Analysis of Conformal Antennas on a Complex Platform

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1 Introduction

Modern air vehicles are usually equipped with many antennas for a variety of communication, detection, tracking, and surveillance purposes. To reduce the radar signature and the adverse effect on the aerodynamic design, the antennas are often conformal to the surface of the vehicle and sometimes embedded in a layered dielectric medium. Placing these antennas on an air vehicle inevitably introduces distortion in their radiation patterns and causes mutual coupling. The distortion in the radiation patterns may reduce the desired coverage for effective communications and compromise the accuracy for isolating and locating targets. The existence of mutual coupling, caused by space waves, surface waves, and scattering by the platform, reduces the electromagnetic isolation between the antennas and consequently makes it difficult to operate the antennas simultaneously. Therefore, it is important to develop accurate numerical prediction tools to characterize the radiation patterns and mutual coupling of the antennas mounted on a complex, often large, platform.

In this paper, we present a novel hybrid technique, which is our first attempt to deal with this complex problem. This technique is based on a recently developed finite element–boundary integral (FE–BI) method [1]. It employs higher-order vector elements to accurately model complex geometries and reduce the number of unknowns for large-size problems and incorporates a highly effective preconditioner [2] to accelerate the convergence of the iteration solution of the FE–BI system and the multilevel fast multipole algorithm (MLFMA) [3] to speed up the evaluation of boundary integrals.

2 Formulation

Consider conformal antennas, such as microstrip patch antennas, embedded in a dielectric medium which is situated on a complex platform (Fig. 1). The dielectric medium is characterized by relative permittivity ϵ_r and permeability μ_r, which may be functions of position for an inhomogeneous medium. To formulate a numerical analysis for this problem, we introduce a closed surface S_o to tightly enclose the entire object and leave a small distance, typically 0.05λ to 0.1λ, between S_o and the surface of the object. With this, the entire computational domain is divided into

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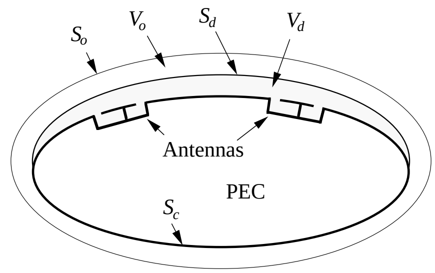

Figure 1: Conformal antennas embedded in a dielectric medium situated on a large platform.

two regions. The first is the narrow, free-space region between S_o and the surface of the object, which is denoted by V_o. The second is the dielectric region, denoted as V_d, whose interface with V_o is denoted by S_d. The surface of the object comprises S_d and conducting surface S_c (Fig. 1).

We first consider the dielectric region V_d. A higher-order vector finite element discretization [4] yields a sparse matrix equation

$$\begin{bmatrix} \mathbf{A}_{(E_{V_d},E_{V_d})} & \mathbf{A}_{(E_{V_d},E_{S_d})} & \mathbf{0} \\ \mathbf{A}_{(E_{S_d},E_{V_d})} & \mathbf{A}_{(E_{S_d},E_{S_d})} & \mathbf{A}_{(E_{S_d},H_{S_d})} \end{bmatrix} \begin{Bmatrix} x_{E_{V_d}} \\ x_{E_{S_d}} \\ x_{H_{S_d}} \end{Bmatrix} = \begin{Bmatrix} b_{E_{V_d}} \\ 0 \end{Bmatrix} \tag{1}$$

where $\{x_{E_{V_d}}\}$ and $\{x_{E_{S_d}}\}$ denote vectors storing the discrete unknowns of the electric fields inside V_d and on S_d, respectively, $\{x_{H_{S_d}}\}$ is a vector storing the discrete unknowns of the magnetic field on S_d, and $\{b_{E_{V_d}}\}$ is a known vector due to the antenna excitation. Applying a similar discretization to the region V_o bounded by S_o, S_d, and S_c yields a sparse matrix equation

