Finite Array Analysis Through Combination of Macro Basis Functions and Array Scanning Methods

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Abstract – The Macro Basis Functions (MBF) approach receives increasing attention for the evaluation of the effects of array truncation. In this paper, we show how physically based MBFs can be obtained from solutions for infinite arrays and for arrays of minimal size. The method is first explained and illustrated for the case of finite-by-infinite arrays of electrically connected tapered-slot antennas. It is then extended to the case of planar arrays. Very low error levels are achieved with a small number of MBFs, in terms of port currents as well as in terms of radiation patterns.

I. INTRODUCTION

In the last few years, very efficient techniques appeared in the literature for the Method-of-Moments (MoM) analysis of large finite periodic antenna arrays. Some methods rely on the infinite-array solution, with corrections for the effects of array truncation [1–3]. Those methods are generally valid for very large arrays and entail several approximations. Other approaches involve fast iterative methods, in which matrix-vector products are accelerated with the help of multipole decompositions or Fast Fourier Transforms, combined with efficient preconditionners [4]. In [5], the FFT approach is advantageously combined with the concept of subentire-domain basis functions, which consists of assuming that the currents on a given antenna in the finite array can be decomposed in terms of a limited number of known current distributions, obtained through the solution of smaller problems. This underlying idea has been found in many publications, where the "macro basis functions" [6, 7] are also called "characteristic basis functions" [8]. Among recent works on this subject, we should note [9] and [10], where primary and secondary distributions are considered, in order to accurately catch the effects of mutual coupling. A very fast implementation of this method has been described in [11], where the interactions between macro basis and macro testing functions are computed with the help of a multipole approach. This method allows the efficient computation of all coupling coefficients of the finite array. Besides this, the patterns of macro basis functions, which are side-products of this method, are then used to rapidly compute the embedded element patterns and, in turn, the array pattern for any excitation law. A similar approach, involving an iterative scheme, is presented in [12].

At first glance, finite and infinite-array approaches seem very distinct. For large arrays, an initial design can be obtained from the infinite-array simulations, potentially with approximate corrections for truncation, while the behavior of the finite array is verified with the help of an efficient iterative or multiscale approach [13]. The present paper consists of making one more step toward the reconciliation of infinite-array and finite-array approaches. A first set of macro basis functions is obtained from the infinite-array analysis in a very specific and physically-based way, which finds its justification in the Array Scanning Method [14]. A second set of MBFs is obtained from the solution of very small (2×1 or 2×2) arrays. In [15], MBFs (named "standard distributions") were also obtained from infinite array solutions, but this method was limited to finite-by-infinite arrays and, more importantly, to periodic excitation, thus requiring only one infinite-array solution (besides single-element and semi-infinite array solutions). The combination of ASM and MBF approaches, for the solution of the array excited at a single port, was first shown in [16], where only finite-by-infinite arrays are considered, while full-wave treatment of edge elements was needed. In the present paper, the method shown in [16] is extended to planar arrays, while special MBFs are included to represent currents on elements on the array periphery.

This paper is organized as follows. In Section 2, the phenomenology of current waves in infinite arrays excited at one element is recalled, and its quantitative evaluation is obtained with the help of the Array Scanning Method in Section 3. In Section 4, the method for extraction of edge MBFs is explained and the numerical examples are given in Section 5 for finite-by-infinite arrays of tapered-slot antennas. The method is extended to arrays finite in both directions in Section 6, where examples are shown in terms of port currents and radiation patterns. The method is summarized and discussed in Section 7.

II. CURRENT DISTRIBUTIONS IN INFINITE ARRAYS

To properly assess the efficiency of the method explained below, it is interesting to consider worst-case situations in terms of coupling between elements. This is

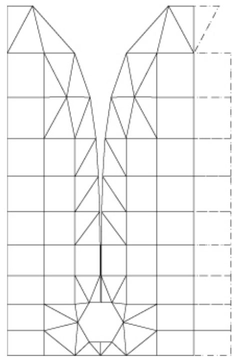


Fig. 1. Discretization of tapered-slot antenna with overlapping basis functions (dashed).

