models of potentially dangerous EM SC and those of susceptibility characteristics of RR, with identification of situations in which the danger of RR damage by nonlinear radio interferences is revealed by the results of analysis.

8) Determination of technical (filtering, shadowing, etc.) and organizational (time division, frequency sharing, etc.) measures (not related to change of relative antennas location) to eliminate nonlinear radio interferences.

9) In the course of EMC diagnostics of on-board CLRS, it is essential to take into account other kinds of EM SC (antenna-to-cable, cable-to-cable, antenna-to-equipment case, external EM field-to-cable, etc.) along with RT antenna-to-RR antenna ones; to this end, procedures 1-7 are carried out as part of EMC analysis based on simulation of these SC.

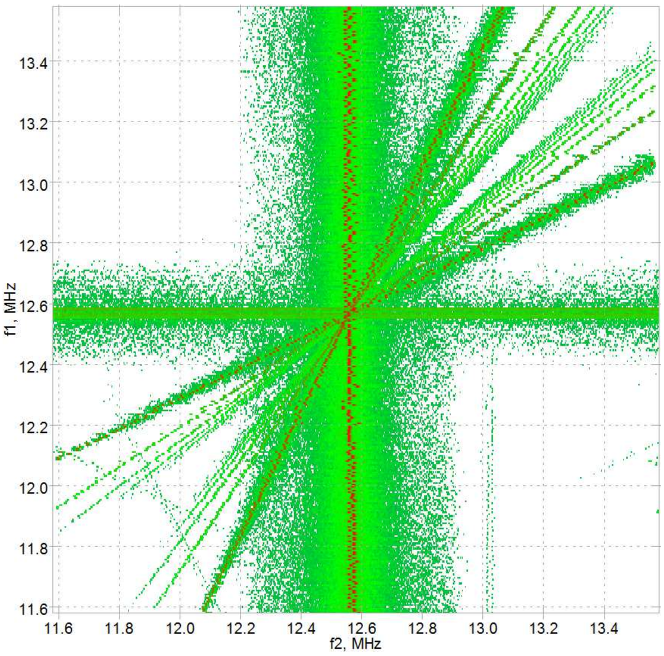

Fig. 5. 2D plot of DFD of ship HF RR at the level of –95 dBm for the tuning frequency of 12.579 MHz and levels of test signals of –22 dBm [5]. Intermodulation components of 3…15 order are detected and measured.

III. Detailed Analysis of Potentially Dangerous "Antenna-to-Antenna" Couplings

Detailed analysis of antenna-to-antenna coupling is performed in accordance with technique based on the consideration of the set of S-parameters AFC obtained by the numerical simulation of the coupling between antennas when parameters of antennas and their location are varied. The result of this procedure is the worst-case envelope of AFC of S-parameters for each antenna:

$$H_{ik}(f) = E_{nv}\{H_{1ik}(f), H_{2ik}(f), \ldots, H_{Nik}(f)\}, \qquad (1)$$

where f is the frequency, $H_{1ik}(f)$ is AFC of S-parameter S_{ik} obtained for the coupling between antennas with the numbers i and k for the first fixed set of antenna parameters, $H_{2ik}(f)$ is AFC of S_{ik} obtained for the second set of antenna parameters, etc. E_{nv} denotes the procedure of the worst-case envelope plotting described in [2-5].

In accordance with this technique, it is necessary initially to define the reference value of antennas parameters and locations based on information presented in corresponding technical specifications.

Fig. 6 presents results of numerical calculation of SC between ship VHF monopole antennas performed by FDTD [5]. The red solid line corresponds to the worst-case envelope of the simulation results obtained by variation of the following parameters: conductivity of underlying surface, antenna length, position of antenna mounting. Black solid line corresponds to the initial (reference) set of parameters and the antenna placements, black dotted line and black dashed line – to the maximum (+25% from initial) and minimum values (-25%) of varied parameters respectively.