$$\begin{bmatrix} \mathbf{A}_{(H_{S_c},H_{S_c})} & \mathbf{0} & \mathbf{0} & \mathbf{A}_{(H_{S_c},H_{V_o})} & \mathbf{A}_{(H_{S_c},H_{S_o})} & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_{(H_{S_d},E_{S_d})} & \mathbf{A}_{(H_{S_d},H_{S_d})} & \mathbf{A}_{(H_{S_d},H_{V_o})} & \mathbf{A}_{(H_{S_d},H_{S_o})} & \mathbf{0} \\ \mathbf{A}_{(H_{V_o},H_{S_c})} & \mathbf{0} & \mathbf{A}_{(H_{V_o},H_{S_d})} & \mathbf{A}_{(H_{V_o},H_{V_o})} & \mathbf{A}_{(H_{V_o},H_{S_o})} & \mathbf{0} \\ \mathbf{A}_{(H_{S_o},H_{S_c})} & \mathbf{0} & \mathbf{A}_{(H_{S_o},H_{S_d})} & \mathbf{A}_{(H_{S_o},H_{V_o})} & \mathbf{A}_{(H_{S_o},H_{S_o})} & \mathbf{A}_{(H_{S_o},E_{S_o})} \end{bmatrix}$$
$$\times \begin{Bmatrix} x_{H_{S_c}} \\ x_{E_{S_d}} \\ x_{H_{S_d}} \\ x_{H_{V_o}} \\ x_{H_{S_o}} \\ x_{E_{S_o}} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{2}$$

where $\{x_{H_{S_c}}\}$ is a vector storing the discrete unknowns of the magnetic field on S_c, $\{x_{H_{V_o}}\}$ and $\{x_{H_{S_o}}\}$ denote vectors storing the discrete unknowns of the magnetic fields inside V_o and on S_o, respectively, and $\{x_{E_{S_o}}\}$ is a vector storing the discrete unknowns of the electric field on S_o.

To form a complete system, a set of equations must be generated for $\{x_{E_{S_o}}\}$ or $\{x_{H_{S_o}}\}$, which incorporates the information about the field exterior to S_o. This set of equations can be generated from the combined field integral equation (CFIE), yielding a matrix equation

$$\begin{bmatrix} \mathbf{B}_{(E_{S_o},H_{S_c})} & \mathbf{B}_{(E_{S_o},E_{S_d})} & \mathbf{B}_{(E_{S_o},H_{S_d})} & \mathbf{A}_{(E_{S_o},E_{S_o})} & \mathbf{A}_{(E_{S_o},H_{S_o})} \end{bmatrix} \begin{Bmatrix} x_{H_{S_c}} \\ x_{E_{S_d}} \\ x_{H_{S_d}} \\ x_{E_{S_o}} \\ x_{H_{S_o}} \end{Bmatrix} = \{0\} \tag{3}$$

where $\mathbf{B}_{(E_{S_o},H_{S_c})}$, $\mathbf{B}_{(E_{S_o},E_{S_d})}$, and $\mathbf{B}_{(E_{S_o},H_{S_d})}$ are full matrices, and $\mathbf{A}_{(E_{S_o},E_{S_o})}$ and $\mathbf{A}_{(E_{S_o},H_{S_o})}$ are sparse matrices.

Since matrices $\mathbf{A}$'s are sparse and matrices $\mathbf{B}$'s are full, the complete matrix formed by (1), (2), and (3) is a partly full and partly sparse matrix. Because of the large number of unknowns involved for large-scale problems, the complete system has to be solved using an iterative solver such as the generalized minimum residual (GMRES) algorithm. It has been found, however, that the iterative process converges very slowly, especially when higher-order vector finite elements are employed [2]. To speed up the convergence, we must employ a highly effective preconditioner. Our recent study [2] showed that such a preconditioner can be constructed by replacing the CFIE with the first-order absorbing boundary condition.

