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Robust Antenna Diagnostics Method using Equivalent Elemental Dipoles and The Spherical Wave Expansion

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Abstract— A robust method for antenna diagnostics that can provide the reconstruction of the aperture field from spherical near- or far-field measurements, is presented. This method is based on the equivalence principle which consists in the rewriting of the spherical wave expansion of the radiated field in terms of infinitesimal electric and magnetic dipoles distributed over the antenna main surface. This method presents the advantage of being very stable and extremely robust beside the measurement noise. Synthesized data (simulated antenna) used with different level of noise will show the viability of this technique for antenna diagnostics purpose.

I. INTRODUCTION

The existence of electrical and mechanical defaults in an antenna is usually detected by anomalies in the far-field pattern. These defaults are often due to the manufacturing procedure and may influence the antenna's performances. In most cases, we are unable to identify and localize clearly the origin of the problem directly from the far-field pattern discrepancies, unless, using invasive diagnostic techniques.

However, the analysis of the antenna extreme near-field can provide an efficient non-invasive tool to identify and localize the antenna defaults. To this end, methods have been earlier developed to reconstruct the extreme near-field from near- or far-field measurements. These methods are referred as antenna diagnostics. The extreme near-field can be determined from the knowledge of the radiated near- or far-field based on several formalisms. In [1], they have used the spherical near-field measurements to detect the errors induced by the radome defects. More recently, a comparison between two new antenna diagnostics methods is developed in [2]. The first method exploits the spherical wave expansion to plane wave expansion (SWE-PWE) relationship. The source reconstruction method (SRM), which is the second method, is based on the solution of the integral equations relating fields and currents and the application of the equivalence principle.

The equivalence principle dictates that one can define an equivalent problem of an antenna of arbitrary geometry using a surface distribution of both electric and magnetic equivalent current sources. These sources must be placed on a surface enclosing the original antenna. In these conditions, the superposition of the fields radiated by the equivalent sources must fit the field radiated by the actual antenna outside the surface enclosing the antenna. In [3], we have developed an antenna modelling technique which is based on the

equivalence principle. It consists in the replacement of the actual antenna by a spherically distributed set of electric and magnetic dipoles placed over the antenna minimum sphere.

In addition, providing the antenna a priori information, we have shown in [4] that the equivalence principle can be applied even with finite dimensions equivalent planar surface. To this end, we regularly place a set of tangential elemental dipoles over an antenna array upper surface and we determine the excitation of each dipole while solving a set of linear equations in the form $AX=B$. This linear problem makes use of the spherical wave coefficients (transmission coefficients) of the measured spherical near or far field.

Firstly, we determine the spherical wave expansion of the near- or far-field measurement data (array B) and we exploit the translational and rotational addition theorems [9] to carry out the transition matrix A, which expresses the linear relation between the transmission coefficients of the actual antenna (array B) and the unknown transmission coefficients of each dipole (array X). Since then, we try to fit the transmission coefficients of the contribution of all the dipoles with the actual antenna transmission coefficients. To this end, we use the lsqr routine from MatLab (least square data fit) to solve the over-determined matrix equation $AX=B$.

In the present paper, we propose a method combining the spherical wave expansion and the source reconstruction method (SWE-SRM). This method, which is situated between the SWE-PWE depicted in [5] and the SRM presented in [6].

In order to show the viability of this method, an antenna array has been studied with and without a default. The antenna spherical field measurement data are issued from the simulation of this antenna in a commercial simulation software (MoM) firstly without a default and secondly with a default. By studying the elemental equivalent dipoles magnitude we can localize easily the default.

