Revision of Diagnosis Techniques: Holographic and Equivalent Currents Reconstructions

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***Abstract*—This overview paper, included in the convened session "Fast, low-invasive visualization of EM-Very-Near Field distributions around wireless communication/sensing devices: from anechoic chamber to microscope", revises the reconstruction techniques used in antenna design and antenna measurements. Among them, the two classical approaches are presented: holographic techniques and equivalent currents, showing later some applications and examples. These techniques are very powerful tools for being able to afford the design of very large antennas and for the reduction of uncertainty in some antenna measurement problems.**

***Index Terms*—antenna measurements, holographic techniques, equivalent currents, source reconstruction.**

I. INTRODUCTION

The reconstruction of the electromagnetic (EM) equivalent currents are one of the most powerful low-invasive visualization of the electromagnetic very near field distribution. This paper presents the two more classical techniques: the equivalent currents (EQC) and the holography used for this objective. The algorithm used for the equivalent currents' reconstruction uses the Love's Equivalence Principle and can be found in [1]. In this way, from the measurement of two tangential components of the electric field on a surface around the antenna under test (AUT) (e.g. typically, but not limited to, a spherical near field acquisition) the electric and magnetic currents on a very near field volume enclosing our AUT can be calculated. This is the principle employed in the software Insight [2], from MVG, that will be used for the examples shown in this paper.

The second technique is called in the literature backward transformation or holographic technique, and it is the most employed in antenna diagnostic technique due to its mathematical simplicity and low processing time, since it uses the Fourier Transform for the calculation of the electromagnetic sources from the electric or magnetic field. Holographic technique is based on the direct relationship between the field acquired in the forward hemisphere of the far-field region and the visible portion of the Plane Wave Spectrum (PWS). Then, the field distribution over the AUT plane is calculated performing a Fourier transform to the PWS [3]. The main advantage of this technique is that it allows to calculate directly the sources from the radiated far field (or even easier from a planar near field acquisition). However, in principle, the main limitation is that the resolution is limited to half wavelength (although there are some methods to improve this limit). Another limitation is that this method is appropriate for directive array or aperture antennas, where the currents can be calculated.

The use of these techniques has been extensively used in antenna design. However, the increase in the capability of computers allows to combine these techniques with some post-processing algorithms to improve the results of the antenna characterization or to afford design of very large antennas combining simulation and measurements. These applications can be summarized in antenna diagnostics, cancellation of spurious signals (echoes or leakage), filtering of some elements of the antenna measurement set-up, near to far field transformation, increase of the signal to noise ratio, extrapolation of the radiation pattern, or the combination of simulations and measurements to be able to simulate, for instance, the effect of the antennas integrated in large and complex structures for automotive, defense or space applications [4].

This paper is divided into the following sections: section II shows the theory of the equivalent currents' technique, section III the basic theory of holographic techniques, and section IV some examples of application of these techniques for the visualization of the electromagnetic fields and its application. Finally, section V concludes the paper.

II. SOURCE RECONSTRUCTION USING EQC TECHNIQUE

The source reconstruction technique using equivalent currents (EQC) consists in the calculation of the electric and magnetic currents distribution that represent the radiation of one antenna and radiate the same electric and magnetic field outside the AUT. The explanation of the method can be found in [4], where also the uniqueness of the solution is demonstrated. A summary is here explained.

The AUT includes all the conductors and dielectrics and radiates a specific electric and magnetic field (E, H) outside the surface surrounding it. According to the Love's Equivalence Principle, if the AUT is replaced by a surface enclosing the antenna, and we force a null EM field inside this surface, not only the radiated field for both structures is the same, but we can perform diagnostic, since there is uniqueness of the solution, with the currents proportional to the field in the surface of the geometry. Another advantage of the zero-field inside, is that we can place objects inside the Huygens box to increase the accuracy of some specific computations. Therefore, it is possible to calculate these fields from the radiated field of the AUT, having the same electromagnetic solution.

