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Comparative Study of Omnidirectional Shaped Reflector Antenna Analyses

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Abstract — The implementation of methods for the EM analysis of reflector antennas based on the integration of (surface and edge) induced currents is compared with that of a numerical analysis based on the Method of Moments, chosen as a reference due to its ability of properly addressing the interaction between reflector and feed structures. This is explored herein in connection with the synthesis of shaped reflectors encountered in certain terrestrial systems prescribing omnidirectional coverage. These antennas are usually employed in a LMDS system base station to operate with the distribution of digital TV signals.

Keywords-EM analysis; omnidirectional reflector antennas; digital TV

I. INTRODUCTION

Wireless links at millimetric waves length can be attractive for last-mile broadband access usually employed for the distribution of high-speed internet or high definition digital TV systems. For these services, single and dual reflector antennas have been investigated for omnidirectional coverage [1,2]. The reflector surfaces are bodies of revolution obtained by spinning confocal conic sections or shaped generating curves about a symmetry axis, as illustrated in Figure 1. In polarized design examples, the vertically those omnidirectional antennas are fed by a coaxial horn designed to propagate the TEM mode along the frequency band of operation.



Figure 1 - Circular symmetric reflector surface.

Based on Geometrical Optics approximations, shaped reflectors techniques have also found sanctuary in certain terrestrial systems prescribing omnidirectional coverage of cell-type areas [1,2]. To account for the diffractive effects,

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usual (surface) synthesis procedures involve the minimization of "objective" functionals whereby pre-specified radiation patterns are confronted with those calculated for the step at hand. To fulfill this task, not only properly optimized synthesis algorithms must be implemented for the sake of computational costs as increasingly complex design specifications are presented, but a conscious choice of EM field analysis must also be made.

This work explores the analysis of circularly symmetric omnidirectional reflector antennas with a view towards addressing the adequacy of an algorithm in which the calculation of antenna radiated fields poses as an important issue. The use of the Physical Optics (PO) and Equivalent Edge (EEC) currents is explored herein for the eletromagnetic analysis of compact single reflector omnidirectional antennas. For the reflector shaping, the analysis scheme is associated with optimization an algorithm to generate a specified farfield radiation pattern in the elevation plane. For validation purposes, the omnidirectional antennas are analysed by using the Method of Moments to solve the Field Integral Equations, thereby accounting for all electromagnetic effects present in the reflector and feed structure [1-3].

II. METHOD OF MOMENTS ANALYSIS

In order to estimate the electrical performance of the proposed design procedure, a full-wave stepped-waveguide model and MoM/HFIE method are combined to analyse both the fields in the interior region and the exterior current contributions of the feed horn [4]. The interaction is accurately analysed by using the EFIE on the exterior surfaces of the coaxial horn. The equivalence currents principle is introduced to formulate the HFIE on the radiating aperture which combines the interior field transition problem with the exterior radiation. Due to the TEM mode excitation, only the TEM and TM modes are considered at the transition.

The analysis is subdivided in two parts, starting from the analysis of the transition between the feeding waveguide and the coaxial horn aperture. The horn is represented as series of stepped coaxial waveguides sections and Mode Matching is performed by rigorously enforcing the boundary conditions at each step. It results a scattering matrix [S] for the entire transition region:

$$\begin{bmatrix} b^{C} \\ b^{A} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a^{C} \\ a^{A} \end{bmatrix}$$
(1)

which relates incident and reflected modes at the two extremes of the transition region. In (1), the vectors $[a^{C}]$ and [a^A] contain the amplitudes of incident modes at the region 'C' and 'A', respectively, whereas the vectors $[b^{C}]$ and $[b^{A}]$ contain the amplitudes of reflected modes at the connector 'C' and aperture'A', respectively (see Figure 2). Considering the TEM fundamental mode as the only incident mode at region C and the circularly symmetric structure, only the TEM and TM are excited throughout the entire transition region, as the TE mode do not couple with the TEM excitation. The matrix [S] depends on the geometrical parameters and on the wavelength as well as the number of modes considered to ensure continuity of the electric and magnetic throughout the transition region. Part of the power of the modes reaching the aperture, region A, is radiated into the space while the rest is guided back into the horn.



