Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 53(1), 49–55(2012)

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Antenna Diagnostics Using Phaseless NF Information

DOI: 10.7305/automatika.53-1.138
UDK 621.396.67.08.09
IFAC 5.8.3; 3.1

Original scientific paper

An extension of the Sources Reconstruction Method (SRM) for antenna diagnostics using phaseless information is presented. The aim of this work is to extend the method's capabilities from planar field acquisition domains to arbitrary ones. To achieve this goal, the SRM capabilities for handling arbitrary-geometry domains are combined with phase retrieval technique. The consideration of the radiation inverse problem with a general integral equation formulation using arbitrary-geometry field and currents domains, and field phaseless information, supposes a challenging ill-posed problem that is solved using iterative minimization techniques for non-linear problems. An application example is presented, comparing the proposed method's performance with amplitude and phase results.

Key words: Antenna diagnostics, Integral equations, Equivalent currents, Phaseless measurements, Sources Reconstruction Method

Dijagnostika antena s pomoću bezfazne NF informacije. Predstavljeno je proširenje metode za rekonstrukciju izvora (eng. Sources Reconstruction Metod - SRM) za ispitivanje antena pri čijoj primjeni nije potrebno poznavanje informacije o fazi izračenog elektromagnetskog polja. Cilj rada je proširiti mogućnosti spomenute metode na način da se osim planarnih mogu analizirati i proizvoljne geometrije plohe uzorkovanja. Za postizanje ovog cilja mogućnosti SRM-a za proizvoljnu geometriju su spregnute s tehnikom određivanje faze. Problem računanja struja iz zračenog polja bez informacije o fazi, počevši od općenite formulacije integralnim jednadžbama, predstavlja matematički neodređeni problem koji je riješen primjenom minimizacijskih tehnika za nelinearne probleme. Rezultati metode uspoređeni su s postojećim rješenjima na primjeru kod kojeg je poznata i amplitudna i fazna distribucija.

Ključne riječi: dijagnostika antena, integralne jednadžbe, ekvivalentne struje, bezfazna mjerenja, metoda za rekonstrukciju izvora

1 INTRODUCTION

Antenna diagnostics methods are becoming a key issue as non-invasive techniques: these techniques provide the extremely near field (NF) on the antenna surface, which can be used to detect antenna anomalies, avoiding the use of invasive diagnostics methods.

Diagnostics techniques are mostly based on far-field/near-field to near-field (FF/NF-NF) transformation, in order to determine the extremely NF on a surface close to the antenna-under-test (AUT). For example [1-2] present some applications for detecting faults in reflector antennas, based on the backward transformation of the fields using the Fourier Transform. [3] extends modal wave expansion-based formulation from planar acquisition domains to spherical ones. However, wave mode-based FF/NF-NF methods are restricted to canonical acquisition and diagnostics geometries (planar, cylindrical, and spherical). This limitation has been overcome by the introduction of the Sources Reconstruction Methods (SRM), an integral equation technique that characterizes the Antenna Under Test (AUT) through a set of equivalent electric and/or magnetic currents distribution.

The first SRM applications for NF/FF transformation and antenna diagnostics were restricted to planar domains [4-5]. Later, they were extended to arbitrary geometries as described in [6], where the equivalent currents are reconstructed on an equivalent surface close to the AUT.

The related antenna diagnostics techniques [1-6] are conceived to work with complex values of the field radiated by the AUT (i.e. field amplitude and phase). However, due to technical measurement system restrictions, phase acquisition is not always possible. Moreover, the growing interest in submillimeter and terahertz bands makes the phaseless antenna diagnostics methods to have potential interest for applications in these bands due to existing limitations for phase measurements [7].

The problem of antenna diagnostics using amplitude-only information has been studied under different approaches. One of the most significant contributions in this topic has been described in [8-9], where a plane-to-plane iterative backpropagation method for phase retrieval is proposed both for NF-FF and antenna diagnostics applications. These techniques require an initial guess of the field phase (sometimes, this initial guess is done in the plane wave spectrum), which can be determined from the AUT characteristics or from theoretical models.

Another approach based on the SRM has been described in [10], where an equivalent magnetic currents distribution is calculated from the minimization of a functional that relates the amplitude of the measured field and the contribution due to the reconstructed equivalent currents. Combination of this phaseless technique together with the SRM for arbitrary-shape geometry domains [6] provides an amplitude-only SRM for antenna diagnostics, which is the scope of this contribution.