III. Source Reconstruction Using Holographic Techniques

Source reconstruction using holographic techniques is also called in the literature backward transformation. This has been the most employed in antenna diagnostic technique due to its low processing time. Holography is based on the direct relationship between the field acquired in the forward hemisphere of the far-field region and the visible portion of the Plane Wave Spectrum, (PWS) [3], being able to calculate the sources on the AUT plane through the FFT. This technique has been widely applied to different EM problems, and it is particularly useful for large array antennas or aperture antennas as reflectors [5], [6]. The relation between field on the aperture and PWS (Eq.1) is shown in [7], and can be calculated using a two-dimensional FFT.

$$\vec{E}_{ap}(x,y)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\vec{P}(k_x,k_y)\cdot e^{-j(k_x x+k_y y)}dk_x dk_y \quad (1)$$

where $P(k_x,k_y)$ represents the plane wave spectrum and (k_x,k_y) is the components of wave number in x and y.

The main advantage of the holographic technique is that it can be used from the far field, since there is a direct relation between the far field and the plane wave spectrum. Fig. 1 shows an example of application: the diagnosis of a 4x5 array antenna. It can be observed that there are 4 elements with several problems, being difficult to detect with the radiation pattern. Also, since FFT is computationally very efficient, although it requires samples distributed on a regular grid in both domains: the samples of the extreme near-field are obtained on a regular x-y grid, and the PWS samples must be known on a regular k_x-k_y grid. When the algorithm uses the far field information, the samples use to be calculated on a regular θ-ϕ grid, and therefore, a two dimensions interpolation is required to calculate the samples in the required grid. This solution introduces an interpolation error that must be considered, but it does not require a great computational cost.

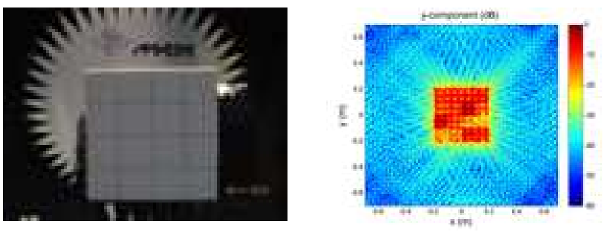

Fig. 1. Example of application of holographic techniques: diagnosis of an array antenna.

The application of the holographic technique to planar near field measurements is also direct since the PWS is obtained performing an inverse Fourier transform of the measured samples (although the probe correction should be applied). Since this PWS is referred to the measurement plane, a backpropagation to the antenna aperture plane is used to determine the appropriate PWS (Eq.2), and then, the currents on the antenna aperture are obtained through a Fourier transformation of the PWS, Where d is the separation between the AUT and the planar scanner.

$$\vec{P}(k_x,k_y)=\vec{P}(k_x,k_y,z=d)\,e^{jk_z d} \quad (2)$$

Since the PNF measurement uses to be performed at few wavelengths from the AUT, the contributions coming from the evanescent modes are negligible. Therefore, there is no information about the PWS in the invisible region, as in the far-field case, and the maximum spatial resolution is half a wavelength. In fact, in the case of the planar acquisition, since the PWS is only reliable in a reduced angular range, depending on the geometry of the measurement system, AUT and position of it in the planar system, the spatial resolution is lower than half wavelength.

In the case of spherical near field acquisitions, Cappellin in 2007 [10] proposed the use of a direct transformation between spherical modes and plane wave spectrum as the basis of a diagnostic technique for spherical near field measurements and, therefore, without losing the spatial resolution. This is obtained since the information of the invisible region is used in this process.

As it was mentioned previously, the main limitation of the holographic techniques is the maximum resolution, since it is limited to half wavelength, since it is only valid the information in the visible range. However, some methods to extrapolate the plane wave spectrum, out of this visible region, using the information of the geometry of the AUT have been implemented. The Gerchberg-Papoulis algorithm was extended to the EM problems by Rahmat-Samii [8]. Another example of application of this algorithm, using information of the position, orientation and dimension of the slots in a radial line slot antennas was proposed in [9]. In this case (Fig. 2), the currents on the slots could be reconstructed with a separation of a quarter wavelength.