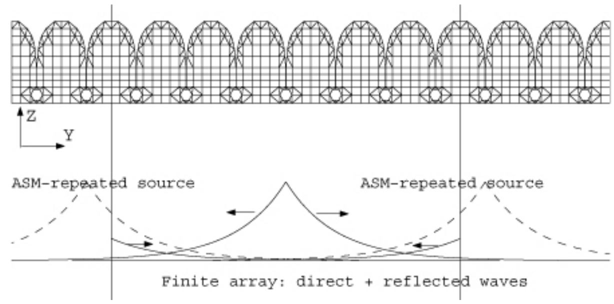


Fig. 2. Wave phenomenology in a finite-by-infinite array excited along one infinite row. The currents on a given point of successive antennas can be regarded as progressive waves launched by the excited element and reflected by the ends of the array (vertical lines). If the Array Scanning Method is implemented with the help of a finite summation, the source is repeated (cf. auxilliary peaks).

why arrays of electrically connected tapered-slot antennas [15, 17], will be taken as examples (see Figs. 1 and 2 for meshes of the antennas and of the array): first, near the lowest frequency end, the wavelength can be large compared to the array spacing, which often leads to stronger couplings and, second, the electrical connection between elements also leads to very strong couplings and to a quite different current distribution on elements located on the periphery of the array. A first possibility for determining the macro basis functions consists of considering a large spectrum of plane-wave excitations of the antenna, as well as source excitations. In practice, when successive elements are electrically connected, the currents can flow from one element to the next, with currents essentially concentrated on the edges of conductors. If a free-standing element is cut out of the array and excited, currents will also flow along the cutting lines. This will not lead to an acceptable representation of current distributions in array conditions. Hence, some authors [18] proposed to extend the subdomains to two or three antennas and to carefully avoid singular currents by a spatial windowing to the obtained current distributions. Despite the very good results obtained for certain configurations [18], it is difficult to say in how far the macro basis functions generated in this way form a complete set of solutions. Here, "complete" means that any current distribution that can appear on the array can also be described as a linear combination of the proposed set of macro basis functions.

III. ARRAY SCANNING METHOD AND MBFS

While attempting to answer the latter question, it is useful to come back to the physical interpretation of fields in infinite and finite arrays. Let us assume a finite array excited at one given element. The currents excited on the whole structure can be regarded as those present in an infinite array, plus currents reflected (or "diffracted") by the edges of the array. Let us first consider the case of excitation at one port in an infinite array. In this case, the currents can be obtained from infinite-array simulations, with the help of the Array Scanning Method (ASM) [14, 19, 20]. The method is recalled in [21] for the case of planar arrays, where examples are provided for wideband phased arrays. In this section, it will be illustrated for a simpler problem, involving arrays infinite along $\hat{x}$, and with M elements along $\hat{y}$. The complexity of the method is then reduced to that of a linear array (see Fig. 2). If element 0 (or *row* 0) is excited, the current on element m (or *row* m) reads,

$$I(m) = \frac{1}{2\pi} \int_0^{2\pi} I^\infty(\psi)\, e^{-j\, m\, \psi}\, d\psi \tag{1}$$

where $I^\infty(\psi)$ is the infinite-array current distribution obtained with inter-element phasing ψ along $\hat{y}$. As for the phasing along $\hat{x}$, the infinite-array direction, it is assumed identical for infinite-array and finite-by-infinite array solutions.

The Array Scanning Method assumes the integration of current distributions for all possible phase shifts, from 0 to 2π, between successive elements. In practice, solutions will be computed for a finite set of phase shifts. The simplest approximation, computing integral of equation (1) with rectangles in the reciprocal (phase-shift) domain, then comes down to a DFT approach,

$$I(m) \simeq \frac{1}{N} \sum_{p=0}^{N-1} I^\infty(\psi_p)\, e^{-j\, m\, \psi_p} \tag{2}$$

with $\psi_p = 2\,\pi\, p/N$.