2 SOURCES RECONSTRUCTION METHOD OVERVIEW

The Sources Reconstruction Method (SRM) is based on the calculation of an equivalent electric and magnetic currents distribution ($J_{eq}(\mathbf{r}')$, $M_{eq}(\mathbf{r}')$) on a surface S' that encloses the Antenna-Under-Test (AUT). The calculated equivalent currents distribution radiates the same field outside that surface as the AUT (electromagnetic Equivalence Principle, [11]). Thus, the knowledge of the equivalent currents makes possible the determination of the fields in any point outside the equivalent currents domain (S').

The equivalent currents are calculated from the field acquired on the field observation domain, by solving the Integral Equations (1) and (2) [11], which relate the fields radiated by electric and magnetic currents distribution:

$$\begin{aligned}\vec{E}_J(\vec{r}) = -\frac{j\eta}{4\pi k_0}\int_{S'}\Bigg\{ & k_0^2\frac{e^{-jk_0R(\vec{r};\vec{r}')}}{R(\vec{r};\vec{r}')}\vec{J}_{eq}(\vec{r}') \\ & + \nabla\left(\nabla\cdot\left(\frac{e^{-jk_0R(\vec{r};\vec{r}')}}{R(\vec{r};\vec{r}')}\vec{J}_{eq}(\vec{r}')\right)\right)\Bigg\}dS'\end{aligned} \tag{1}$$

$$\vec{E}_M(\vec{r}) = -\frac{1}{4\pi}\int_{S'}\nabla\times\left(\frac{e^{-jk_0R(\vec{r};\vec{r}')}}{R(\vec{r};\vec{r}')}\vec{M}_{eq}(\vec{r}')\right)dS' \tag{2}$$

Where k_0 is the wavenumber, h is the intrinsic impedance of the medium. Positioning vectors, **r** and **r**', are defined as (3):

$$\begin{aligned}\vec{r} &= \vec{r}(x,y,z) \ \in \ S_{obs}\\ \vec{r}' &= \vec{r}'(x',y',z') \ \in \ S' = S_{sources}\\ R(\vec{r};\vec{r}') &= \left((x-x')^2+(y-y')^2+(z-z')^2\right)^{1/2}\end{aligned} \tag{3}$$

Regarding numerical solution of Eq. (1) and (2), they can be rewritten in a matrix form relating the field components (E_{t1}, E_{t2}) tangential to the observation domain's surface/s with the equivalent currents components (J_{t1}, J_{t2}; M_{t1}, M_{t2}, which are tangential to the source domain S') (4):

$$\begin{aligned}\begin{pmatrix}E_{t_1}\\E_{t_2}\end{pmatrix} &= \begin{pmatrix}Z_{(E_{t1};I_{t1})} & Z_{(E_{t1};I_{t2})}\\ Z_{(E_{t2};\,I_{t1})} & Z_{(E_{t2};\,I_{t2})}\end{pmatrix}\cdot\begin{pmatrix}I_{t_1}\\I_{t_2}\end{pmatrix}\\ Z_{(E_{t1};I_{t1})} &= \begin{pmatrix}Z_{(E_{t1};J_{t1})} & Z_{(E_{t1};M_{t1})}\end{pmatrix}\\ I_{t_1} &= \begin{pmatrix}J_{t_1}\\M_{t_1}\end{pmatrix}\end{aligned} \tag{4}$$

Thus, the equivalent currents that characterize the AUT are obtained by solving the mentioned system of equations (4). Different numerical techniques are implemented: for example, [6] propose the Conjugate Gradient [12] for solving the matrix system. The minimization of cost function F (5) is done in a least mean squares sense:

$$F = \left\|\begin{pmatrix}E_{t_1}\\E_{t_2}\end{pmatrix} - \begin{pmatrix}Z_{(E_{t1};I_{t1})} & Z_{(E_{t1};I_{t2})}\\ Z_{(E_{t2};\,I_{t1})} & Z_{(E_{t2};\,I_{t2})}\end{pmatrix}\cdot\begin{pmatrix}I_{t_1}\\I_{t_2}\end{pmatrix}\right\|^2 \tag{5}$$

3 SOURCES RECONSTRUCTION USING PHASELESS INFORMATION

The knowledge of the field amplitude and phase information makes possible the utilization of just one observation surface for recovering the equivalent currents. However, when phase information is not available, it must be retrieved from the amplitude data collected at two or more observation domains. For the amplitude-only case, the cost function (5) has to be reformulated (6), so the quantity to be minimized is the difference between the amplitude of the electric field radiated by the equivalent currents and the measured one.

