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A Hybrid Technique for Combining the Moment Method Treatment of Wire Antennas with the GTD for Curved Surfaces

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Abstract—**This hybrid technique is a method for solving electromagnetic problems in which an antenna is located near a conducting body. The technique accomplishes this by casting the antenna structure in a moment method (MM) format, then modifying that format to account for the effects of the conducting body via the geometrical theory of diffraction (GTD). The technique extends the moment method to handle problems that cannot be solved by GTD or the moment method alone. Wire antennas are analyzed to find their input impedance when they are located near perfectly conducting circular cylinders, although the methods used are not restricted to circular cylinders. Three orthogonal orientations are identified, and antennas to match them are analyzed. For each case, the hybrid solution is checked with one of three independent solutions: an MM-eigenfunction solution, image theory, or experimental measurement. In almost all cases, excellent agreement is obtained due in large part to the fact that the moment method near fields are, for the first time, cast into a ray optical form.**

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I. INTRODUCTION

THE HYBRID TECHNIQUE presented in this paper is a method for solving electromagnetic problems in which an antenna is located on or near a conducting body, such as antennas on ships or aircraft, feed antennas near the reflecting surfaces of reflector antennas, or slots on finite conducting surfaces [1]. The technique solves these kinds of problems by properly analyzing the interaction between the antenna and the conducting body or between the antenna and a discontinuity in the conducting body. This is accomplished by representing the antenna by the moment and then using the geometrical or uniform theory of diffraction (GTD or UTD) to account for the interaction. Thus the hybrid technique uses the GTD or UTD to extend the usefulness of the moment method to problems that could not be treated by either the moment method or GTD alone. This approach should be contrasted with other methods that extend the usefulness of the GTD by using the moment method as a tool to do so, such as the GTD-MM technique in [2].

The basic hybrid MM-UTD technique used in this paper was first described in the literature by Thiele and Newhouse [1]. In that paper the technique was applied to antennas on finite planar surfaces. The moment method solution was modified to account for the planar surfaces being finite rather than infinite using UTD wedge diffraction theory.

In the present paper a hybrid technique for combining the moment method treatment of wire antennas with the GTD for

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curved surfaces will be presented. Specifically, wire antennas will be analyzed near perfectly conducting circular cylinders. The wire antenna will be cast in a moment method format used by Richmond [3], [4], in his computer program for thin-wire structures. The use of piecewise sinusoidal basis functions will be modified and exploited. It will be shown that the near fields from the piecewise sinusoidal basis functions can be cast into rap optical form, thereby making the moment method fields completely compatible with the GTD. Because of this important fact, it will be seen that a wire antenna can be placed arbitrarily close to the curved surface of the cylinder and the interaction with the curved surface accurately accounted for.

In the next section, the hybrid MM-UTD technique is described in some detail. The very effective way in which the GTD is incorporated into the thin-wire theory is presented and demonstrated.

Section III is the results section, in which the hybrid technique is applied to find the input impedance of antennas as a function of their distance from the circular cylinder. For each case, the hybrid solution is checked with one of three independent solutions, an MM-eigenfunction solution, image theory, or experimental measurement.

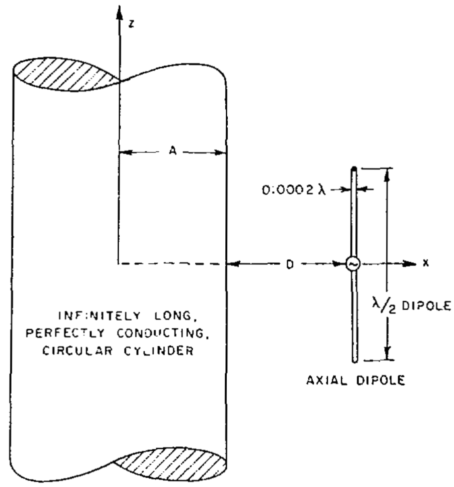


Fig. 1. Half-wave dipole axially oriented distance D from perfectly conducting circular cylinder of radius A.

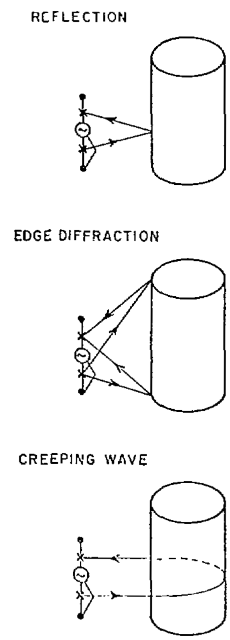


Fig. 2. Scattering mechanisms for dipole interaction with cylinder.