The effect of this approximation is that excited currents are obtained as if the source were repeated every N elements (see dashed lines for port currents in Fig. 2 for $N = 4$). This poses a problem when the exact solution for a single excitation is looked for, but, as will be seen further, it is not really a drawback when we are just looking for characteristic current distributions, or "macro basis functions". Indeed, in an infinite array, and far from the source, the currents along successive antennas may be regarded as a "wave" with a given decay rate in terms of amplitude and with a given phase velocity [22]. Far enough from the source, say beyond $N_\circ$ elements away from it, the successive current distributions may -within a constant factor- be very similar, while they can differ quite a lot near the source. Hence, the repetition of excitation every $N_\circ$ antennas, as implicitly incurred by the use of equation (2), is not a problem when the number of linearly independent current distributions available remains sufficient, i.e., as long as N is not too small compared to $N_\circ$. Moreover, the repetition of the sources does not really "spoil" the generated current distributions, since the added current component is very similar to the characteristic current distributions looked for.

Besides this, when the array is finite, the difference with the solution considered above may be regarded as currents reflected by the edges of the array. This has been illustrated in [22] for linear arrays of broadband dipoles. In general, except for the elements right at the edges of the array (which will be treated below), these "reflected" current distributions are very similar to those found in an infinite array excited by a single source. This supports the use of the currents obtained from the ASM analysis as macro-basis functions for the finite array. It is also interesting to notice that, as a result of the physical ground for the choice of current distributions, the distributions obtained in this way will naturally exhibit continuous currents at the boundaries between electrically connected elements.

The explanation above provides a physically-based choice of macro basis functions for elements inside the array (i.e., for all elements, except those located right at the edges of the array). This means that, considering the excitation of any element in the array, the currents on a given antenna can be written as a linear combination of the current distributions obtained with the ASM method. In turn, through superposition of excitation at individual elements of the array, the ASM-based method should provide accurate results for any active excitation law of the array. Furthermore, since the ASM results are obtained as linear combinations of infinite-array results, we can also say that the currents for any excitation law should be a linear combination of currents obtained in the infinite-array case. Hence, the set of MBFs is simply made up of all $I^{\infty}(\psi_p)$ current distributions. The only constraint, for the physical justification above to hold, is that the infinite-array solutions be obtained by sampling regularly in the reciprocal (i.e., phase-shift ψ) domain, i.e., $\psi_p = 2\,\pi\,p/N$, with p integer between 0 and $N-1$. This includes solutions outside the visible space, for which the antenna active impedances are purely reactive.

IV. EDGE MBFS

As explained previously, the wave phenomenology described above may not hold for the elements on the edges of the array. This is particularly true for arrays made of connected elements, since, in that case, the edge elements may support significantly different types of current distributions. Those are not well captured through the ASM procedure. In the following, they will be obtained by solving very small arrays, consisting of edge elements only. In the finite-by-infinite array example, such an array contains only two electrically connected elements; or more precisely, a two-by-infinite array. Current distributions may be different on left and on right edge elements. These elements may be fed directly, or they may be illuminated through the feeding of another element in the array. In the two-elements case, this leads to four possible current distributions. This requires the full-wave solution of a two-elements array, which, compared to other steps in the computation procedure, takes a relatively small computation time. The resulting four MBFs are simply added to the set of N distributions obtained from the ASM procedure. As already considered in [23], MBFs are then orthogonalized through the SVD (Singular Value Decomposition) procedure, in order to preserve a good conditioning for the reduced system of equations.

V. FINITE-BY-INFINITE ARRAY EXAMPLE

Simulation examples will be shown for an array made of metallic tapered slot antennas, with the discretization shown on Fig. 1. The surface is meshed with the help of 132 elementary basis functions, which are of rooftop and RWG ("Rao-Wilton-Glisson" [24]) types, with half basis functions electrically connecting the antenna to the infinite ground plane and overlapping basis functions (dashed) connecting antennas with each other in the E-plane. Based on comparisons with results obtained with finer meshes, the meshing used here has been found to provide a satisfactory representation of the main antenna characteristics, while still allowing the brute-force solution of intermediate-size finite arrays. For instance, with this discretization, as well as with finer ones, the standing wave ratio for the array scanned at broadside is below 2 from 0.42 GHz to 1.5 GHz.

