Experimental Analysis of Radio Receiver Susceptibility to Out-of-Band Interference by Means of Double-Frequency Test System

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

Abstract — **The application of a double-frequency test technology and automated system using two frequency-sweeping test signals for detection, identification, and parameter measurement of all linear and nonlinear interference responses (spurious, intermodulation, etc.) of radio receivers is described. An experimental analysis of receiver susceptibility to out-of-band interference at its antenna input, including the measurement of high-order intermodulation, is presented. Opportunities and advantages of using the double-frequency test technology for detection of nonlinear noise and spurious generation areas in receivers are discussed. A new technique for identification (recognition) of the receiver responses to interference is proposed.**

Keywords — receiver, spurious response, intermodulation, measurements, behavior simulation

I. Introduction

A peculiarity of reception in severe electromagnetic environment (EME) is the presence of a number of strong signals at the radio receiver (RR) input. These signals may cause nonlinear effects (blocking, crosstalk, intermodulation, reciprocal mixing) and interference in spurious response receiver paths. Since local on-board systems (aircraft, ship, etc.) and regional ground-based systems generally must function in severe EME, information about standardized susceptibility and EMC characteristics of receivers (typically, frequency selectivity characteristic, third-order intercept point, 1-dB compression point, two-signal spurious-free dynamic range, etc.) may be insufficient for EMC analysis and prediction. Developers of collocated radio systems usually have to conduct extensive additional research on susceptibility of receivers. This research involves detection and identification of all possible interference impact paths, evaluation of the interference effects at the receiver antenna input, and measurement of the path and interference characteristics.

The technique for double-frequency testing presented in [1] is a very efficient technique for extracting information about receiver susceptibility at the antenna input. Unlike widely used techniques based on two- and multisignal testing to determine the EMC of receivers, this technique permits prompt detection and identification of all existing linear and nonlinear signal paths that cause interference at the receiver output. This technique has been verified and has proved to be highly informative and efficient [2, 3]. The technique is very helpful at all stages of system's life cycle, but it is especially useful at the early development stages since it enables the EMC engineer to conduct painstaking research in order to provide detailed data, thus facilitating design decisions.

Previous versions of the automated double-frequency test system (ADFTS) for testing radio receivers and radio components (RFA, mixers, low-power generators, etc.) were developed with the use of simple analog frequency-sweeping RF oscillators (standard RF sweep-generators of earlier generations) [1, 4]. Those versions have limitations caused by low stability and accuracy of frequencies and amplitudes of test signals. The mentioned limitations are appreciably overcome in advanced ADFTS versions constructed on modern metrological and control base (with the use of digitally-controlled analog RF generators of last generations providing high-stable and low-noise test signals, digital spectrum analyzers with high input dynamic range and adjustable analysis band, and high-speed LAN control of measuring equipment).

In this paper, opportunities of the advanced ADFTS to detect nonlinear effects and interference responses in radio receivers and radio-frequency amplifiers (RFA) are illustrated by way of examples, and a new technique for recognition of the detected responses is proposed.

The paper is organized as follows. The ADFTS structure and principle of operation are briefly summarized in Section II. Then, a number of test results illustrating ADFTS opportunities are given: detection of nonlinear noise and spurious generation areas (Section III) and testing of high-order intermodulation in RR and RFA (Section IV). A new technique for identification (recognition) of the receiver responses to interference is proposed in Section V. Finally, advantages of the new ADFTS version are summarized in Conclusion.

II. ADFTS Principles

The basic ADFTS structure is given in Fig.1. The main differences between ADFTS and standard systems of two- and three-signal testing of radio receivers are in the following:

- In special algorithms for controlling of test signals' frequencies – a linear frequency sweep with essentially different velocity is provided (Fig.2);
- In special "radar" methods for processing and visualization of a level of a response signal of the radio receiver under test (RUT) synchronously with the frequencies of the test signals.

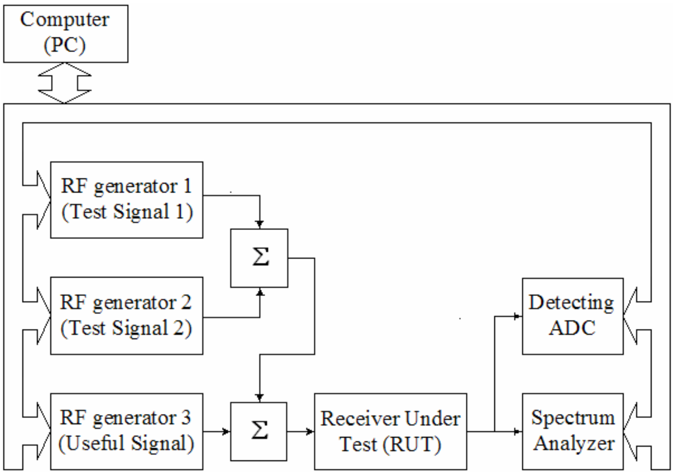

Figure 1. Basic ADFTS structure.