II. THE HYBRID MM-UTD TECHNIQUE

In the paper by Thiele and Newhouse [1], pulse functions and point matching were employed to represent the antenna. A second paper by Thiele and Chan [5] used the piecewise sinusoidal function in a Galerkin formulation. Both papers utilized the UTD of Kouyoumjian and Pathak [6]. The fundamental aspects of the hybrid technique are presented in both of these papers and need not be repeated here. However, we will need to examine the calculation of the $[\Delta Z]$ matrix in some detail.

To facilitate the discussion, consider the half-wave dipole, axially oriented near a perfectly conducting cylinder as shown in Fig. 1. The free space impedance matrix $[Z]$ which characterizes the dipole (only) is a function of the dipole geometry alone. The effect of the circular cylinder on the dipole current is accounted for by a delta impedance matrix $[\Delta Z]$. When the delta impedance matrix is added to the free space impedance matrix, the resulting modified impedance matrix $[Z']$ characterizes the dipole in the presence of the cylinder. Thus

$$[Z'] = [Z] + [\Delta Z]. \tag{1}$$

It is the calculation of $[\Delta Z]$ that is of interest in this paper. We can express the calculation of the jkth element in $[\Delta Z]$ by

$$\Delta Z_{jk} = -\int_{\text{rec mode } k} \bar{E}_j^s(l) \cdot \bar{I}_k(l)\, dl \tag{2}$$

where $\bar{I}_k(l)$ is the piecewise sinusoidal distribution on the receiving mode dipole k and $\bar{E}_j^s$ is the field scattered from the cylinder when illuminated by the test source $\bar{I}_j(l)$ which also has an assumed piecewise sinusoidal distribution. This integration is carried out numerically with the aid of the GTD in finding $\bar{E}_j^s(l)$.

To find $\bar{E}^s(l)$ using a GTD format would require breaking $\bar{E}^s(l)$ into three basic components as sketched in Fig. 2. $\bar{E}^s(l)$ contains a reflected component originating from the source segment and reflecting directly to the receiving or observation segment. $\bar{E}^s(l)$ also contains edge-diffracted components originating from the source segment and diffracting off the cylinder ends. Finally, $\bar{E}^s(l)$ contains a creeping wave contribution coming from the source segment, attaching to the cylinder, then propagating around the cylinder as a surface wave and finally shedding to the observation segment. Other components (such as from the source to an edge diffraction, to the surface wave, to another edge diffraction, to the observation segment) are possible, but these contributions would be minute and are justifiably neglected.

For the particular geometry under initial consideration in this paper, two temporary assumptions are made. The cylinder is assumed to be electrically long so that diffraction from the ends is negligible, and the circular cylinder is assumed to have a large electrical diameter so that the creeping wave contribution is minute and may be ignored. These assumptions are made to simplify the problem temporarily and are not restrictions on solvable geometries. For the case in study, the dominant contribution to the scattered field $\bar{E}^s(l)$ is the reflected field $\bar{E}^r(l)$. Thus the problem has been reduced to one of finding the reflected field $\bar{E}^r(l)$ at observation points on the receiving segment given an incident field from the source segment. To find this reflected field, GTD (or in this case geometrical optics (GO)), is applied.

The field expressions for $\bar{E}_j^s$ are obtained using the uniform GTD given by Kouyoumjian and Pathak [6]. The application of the UTD to the cylinder is based on techniques presented by Marhefka [7].

The GO field at an observation point is

$$\bar{E}^r(s) = \bar{E}^i(Q_R) \cdot \bar{\bar{R}} \sqrt{\frac{\rho_1{}^r \rho_2{}^r}{(\rho_1{}^r + s)(\rho_2{}^r + s)}}\, e^{-jks} \tag{3}$$

where $\bar{E}^i(Q_R)$ is the field incident at the reflection Q_R generated by the test current on the source segment and where $\bar{\bar{R}}$ is the dyadic reflection coefficient

$$\bar{\bar{R}} = \hat{e}_{\parallel}{}^i \hat{e}_{\parallel}{}^i - \hat{e}_{\perp}\hat{e}_{\perp} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}. \tag{4}$$

The quantities $\rho_1{}^r$ and $\rho_2{}^r$ are the principal radii of curvature of the reflected wavefront at the reflection point Q_R. Kouyoumjian and Pathak [6] show how to find these values for an arbitrary wavefront by diagonalizing the curvature matrix for the reflected wavefront given by Deschamps [8]. The field $\bar{E}^i(Q_R)$ is known exactly for a monopole segment with a piecewise sinusoidal current distribution.This field will be considered in detail shortly.