The array analyzed here is infinite along $\hat{x}$ (perpendicular to the figure), without a phase shift between elements in that direction, and has 32 elements along $\hat{y}$ (from left to right). The element spacing is 12.7 cm, while the wavelength is 30 cm. The elements are excited successively (excitation of successive infinite rows) and the currents are compared with the "brute-force solution", obtained through inversion (or LU decomposition) of the MoM impedance matrix. Results are shown in Fig. 3 for excitation at port 1 and at port 16. The upper plot shows the port currents, while the lower plot shows the error w.r.t. the brute-force solution, with a scale enlarged by a factor of 6000. It can be seen that the residual error is extremely small.

The remaining question is how many MBFs are necessary to obtain a sufficient accuracy; in other terms,

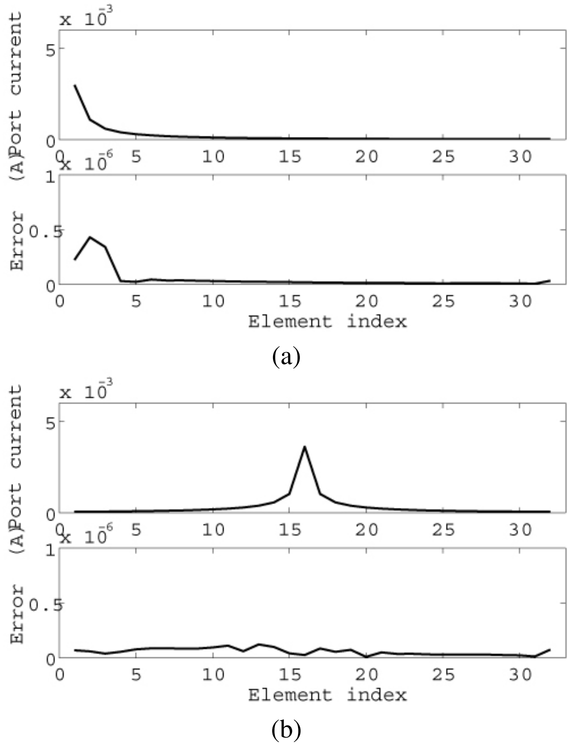


Fig. 3. Port currents in array of tapered slot antennas, with 32 elements in one direction and infinite in orthogonal direction, excited along one infinite raw. Array spacing: 12.7 cm, wavelength: 30 cm. Top: port currents. Bottom: with scale enlarged by a factor 6000, errors between full-wave solution and MBF approach (a) first row of antennas excited, (b) row 16 excited.

how large should N be in the Array Scanning Method? In the case of weakly coupled arrays, for instance when elements are located far apart, it is expected that current distributions on antennas away from the excited element should be very similar. In that case, N can be very small. For strongly coupled arrays, and a fortiori, for electrically connected elements, N can become larger, because of the large variety in possible current distributions. The maximum port error, normalized relative to current at the excited port, is represented in Fig. 4 for increasing values of N. It can be seen that the error suddenly drops to very low values for $N > 7$. If the SVD procedure is not used, the error increases again after $N = 10$ (crosses), because an ill-conditioned system of equations is obtained through the use of very similar basis functions. It can be seen that the use of the SVD procedure (circles) avoids this difficulty.

VI. EXTENSION TO PLANAR ARRAYS

A similar procedure can be used for planar arrays, like finite arrays of tapered-slot antennas (Fig. 5). In this case, the 2-D version of the ASM is exploited. The current on antenna (m, n) for excitation of antennas with indices

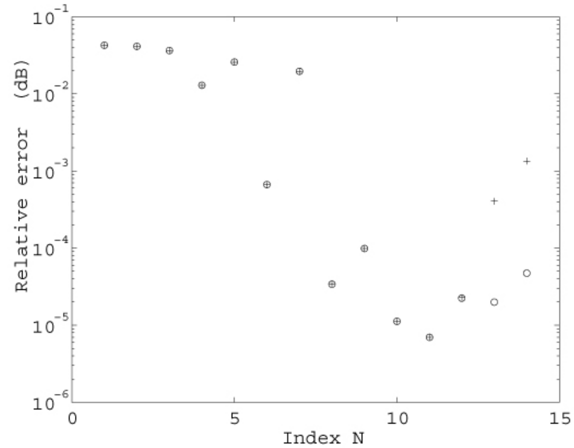


Fig. 4. For 32-by-infinite array, with row 16 excited, maximum relative error in port currents, versus value of N in ASM. Circles: with SVD procedure. Crosses: without SVD procedure.