Finally, to solve complete matrix formed by (1), (2), and (3) iteratively, one has to compute the matrix-vector product for each iteration. The most time-consuming part of this computation is to compute the submatrix-vector products $\mathbf{B}_{(E_{S_o},H_{S_c})}x_{H_{S_c}}$, $\mathbf{B}_{(E_{S_o},E_{S_d})}x_{E_{S_d}}$, and $\mathbf{B}_{(E_{S_o},H_{S_d})}x_{H_{S_d}}$, since the rest involves only the sparse matrices. This computation is carried out using the MLFMA [3], which reduces the memory requirements and computation time from $O(N_s^2)$ to $O(N_s \log N_s)$, assuming that the number of unknowns on S_o is N_s and the number of unknowns on $S_c + S_d$ is similar.

3 Numerical Example

To demonstrate the capability of the numerical method described above, we consider a microstrip patch antenna housed in a cavity that resides on a platform consisting of a conducting circular cylinder and a conducting plate (Fig. 2). The microstrip patch antenna is designed to operate at 3.3 GHz and its long edge is aligned with the cylinder's axis. The normalized radiation pattern in the H-plane is shown in Fig. 3 for two cases. In one case, the patch antenna is placed $\alpha = 28°$ from the wing and in the other case, it is placed $\alpha = 45°$ from the wing. Also shown are the measured data [5], and it is seen that the numerical results agree well with the measurement for both co- and cross-polarizations.

References

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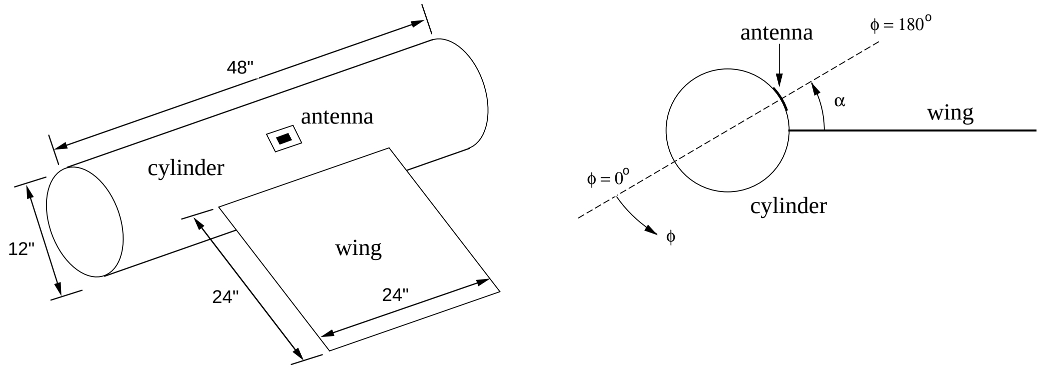
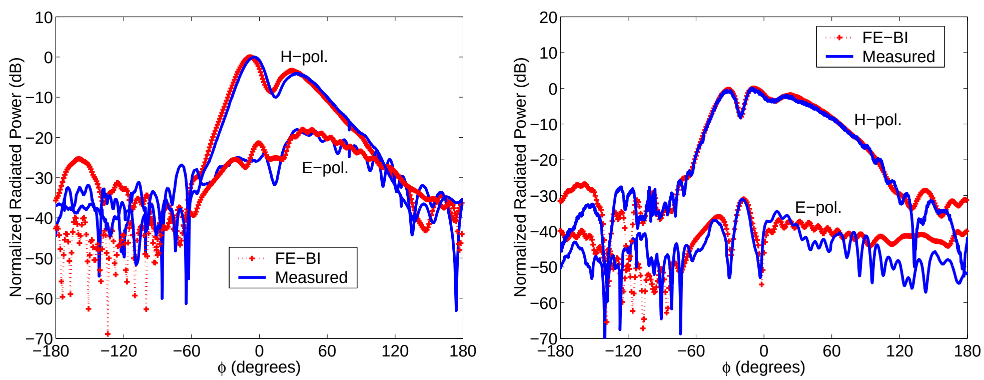


Figure 2: Patch antenna mounted on a cylinder with a wing.



(a) (b)

Figure 3: H-plane radiation patterns. (a) $\alpha = 28°$. (b) $\alpha = 45°$.

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