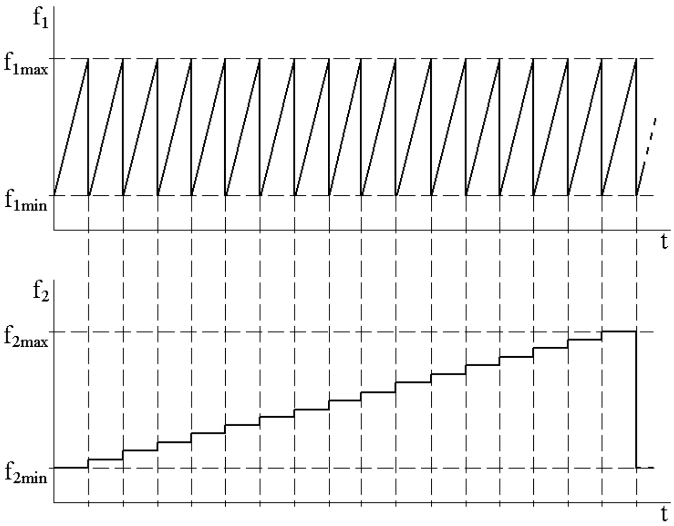

Figure 2. Frequency sweep in ADFTS: f_1 – frequency of a fast-sweeping test signal, f_2 – frequency of a slow-sweeping test signal.

Main results of a base stage of RUT testing with the use of the above-mentioned "radar" technology are 3D and 2D images of RUT susceptibility characteristics:

- 3D image of a double-frequency characteristic (DFC) – three-dimensional dependence of a level of the RUT output response on the frequencies of each of two sweeping test signals having constant levels (Fig.3),
- family of 2D images of the DFC: each 2D image is called the double-frequency diagram (DFD) – it is a color map of 3D DFC image for a given threshold (minimum level of display) of RUT output signal (Fig.4).

Lines presented in DFD (ref. Fig.4) are images of all existing linear and nonlinear signal paths that cause interference at the receiver output: pairs of horizontal and vertical lines crossed on DFD diagonal 45º are images of RUT's desired and spurious responses, inclined lines are images of RUT intermodulation responses.

Identification and measurement of parameters of the detected signal paths in RUT makes it possible to solve the most complicated EMC problems for different future operational conditions of RUT and also considerably increase an adequacy of RUT behavior simulation in severe EME.

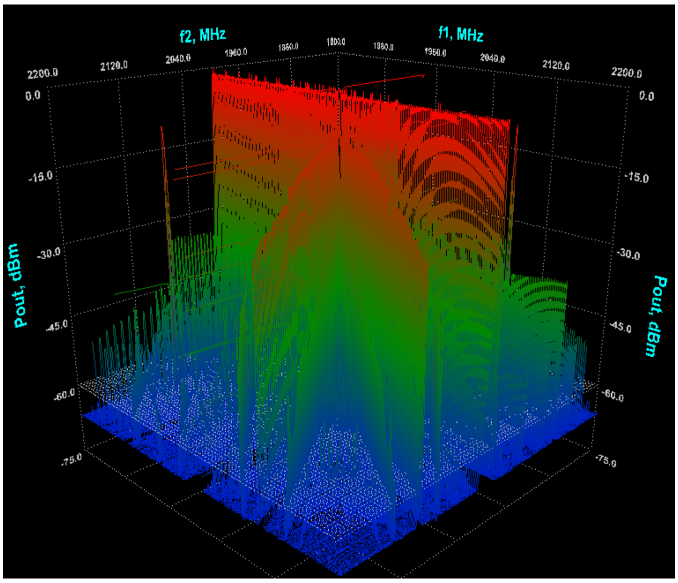

Figure 3. 3D image of DFC for "Schaffner SMR 4518" receiver tuned at 2 GHz (both continuous-wave test signals have the same level of 5 dBm and frequency sweep from 1.8 GHz to 2.2 GHz).

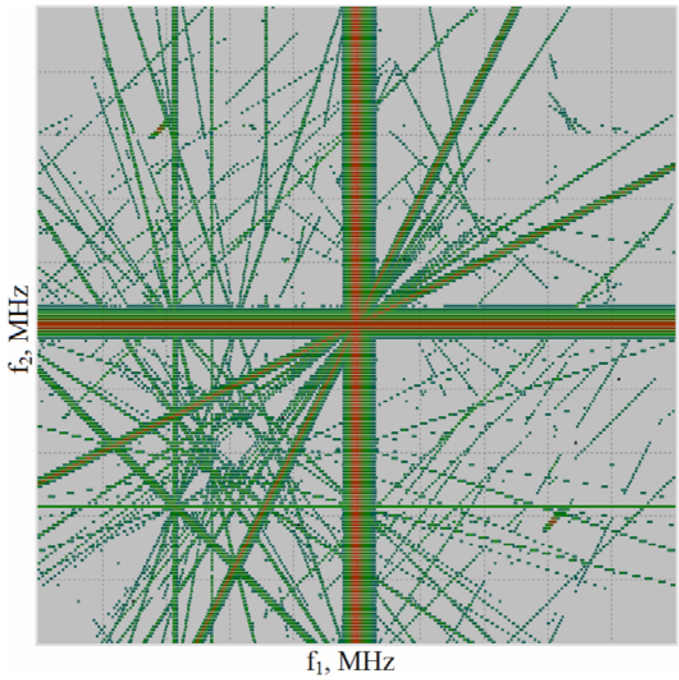

Figure 4. 2D image (DFD) of the DFC given in Figure 3 (the display threshold is of -60 dBm, which is 6 dB above the noise level).