The studied antenna is a linear microstrip array of aperture-coupled patches operating at the frequency 5.82 GHz. The antenna dimensions are $D_{AUT}^x = 0.1464m$ (2.84λ) along the x-axis, $D_{AUT}^y = 0.06m$ (1.16λ) along the y-axis, and $D_{AUT}^z = 0.0031m$ along the z-axis with $r_{min} = 0.085m$ (1.65λ) (Fig.1). The antenna is composed of a linear array of four rectangular patches printed on a dielectric support. Each patch is aperture-coupled to the microstrip line. A common ground plane separates the radiating part from the microstrip feeding network. The

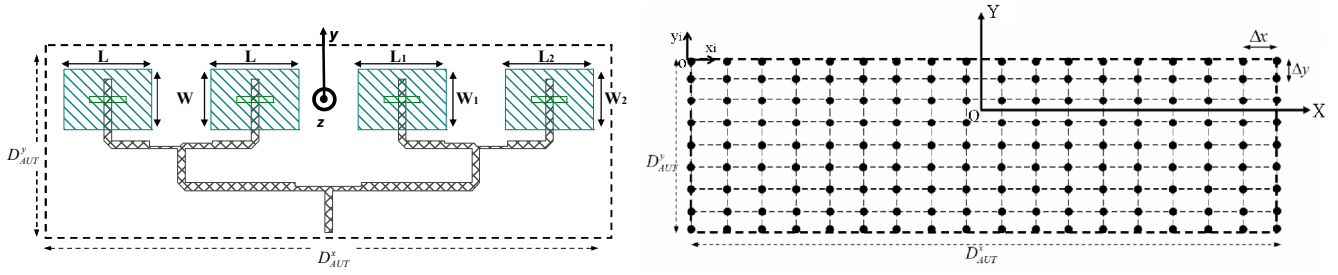


Fig.1 The description of the antenna array (left) and the equivalent current sources distribution over the antenna surface (right). $W=14.4\text{mm}$, $L=21\text{mm}$, $\Delta x=0.15\lambda$ and $\Delta y=0.14\lambda$.

antenna is issued from Antenna Center of Excellence benchmarking data base. The antenna detailed description is provided in [7].

II. THE PRINCIPLE OF THE METHOD

In this paper we intend to use the modelling method presented in [4] for antenna diagnostics. The detailed theoretical developments are provided in [4]. However, we recall the essential part that governs the method.

Initially, we express the spherical wave expansion of the E-field radiated by an antenna circumscribed by a minimum sphere of radius $r_{\min}$ [8]

$$\begin{aligned}\vec{E}_{AUT}(\vec{r}) &= \frac{k}{\sqrt{\eta}} \sum_{s=1}^2 \sum_{n=1}^{N_{tr}} \sum_{m=-n}^{m=n} Q_{s,m,n} \vec{F}_{s,m,n}^{(3)}(\vec{r}) \\ &= \frac{k}{\sqrt{\eta}} \sum_{j=1}^{J_{\max}} Q_j \vec{F}_j^{(3)}(\vec{r})\end{aligned}\quad (1)$$

Where $N_{tr} = [kr_{\min}] + 10$, $J_{\max} = 2N_{tr}(N_{tr} + 2)$

Equation (1) stay valid in a fixed coordinate system for which the minimum radius of the antenna is $r_{\min}$. For example, the field $\vec{E}^{e,z}$ radiated by an infinitesimal $\vec{z}$ -directed electric dipole placed at the origin of a coordinate system $(o, \vec{x}, \vec{y}, \vec{z})$ is expressed in the spherical coordinate system $\vec{r}(r, \theta, \varphi)$ associated with $(o, \vec{x}, \vec{y}, \vec{z})$ as

$$\vec{E}^{e,z}(\vec{r}) = \frac{k}{\sqrt{\eta}} \alpha^{e,z} \vec{F}_4^{(3)}(\vec{r}) \quad , \quad \text{with } \alpha^{e,z} = -\frac{k}{\sqrt{6\eta\pi}} I^{e,z} l \quad (2)$$

In a different coordinate system $(O, \vec{X}, \vec{Y}, \vec{Z})$ for which the distance between the origins 'o' and 'O' is equal to $r_{\min}$, the spherical wave expansion of $\vec{E}^{e,z}$ is expressed by,

$$\vec{E}^{e,z}(\vec{r}) = \frac{k}{\sqrt{\eta}} \alpha^{e,z} \sum_{j=1}^{J_{\max}} A_j^{e,z} \vec{F}_j^{(3)}(\vec{r}) \quad (3)$$

due to the fact that the vector spherical wave function $\vec{F}_4^{(3)}(\vec{r})$ is expressed in the new coordinate $(O, \vec{X}, \vec{Y}, \vec{Z})$ system as

$$\vec{F}_4^{(3)}(\vec{r}) = \sum_{j=1}^{J_{\max}} A_j^{e,z} \vec{F}_j^{(3)}(\vec{r}) \quad (4)$$