Figure 2 - Horn represented as series of stepped coaxial waveguides sections

In the second part of the analysis scheme, to calculate the radiate fields and the amplitude of the reflected modes $[b^A]$, the MoM is employed to solve the EFIE and MFIE, as described in [3]. To apply the above strategy, an equivalent to the actual electromagnetic problem is defined by replacing the feed radiating aperture by a sheet of perfect conductor with an equivalent magnetic current density

$$\vec{M}\left(\left[a^{A}\right],\left[b^{A}\right]\right) = -\sum_{l=1}^{N_{M}} \left(a_{l}^{A} + b_{l}^{A}\right)\left(\hat{n} \times \hat{e}_{l}^{A}\right)$$
(2)

where \hat{n} is the unit vector normal to the aperture, \hat{e}_l^A is the electric field of the modes internal to the aperture. The magnetic current density \vec{M} radiates into the space and induces an electric surface current \vec{J} on the metallic wall of the equivalent problem.



These currents ensure the continuity of the tangential magnetic field across the aperture and zero tangential electric field on the metallic surface at the aperture and reflectors:

$$\vec{n} \times \left[\vec{E}^{S}(\vec{J}) + \vec{E}^{S}(\vec{M}) \right] = 0$$

$$\vec{n} \times \left[\vec{H}^{S}(\vec{J}) + \vec{H}^{S}(\vec{M}) \right] = \hat{n} \times \vec{H}^{A}$$
(3)

where \vec{E}^{S} and \vec{H}^{S} are electromagnetic field scattered by the currents \vec{M} and \vec{J} . To apply the MoM solution, the current densities \vec{M} and \vec{J} are expanded by sub sectional roof-top patch modes \vec{P}_{i}^{J} and \vec{P}_{k}^{M} respectively :

$$\vec{J} = \sum_{j=1}^{N_S} J_j \vec{P}_j^J$$
 and $\vec{M} = \sum_{l=1}^{N_M} M_l \sum_{k=1}^{N_A} V_{lk} \vec{P}_k^M$ (3)

where N_S and N_A are the number of roof-top patch modes on the entire surface and on the aperture, respectively, and N_M is the number of modes TEM and TM used to approximate the aperture fields. By testing the EFIE with \vec{P}_i^J and the MFIE with $\hat{n} \times e_i^A$, it leads to two matrix equations that combined with the relation (1), it is possible to define a relation between the vectors $[a^A], [b^C], [b^A]$ and $[a^C]$, associated with the TEM excitation at the connector.

III. PHYSICAL OPTICS AND EQUIVALENT EDGE CURRENTS

It is a well-known fact that ray tracing methods fail in the determination of diffracted fields at caustic regions, this difficulty being a commonplace in the analysis of axially symmetric reflectors, where the observation points may be located over the antenna axis. The traditional route of evaluating Physical Optics (PO) currents and integrating them over the lit portion of the reflector, while failing to accommodate the non-uniformity of induced currents in the vicinity of the rim, is also known to mislead the determination of sidelobe distributions related to higher edge illumination levels. This short-comings can be overcome by integrating equivalent edge currents (EEC's) over the reflector rim to provide the diffracted fields at any observation point, regarding that all possible singularities on the EEC's are removed. Also, these EEC's may be formulated as the sum of an uniform PO-like component and their non-uniform counterparts, the so called fringe wave currents (FC's). These may then be integrated over the reflector rim thereby providing a valuable asymptotic add-on improvement to otherwise (at times) imperfect PO-field descriptions [5-8]. This route will be adopted in what follows.