In applying (3), two important points warrant special attention. First to find Q_R on the cylinder, a source and observation point must be specified. The observation point presents no problem. In finding the segment-to-segment impedance terms a numerical integration is performed over the observation segment. The observation segment is divided into a specified number of integration sampling points which also serve as observation points. Specification of the source point, however, poses a problem. The source of $\bar{E}^i(Q_R)$ is actually distributed over the source segment, so an assumption must be made that the source appears to radiate from one specific point located on the source segment. This assumption allows the location of Q_R to be determined.

The second important point for consideration involves the ray optical nature of the GTD or GO. The field $\bar{E}^i(Q_R)$ is known at the reflection point Q_R, but in finding $\bar{E}^r(l)$ only the components of $\bar{E}^i(Q_R)$ which are perpendicular (⊥) to the incident ray path are used as seen in (4). The GTD does not provide a method of including components of the field along the ray path. The assumption that must be made, then, is that the ray path component of $\bar{E}^i(Q_R)$ is negligible. In the near field, this is a poor assumption.

A careful look at the exact near-field expressions from a monopole segment with a piecewise sinusoidal current distribution shows how making both of the above assumptions can be avoided. The fields radiated from the monopole segments are given by Richmond [3]. Fig. 3 shows the z-oriented monopole segment. The piecewise sinusoidal current distribution is

$$I(z) = \frac{I_1 \sinh \gamma(z_2 - z) + I_2 \sinh \gamma(z - z_1)}{\sinh \gamma d} \tag{5}$$

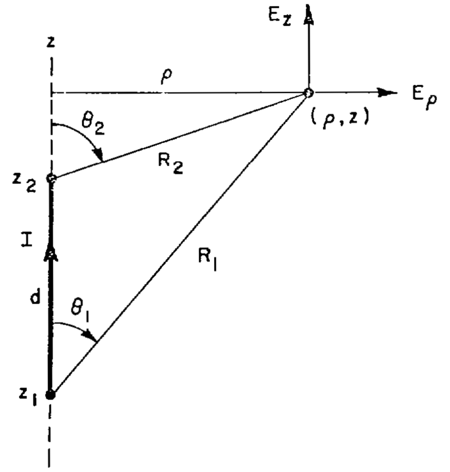


Fig. 3. z-directed monopole segment source with observation point (ρ, z).

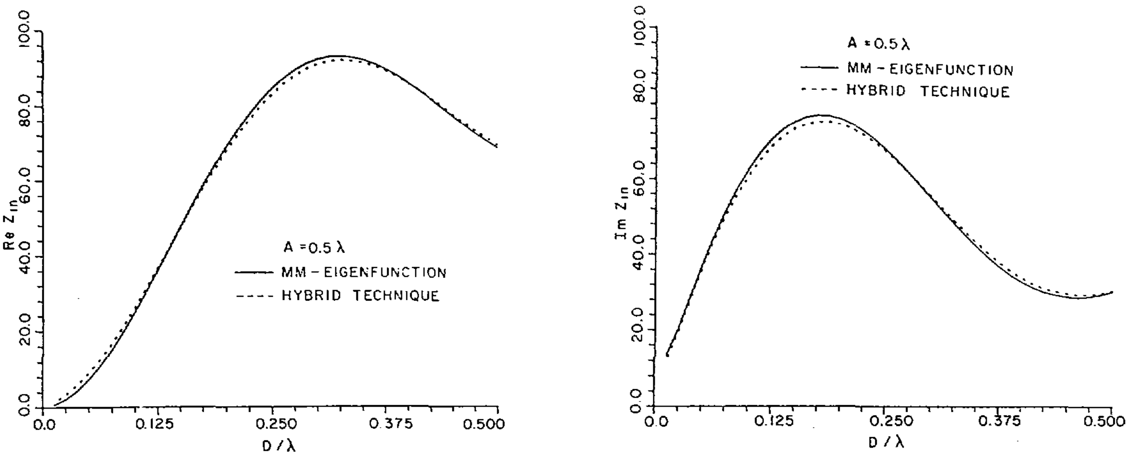
where I_1 or I_2 is zero, γ is the complex propagation constant, d is the segment length, and z_1, z_2 are the endpoints. The resulting fields at any point (ρ, z) are

$$E_\rho = \frac{\eta}{4\pi\rho \sinh \gamma d} [(I_1 e^{-\gamma R_1} - I_2 e^{-\gamma R_2}) \sinh \gamma d + (I_1 \cosh \gamma d - I_2) e^{-\gamma R_1} \cos \theta_1 + (I_2 \cosh \gamma d - I_1) e^{-\gamma R_2} \cos \theta_2] \tag{6}$$