III. DETECTION OF NONLINEAR PATHS AND AREAS

The double-frequency test technology provides an opportunity to detect and recognize areas of the increased level of nonlinear noise and areas of spurious generation in RUT in presence of high-level out-of-band signals at its antenna input. These effects are important for solving EMC problems of radio systems: by detecting such areas in DFDs, it is possible to estimate the most undesirable combinations of frequencies of out-of-band signals at the input.

Let us consider the following example: in Fig. 5, the DFD image of a RR having two frequency conversions and tuned at 1.5 GHz is given. Three areas of the increased level of nonlinear noise, including 2 areas of spurious generation, are detected in first, second, and fourth quadrants of this DFD. More detailed 2D and 3D images of these areas are given in Figs. 6, 7, 8, and 9.

DFD image of the area with high level of nonlinear noise, which is detected in the first quadrant of the DFD given in Fig.5, is shown in Fig.6. This area includes a numerous images (lines) of spurious and intermodulation responses which form the peculiar area of increased RR susceptibility.

DFD images of the areas with high level of nonlinear noise and spurious generation, which are detected in the second and fourth quadrants of the DFD given in Fig.5, are shown in Fig.7 and Fig.8, correspondingly. Color coding of output signal levels exceeding the display threshold of DFD makes it possible to detect curvilinear areas of powerful parasitic generation (red areas in Figs.7 and 8, main “ridge” in Fig.9). These areas are present simultaneously with a lot of intermodulation response images; outside these areas, a danger of intermodulation interference is much lower. It is practically impossible to predict position of similar areas in DFD, however the double-frequency test technology allows one to detect and identify such areas confidently.

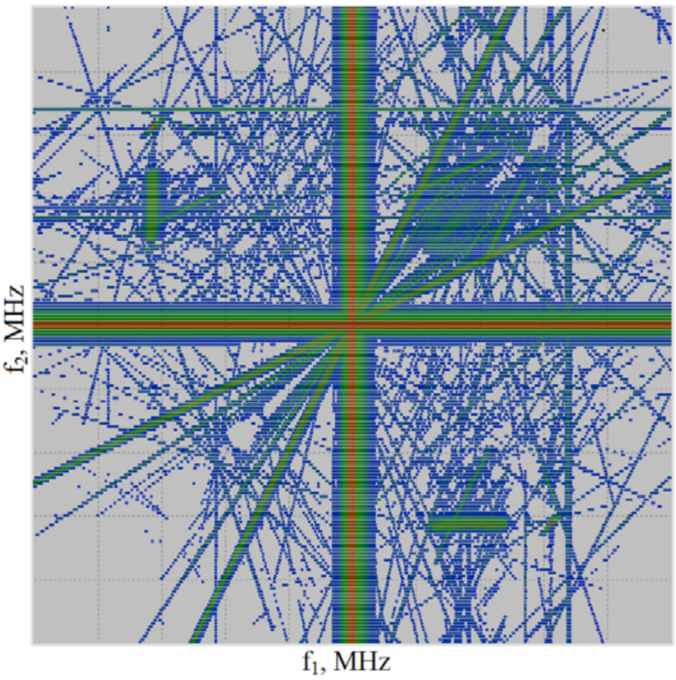

Figure 5. DFD of “Schaffner SMR 4518” receiver tuned at 1.5 GHz. Test signal levels are 5 dBm (95 dB above the RR sensitivity), frequency sweep ranges are 1.3–1.7 GHz, and display threshold is -64 dBm.

DFC images in Figs.5–9 are obtained at the output of the second intermediate frequency (IF) of RUT. Images in Figs. 5, 6, 7, and 9 are received for spectrum analyzer bandwidth

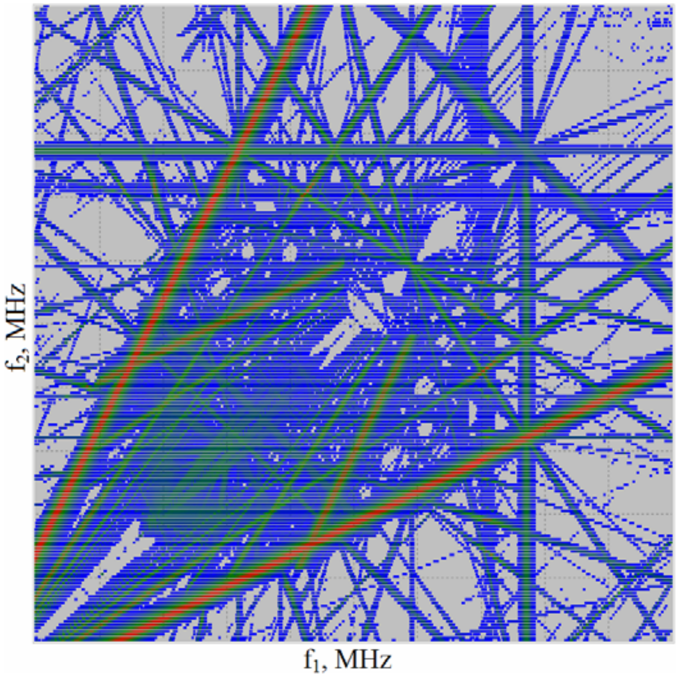

Figure 6. DFD of the area with high level of nonlinear noise, which is detected in the first quadrant of the DFD given in Fig.5. Frequency sweep ranges are 1.52–1.67 GHz, spectrum analyzer bandwidth is 30 MHz, and display threshold is -66 dBm (which is 6 dB above the noise level).