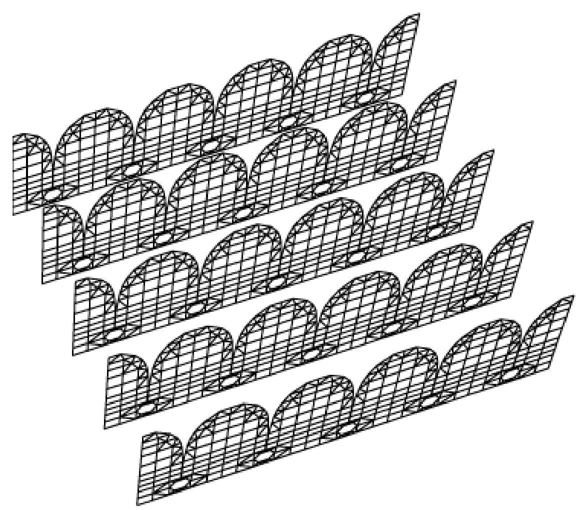


Fig. 5. 5×5 array of tapered-slot antennas.

(rN, sN), with r and s integer, is given by,

$$I_{m,n} = \frac{1}{N^2} \sum_{p=1}^{N} \sum_{q=1}^{N} I^{\infty}(\psi_{x,p}, \psi_{y,q})\, e^{-j\, m\, \psi_{x,p}}\, e^{-j\, n\, \psi_{y,q}} \tag{3}$$

with

$$\psi_{x,p} = 2\,\pi\, p/N \qquad \text{and} \qquad \psi_{y,q} = 2\,\pi\, q/N. \tag{4}$$

In equation (3), $I^{\infty}(\psi_x, \psi_y)$ is the infinite-array current obtained with inter-element phasings along X and Y equal to ψ_x and ψ_y, respectively.

As in the finite-by-infinite array case, if N is large enough, this procedure provides a sufficiently complete set of MBFs for large arrays, except for elements on the outer edge, which may support significantly different current distributions. This time, the problem is solved by adding to the set of MBFs a few current distributions

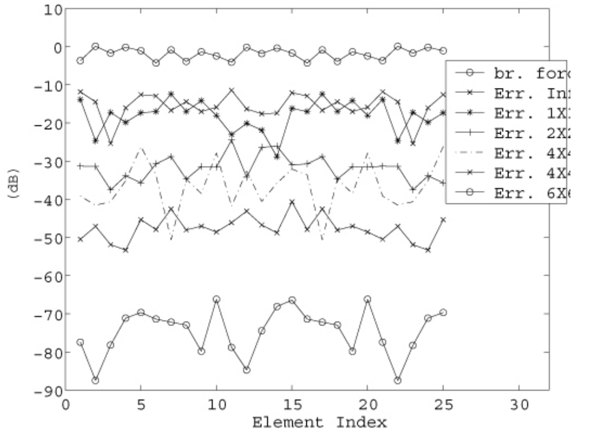
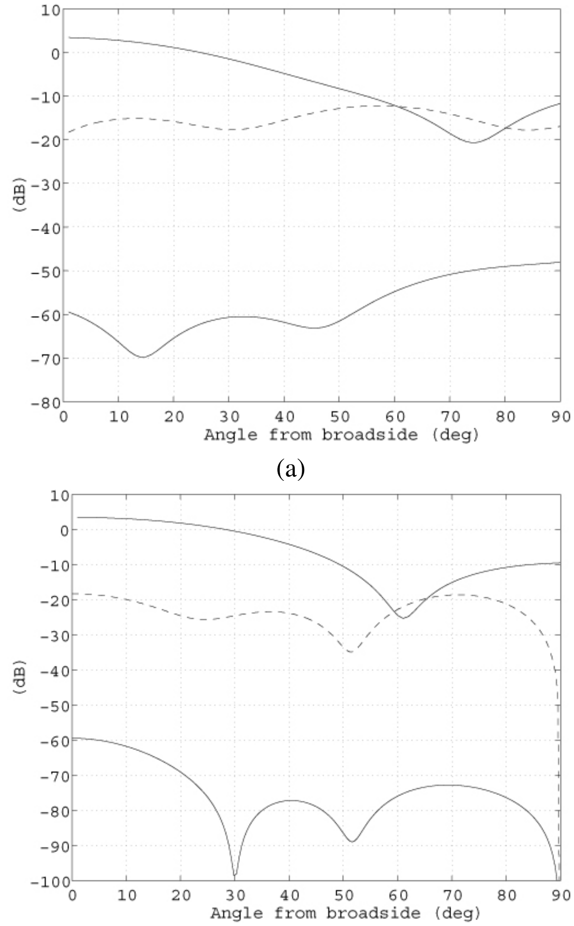