The idea is to decompose $\vec{E}_{AUT}$ into a summation of the E-field radiated from elemental dipoles placed over the antenna upper surface. To reach this goal, we solve a linear system of equations, relating the excitation of the dipoles with the antenna spherical wave coefficients in the form $AX=B$. Thereafter, by studying the magnitude of the dipoles we get access to an equivalent representation of the actual electric and magnetic antenna surface current.

First, we determine the spherical coefficients (Q_j) of the antenna radiated field measured or calculated over a sphere (near or far field). Then, we place a distribution of equivalent tangential dipoles over the antenna main surface and we calculate their current excitation. By comparing the equivalent currents magnitude for an antenna with and without defaults we can easily localize the default.

III. RESULTS

The proposed antenna diagnostics method is applied to analyse and localise an eventual default in the design of a 4-patches antenna array. To this end, the electric field radiated from the antenna under test (AUT) presented in Fig. 1 has been calculated at the frequency 5.82GHz using a commercial simulation software (Method of Moment). Then, we determine the antenna Q_j coefficients from the tangential field E_θ and E_ϕ collected over a sphere of radius $R_{\text{meas}}=75\text{cm}$ respecting the angular spacing $\Delta\theta=\Delta\phi=5^\circ$. These coefficients are presented in Fig. 4.

Based on the AUT Q_j coefficients we determine the excitations of 18×9 current sources regularly placed over the surface that spatially coincides with the AUT upper surface (Fig. 2). Each current sources is composed of 2 tangential electric dipoles and 2 tangential magnetic ones.

Thereafter, we artificially introduce different defaults in a patch composing the AUT by simply changing its dimensions (L_1, L_2, W_1, W_2). The actual patch dimensions are $W=14.4\text{mm}$ and $L=21\text{mm}$.

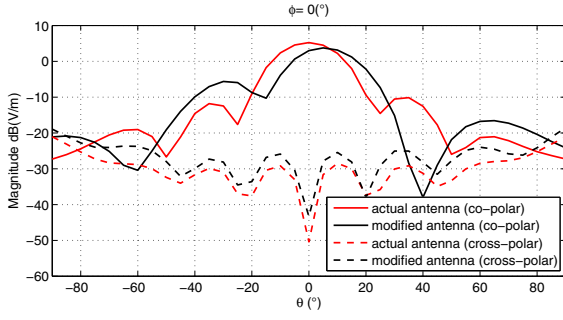


Fig.2 Comparison of co-polarized and cross-polarized components of the fields at the measurement distance $R_{\text{meas}}=75\text{cm}$. The comparison includes: the actual antenna radiation pattern and the field radiated by the modified antenna ($W1=W-2\text{mm}$) for $\phi=0$.