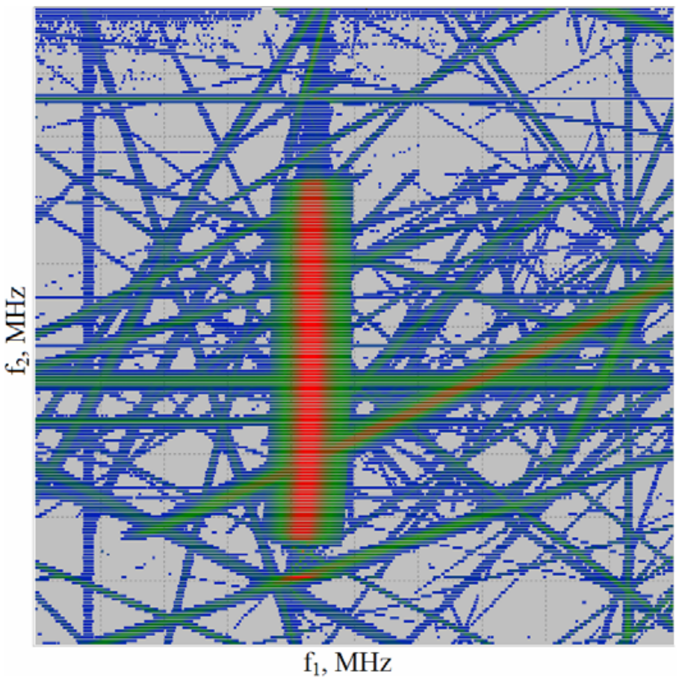

Figure 7. DFD of the area with high level of nonlinear noise and spurious generation, which is detected in the second quadrant of the DFD given in Fig.5. Frequency sweep ranges are 1.34–1.42 GHz for f_1 and 1.54–1.62 GHz for f_2, spectrum analyzer bandwidth is 30 MHz, and display threshold is -67 dBm.

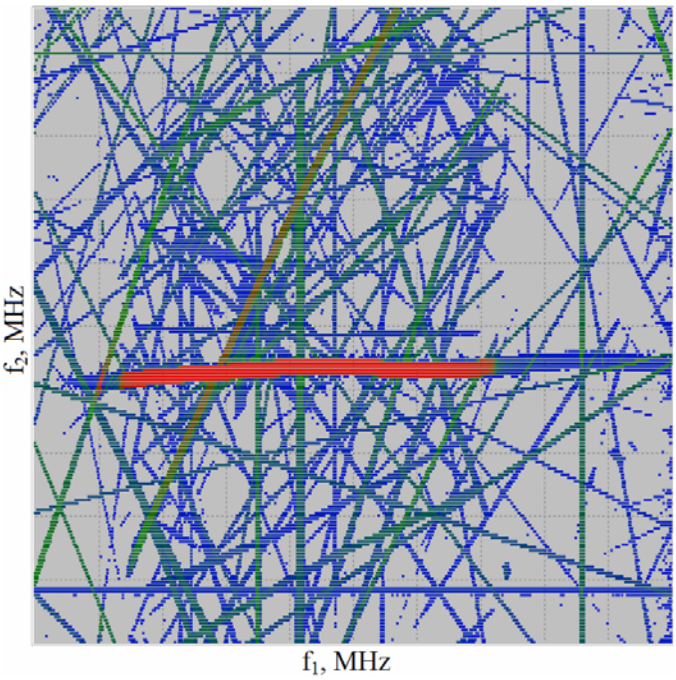

Figure 8. DFD of the area with high level of nonlinear noise and spurious generation, which is detected in the fourth quadrant of the DFD given in Fig.5. Frequency sweep ranges are 1.54–1.62 GHz for f_1 and 1.34–1.42 GHz for f_2, spectrum analyzer bandwidth is 2 MHz, and display threshold is -69 dBm.

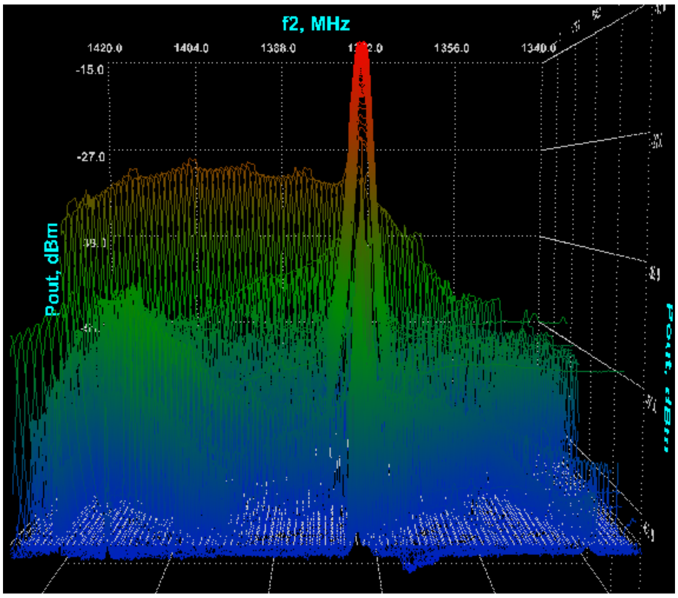

Figure 9. 3D image of DFC for the area given in Fig.8.