$$\begin{aligned}F = \Bigg\| & \left|\begin{pmatrix}E_{t_1}\\E_{t_2}\end{pmatrix}\right|^2 - \\ & \left|\begin{pmatrix}Z_{(E_{t1};I_{t1})} & Z_{(E_{t1};I_{t2})}\\ Z_{(E_{t2};\,I_{t1})} & Z_{(E_{t2};\,I_{t2})}\end{pmatrix}\cdot\begin{pmatrix}I_{t_1}\\I_{t_2}\end{pmatrix}\right|^2\Bigg\|^2\end{aligned} \tag{6}$$

While the cost function (5) is related to a linear system of equations, (6) corresponds to a non-linear cost function [13]. Thus, the use of iterative non-linear minimization methods is proposed for solving Eq. (6), such as inexact Newton-Raphson [14] and Levenberg-Marquardt [14].

For the sake of simplicity, the previous system of equations (6) will be particularized for a configuration which is of interest in several antenna measurements applications: the radiated field acquisition domain will be a (hemi-)

spherical surface, and the equivalent currents domain, a plane over the antenna aperture. Thus, the particularized system of equations is (7):

$$F = \left|\left| \left| \begin{pmatrix} E_\theta \\ E_\varphi \end{pmatrix} \right|^2 - \left| \begin{pmatrix} Z_{(E_\theta;M_x)} & Z_{(E_\theta;M_y)} \\ Z_{(E_\varphi;M_x)} & Z_{(E_\varphi;M_y)} \end{pmatrix} \cdot \begin{pmatrix} M_x \\ M_y \end{pmatrix} \right|^2 \right|\right|^2 \qquad (7)$$

In order to refine the solution provided by the minimization of Eq. (7), a two-stage iterative technique is introduced.

In the first stage (Fig. 1), a cost function relating the difference between measured and estimated field amplitude is minimized. Due to the fact that the cost function (7) is non-linear with respect to the optimization variables (M_x, M_y), non-linear minimization methods (Newton-Raphson, Levenberg-Marquardt) are used.

The second stage (Fig. 2) uses the calculated M_x, M_y currents from the first stage as initial solution. Here, a quadratic functional relating the measured amplitude of the tangential field components (E_θ, E_φ) and the estimated field phase is minimized, considering amplitude and phase information (6) Field amplitude is given by the measurements, and phase estimation comes from the field radiated by the calculated M_x, M_y. Cost function (6) is linear with respect to the optimization variables (equivalent currents), allowing the application of the Conjugate Gradient method [12].

Regarding iterative methods convergence, amplitude and phase knowledge requires less iterations to converge (typically $M < 20$, where M is the number of iterations for the second stage) than the amplitude-only case ($N = 40 - 80$ iterations, with N the number of iterations for the first stage).

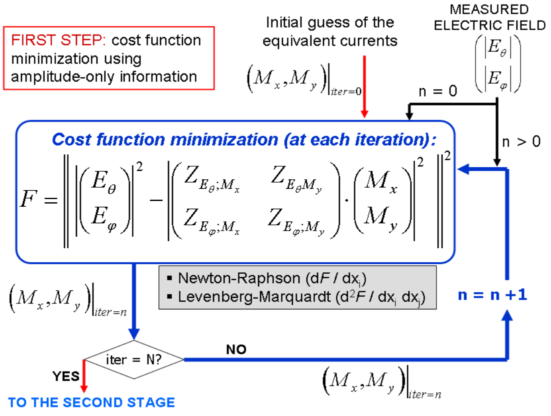

Fig. 1. Block diagram of the iterative scheme first stage (non-linear cost function minimization)

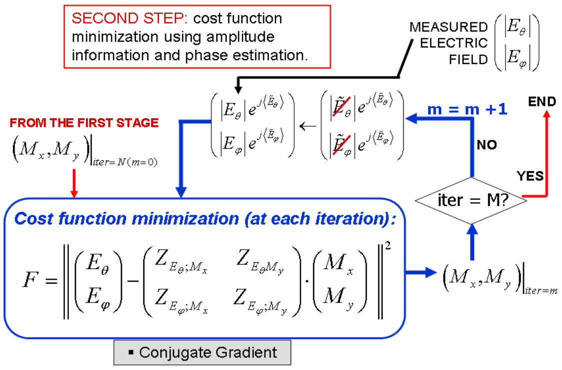

Fig. 2. Block diagram of the iterative scheme second stage (linear cost function minimization)

4 RESULTS

4.1 Application Example 1

The first example is based on the electric field radiated by a theoretical magnetic current distribution. The distribution is the same that Example No. 1 of [15], where planar field acquisition domains are considered. Here, a hemi-spherical field acquisition domain will be used. Theoretical magnetic current (M_x) follows a chessboard distribution, being the maximum values of 0 dB and minimum of -20 dB. Magnetic current domain is $2\lambda \times 2\lambda$.

