Probe Correction Technique of Arbitrary Order for High Accuracy Spherical Near Field Antenna Measurements

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Abstract—Probe correction in standard spherical near field measurements are typically limited to probes with $|\mu|=1$ spherical wave spectrum when performing spherical wave expansion [1-3]. The design of such probes is often a trade-off between achievable performance, modal purity and bandwidth [4-5]. Compensation techniques for probes with higher or full order modal spectrum have recently been proposed [6-11]. The advantages of such techniques are more freedom in the selection of the probe for a given measurement scenario and increased bandwidth. The technique reported in this paper is valid for probes with a known modal spectrum of arbitrary order. Probe compensation is performed directly on each spherical wave function before expanding the measured field. This leads to a computationally very effective algorithm [11]. In this paper, the accuracy of the new algorithm is validated experimentally for different higher order probes in the measurement of a standard gain horn. For each scenario, the accuracy and computational requirement of the new algorithm is compared to standard transformations.

I. INTRODUCTION

In high accuracy Spherical Near-Field (SNF) measurements the averaging of the probe aperture on the acquired data is often compensated in the Near-Field to Far-Field (NF/FF) transformation [1-3]. The probe impact on measurement accuracy is stronger for larger view angles of the measured antenna/device and for probes with high directivity. A widely used probe compensation (PC) procedure is of first order which is applied directly during the Spherical Wave Expansion (SWE) [3]. This procedure has been demonstrated to be very accurate and computationally efficient. However, it impose stringent requirements on the probe as its spherical wave spectrum should be limited to first order azimuthal mode $(|\mu|=1)$. Probes, satisfying this requirement are often called "first-order" probes. Higher order modes ($|\mu|>1$) in the probe spectrum will impact measurement accuracy due to the modal truncation of the probe spectrum in the NFFF expansion.

Probe performance is often a trade-off between modal purity and bandwidth. Classical first order probes are often limited to bandwidth of 20% or less. For this reason, significant design efforts have been devoted to the developments of probes compliant with modal purity requirement on wider bandwidths compatible with modern measurement needs [4-5]. In order to have less restrictions in the selection of the probe, different full PC techniques have been recently proposed [6-10]. The full PC reported in this paper is based on the modification of the SWE basis functions that are properly elaborated taking into account the effect of the (known) probe and then used in the SWE directly compensating for the probe pattern without any assumption on the probe itself [11].

In this paper, the proposed full PC technique is validated by SNF measurements of a standard gain horn. Two wide-band antennas are used as probes in the validation each with a significant content of higher order spherical modes. The obtained results will be compared with the reference data and data obtained without PC and with first order PC.

II. FULL PROBE CORRECTION TECHNIQUE

As in the typical first order PC properly described in [3], the full PC technique proposed here is also applied during the spherical NF/FF transformation process involving the Spherical Wave Expansion (SWE) of the field and so called transmission formula reported in (1):

$$w(r,\chi,\theta,\varphi) = = 0.5 \sum_{\substack{smn \\ \sigma\mu\nu}} Q_{smn}^{(3)} e^{jm\varphi} d_{\mu m}^{n}(\theta) e^{j\mu\chi} C_{\sigma\mu\nu}^{sn(3)}(kr) R_{\sigma\mu\nu}^{p}$$
(1)

Such formula expresses the complex signal received by a probe (w) of known coefficients $(R^p_{\sigma\mu\nu})$ as a function of the probes coordinates (r, θ, φ) and orientation (χ) when an AUT described by its own spherical wave coefficient $(Q^{(3)}_{smn})$ is transmitting. The symbols $d^n_{\mu m}(\theta)$ and $C^{sn(3)}_{\sigma\mu\nu}(kA)$ are respectively rotation and translation operators that, together with the two complex exponentials $(e^{jm\varphi}$ and $e^{j\mu\chi})$, are used to describe the probe position/orientation in each measurement point.

In order to fully compensate for the probe effect the spherical basis functions are properly computed taking into account the effect of the probe, previously characterized through a dedicated measurement campaign or analytical / full-wave models. In order to describe this concept, let us take into

account the general expression of the SWE widely discussed in [3]:

$$E(r,\theta,\varphi) = \sum_{smn} Q_{smn}^{(3)} F_{smn}^{(3)}(r,\theta,\varphi)$$
(2)

where $E(r, \theta, \varphi)$ is the measured field to be represented by the spherical basis functions $F_{smn}^{(3)}(r, \theta, \varphi)$ and the corresponding complex weighing AUT coefficients $Q_{smn}^{(3)}$. It should be noted that (2) can be also used to evaluate $Q_{smn}^{(3)}$ simply setting up and solving a linear system where the central matrix is composed by $F_{smn}^{(3)}(r, \theta, \varphi)$ and the forcing term is $E(r, \theta, \varphi)$. Beside the computational inefficiency, this approach doesn't account at all for the probe compensation. Nevertheless, the effect of the probe can be easily taken into account using (1) as follows:

$$\tilde{F}_{smn}^{(3)}(r,\theta,\varphi) = = 0.5 \sum_{\sigma\mu\nu} e^{jm\varphi} d^n_{\mu m}(\theta) e^{j\mu\chi} C^{sn(3)}_{\sigma\mu\nu}(kr) R^p_{\sigma\mu\nu}$$
(3)

where $\tilde{F}_{smn}^{(3)}(r, \theta, \varphi)$ are a modified version of spherical wave functions that includes the effect of the probe. The probe corrected AUT coefficients $(Q_{smn}^{(3)})$ can thus been computed solving the following formula:

$$E(r,\theta,\varphi) = \sum_{smn} Q_{smn}^{(3)} \tilde{F}_{smn}^{(3)}(r,\theta,\varphi)$$
(4)

It should be noted that in this process no assumptions on the probe has been done, thus any type of probe can theoretically be used. It also highlighted that the inversion of (4) can be made more efficient recognizing from (1) that the φ -dependence can be expressed as a Fourier series, thus using an FFT.

The analytical approach based on the modified spherical wave basis functions above mentioned leads to an effective full probe correction scheme comparable with the formulation described in [9].

III. RESULTS

A preliminary investigation of the effectiveness of the proposed full PC technique has already been presented in [11], where a standard gain horn antenna with higher order modes was used as a probe. The results of further investigations concerning the effectiveness of the algorithm when applied to SNF measurement performed with other higher order probes of practical interest are reported in this section. In particular two wide-band antennas designed by MVI have been selected as probe for the validation (see Figure 1):

- SH800 dual-ridge horn [12]
- *QH800 open boundary quad-ridge horn* [13]

Both devices are reference antennas typical used for calibration purposes and to check the response of measurement systems. They both work in the wide frequency range 0.8-12 GHz so they are very suited for wide-band applications.

Beside their wide-band applicability, the interest of these two antennas regarding their usage as probes is also due their robustness, their stability and their repeatability. Furthermore, the QH800 is also a dual polarized device, making it even more appealing for usage as probe since it is able to measure simultaneously two orthogonal field components.



Figure 1. Wide-band antennas used as probes: MVI SH800 dual-ridge horn (left); MVI QH800 open boudary quadridge horn (right).

The AUT selected for the validation is the MVI SGH820, a standard gain horn working at X-Band. The aperture dimensions of the SGH820 are 198x148 mm, while the AUT height is 353 mm. Such antenna is electrically large enough to enhance the distortion of the radiated field measured by the two probes.

Measurements have been performed in the Italian office of MVG sited in Pomezia (Rome), using a robotic arm system [14], already involved in other activities [15]. Such robot can be programmed so that it can perform different scanning schemes (e.g. planar, spherical). For this measurement validation campaign, hemispherical NF measurements have been performed placing the AUT on the robotic arm and the probe on a tower located in front of the robot as illustrated in Figure 2. The alignment of the AUT and probe positioners is provided by slicing the probe tower in proximity of the robot and driving the robotic arm so that the AUT mechanical interface matches the probe interface. After that, the robot zeroposition is reset and the probe tower is sliced back to its original position.



Figure 2. MVI SGH820 during measurement with MVI DOEW6000 first order probe.

A reference measurement has been performed using the MVI DOEW6000 as probe [16]. Measurement setup is shown in Figure 2. As shown in [11], the DOEW6000 is a first order probe (it only radiates $|\mu|=1$ azimuthal modes) and has a directivity of approximately 10 dBi @ 12GHz. Measurements

have been conducted with the interface of the AUT corresponding to the center of rotation. Based on this displacement and on the AUT dimension a sampling step of 1.5° along and the θ -axis and of 5° along the ϕ -axis have been chosen. The measurement radius (distance from the center of rotation and the probe aperture) is approximately 1.1m.

Reference FF data have been obtained applying the NF/FF transformation including first order probe correction to the NF data acquired with the above described setup. The probe radiation characterization have been obtained from full-wave simulation [17].

Using the same measurement setup, hemispherical NF measurements of the same AUT have been performed also using the two wide-band higher order probes mentioned above. The corresponding results are shown in the following. It is highlighted that for both cases the characterization of the probe radiating performance has been obtained from full-wave simulation [17] (no probe calibration measurements have been conducted).