(in which the RUT response level is measured) of 30 MHz which is much wider then the second-IF bandwidth of the RUT. Fig.8 is received for spectrum analyzer bandwidth of 2 MHz which is equal to the second-IF bandwidth. A much better resolution of images of intermodulation responses and spurious generation in this DFD (in comparison with DFDs given in Figs. 6 and 7) is evident. By decreasing the spectrum analyzer bandwidth, it is possible not only to improve resolution in DFDs, but also to receive DFD images for lower levels of the display threshold (because the noise level is decreased with the bandwidth).

IV. RFA High-Order Nonlinearity Testing

The basic idea of RFA testing with the use of ADFTS is that the structure «RFA under test – Frequency filter – Spectrum analyzer» can be considered as a model of a radio receiver under rest (RUT) in which all researched phenomena and interference channels are formed due to nonlinearity and insufficient frequency selectivity of the entrance module – RFA. As a result, all measurements of nonlinear effects and channels formed by RFA are carried out similarly to corresponding measurements for RUT.

In Figs.10–13, DFD images used for definition of the highest order of nonlinearity detected in RFA are shown. In Fig.10, a DFD of RUT model in vicinity of its tuning frequency is given. The most dangerous odd intermodulation components of the third (n=3) and fifth (n=5) orders are marked. A lot of high-order intermodulation responses are detected but their images are blended. For resolving the images, it is necessary to restrict sweep ranges of the test signal frequencies.

In Fig.11, a DFD of RUT model for the restricted area (marked by a red square in Fig.10) is given. The odd intermodulation components from the third (n=3) and up to eleventh (n=11) order are marked. Resolution of images of high-order intermodulation responses (n>25) is also insufficient here, so the next step for restriction of sweep ranges must be done.

In Fig.12, the next DFD of RUT model for smaller double-frequency area (specified in Fig.11 by a red square) is shown. The odd intermodulation components from the eleventh (n=11) and up to twenty ninth (n=29) order are marked. Resolution of images of high-order intermodulation responses (n>35) is also unsuitable here, and the last step for restriction of frequency sweep ranges is done.

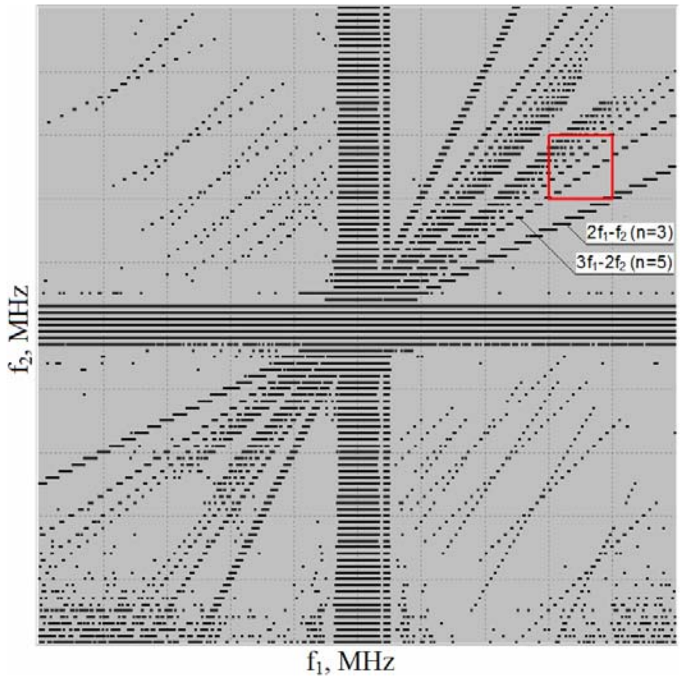

Figure 10. DFD of RUT in vicinity of its tuning frequency of 2 GHz. Parameters of test signals: sweep ranges are 1990–2010 MHz, levels are 0 dBm. n – order of intermodulation response.

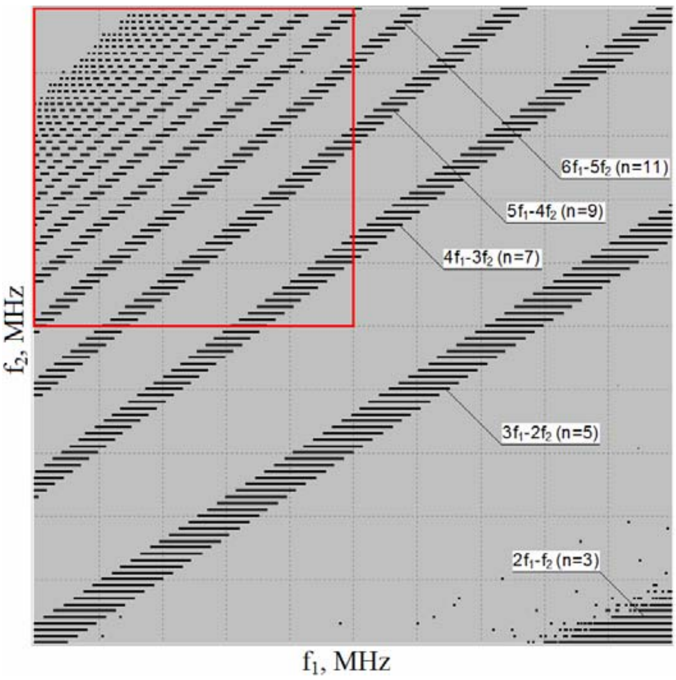

Figure 11. DFD of RUT model for restricted area (f1=2006–2008 MHz, f2=2004–2006 MHz) specified in Fig.10 by a red square.