Electric field due to this current distribution has been calculated in two hemi-spherical domains, being the acquisition distance $R_1 = 3\lambda$ and $R_2 = 5\lambda$. Angular sampling is $5°$ in θ and $5°$ in φ. Concerning reconstruction domain, it has been chosen to be the same than the theoretical magnetic current distribution (a $2\lambda \times 2\lambda$ domain). The geometry configuration of this example is depicted in Fig. 3.

The resulting system of equations relating the spherical field tangential components and the equivalent magnetic

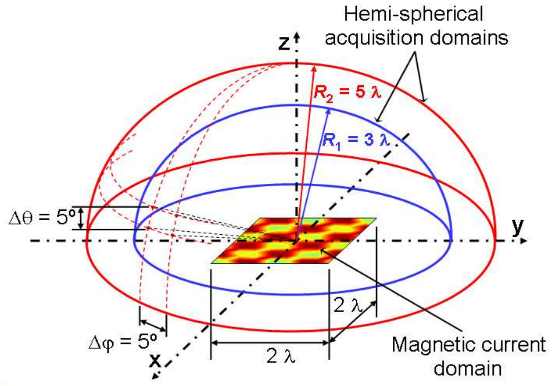

Fig. 3. Geometry configuration for the first application example

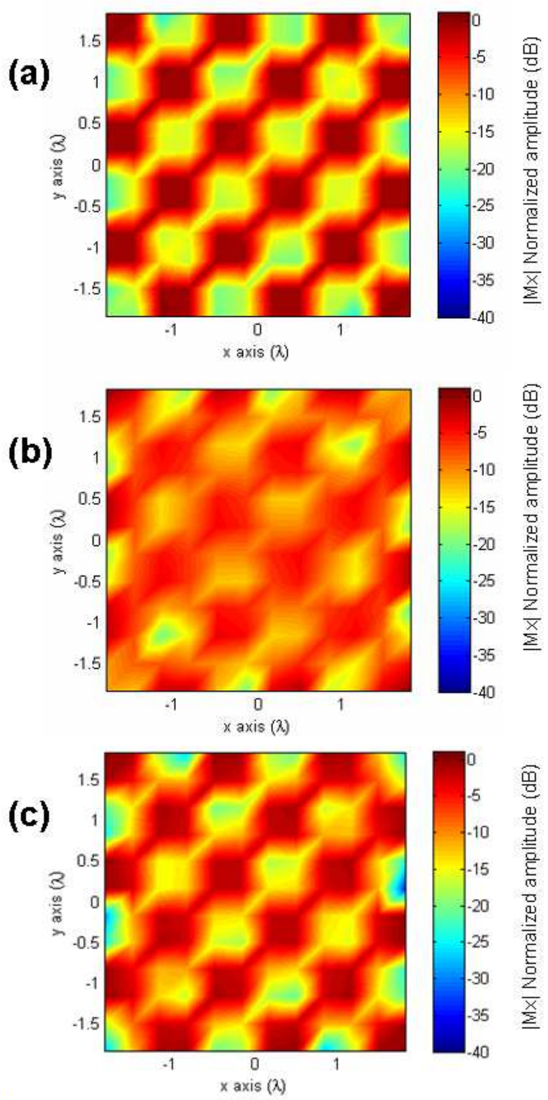

Fig. 4. Reconstructed equivalent M_x (normalized amplitude, dB) using (a) amplitude and phase information, (b) phaseless information results before the second stage of the proposed method, and (c) phaseless information results after the second stage

current distribution is, for this problem (8):

$$\begin{pmatrix} E_\theta \\ E_\varphi \end{pmatrix} = \begin{pmatrix} Z_{E_\theta,M_x} \\ Z_{E_\varphi,M_x} \end{pmatrix} \cdot (M_x) \tag{8}$$

Reconstructed M_x using amplitude-only field information is compared with the results based on the knowledge of the field phase (see Fig. 4(a)). Fig. 4(b) shows the reconstructed M_x after the first stage of the reconstruction method, that is, before introducing field phase estimation in the cost function. It is possible to appreciate the placement of the maximum and minimum of the chessboard distribution.