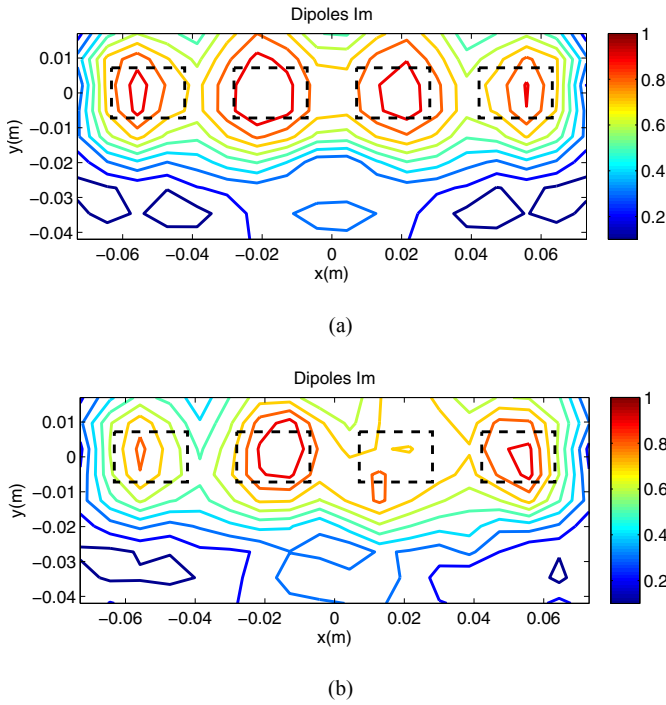


Fig.3 The normalized magnitude of the equivalent magnetic dipoles distributed over the equivalent antenna aperture after the introduction of a default in the third antenna patch ($W1=14.4\text{mm}$ in (a) and $W1=12.2\text{mm}$ in (b)). The dashed rectangles represent the actual antenna patches.

In order to show the viability of the proposed method, we introduce artificial defaults by changing, in the first example, the width of the AUT third patch by considering $W1=W-2\text{mm}=0.86W$. The dimensions of the other patches stay unchanged. In the second example, we modify the length of the AUT fourth patch by considering $L2=L-2\text{mm}=0.9L$, when the other patches dimensions stay invariable. The introduced default let think that when $W1=W-2\text{mm}=0.86W$, this implies a significant effect over the antenna radiation pattern. In the second example, where $L2=0.9L$, this will slightly affects the antenna radiation pattern.

We distinguish between these two default kinds by minor and major default. Minor default implies minor effects on the

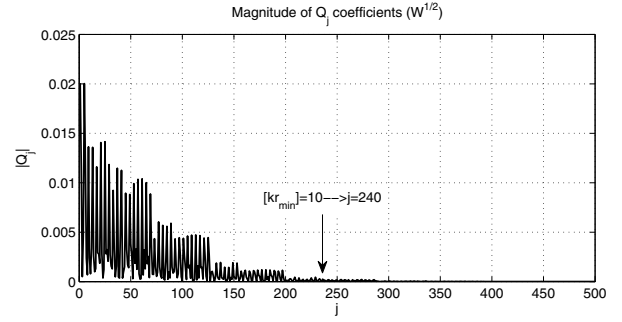


Fig.4 Magnitude of the antenna array Q_j coefficients calculated from the tangential components E_θ and E_ϕ collected over the spherical surface of radius $R_{\text{meas}}=75\text{cm}$.

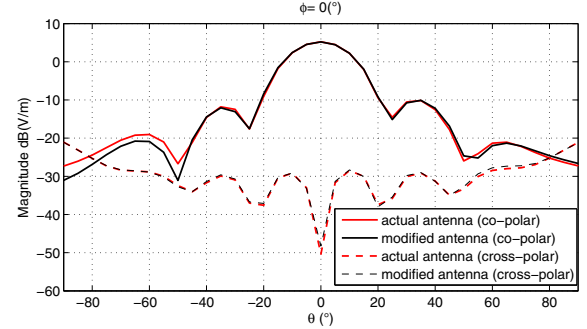


Fig.5 Comparison of co-polarized and cross-polarized components of the fields at the measurement distance $R_{\text{meas}}=75\text{cm}$. The comparison includes: the actual antenna radiation pattern and the field radiated by the modified antenna ($L2=L-2\text{mm}$) for $\phi=0$.

initial AUT radiation pattern. Major default affects significantly the actual antenna radiation pattern.

A. Major Default: $W1=W-2\text{mm}=W-0.04\lambda$ and $L1=L$

Using the MoM, the modified antenna radiation pattern is calculated over the sphere of radius $R_{\text{meas}}=75\text{cm}$ taking into account the new dimensions of the third antenna patch ($W1=W-2\text{mm}=W-0.04\lambda$, $L1=L$, $L2=L$ and $W2=W$). In Fig. 2, we compare the actual and modified antenna radiation patterns for $\phi=0$. As shown in Fig. 2, the introduced default have considerably changed the radiation pattern of the antenna.