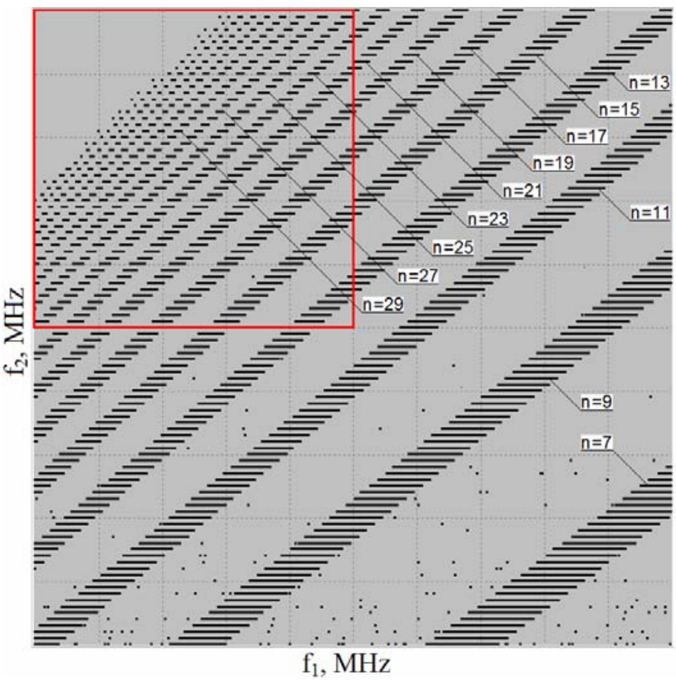

Figure 12. The DFD of RUT model for restricted area (f1=2006–2007 MHz, f2=2005–2006 MHz) specified in Fig.11 by a red square.

In Fig.13, the last DFD image of RUT model for the reduced sweep area (specified by a red square in Fig.12) is given. All detected high-order odd intermodulation components from twenty-seventh (n=27) and up to forty-first (n=41) order are marked here. The corresponding 3D image of DFC is given in Fig.14.

Earlier ADFTS versions could measure intermodulation responses only up to 21st order [4] because of the low stability and setting accuracy of the test signal frequencies.

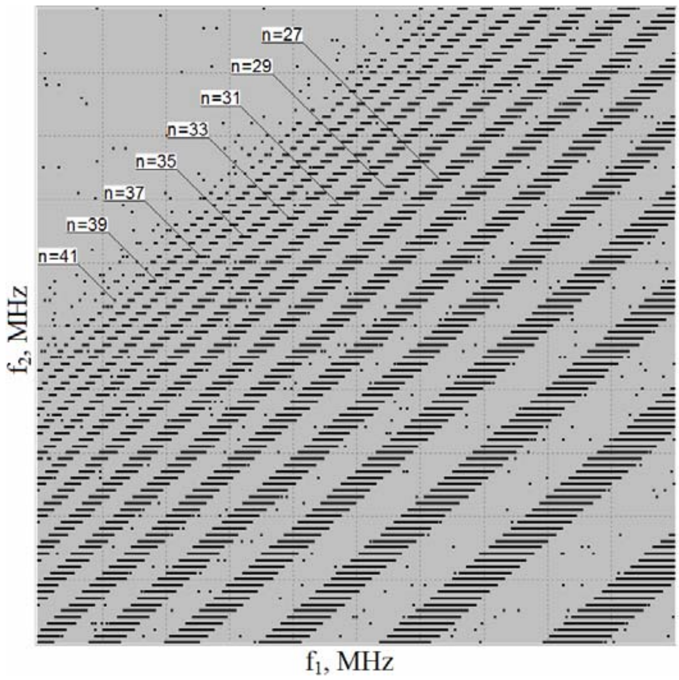

Figure 13. The DFD of RUT model for restricted area (f1=2006–2006.5 MHz, f2=2005.5–2006 MHz) specified in Fig.12 by a red square.

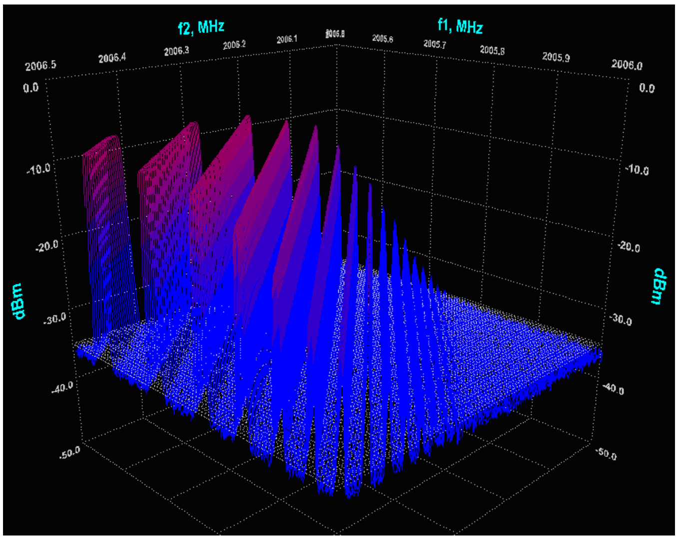

Figure 14. The 3D DFC image of RUT model for the sweep area given in Fig.13.