The second stage of the algorithm introduces the phase estimation based on the field radiated by the M_x retrieved in the first stage. Reconstructed M_x after the second stage is plotted in Fig. 4(c), showing better agreement with the reference results (Fig. 4(a)) than Fig. 4(b).

4.2 Application Example 2

The second application example aims to simulate a more realistic case. The antenna-under-test (AUT) is a 21 $\lambda/2$ y-oriented dipoles array placed along x-axis, working at $f = 1030$ MHz. Separation between array elements is 20 cm (~ 0.7 λ). Two of the elements present distorted amplitude and phase values in order to simulate antenna array malfunction.

As the AUT is a linear array, just the cut for $\varphi = 0°$ (H-plane) is considered. In this case, the system of equations relating the radiated field and the equivalent currents can be simplified to (9):

$$(E_\varphi) = (Z_{E_\varphi,M_x}) \cdot (M_x) \tag{9}$$

The field radiated by the AUT is evaluated in two 180°-arcs placed at $R_{acq} = 15$ m, and $R_{acq} = 25$ m, which belong to the AUT near field region ($R_{FF} = 110$ m). The proposed phaseless SRM method is applied for recovering the equivalent currents (M_x) on a linear domain from $x = -3$ m to $x = +3$ m. An scheme of the antenna array, the radiated field acquisition domains, and the reconstruction domain, is plotted in Fig. 5.

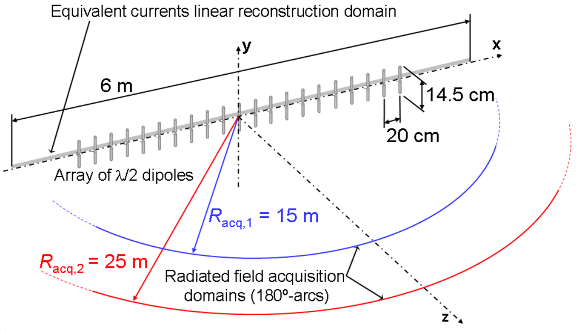

Fig. 5. Geometry configuration for the second application example

The reconstructed M_x is depicted in Fig. 6 along with the nominal excitations and the reconstructed M_x considering both amplitude and phase information of the acquired radiated field. It is seen that the amplitude distribution retrieved using amplitude and phase information (dashed line) follows the nominal excitation values (black squares).

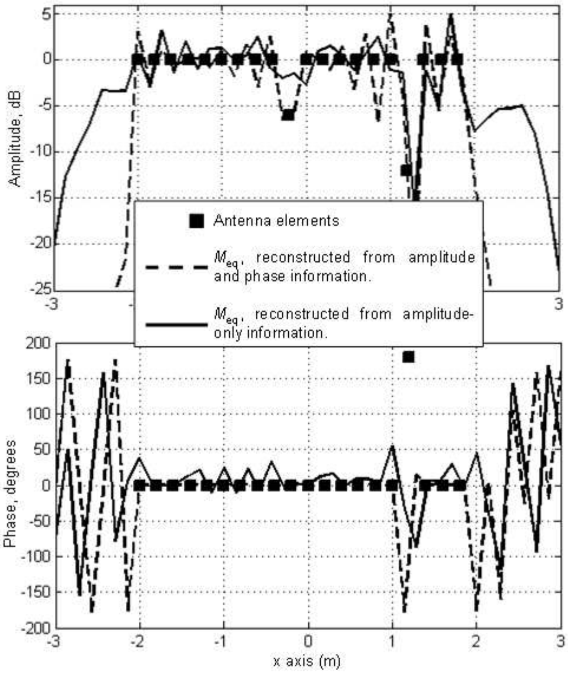

Fig. 6. Nominal excitations and reconstructed equivalent currents

The amplitude distribution retrieved from phaseless measurements is slightly worse, but the two malfunctioning elements are still able to be detected.

Next, the near field radiated by the AUT and by the reconstructed equivalent currents is plotted in Fig. 7. Apart from the agreement between both fields, it must be remarked the different field distribution for the two acquisition distances, confirming that the field has been acquired within the AUT near field region. Also note that the AUT main lobe is not conformed.