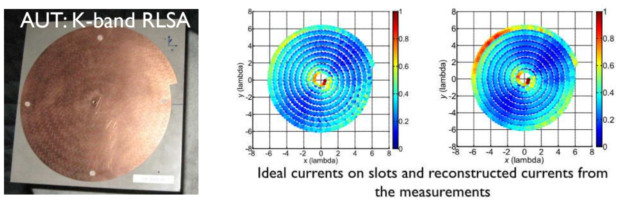

Fig. 2. Example of application of Gerchberg-Papoulis algorithm in the reconstruction of slot currents in a radial line slot antenna.

IV. Applications of the Source Reconstruction to Antenna Design and Measurement

Sections II and III have explained the two most used techniques for reconstructing the currents on the antenna aperture or on a surface enclosing the antenna. The main application is for antenna diagnosis, as is shown in the previous section. However, this information can be exploited to other uses, at is explained in Fig. 3, both to help in the antenna design, to improve the quality of the antenna measurements or even to afford the characterization or complex antennas or antennas integrated in the environment. This section explains some of the applications of the source reconstruction.

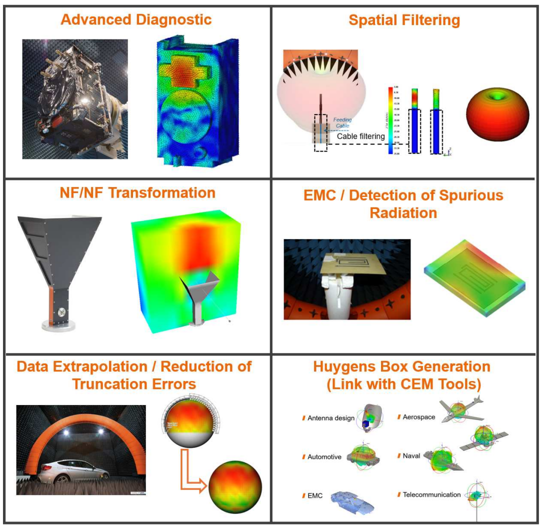

Fig. 3. Some Applications of the Equivalent Currents in Antenna Design and Measurement.

A. *Echo supression and spatial filtering*

The echoes in antenna measurements are difficult to cancel, especially in outdoor or in low frequency systems. During the last years, different techniques using spherical or cylindrical modes have been studied. Also, the use of equivalent currents has been exploited, both using holographic techniques and the calculation of the currents on a surface enclosing the AUT. Any of these techniques can remove the unwanted contributions, that significantly modify the actual antenna properties, producing mainly some ripples in the radiation pattern.

The method explained in this section uses the source reconstruction on a large plane using the holographic techniques and the image theory. If the AUT is on a ground plane, the electromagnetic problem, applying the image theory can be replaced by the AUT and its image. If now, we calculate the equivalent currents on a surface enclosing the AUT and extending this surface to include also the image, we can obtain not only the currents associated to the AUT but also the ones associated to the reflected rays. Filtering out the currents associated to the image, the effect of the echoes in the radiation pattern can be removed. Since the dimension of the reconstruction surface depends on the step in the plane wave spectrum, an interpolation should be carried out to be able to filter out the spurious samples.

Fig. 4 shows an experiment performed at UPM planar field system. An antenna horn is measured with a large ground plane to create the undesired echo. The holographic technique is applied and both AUT and its image are located. The image is filtered out, and the radiation pattern can be recalculated. Fig. 5 compares the reference pattern with the unfiltered and the filtered one, showing excellent agreement. The main advantage of this system is that only one frequency is measured, with a conventional vector network analyzer. The main disadvantage is that the echoes can only be cancelled if the echo is in the same relative position respect the AUT: for example, this happens in planar systems, in cylindrical systems in the z-axis and in multiprobe spherical systems in the multiprobe axis. Also, this technique is valid for aperture antennas as horns, reflectors and array antennas.