Modern ADFTS versions make it possible to measure parameters of RUT/RFA nonlinearity of any high order that is necessary for creation of its nonlinearity model. At the initial stage of the model creation, the forecast of the highest possible levels of input signals is made. At the next stage, RUT/RFA tests are conducted for these expected input levels by the concerned technique, and parameters of intermodulation responses of all orders detected in RUT/RFA are measured. And at the final stage, the RUT/RFA nonlinearity model adequate for RUT/RFA behavior simulation in expected operation conditions (i.e., in expected EME, which may be arbitrary complex) is synthesized [3].

V. Identification of DFD Images

A. Problem of Response Recognition

Generation of responses (desired, spurious, intermodulation ones) in radio receiver can be described by the following equation, which is referred to as channeling equation:

$$z_1 \cdot f_1 + z_2 \cdot f_2 + C = 0 , \qquad C = f_{NL,LO} - f_{out} , \tag{1}$$

$$f_{NL,LO} = \begin{cases} 0 , \quad N_{fc} = 0; \\ z_3 \cdot f_{LO1} , \quad N_{fc} = 1; \\ z_3 \cdot f_{LO1} + z_4 \cdot f_{LO2} , \quad N_{fc} = 2; \\ z_3 \cdot f_{LO1} + z_4 \cdot f_{LO2} + z_5 \cdot f_{LO3} , \quad N_{fc} = 3, \end{cases} \tag{2}$$

where z_1, z_2, z_3, z_4, z_5 are integer coefficients; f_1 and f_2 stand for the frequencies of the first and second test signals at the receiver input, respectively; $f_{NL,LO}$ denotes the frequency of a (existing or imaginary) combination component created from signals of the local oscillators; f_{out} is the carrier or intermediate frequency of the desired signal at the receiver output under analysis (for direct conversion receiver it is necessary to take the last intermediate frequency equal to zero); f_{LO1}, f_{LO2}, f_{LO3} – frequencies of the first, second, and third local oscillator, correspondingly; N_{fc} is the number of frequency conversions in the receiver.

Equation (1) generalizes the spurious and intermodulation response generation equations given in standards [5, CS108/109, CS110/111], [6, GOST 22580-84, GOST 12252-86, etc.].

In compliance with (1), each response is displayed as a straight line on the double-frequency diagram in coordinates (f_1, f_2). The problem of response identification (recognition) is to find values of the coefficients $z_1 ... z_5$ in channeling equation (1) from the given image of response in the double-frequency diagram. Having these values, the user can determine the most probable physical effects which cause the emergence of the nonlinear interference corresponding to the recognized response.

B. Proposed Recognition Technique

Known methods of response recognition are considered in [1], [4]. The only method that is able to solve the recognition problem completely (i.e., to find all the coefficients $z_1, z_2, ...$ of an arbitrary response for receiver having any number of frequency conversions) is “Method of frequency measurement and solving the system of linear algebraic equations (SLAE)” [1, Section IV, method 3].

In this paper, we propose a recognition technique which is obtained by development of the SLAE method mentioned above in the following directions:

1) In [1], the number of equations in the system is equal to the number of unknown coefficients $z_1 ... z_5$: depending on N_{fc} value, we get from 2 to 5 equations – ref. (2). In order to improve the precision of identification by averaging the results of a large quantity of measurements, we propose to use an overdetermined SLAE of the kind (3) and to solve it in the least-squares sense. For example, as it follows from (1) and (2), we get the following SLAE if $N_{fc} = 3$:

$$\begin{cases} z_1 \cdot f_{1,i} + z_2 \cdot f_{2,i} + z_3 \cdot f_{LO1,i} + z_4 \cdot f_{LO2,i} + \\ \qquad + z_5 \cdot f_{LO3,i} = f_{out,i} , \qquad i = 1, 2, ... N_{rp} , \end{cases} \tag{3}$$

where N_{rp} denotes the number of recognition points $(f_{1,i}; f_{2,i}; f_{LO1,i}; f_{LO2,i}; f_{LO3,i}; f_{out,i})$ in which the simultaneous measurement of frequencies is performed; i is the index of the recognition point under consideration. The number of equations in SLAE (3) is arbitrary and it is equal to the number N_{rp} of recognition points.

2) In [1], the system of equations is solved in real numbers and the obtained values of coefficients $z_1 ... z_5$ are rounded to the nearest integers, but such approach does not guarantee that the best integer solution will be achieved. High performance of modern PCs makes it possible to remove that drawback in the simplest way: in this paper, the solution of SLAE is found by exhaustive search through all potential solutions (i.e., integer combinations $(z_1, z_2, z_3, z_4, z_5)$) of order not higher than the maximal recognition order $M_{\max}$ specified by the user:

$$\begin{gathered} z_1,\, z_2,\, z_3,\, z_4,\, z_5 = 0, \pm 1, \pm 2, ... , \pm M_{\max} , \\ |z_1| + |z_2| \neq 0, \qquad \sum_{k=1}^{5} |z_k| \leq M_{\max} . \end{gathered} \tag{4}$$

Even in the most complicated situation (receiver has three frequency conversions and $M_{\max} = 50$) the time of solving the SLAE by the considered technique on PC Pentium IV does not exceed 5 seconds, which is quite acceptable for practice.