Fig. 6. Port currents for all elements of 5×5 array excited (upper line) and errors produced by the infinite-array approximation (crosses around -15 dB) and by ASM+MBF with different values of N for the two-dimensional ASM and with 8 additional MBFs from 2×2 array. The 4×4 case denoted with dashed lines does not include the 8 additional MBFs.

obtained through the full-wave analysis of a small array, e.g. a 2×2 array, which contains only edge elements. Four elements and four independent excitations lead to 16 possible MBFs. However, if some symmetry is present in the array, fewer distributions need to be considered. In the present example with tapered-slot antennas, since two parallel columns are perfectly symmetrical, this leads to 8 different current distributions. Adding these distributions to those stemming from the ASM procedure with $N = 4$, for example, leads to 24 MBFs, instead of the original 132 elementary basis functions per antenna. This reduction by a factor 5.5 of the number of unknowns leads to a reduction by a factor 166 in terms of direct solving time. Larger time saving factors are expected for more complex antennas.

Figure 6 shows results obtained for port currents in a 5×5 array of electrically connected tapered-slot antennas (Fig. 5). Overlapping basis functions ensure the electrical connection between antennas. It should be noted that, for simplicity, these overlapping basis functions have been kept on the last elements in each row. In the first numerical example, all antennas are excited with a uniform voltage excitation, with 100 Ω series impedances. The 25 port currents are represented by the upper line in the right plot of Fig. 6. It can be seen that variations of the order of 3 dB appear, which underscores the strong effects of array truncation. Errors, defined as the magnitude of the complex difference between brute-force and approximate solutions, are presented by the lines below. The errors produced by the infinite-array solution are less than 10 dB below the brute-force solution. Slightly better results are obtained when considering only one MBF, that corresponds to the infinite-array solution for scanning at broadside. Except

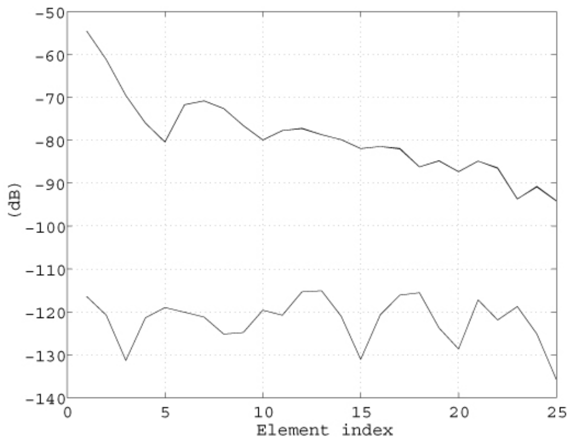


(b)