and

$$E_z = \frac{\eta}{4\pi \sinh \gamma d} \left[(I_1 - I_2 \cosh \gamma d) \frac{e^{-\gamma R_2}}{R_2} + (I_2 - I_1 \cosh \gamma d) \frac{e^{-\gamma R_1}}{R_1} \right] \tag{7}$$

where η is the impedance of the propagation medium. These expressions are for a z-oriented segment. They work, however, for a general segment with any skewed orientation through a simple coordinate transformation. To be correct, these E-fields are only complete when added to the E-fields of a connecting monopole segment. These connected monopole segments make a dipole mode that is used in the thin-wire theory. The crucial fact to note about these E-fields is that they may be separated into fields emanating from the two endpoints. Moreover, these separated field contributions have an $e^{-\gamma R}/R$ term multiplied by a pattern factor form and are recognized as spherical waves emanating from the endpoints, a fact which by itself is well-known. These observations may be exploited with remarkable results to improve the integration of the GTD with thin-wire theory. At the observation point on the dipole, the reflected field $\bar{E}^r(l)$ will now be the superposition of the contribution from one endpoint of the source segment plus the contribution from the other endpoint. Each endpoint will have its own reflection point on the cylinder. By separating the fields in this way the distributed nature of the source has been properly accounted for. Less obvious is the fact that the ray path components of the separated fields are zero so that the assumption that they are negligible is exact. Thus the incident field from the source segment at the reflection points is



(a) (b)

Fig. 4. Axial dipole input impedance near cylinder of radius $A = 0.5\ \lambda$. (a) Real part. (b) Imaginary part.

separated to make it perfectly compatible with the ray optical nature of GTD.

Once $\bar{E}^r(l)$ is known, it is dotted with $I(l)\overline{dl}$ on the observation or receiving segment. The segment-to-segment impedance terms are found by carrying out the integration indicated in (2) numerically. These terms are combined to get the ΔZ mode-to-mode impedance terms, thus forming the $[\Delta Z]$ matrix. This matrix, representing the cylinder effects, is added to $[Z]$ to form $[Z']$ the modified impedance matrix which is solved in the normal moment method manner. The matrix is inverted and multiplied by the voltage source column giving the desired current distribution. The input impedance of the dipole is found directly from the current distribution.

III. WIRE ANTENNAS NEAR CIRCULAR CYLINDERS

The circular cylinder is chosen as the curved surface whose presence is to be incorporated into the hybrid technique because the circular cylinder is one for which other solutions are available for purposes of comparison. The electromagnetic problems solved in this section will all involve the calculation of input impedance of the radiator as a function of distance from the cylinder. The current distribution and correspondingly the input impedance of the radiators is very sensitive to the location of the nearby circular cylinder. Thus solving for input impedance is a good test of the capabilities of the hybrid technique.

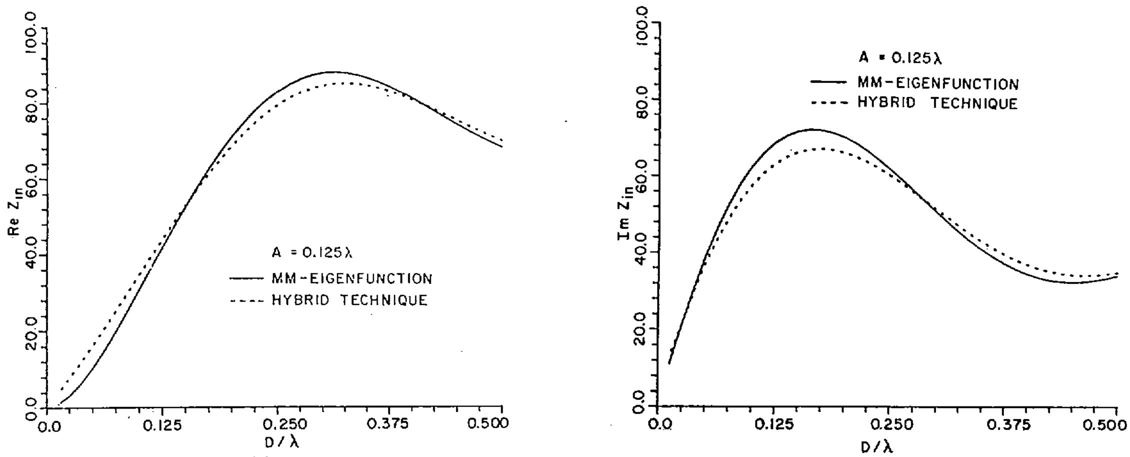
Three orthogonal directions or orientations can be identified in relationship to the cylinder. These orientations are axial (parallel to the axis of the cylinder), radial (perpendicular to the surface of the cylinder), and circumferential (tangent to the surface and perpendicular to the axis). Antennas or radiators are chosen with orientations to match one of these three directions with respect to the cylinder. If the method can correctly solve these three independent orientations then it can solve any arbitrary combination of them in the presence of the cylinder.