The geometrical parameters relevant to the evaluation of fringe wave currents on reflector antennas are shown in Figure 4 for an axis-symmetric focus-fed configuration, where angles ϕ'_0 , ϕ_0 , β'_0 , and β_0 are obtained from vectors \vec{r}' (connecting source and rim points), \vec{r} (connecting rim and observation points), \hat{t} (unit vector tangent to the reflector rim), and \hat{N} (unit vector normal to the reflector surface at the rim) as:

$$\beta_{0} = \arccos\left(\frac{\vec{r}}{|\vec{r}|} \cdot \hat{t}\right) \qquad \beta_{0}^{i} = \arccos\left(\frac{\vec{r}}{|\vec{r}'|} \cdot \hat{t}\right)$$

$$\cos\phi_{0} = \frac{-\vec{r} \cdot (\hat{N} \times \hat{t})}{|\vec{r}| \operatorname{sen} \beta_{0}} \qquad \cos\phi_{0}^{i} = \frac{-\vec{r} \cdot (\hat{N} \times \hat{t})}{|\vec{r}'| \operatorname{sen} \beta_{0}} \qquad (4)$$

$$\operatorname{sen}\phi_{0} = \frac{-\vec{r} \cdot \hat{N}}{|\vec{r}| \operatorname{sen} \beta_{0}} \qquad \operatorname{sen}\phi_{0}^{i} = \frac{-\vec{r} \cdot \hat{N}}{|\vec{r}'| \operatorname{sen} \beta_{0}^{i}}$$

$$(4)$$

$$\int_{\mathbb{R}^{n}} \frac{1}{|\vec{r}| \operatorname{sen} \beta_{0}} \qquad \operatorname{sen}\phi_{0}^{i} = \frac{-\vec{r} \cdot \hat{N}}{|\vec{r}'| \operatorname{sen} \beta_{0}^{i}}$$

Figure 4 - Geometry of an axis-symmetric focus-fed reflector antenna

Magnetic and electric FC's are then expressed as [4-8]

$$M^{f}(\vec{r}') = [\vec{H}_{i}(\vec{r}')\hat{t}]\eta \frac{D_{h}^{M,f}(\vec{\beta}_{0},\beta_{0},\phi_{0},\phi_{0})}{jk}$$

$$I^{f}(\vec{r}') = [\vec{E}_{i}(\vec{r}')\hat{t}] \frac{D_{e}^{I,f}(\vec{\beta}_{0},\beta_{0},\phi_{0},\phi_{0})}{ink} + [\vec{H}_{i}(\vec{r}')\hat{t}] \frac{D_{h}^{I,f}(\vec{\beta}_{0},\beta_{0},\phi_{0},\phi_{0})}{ik}$$
(5)

with η and k denoting the free-space intrinsic impedance and wave number, respectively, $\vec{H}_i(\vec{r})$ and $\vec{E}_i(\vec{r})$ are the incident magnetic and electric field on the reflector rim. The expressions for the diffraction coefficients D_e^{If} , D_e^{Mf} , D_h^{Mf} are found in [4-8].

Corresponding electric field in the far observation region is obtained accordingly, via integration of FC's over the rim:

$$\vec{E}^{fe}(\vec{r}) = -\frac{1}{4\pi r} \int_{c'} \{ [\vec{E}_i(\vec{r})\hat{i}] D_e^I(\beta_0, \beta_0, \phi_0, \phi_0) + [\vec{H}_i(\vec{r})\hat{i}] \eta D_h^I(\beta_0, \beta_0, \phi_0, \phi_0) \} [\hat{t} - (\hat{t} \cdot \hat{i}_r)\hat{i}_r] e^{-jk|\vec{r} - \vec{r}|} dl' + \frac{(6)}{4\pi r} \int_{c'} (\hat{i}_r \times \hat{t}) [\vec{H}_i(\vec{r})\hat{i}] \eta D_h^M(\beta_0, \beta_0, \phi_0, \phi_0) e^{-jk|\vec{r} - \vec{r}|} dl'$$