A. Measurement with SH800 dual-ridge horn

The SH800 dual-ridge horn mounted on the probe tower is illustrated in Figure 1 (left). The main cuts radiation pattern of the SH800 @ 12 GHz (obtained from full-wave simulation [17]) are reported in Figure 3 (left). As can been seen, the probe directivity is approximately 16.0 dBi and there are no cxpolar contributions on the main cuts. Furthermore, it is highlighted that the probe pattern is pretty symmetric.



Figure 3. MVI SH800 @ 12GHz: Simulated pattern (left); Spherical modal content (right).

The spherical wave spectrum of the SH800, obtained from the simulated pattern shown in Figure 3 (left), is illustrated in Figure 3 (right). As can be seen it is characterized by many azimuthal (or $|\mu|$) higher order odd modes (up to $|\mu| = 35$ considering a threshold level of -50 dB). It should be noted that the even $|\mu|$ -modes are all negligible. As also pointed out in [5], such behavior of the spherical wave spectrum is a consequence of the symmetry of the probe radiation pattern cuts.

Neglecting the even $|\mu|$ -modes (thus considering a total number of 18 $|\mu|$ -modes), the spherical wave spectrum above reported has been used as input to the proposed full PC algorithm together with measured NF data.

Figure 4 shows the measured AUT directivity pattern comparison between: reference (blue trace), NF/FF transformation without PC (red trace), NF/FF transformation with first order PC (black trace) and NF/FF transformation with full PC (green trace). Focusing on the co-polarized pattern, it is observed that not negligible errors on the side-lobes are obtained if probe correction is not applied at all. First order PC is capable of improving the accuracy of the results but residual errors on the side-lobes are still appreciable. Instead, if the full PC algorithm is applied the agreement with the reference is excellent. On the other hand, good cx-polar results are obtained using the three different NF/FF transformations. In fact, the AUT should ideally have no cx-polar component along its axis and the obtained on-axis cx-polar discrimination (XPD) is better than 45dB. Such good results are due to the also excellent cx-polar of the SH800 which, as illustrated in Figure 3 (left), is ideally null.



Figure 4. Directivity H-Plane pattern comparison of the SGH820 @ 12 GHz measured with the SH800.

B. Measurement with QH800 open boundary quad-ridge horn

Second validation measurement has been performed using the QH800 open boundary quad-ridge horn as a probe (see Figure 1 (right)). Despite the dual-polarization of the antenna, for the sake of simplicity of the measurement setup, data have been collected involving only one port.



Figure 5. MVI QH800 @ 12GHz: Simulated pattern (left); Spherical modal content (right).

The main cut radiation pattern of the considered port of the QH800 @ 12GHz (obtained from full-wave simulation [17]) are reported in Figure 5 (left). The directivity of the QH800 is similar to the one of the probe considered in the previous

measurement (approximately 15.1 dBi) but, in contrast to that case, the QH800 is characterized by a not negligible cx-polar pattern and an asymmetric co-polarized pattern (especially the E-Plane).

The spherical wave spectrum of the QH800 @ 12GHz is shown in Figure 5 (right). Similar to the previous case, the $|\mu|$ modes are populated up to $|\mu| = 33$ (considering a threshold level of -50 dB). Nevertheless, it should be noted that in this case the spectrum is characterized by the presence of many even $|\mu|$ -modes which are caused by the asymmetry of the pattern cuts. As already reported in [8-9], it also important to highlight that, in case the probe spectrum is characterized by even $|\mu|$ -modes (as in this case), in order to be able to correctly apply the FFT along the φ -axis, the data should be acquired with a periodic scanning along φ ($\varphi \in [0, 360[$).

It goes without saying that each of these remarks make this second test case more challenging than the first one.

The spherical wave spectrum above reported has been used as input to the proposed full PC algorithm together with the second set of measured NF data (a total number of 29 $|\mu|$ -modes have been considered).

Similar to the previous case, Figure 6 reports the measured AUT directivity pattern comparison between: reference (blue trace), NF/FF transformation without PC (red trace), NF/FF transformation with first order PC (black trace) and NF/FF transformation with full PC (green trace).



Figure 6. Directivity H-Plane pattern comparison of the SGH820 @ 12 GHz measured with the QH800.

Focusing on the co-polarized pattern, it is even in this case observed that if the full PC algorithm is not involved not negligible errors on the side-lobes are obtained. In this case results obtained with first order PC are even worse than those obtained without applying any PC. Instead, as can be seen, the full PC algorithm is able also in this case to properly compensate the unwanted effects introduced by the probe. Concerning the cx-polarization results, it is evident that the relative high level of the cx-polar present in the probe pattern directly reflects on the AUT cx-polar pattern unless a proper compensation is not adopted (see red dotted trace). When the first order PC is applied, the on-axis XPD is improved but a strong residual error is introduced off-axis (see black dotted trace). Only the full PC algorithm, taking into account the complete behavior of the probe, is capable to give also good results in terms of both on-axis and off-axis cx-polar performance (see green trace).

