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Finite Element Analysis of Conformal Array Antennas

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Modern air and land combat vehicles and warships are usually equipped with array antennas for a variety of communication, detection, tracking, and surveillance purposes. To reduce the radar signature and any adverse effect on the aerodynamic design, the antennas are often conformal to the surface of the platform and sometimes embedded in layered dielectric media. Placing these antennas on a platform 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 array elements and consequently makes it difficult to operate the array antennas simultaneously. Therefore, it is important to develop accurate numerical prediction tools to characterize the radiation patterns and mutual coupling of array antennas mounted on a complex, often large, platform. As a first step, it is necessary to develop efficient tools that can be used to simulate and optimize the design of conformal array antennas.

Because of its capability of modeling complex structures and inhomogeneous materials, the finite element method (FEM) [1] is best suited to simulating complex array antennas embedded in dielectric media. During the past several years, we have developed a suite of simulation tools based on the FEM to deal with a variety of array antennas. These include (i) infinitely large periodic phased arrays, (ii) array antennas that are finite in one dimension and infinite in the other dimension, (iii) finite array antennas with arbitrary array elements, and (iv) an accurate antenna feed model. These are described in more details below.

Infinitely large periodic phased arrays [2]. In this case, the Floquet theorem is employed to reduce the domain of analysis to a single unit cell. Periodic boundary and radiation conditions are enforced on the surface of a single unit cell. The asymptotic waveform evaluation (AWE) technique is combined with the FEM to perform fast frequency and angular sweeps. The computed antenna parameters are compared with previously published results and good agreement is obtained. One example concerns with a circular patch array fed with coaxial lines. The periodic lengths are given by T_x = 34 mm and T_y = 36.1 mm, and the patch radius is a = 14.29 mm. The outer and inner radii of the coaxial line used in the simulation are 1.492 and 0.456 mm, respectively. The S_{11} parameter at the coaxial port is shown in Figure 1. Both the magnitude and phase of the calculated S_{11} parameter agree with the results obtained by the hybrid generalized scattering matrix (GSM) and the FEM [3].

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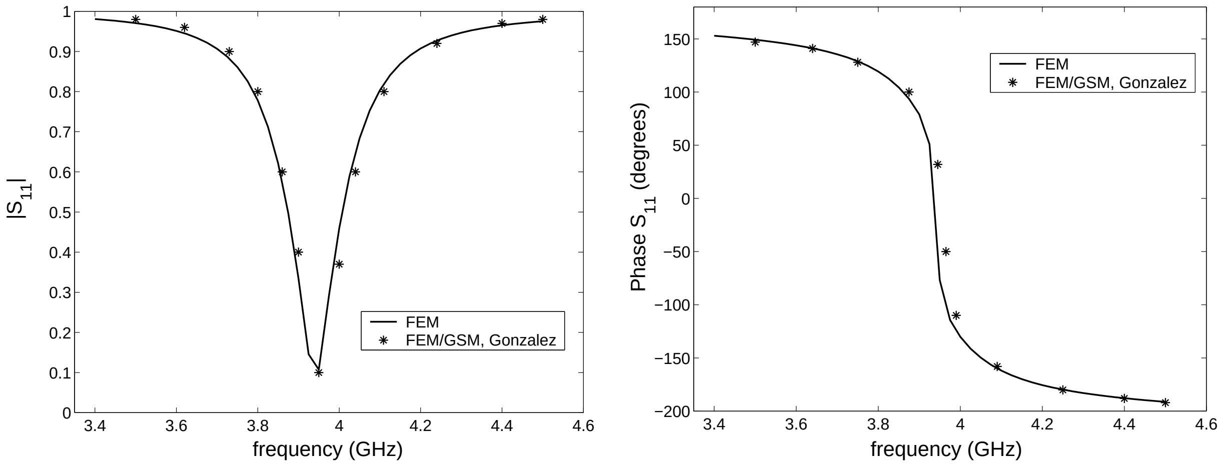

Figure 1: Magnitude and phase of the S_{11} parameter for the microstrip patch array consisting of circular patches with radius a = 14.29 mm, substrate thickness h = 0.79 mm, and relative permittivity of 2.33. The feed is modeled using a precise coaxial line model.