Based on the Q_j coefficients resulting from each antenna configuration (actual and modified), we determine the corresponding excitation of the equivalent dipoles. In Fig. 3, we present the equivalent magnetic dipoles magnitude issued from the actual antenna (Fig. 3 (a)) and the magnetic dipoles magnitude resulted from the modified antenna (Fig. 3 (b)). As it can be seen, the hotspots are focused in the patch's locations either for actual or modified antenna. However, the modification of the third patch dimensions ($W1=W-2\text{mm}=W-0.04\lambda$) have caused a significant alteration of the equivalent dipoles distribution. Although we have changed the geometric properties of only the third patch, the magnitude of the whole equivalent current have been modified. Especially, the hotspot corresponding to the third patch of the antenna has been significantly distorted. This alteration around the third patch can be interpreted as being the localization of the antenna default.

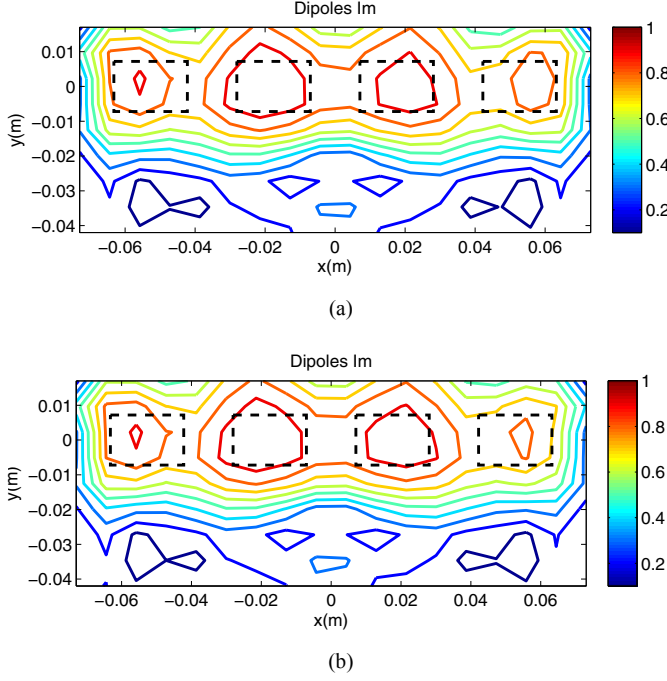


Fig.6 The normalized magnitude of the equivalent magnetic dipoles distributed over the antenna aperture after the introduction of a default in the fourth antenna patch ($L_2=21\text{mm}$ in (a) and $L_2=19\text{mm}$ in (b)). The dashed rectangles represent the actual antenna patches

B. Minor Default: $W_2=W$ and $L_2=L-2\text{mm}=L-0.04\lambda$

Similarly, we consider this time a different antenna configuration for which $W_1=W$, $L_1=L$, $L_2=L-2\text{mm}=L-0.04\lambda$ and $W_2=W$. We have used the simulation software (MoM) to calculate the E-field tangential components of this new antenna configuration over the sphere of radius $R_{\text{meas}}=75\text{cm}$. Based on these data, we determine the corresponding spherical wave coefficients Q_j .

For $\varphi=0$, we present a comparison between the actual and the modified antenna radiation patterns in Fig. 5. As it can be seen, the modification introduced to the fourth patch does not significantly affect the radiation pattern of the AUT. This means that the localisation of the introduced default will be difficult since it slightly disturb the antenna radiation pattern.

In order to detect the antenna default, we determine the excitation magnitude of the equivalent dipoles resulting from the Q_j of the actual antenna and the Q_j associated with the modified antenna. For both cases we consider the truncation number $N_{tr}=kr_{\min}=10$. The results are plotted in Fig. 6.

The two graphs presenting the magnitude of the equivalent magnetic dipoles, corresponding to the actual antenna (Fig. 6 (a)) and to the modified antenna (Fig. 6 (b)), are very similar. However, it is seen that the slight difference between the two graphs (a) and (b) is apparent for the hotspot located in the third and especially in the fourth antenna patch positions.