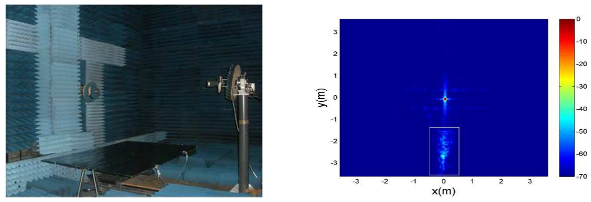

Fig. 4. Experiment in UPM planar near field system: measurement of a Ku band antenna and source reconstruction

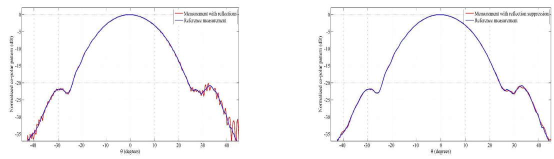

Fig. 5. Comparison of measured, reference and filtered radiation pattern.

B. *Extrapolation of the radiation pattern*

The use of holographic techniques together with iterative methods based on Gerchberg-Papoulis algorithms [12],[13] can be used to extrapolate the radiation pattern. This method is applied by Martini et al. [14] to planar near field measurements. Once a measurement is done in a plane, the plane wave spectrum can be calculated, and it can be assumed that the measurement is valid in a certain region in *uv* domain, that depends on the geometry of the AUT and antenna measurement system. If the surface where the AUT currents are located is known, this information can be used to consider that the currents out of this area is null. Iterating to both domains (plane wave spectrum and AUT surfaces) using holographic techniques and using the information of the PWS in the valid measured region and the currents on the AUT, the radiation pattern can be extrapolated to one hemisphere. Cano et al. extended this algorithm to cylindrical and spherical acquisitions in [15]. Fig. 6 shows the results for a 14 GHz ku-band reflector antenna measured in the UPM cylindrical range with a validity angle of 25 degrees. It is observed, in red, that the radiation pattern out of the valid region is clearly disturbed, while, applying the Gerchberg-Papoulis algorithm, the pattern can be extrapolated to the hemisphere. Again, the main drawback of this technique is that it is valid if the currents on the AUT are well defined.

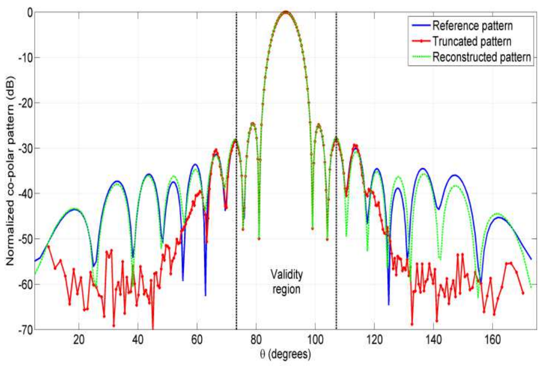

Fig. 6. Experiment of the extrapolation of the radiation pattern at UPM cylindrical near field system.

C. *NF/FF and NF/NF Transformations*

The EQC technique is a powerful tool to perform arbitrary field transformations, such as near-field-to-near-field (NF/NF) and near-field to far-field (NF/FF). Like the conventional field transformation based on the Spherical Wave Expansion (SWE) of the field [16], from the computed EQC the field can be evaluated everywhere outside the reconstruction geometry. The main advantage of the EQC technique over the SWE is the possibility to compute the field at much closer distances, since there are no constraints due to the minimum sphere of the AUT [16]. Moreover, as shown in [17], the EQC is usually more robust again errors due to the truncation of the scanning area, resulting in more accurate field computations in case of partial spherical near field (SNF) acquisitions.

An interesting application of the NF/NF transformation based on the EQC is the calculation of the Power Density (PD) from SNF scanning [18]. Specific PD measurements are needed to verify compliance of the EM field emission of modern mobile terminals. Typical PD testing are based on robotic arms or planar scanners, where a probe is used to measure EM field at the required distances. Such operations can be very time consuming especially with modern 5G devices, where many antenna configurations and services must be tested. The measurement technique proposed in [18] is instead based on fast SNF measurement of the DUT combined with the calculation of the EQC around the device, followed by the computation of the field in the planes of interest, and finally the evaluation of the PD.