3) The method is expanded to the case of recognition without frequency measurement: in this case, instead of the results of simultaneous measurement of all or several frequencies from the set $\{f_{LO1}; f_{LO2}; f_{LO3}; f_{out}\}$ at every recognition point, the nominal (or singly measured) values of that frequencies are used – these values are the same for all recognition points. As a rule, the measurement of frequencies f_1 and f_2 is not necessary, which results from high stability and accuracy of frequency setting in modern signal generators.

4) Practical application of the above-described improvements in the SLAE method has shown an important drawback: the obtained solution (recognized response line) is not always located in the nearest possible way to the image of the response under recognition in the double-frequency diagram (as a result, the recognized response line may move away from the line under recognition when the maximal recognition order $M_{\max}$ is increased). Therefore, the criterion of optimization (solving the SLAE) is changed: instead of sum of squares of residuals, the geometrical criterion “Sum of squares of distances (by perpendicular) from the recognition points to a recognized response line on the double-frequency diagram” is used.

Squared distance from i-th recognition point ($f_{1,i}$; $f_{2,i}$) to the recognized response line (1) can be given by [7, eq.(2.3-1)]

$$\delta_i^2 = (z_1 \cdot f_{1,i} + z_2 \cdot f_{2,i} + C)^2 / (z_1^2 + z_2^2), \quad i = 1, 2, \ldots N_{rp}. \quad (5)$$

Then the optimization criterion can be represented as

$$J = \sum_{i=1}^{N_{rp}} \delta_i^2 = \frac{1}{z_1^2 + z_2^2} \cdot \sum_{i=1}^{N_{rp}} [z_1 \cdot f_{1,i} + z_2 \cdot f_{2,i} + C]^2, \quad C \equiv C(z_3, z_4, z_5); \quad J(z_1, z_2, z_3, z_4, z_5) \to \min, \quad (6)$$

where C is defined in compliance with (1) and (2).

If at least one of the frequencies $\{f_{LO1}; f_{LO2}; f_{LO3}; f_{out}\}$ is measured at each recognition point, then the value of C varies from one recognition point to the other one, i.e., $C \equiv C_i(z_3, z_4, z_5)$; therefore, the geometrical interpretation of the criterion (6) becomes approximate (it can be considered as approximate one, because the changes in frequencies $\{f_{LO1}; f_{LO2}; f_{LO3}; f_{out}\}$ with recognition point are much less than in frequencies f_1 and f_2).

5) The method is expanded to the situation in which there is no information about the internal configuration of the receiver under test: if the frequencies of local oscillators are unknown, then one real-valued parameter $f_{NL,LO}$, which is defined in (2) and which takes into account all frequency conversions in the receiver, is used for response recognition instead of integer parameters z_3, z_4, and z_5. Integer coefficients z_1 and z_2 (which are held by the test signal frequencies) are searched in compliance with (4), and the real value of $f_{NL,LO}$ (which may also be negative) is calculated in such a manner to minimize the geometrical criterion (6) under given z_1 and z_2.

The universality is a practically-important advantage of the developed recognition technique: the technique is able to recognize an arbitrary response of receiver having any number of frequency conversions; the technique can perform successful recognition based on different volume of initial data (based on measurements of all or several frequencies at every recognition point, or without measurement of frequencies, or even without information about internal configuration of the receiver under test). High efficiency of the technique is confirmed by practice.

VI. Conclusion

As compared with the systems of previous generations [1, 4], the new version of ADFTS has the following advantages.

1) Increased accuracy of measurements:

1.1) Images of interference responses in DFDs are practically perfect straight lines (compare the DFDs given in this paper to DFDs from [1, 4]), which is provided by high accuracy of setting and high linearity of sweeping the frequency in modern measuring generators. This allows one to recognize the detected interference responses without additional measurements of frequencies (i.e., only by computer processing of the DFD picture – ref. Section V).

1.2) The error in measurement of parameters of detected interference responses is reduced to 1 dB (from 3–10 dB in the previous versions of ADFTS), which is provided by high accuracy of setting the test signals' amplitudes at the RUT input and by high accuracy of measuring the level of RUT output signal.

2) Improved abilities for detection of interference responses (ref. Sections III and IV):

2.1) The ability to increase resolution in DFD pictures, and also to decrease the minimum level of analysis for RUT output signal, by filtering the output signal in the spectrum analyzer. This feature is provided by the increased stability of the test signal frequencies (by 3–5 orders of magnitude with respect to the previous versions of ADFTS). In the extreme case, the spectrum analyzer bandwidth (in which the output signal level is measured) can be much less than the bandwidth of the desired response of RUT – such measurements may be useful for extracting the nonlinear model of RUT.

2.2) The ability to analyze a high-dynamic-range receiver near to its tuning frequency, which is provided by low level of measuring generators' noise.

3) Increased accuracy and reliability of recognizing the detected interference responses (at the expense of the new recognition technique – ref. Section V).

4) The ability of automated extracting the nonlinear behavioral model of receiver, RFA, or mixer under test from ADFTS measurement results [3].

5) The ability of numerical and/or physical modeling the RUT operation in the user-defined EME ("Virtual Testing Area" function) [3].

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