A Technique for Analyzing Radiation from Conformal Antennas Mounted on Arbitrarily-Shaped Conducting Bodies

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1. ABSTRACT

This paper presents an efficient method to solve the problem of radiation from conformal aperture and microstrip antennas mounted on arbitrarily shaped conducting bodies. The method, based on the surface equivalence and reciprocity principles, uses a combination of the Finite Difference Time Domain (FDTD) and Method of Moments (MoM) techniques to substantially improve the computational efficiency of the radiation pattern calculation. When the geometry and location of the radiating element are modified, only a small portion of the overall analysis requires re-simulation. This leads to a significant improvement in computational efficiency over presently used techniques, and can substantially improve design efficiency when included in an optimization loop. The technique is first validated by solving two canonical problems, namely a thin slot which is oriented either axially or azimuthally on an infinitely long, perfectly conducting cylinder. Finally, patterns are computed for a cavity-backed elliptical patch antenna mounted on an infinite-length PEC cylinder and compared to patterns computed by an alternate method.

2. APPROACH

This paper utilizes the reciprocity principle to divide the original problem into two parts [1-3]. A reciprocity approach is also applied in [4]; however, the Finite Element Method (FEM) is used to compute the equivalent magnetic currents on surface $\mathbf{S_1}$ instead of the Finite Difference Time Domain (FDTD) technique. In this paper, the first step is to analyze the region containing the conformal antenna, which is typically inhomogeneous. The FDTD method is used to derive equivalent electric and magnetic currents **J** and **M** on the surface $\mathbf{S_1}$ (see Fig. 1) of the radiating aperture of the antenna. Next, $\mathbf{S_1}$ is backed by a perfect electrical conductor (PEC) to short out the electric currents and the problem reduces to that of computing the radiation from these magnetic currents located on the *closed* PEC body. This calculation takes into account the shape of the PEC body in the vicinity of the antenna.

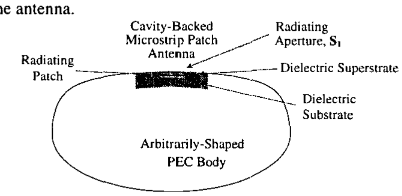


Fig. 1 Problem Geometry

This second step entails the application of the reciprocity principle to address the pattern computation problem. By invoking the reciprocity principle, we can write

$$\int_{V_2} \mathbf{E}_1 \cdot \mathbf{J}_2 \, dV = -\int_{V_1} \mathbf{H}_2 \cdot \mathbf{M}_1 \, dV \tag{1}$$

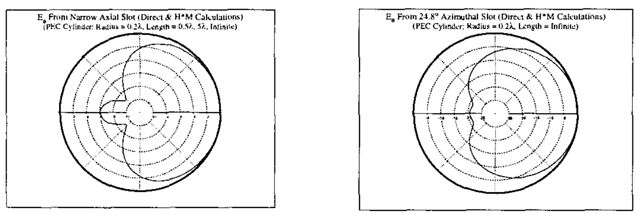
The objective is to compute $\mathbf{E_1}$ radiated by $\mathbf{M_1}$ at a far-zone observation point **P**. An infinitesimal dipole source $\mathbf{J_2}$ is placed at location **P**, and the resultant surface electric currents flowing on the closed PEC body are determined. This problem is well suited for handling by the Method of Moments (MoM). From the electric currents, the equivalent surface magnetic field $\mathbf{H_2}$ is determined and the desired field $\mathbf{E}_1$ is computed by performing the integration on the right-hand side of (1).

Note that once $\mathbf{H}_2$ is determined for the entire mounting structure, only $\mathbf{M}_1$ requires recalculation if the radiating element changes shape or location. The volume integral on the right-hand side of (1) reduces to the surface area of the superstrate (see Fig. 1). This re-simulation requires only a small percentage of the time required for a full-wave analysis of the entire mounting structure.

3. NUMERICAL RESULTS

To illustrate the procedure, the radiation patterns produced by thin slots mounted on an infinite-length PEC cylinder are computed. The slots are oriented in two directions: along the cylinder's axis (axial) and in the circumferential (azimuthal) direction. For the axial orientation, the aperture fields in the slot are ϕ-polarized (across the narrow width of the slot); thus, the $|E_\phi|$ pattern is computed. For the reciprocity calculation, the far-zone dipole source must be polarized in the same direction; therefore, analytical formulas taken from [5] to determine surface currents generated by a TE^z plane wave are used to obtain the necessary H fields (from the surface electric currents). For the azimuthal slot, the polarization of the aperture field is in the z-direction; thus, surface currents generated by a TM^z plane wave are used in the reciprocity pattern computation for $|E_\theta|$. The slot field variation is assumed to be cosinusoidal (dominant mode) and uniform along the length and width of the slot, respectively, for both orientations.

The reciprocity-approach patterns are compared to analytical formulations for these configurations [5] and are found to be in exact agreement (see Fig 2 below).