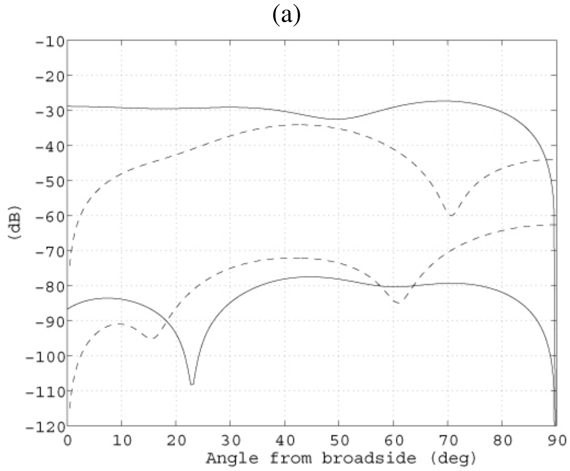
Fig. 7. Pattern for a 5×5 array of tapered-slot antennas, with uniform excitation (a) E-plane, (b) H-plane. Upper lines: brute-force solution. Lower lines: error from ASM+MBF approach. Dashed: error from use of infinite-array solution for surface currents.

for one ($N = 4$, dashed lines), the other examples include the 8 additional MBFs obtained from the 2×2 finite-array case. It can be seen that, for increasing values of N, the errors are steadily going down. Basis functions obtained with $N = 4$ (24 MBFs in total) lead half-way to single machine precision; hence $N = 4$ will be considered sufficient. This involves the calculation of the infinite-array solutions for N^2 different phase shifts. These can be computed very fast, because the domain is limited to a unit cell. Details about fast implementation, involving fast calculation and tabulation of the periodic Green's function, can be found in [3].

Corresponding patterns can be seen in Fig. 7, for cuts in E plane and in H plane. The upper line corresponds to the brute-force solution, the dashed line stands for the error produced by considering the infinite-array solution on all antennas, and the lower line corresponds to the error obtained with the $N = 4$ ASM+MBF approach (24



(a)



(b)

Fig. 8. For a 5×5 array of tapered-slot antennas, excited at a corner element. (a): port currents: brute-force solution and error from ASM+MBF approach. (b): Embedded element pattern in E-plane. Solid: vertical polarisation. Dashed: horizontal polarisation. Upper curves: brute-force solution. Lower curves: error from ASM+MBF approach.

MBFs in total). Compared to the brute-force solution, the errors are located from 60 dB lower at broadside to 30 dB lower at grazing incidence.

The last example concerns excitation at a single port. A worst case has been considered, in terms of array truncation. It corresponds to excitation of a corner element. The accuracy of the result on the 25 antennas (taken along successive columns) is shown in Fig. 8(a) for the port currents, and in Fig. 8(b) for the embedded element pattern in the E plane. Upper curves correspond to the brute-force solution, lower curves represent the errors. As for the patterns, the dashed lines stand for the cross-polar component, due to the asymetric excitation of the finite array. It can be seen that excellent accuracies are achieved, even for the cross-polar fields.

Finally, it is interesting to notice that, although lower frequency cases generally lead to stronger truncation effects, with the method presented here, significantly better accuracies were achieved for a wavelength of 60 cm (not shown here) instead of 30 cm (examples above).

VII. CONCLUSION AND FURTHER PROSPECTS

A physically based choice of macro basis functions has been described for the full-wave simulation of finite antenna arrays. We showed that a good choice corresponds to infinite-array solutions computed on a regular grid in the reciprocal domain (domain of phase shifts between elements in both directions). This method allows capturing of current waves launched at one element, propagating over the passively terminated array, and bouncing back on the edges of the array. This method is also well suited to the particularly difficult case of electrically connected elements, without requiring the development of techniques devoted to tapering of current distributions obtained over domains defined over more than one unit cell.

The method has been demonstrated for metallic arrays of tapered-slot antennas. Since edge elements can exhibit quite different current distributions, a few more MBFs are obtained from very small (2×2) arrays. Excellent results have been obtained for both port currents and radiation patterns. It should be recalled that, once the reduced MoM impedance matrix has been obtained, solutions can be computed simultaneously at negligible computational cost for any excitation law. Future efforts will concentrate on the demonstration of this method to the case of arrays containing dielectric parts.

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