The total field scattered by the reflector may finally be expressed as

$$\vec{E}^{S}(\vec{r}) = \vec{E}^{PO}(\vec{r}) + \vec{E}^{fc}(\vec{r})$$
(7)

with [4-8]

Z

$$\vec{E}^{PO}(\vec{r}) = -\frac{j\eta}{2\lambda} \frac{e^{-jkr}}{r} \iint [\vec{J}_s(\vec{r}) - (\vec{J}_s(\vec{r}).\hat{i}_r)\hat{i}_r] e^{jk(\hat{i}_r,\vec{r})} ds' \qquad (8)$$

denoting the field radiated by PO surface induced currents

$$\vec{J}_{s}(\vec{r}') = \begin{cases} 2\hat{n} \times \vec{H}^{i}(\vec{r}'), & \text{on the lit portion of the surface} \\ 0, & \text{elsewhere} \end{cases}$$
(9)

In order to ascertain the adequacy of the field formulation in (6), the above expressions were implemented to calculate the radiation pattern of the reflector antenna in [1,2], comprised of circularly symmetric reflector fed by a coaxial horn.

IV. CASE STUDIES

For the comparative study, the techniques described before were first applied to the analysis of a single reflector omnidirectional antenna designed to provide a main beam displaced from the horizon by $\alpha=6^{\circ}$. The reflector generating curve is a parabola with focus at the origin, focal distance F, and axis displaced by $\alpha=6^{\circ}$ with respect to the p-axis, as illustrated in Figure 4. The focal distance (F=5.78 λ) and reflector diameter (D=37.52 λ) are adjusted to provide an aperture width $W_A=10\lambda$. Thus, the rays emanating from the focus are reflected along the direction $\theta=96^{\circ}$. The circularly symmetric reflector is obtained by spinning the parabola around the z-axis.



The coaxial feed horn has a coaxial aperture with internal $r_i=0.45\lambda$ and external radii $r_e=0.9\lambda$ [1,2]. As the horn aperture dimensions are electrically small, the feed phase centre at the far-field is practically at the horn's aperture plane. The feed radiation pattern is illustrated in Figure 6. To account for the near field effects, the PO+FC analysis employed a feed model based on the spherical wave expansion obtained from measurements.



Figure 7 shows a comparison of the antenna radiation pattern obtained by the different methods. Analysis of the radiation patterns in Fig. 5 reveals, as expected, a better agreement between (PO + FC's) and (MoM) - obtained radiation patterns throughout the observation region, with larger (< 3 dB) discrepancies arising only at radiation levels below -20 dBi. At the peak direction $\theta=96^{0}$, the MoM analysis predicts a gain peak of 11.9 dBi and the differences between the analysis are less than 0.1 dB.



As a second example, the PO+FC's scheme was embedded in an otimization algorithm to shape the reflector surface. For the task, the reflector generatrix was represented by a parabola plus a Fourier series expansion, where the coefficients of the expansion are adjusted to generate a cosecant squared radiation pattern between 93° and 135°. For the iteration, the parabola described in the previous case was used as a starting solution. Besides the far-field constrains, the coefficients are also adjusted to keep the reflector vertex fixed, as the optimization may displace the reflector, bringing it close to the feed and increasing the coupling effects. The radiation pattern obtained from the analysis of the shaped reflector is depictured in Figure 8, together with the cosecant square pattern and the +/- 3dB limits. To validate the results the omnidirectional reflector antenna was also analysed via MoM and the radiation pattern is show in Figure 8.



V. CONCLUSIONS

A method based on Physical Optics (PO) and Equivalent Edge (EEC) currents was used for the electromagnetic analysis of compact omnidirectional single reflector antenna. The analysis method was used to built a shaping scheme and it was applied to shape a reflector in order to generate a cosecant squared radiation pattern. For validation purposes, the omnidirectionl antennas are analysed by using the Method of Moments to solve the Field Integral Equations, thereby accounting for all electromagnetic effects present in the reflector and feed structure [1-3].

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