Finite-by-infinite array antennas [4]. In this case, the array is infinite and periodic in one dimension and finite and arbitrary in the other dimension. The analysis of this type of array is important because it enables fast and efficient investigation of the truncation (or edge) effect of a finite array. Here, the Floquet theorem is employed to reduce the domain of analysis to one row of array elements. Again, periodic boundary and radiation conditions are formulated for a unique FEM solution of the fields inside the domain of analysis. As an example, consider a 5 x infinite vivaldi array antenna. Figure 2 shows the unit cell geometry of the antenna, with details given in [4], and the normalized radiation power pattern in the E-plane as a function of the receiving angle at 3, 4, and 5 GHz.

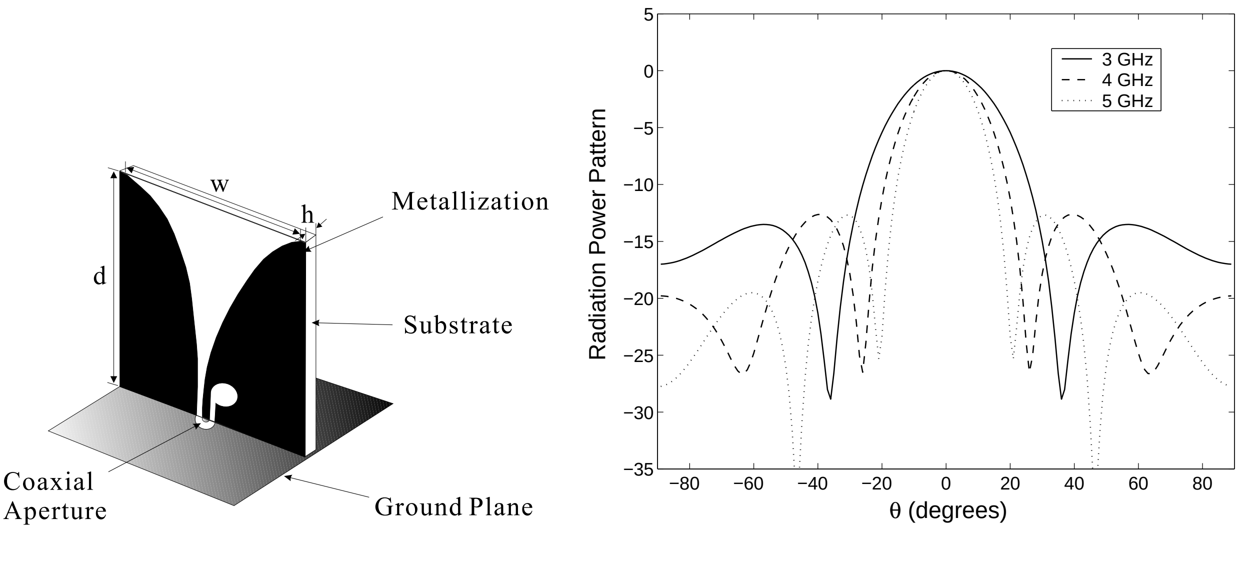

Figure 2: Geometry of the vivaldi array antenna (a single element) and the E-plane radiation pattern of the 5 x infinite vivaldi array antenna.

Arbitrary finite array antennas. Among the three types of arrays considered here, this is most challenging because even for an array antenna of moderate size, the computational requirements become very excessive. This is particularly true when the computational domain is truncated using a boundary integral equation, which yields a fully populated submatrix for the fields over the entire aperture of a finite array. To alleviate this problem, the adaptive integral method (AIM) is employed to efficiently evaluate the boundary integrals with the aid of the fast Fourier transform (FFT). Figure 3 shows the calculation of the mutual coupling (S-parameters) among a 2 x 2 microstrip patch array antenna. More specifically, it gives the plots of the 4 x 4 scattering matrix from 1 to 3 GHz. The FEM results obtained with the boundary integral truncation (circles) compared very well with the results (lines) of another calculation by the time-domain FEM using perfectly matched layers for mesh truncation [5].