The example reported in Fig. 7, is relative to a quad-ridge horn (the QR18000 by MVG) measured at 10GHz in the StarLab multi-probe system by MVG, which allows for fast and accurate SNF scanning. The EQC computed with the MVG-INSIGHT tool, are shown on the right side of Fig. 7. From the EQC, the EM fields on cut planes parallel to the direction of propagation, at several distances from the aperture, are computed. The spatial-averaged PD (sPD) are then computed considering 1cm^2 and 4cm^2 integration areas. Fig. 8 compares the peak of the sPD computed from the measurement and from a high-fidelity full-wave simulation of the same antenna. As can be seen, the agreement between predictions and measurement is excellent at each distance from the antenna.

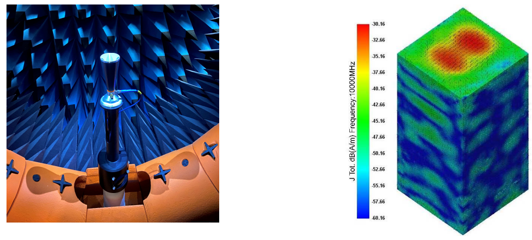

Fig. 7. QR18000 during measurement in the StarLab (left). EQC at 10GHz computed from the SNF measurement of the antenna (right)

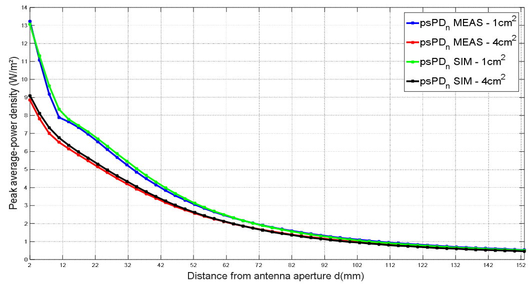

Fig. 8. Comparison between measured and simulated peak sPD at 10GHz.

D. *Combination of Measurements and Simulation in Antenna System Design and Validation*

The availability of the EQC from measurements allows the evaluation of the behavior of the measured antennas in the final operational environment [19]. This can be done by following the workflow shown in Fig. 9. From the measurement of the AUT, the EQC are computed on a so-called Huygens' box which is then imported in Computation EM (CEM) tool to evaluate the performances of the antenna in complex structures such as vehicles, aircraft, satellites, ships etc. The accuracy of the antenna representation significantly enhances the reliability of the results with respect to scenarios in which both the source antenna and the complex structure are fully simulated. It should also be noted that in many cases, the antennas come from a third party, that could be reluctant to share property information of the antenna. In such cases, the Huygens' box approach could be the only solution to share information between different teams. This approach has indeed recently gained significant attention because of its versability and effectiveness. The possibility to accurately predict the antenna performances in the final system already in the preliminary stages of the development allows to significantly reduce the development costs, and the time-to-marked of a product [19]-[22].

Fig. 9. Application of the equivalence theorem to the calculation of the radiated field of one antenna in a complex environment.

The combination of measurements and simulations with the EQC technique has been validated in many scenarios and different applicative examples have been reported in literature [19]-[22]. An accurate representation of the source antenna is paramount, and particular attention must be paid depending on the final application. For example, it has been shown that, in case of flush mounted antennas, it is recommended to measure the antenna with a representative ground plane, to properly enforce the local boundary condition [20]. This allows for accurate antenna placement analysis, for example in automotive scenarios.

Other interesting and very promising applications of the Huygens' box approach are the evaluation of the coupling between antennas installed in complex structures [21], and the evaluation of the Specific Absorption Rate (SAR) of mobile terminals from SNF measurements [22]. The so-called non-invasive SAR measurements are based on the SNF acquisition of the smartphone, the computation of the Huygens's box and the final evaluation of the SAR with a CEM tool where realistic human beings or phantoms are accurately modelled. Like the PD measurements, the main advantage of this approach over the conventional (invasive) SAR technique based on the actual scan of a phantom-liquid fed by the smartphone, is the possibility to significantly speed up the testing time.

V. CONCLUSIONS

This overview paper has revised the source reconstruction techniques as one of the most common low-invasive visualization of electromagnetic near field distributions. Two different techniques have been shown, and different examples of application, for the diagnosis in the antenna design process, for improving the quality of the measurement, or to be able to characterize complex antenna systems have been shown, with several examples.

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