Finally, the AUT far field is evaluated, comparing it with the equivalent currents radiation pattern (Fig. 8). The main lobe and several secondary lobes are in good agreement, at least in a $\theta = \pm 30^\circ$ angular margin.

5 CONCLUSION

A Sources Reconstruction Method formulation for phaseless field measurements, which relates spherical field acquisition domain with planar equivalent currents domain, has been presented. The ill-posed problem is solved by means of a two-stage algorithm which uses field phase estimation from the reconstructed equivalent magnetic currents. The method's capabilities for phase retrieval combined with the extension from planar to spherical field acquisition surfaces, supports its potential interest for sub-millimeter and terahertz antenna measurement applications. In addition, the proposed method can be applied for in-situ evaluation of radar antenna systems (as the one presented in the second example), in which the field amplitude can be acquired with a simple power meter.

ACKNOWLEDGEMENT

This work has been supported by the "Ministerio de Ciencia e Innovación" of Spain /FEDER" under projects CONSOLIDER-INGENIO CSD2008-00068 (TERASENSE), and TEC2011-24492/TEC (iSCAT); by PCTI Asturias under Projects EQUIP08-06, FC09-COF09-12, EQUIP10-31, and PC10-06 (FLEXANT); and by the "Cátedra Telefónica—Universidad de Oviedo".

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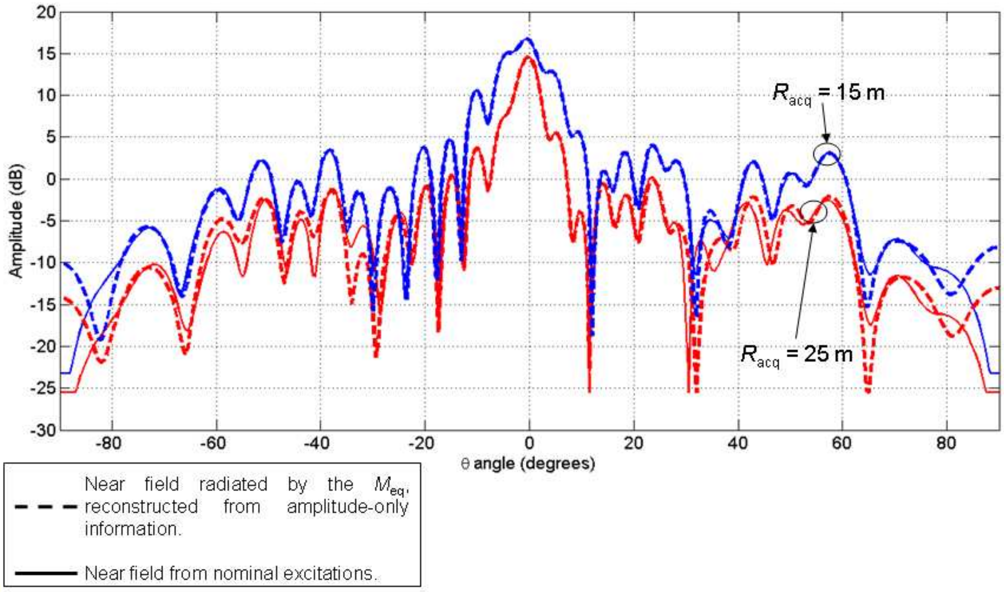

Fig. 7. Near field radiated by the AUT, and near field radiated by the reconstructed M_x

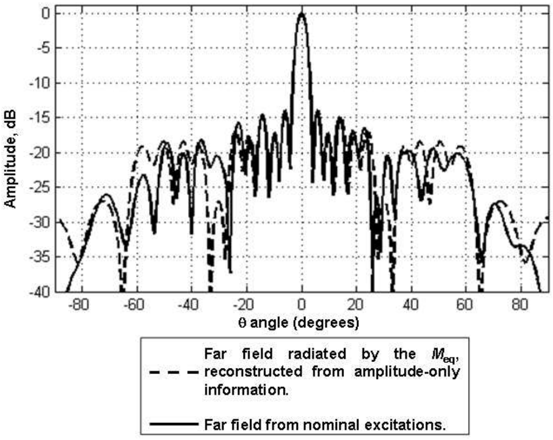

Fig. 8. Far field radiated by the AUT and by the reconstructed M_x

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Received: 2011-12-05
Accepted: 2012-01-23