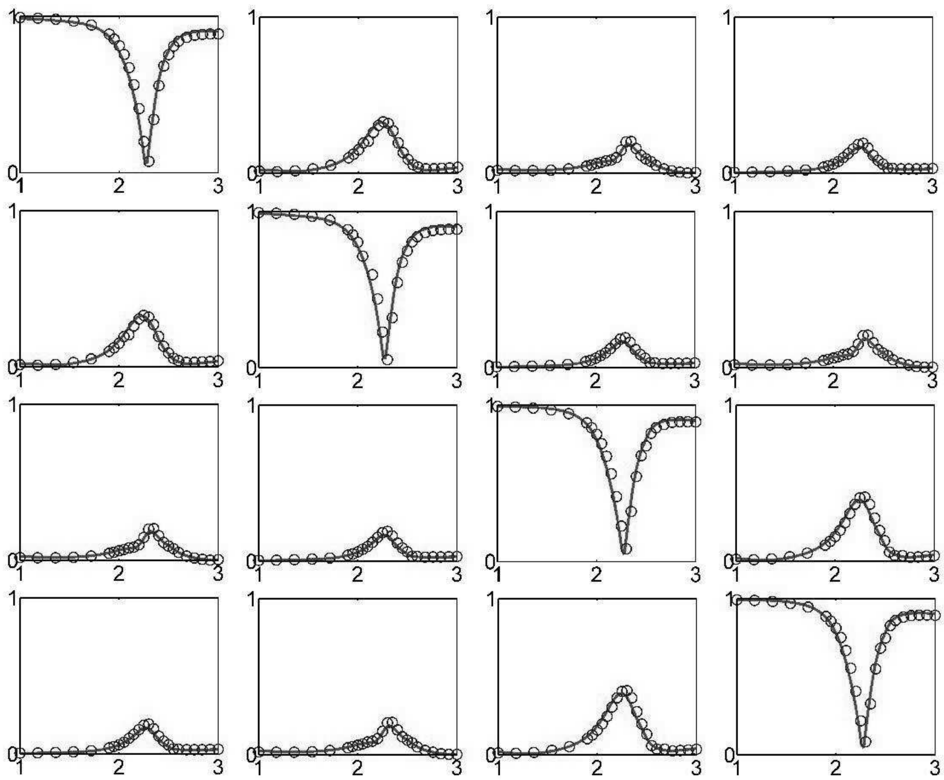

Figure 3: Scattering matrix S(f) of the 2 x 2 microstrip patch array antenna. The graph on the i-th row and j-th column shows $|S_{ij}(f)|$ for the frequency band from f = 1 to 3 GHz.

Accurate antenna feed modeling. One of the very critical aspects in the development of any numerical methods for accurate antenna analysis is the modeling of antenna feeds. Although reasonably accurate results for radiation patterns can be obtained using simplified feed models, accurate characterization of input impedance and mutual coupling (mutual impedances or S-parameters) can only be obtained using accurate feed models. In practice, most antennas are fed by coaxial lines. However, most numerical analyses use simplified models to make the problem more tractable. For example, in the integral equation based method of moments (MoM) and differential equation based FEM, the delta voltage gap and current probe/filament are often used to excite an antenna. Although these simple models are capable of generating accurate radiation patterns and in some cases input impedances for simple wire and patch antennas, they often do not work well for complex antennas and, worst of all, their modeling errors cannot be systematically reduced (controllable). Although the use of a magnetic frill model improves the accuracy of impedance calculation for wire antennas, its practical application is still very limited. In this work, we have developed an accurate method to model a variety of antenna feeds. This model is directly based on the full-wave analysis of electric and magnetic fields in the feed structures, instead of using the voltage and current concepts. This model involves a reference surface, often chosen to be close to the coaxial or waveguide opening, and then represents the total field as the superposition of the incident and reflected waves (including higher-order modes excited by the structures in the vicinity of the feed). An exact boundary condition can then be derived, which can be incorporated into the FEM solution of the antenna problem. As a result, the input for the numerical analysis is the incident field in the feed line and the output is the reflection coefficient (S_{11}), from which the input impedance can be readily calculated. In the case for multiple antennas, which is of particular interest in this project, a full S-parameter matrix can be computed by exciting each antenna. This model is applicable to most antenna feeds (coaxial lines, waveguides, and other transmission lines). Except for numerical discretization, the model is exact and its numerical solution is error controllable. More important, since this model calculates the reflected waves in the feed lines, one can incorporate the effect of feed structures, such as corporate feed, into the array antenna analysis. All the results shown above were obtained using this feed model.

In summary, a number of simulation tools based on the FEM have been developed and tested for simulation of conformal array antennas. Higher-order curvilinear elements were employed to accurate model complex structures. An accurate coaxial feed model was designed to improve the accuracy of the calculated input and mutual impedances (or S-parameters).

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