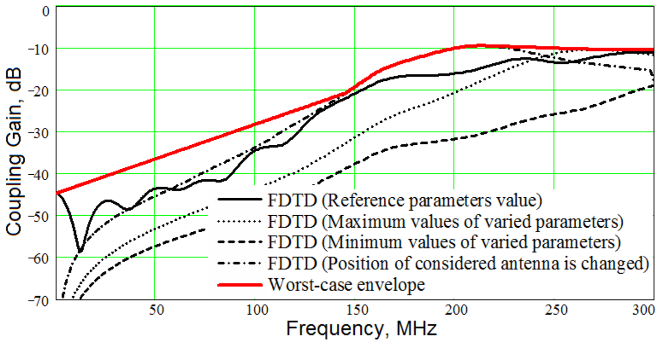

Fig. 6. Worst-case model of AFC of SC between ship VHF antennas [5].

Analytical model based on IEMCAP [1] provides values of coupling between antennas installed on radio cabin of ship near to 0 dB as the result of big length of considered antennas. EMC analysis of CLRS performed with the use of refined numerical worst-case model on Fig.6 allows to establish the absence of mutual interferences between radio-equipment connected to analyzed antennas. But in many cases further analysis reveals the danger of non-linear interference for at least one of the CLRS RR due to the presence of powerful out-of-band signals of CLRS own RTs and/or powerful signals of external EME at its input (especially for RRs of lower ranges - HF & VHF).

IV. Analysis of Nonlinear Interferences and Identification of Their Sources

The DNA of RRs' operation in given EME (formed as a sum of external EME and signals of CLRS RTs) is performed with the use of technique [6,7] for each variant of the CLRS antenna location for which the potential danger of nonlinear interference is detected. Fig. 7 represents an example [4] of results of the modeling: total signal spectra at various test points of the HF RR's behavioral model. The final result is a set of situations in which the danger of nonlinear interference is confirmed.

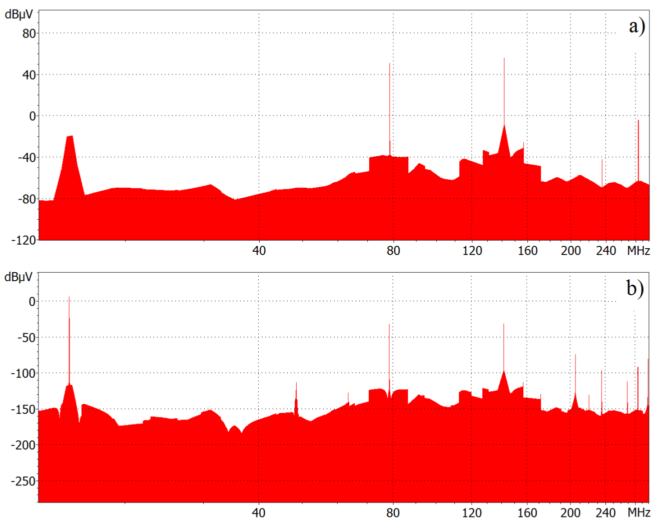

Fig. 7. Spectra at test points of nonlinear model of HF RR tuned at 15 MHz: (a) at the output of RR input filter model, and (b) at the output of the RR nonlinear model (intermodulation interference is identified).

This technique is realized with the use of worst-case models of RR front-end nonlinearity [8], discrete frequency- and time-domain EME models, which include a large number of samples (10^5-10^6 and more) of the total EME. This makes it possible to analyze the operation of CLRS in a very complex EME, including up to 10^3-10^4 modulated signals with a dynamic range of 200-300 dB (if necessary).

The process of searching the sources of nonlinear interference is automated by the use of an effective dichotomous algorithm [9] for identifying EMFs involved in nonlinear interference (intermodulation, etc.).

V. Conclusion

The presented technique of EMC analysis of CLRS has the following advantages that determine its practical importance: high accuracy of representing spectra of RT EM radiations and AFC of SC, as well as susceptibility and nonlinearity characteristics of RR; high computational efficiency of procedures of discrete linear and nonlinear EMC analysis; worst-case nature of EMC estimations and their error tolerance in input data; iterative refinement of the models of potentially dangerous undesired impacts and SC.

The advantages given above are proved by the results of solving practical problems of EMC analysis and diagnostics in a number of real on-board and ground-based CLRSs [2-5]. This makes it possible to recommend the presented technique as a tool for solving EMC problems of CLRSs of various types and levels of complexity.

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