From this example, we conclude that for a minor antenna default this method can be helpful for antenna diagnostics purpose, even if the default has a minor effects on the antenna radiation pattern.

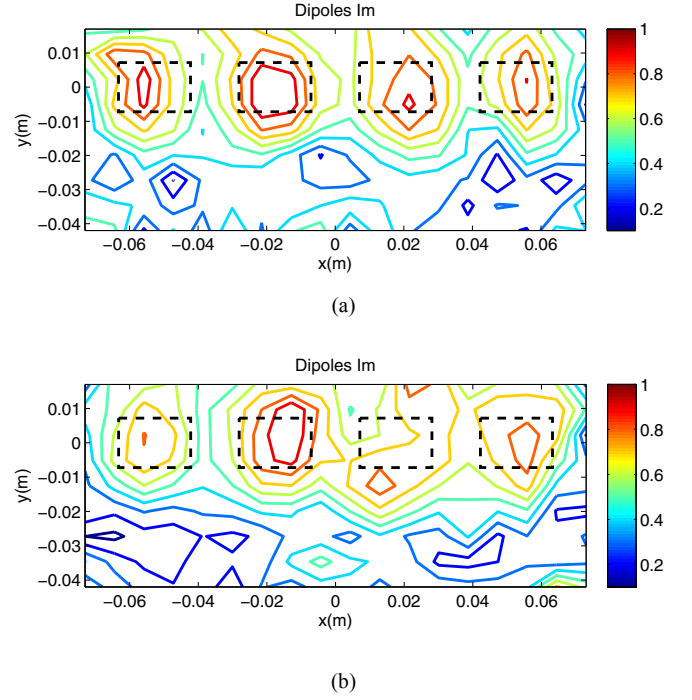


Fig.7 The normalized magnitude of the equivalent magnetic dipoles distributed over the equivalent antenna aperture after the introduction of a default in the third antenna patch ($W_1=14.4\text{mm}$ in (a) and $W_1=12.2\text{mm}$ in (b)). The equivalent dipoles have been calculated using measurement data to which we have added white Gaussian noise in order to reduce the signal to noise ratio to 40dB. The dashed rectangles represent the actual antenna patches.

C. Stability of the proposed antenna diagnostics method

Measurement uncertainties will have some repercussion on the quality of the equivalent current reconstruction, and this aspect is closely linked to the stability of the proposed antenna diagnostics method.

In fact, in an experimental setup, we can be faced with the uncertainty of antenna alignment. If the antenna is not perfectly placed in the centre of the measurement sphere, it will results in off-centred retrieved equivalent dipoles. This makes difficult the diagnostic of a real antenna in a real measurement setup since the surface over which the equivalent current sources are placed will not coincide with the antenna main radiating surface. Nevertheless, a good knowledge of the measurement positioning system can help to come over this limitation. The second limitation that we are faced with concerns the accuracy of the measurement data.

In order to check the effect of a reduced dynamic range measurement data, we have manually added artificial white Gaussian noise (WGN) to the E-field spherical field components issued from the simulation software (MoM).

Using the simulated E-field, for which we have added WGN to reach a measurement data with 40dB dynamic range, we determine the equivalent current sources associated with the actual and modified antenna (Fig. 7 (a) and (b) respectively). For this study we have adopted the

configuration of major antenna default presented in section II-A.

As it can be seen from Fig. 7, the hotspot positions coincide with the antenna patch locations in both figures (a) and (b). However, an important modification of the equivalent dipoles magnitude corresponding to the third patch position indicates that the antenna default is located in the third antenna patch.

In conclusion, even with a measurement data with 40dB dynamic range, the proposed method stays efficient for antenna diagnostics purpose.

IV. CONCLUSION

A method for antenna diagnostics has been presented and validated. Based on spherical near- or far-field, this method has proven to be an efficient tool to identify and localize defaults in an antenna array. The antenna diagnostics is based on an equivalent representation of the actual antenna surface current. Using a set of dipoles distributed over the main antenna surface this method has shown a real capacity to detect either eventual minor or major defaults in antennas design. Furthermore, the stability and the robustness of the method has been studied by adding an artificial noise to the measurement data.

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