$|E_\phi|$ *vs.* ϕ Pattern (Direct and H*M) for Axial Slot in PEC Cylinder (Radius=0.2λ, Length=∞)

$|E_\theta|$ *vs.* ϕ Pattern (Direct and H*M) for 24.8° Azimuthal Slot in PEC Cylinder (Radius=0.2λ, Length=∞)

Fig. 2 Radiation Patterns: Axial and Azimuthal Slots on Infinite-Length PEC Cylinder: Computation by Analytical (Direct) *vs.* Reciprocity (H*M) Methods

The above patterns are computed for slots mounted on a 0.2λ radius PEC cylinder. The subtended angle for the azimuthal slot is 24.8°, which is identical to the one in the example considered in [5]. The 0.2λ radius was selected to allow pattern comparisons to the infinite length case. For a length of 5λ, 7,774 unknowns are required for the model; therefore, the size of the problem becomes intractable for longer lengths.

The radiation pattern produced by a cavity-backed elliptical patch antenna covered by a superstrate and mounted on an infinite-length PEC cylinder is computed. The radius of the cylinder is $0.631\lambda_0$ ($0.5\lambda_0 + 0.2\lambda_d$). The patch considered for this analysis is elliptical with major and minor axes of $0.25\lambda_d$ and $0.2\lambda_d$, respectively, and was placed inside a rectangular block of dielectric ($\varepsilon_r = 2.33$) of length $1\lambda_d$ (x'-direction) and width $0.8\lambda_d$ (y'-direction) with a thickness of $0.2\lambda_d$. The major axis of the ellipse was aligned with the cylinder axis. A diagram of the conformal antenna is shown in Fig. 3 below.

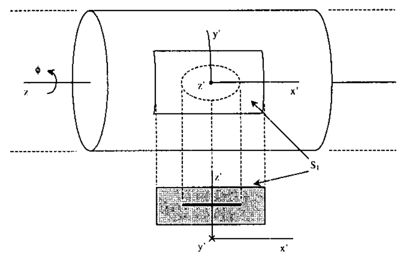


Fig. 3 Elliptical Patch Antenna Mounted on Infinite Length PEC Cylinder

The patterns for the co-polarization (E_θ) radiated fields for the H*M computation on the original geometry (with cavity) and the H*M calculation on an associated geometry (no cavity) [6] are identical. Thus, only the pattern for the original geometry is shown below.

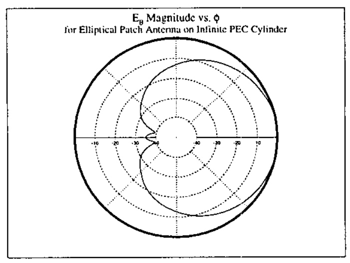


Fig. 4 E_θ H*M Pattern

Even without the cavity, use of the surface electric fields at the position of the cavity (computed by the Method of Moments) yields patterns that are identical with the computation for the original geometry (conformal FDTD computed fields).

For the cross-polarization radiation patterns (E_φ), the patterns computed by both methods compare well. The plots appear below.

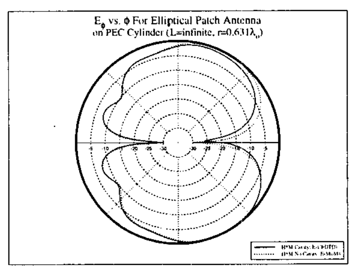


Fig. 5 E_φ: H*M Patterns: Cavity *vs.* No-Cavity

The creeping waves launched from the cavity into the shadow region are less attenuated when compared to the E_θ case. In addition, the "no cavity" pattern contains deeper nulls: these are caused by the higher magnitude creeping waves, which in turn create a stronger standing wave effect. The nulls at $\phi = 0^\circ$ and 180° are caused by the two peaks in the $E_{y'}$ aperture distribution being equal in magnitude, but 180° out of phase.

4. CONCLUSIONS

This paper has presented an efficient method for determining radiation patterns for arbitrarily shaped conformal antennas. Several examples were presented illustrating the procedure for computing a pattern using the reciprocity approach. The technique was first verified against known radiation patterns, then extended to more complex structures. The pattern produced by a cavity-backed elliptical patch antenna was also computed and compared to patterns constructed using an alternate method on an associated geometry. The patterns generated using the proposed method were shown to be in good agreement with the alternate method. The patterns also compared well for the cross-polarization case due to the direction of the aperture fields relative to the cavity edge. The plots also illustrate the effects of a cavity on the radiation pattern.

The mounting structure used for the analyses is a conducting cylinder with a relatively small radius (0.2λ). This size was selected to limit the number of unknowns required for the simulations. It is noted that the technique presented in this paper can also be applied with identical accuracy to larger structures.

The paper also shows how results obtained for the mounting structure can be used for any radiating element shape and location on the structure in the computation of the radiation pattern. This feature of the technique results in significant improvements in computational efficiency when the shape or location of the radiating element is varied. Further work is being pursued on curved radiating patches using an extension of the present locally conformal FDTD algorithm for the magnetic current calculation. The effect of curvature on the flat patch approximation to pattern computation will be addressed and quantified in terms of finding the limit when the approximation is no longer accurate.

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