C. Accuracy of the results and computational time

In order to quantify the accuracy of the achieved results some error metrics have been calculated and reported in Table 1 and Table 2 respectively for the first and second test cases.

TABLE I. ACCURACY OF THE RESULTS AND COMPUTATIONAL TIME OBTAINED WITH 1^{ST} TEST CASE (SH800 as ProBE).

	Dir. Error (dB) ¹	SLL EEL (dB) ²	XPD (dB) ³	Global EEL (dB) ⁴	Time (s) ⁵
No PC	-0.02	-31.1	47.3	-42.2	0.3
1 st order PC	-0.05	-37.9	47.4	-41.2	4.4
Full PC	-0.01	-53.1	46.6	-45.4	28.0

TABLE II. ACCURACY OF THE RESULTS AND COMPUTATIONAL TIME OBTAINED WITH 2^{ND} Test Case (QH800 as Probe).

	Dir. Error (dB) ¹	SLL EEL (dB) ²	XPD (dB) ³	Global EEL (dB) ⁴	Time (s) ⁵
No PC	-0.19	-39.0	25.9	-26.0	0.4
1 st order PC	-0.16	-33.7	38.6	-39.0	3.5
Full PC	+0.05	-54.3	41.6	-48.1	48.8

¹ Reference Directivity = 22.8 dB; ² SLL at θ = 37°; Reference SLL = 18.5 dB.

³ Reference On-Axis XPD = 50.7 dB; ⁴ Computed considering amplitude and phase data. ⁵ Computed on an Intel(R) Core(TM) i-56300 CPU @ 2.40GHz.

The deviation of the peak directivities are reported in the second column. Using any of the NF/FF transformations such error is relatively low in the first test case. Instead, in the second test case, it can be seen that a higher error is obtained if the full PC is not considered.

In the third column the error on the Side Lobe Level (SLL) has been estimated computing the equivalent error level (EEL) with the following formula

$$e_{i}(\theta,\phi) = \left| \frac{E(\theta,\phi) - \widetilde{E}(\theta,\phi)}{E(\theta,\phi)} \right| \cdot \frac{\left| \widetilde{E}(\theta,\phi) \right|}{\left| \widetilde{E}(\theta,\phi) \right|_{MAX}}$$
(5)

where

- $\widetilde{E}(\theta, \phi)$ is the reconstructed pattern,
- $E(\theta, \phi)$ is the reference pattern

As can been seen, in both cases the EEL obtained with the full PC is better that -50 dB, while those obtained without PC or with first order PC are more than 15 dB higher.

The on-axis cx-polar discrimination (XPD) is reported in the fourth column. As already pointed out, a good XPD is obtained using any of the NF/FF transformations applied to the first test case. On the other hand, the improvements obtained using the full PC are remarkable in the second test case.

The global EES, obtained averaging the output of (5) among any (θ, φ) coordinate of the patterns, is reported in the fifth column. Such metric has been computed accounting both for the amplitude and the phase of the patterns. Once again, the improvement obtained with the full PC are remarkable especially in the second test case.

Table 1 and Table 2 also report the performance of the algorithm in terms of computational time. The additional time needed to run the full PC is mainly due to the need of setting up and invert a linear system rather using a fully FFT approach as in the first order PC algorithm.

IV. CONCLUSION

In this paper the effectiveness of a full PC procedure suited for SNF antenna measurement has been experimentally validated. The proposed full PC is based on the modification of the SWE basis functions that are properly elaborated taking into account the effect of the (known) probe and then used in the SWE directly compensating for the probe pattern without any assumption on the probe itself.

The validation has been performed taking into account two wide-band higher order probes (the MVI SH800 and the MVI QH800) and an X-band standard gain horn as AUT (MVI SGH820). Hemispherical NF measurements have performed using a robotic arm system [14]. Reference data have been collected performing the measurement with a first order probe (the MVI DOEW600).

Spherical wave spectrum of the probes have obtained from full-wave simulations [17] and used as input to the algorithm. Comparisons between reference data and data obtained processing the SNF measurements performed with the higher order probes have highlighted the effectiveness of the full PC approach which is capable to give much more accurate results with respect to first order PC and NF/FF transformation without PC. The improvements of the results due to the application of the full PC approach are particularly appreciable in the second test case where the QH800 has been used as probe. Such probe has in fact a richer spherical modal content (characterized by even and odd azimuthal modes) which made the compensation more challenging with respect to the other test case.

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