An independent MM-eigenfunction solution by Ersoy and Wang [9] is available for axially oriented dipoles near an infinitely long perfectly conducting circular cylinder. The solution is found by summing sufficient terms to evaluate an integral expression. The integrand contains a Green's function for the circular cylinder. The dipole has a cos (kz) current distribution. This MM-eigenfunction solution can be considered exact and is a perfect independent method to check the hybrid solution against. The restriction is that in order to achieve the cos (kz) current necessary for correct comparison the hybrid technique must use *only* one mode or two segments to model the half-wave dipole.

The first results comparing the hybrid technique with the MM-eigenfunction solution are shown in Fig. 4(a) and (b). The real and imaginary parts of the input impedance of the dipole were plotted versus dipole distance D from the cylinder. For this case D was varied from near zero to one-half wavelength and the cylinder radius was one-half wavelength. The vertical axes are in ohms, the solid line is the MM-eigenfunction solution, and the dotted curve is the hybrid solution. The two methods give basically the same result. The largeness parameter for the GTD, or in this case the GO, part of the hybrid solution is kA. k is the wavenumber equal to $2\pi/\lambda$. A is the cylinder radius given in wavelengths. The GTD uses an asymptotic approximation which is good when the largeness parameter is greater than one. For the case $A = 0.5\lambda$ shown in Fig. 4(a) and (b) the largeness parameter is about 3.15, much larger than one, and the excellent agreement follows.

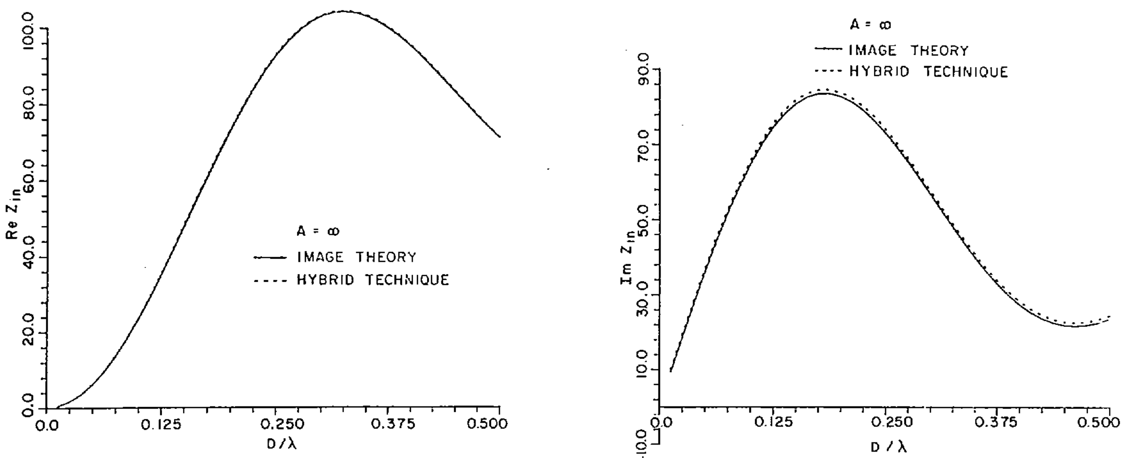
Fig. 5(a) and (b) show the input impedance curves calculated by the two methods when $kA = 0.785$. This case has violated the largeness parameter constraint, yet the agreement between the MM-eigenfucntion and hybrid solutions is still fairly good. Comparing the amount of error in the hybrid solution for these as kA gets smaller, it is seen that the GO breaks down gracefully. One can push the hybrid technique as far as is consistent with the desired accuracy of the particular application and not worry about sudden breakdown.

When the cylinder radius is very large, the MM-eigenfunction solution needs more terms to converge. For this reason and the need to verify the accuracy of the hybrid solution when the dipole is modeled with more than one mode, the method is compared with a ground plane image theory solution. As A goes to infinity the cylinder opens to an infinite planar conducting surface or ground plane. Richmond has adopted his thin-wire program to handle this geometry [10].



(a) (b)

Fig. 5. Axial dipole input impedance near cylinder of radius A = 0.125 λ. (a) Real part. (b) Imaginary part.



(a) (b)

Fig. 6. Axial dipole input impedance near cylinder of radius A = ∞. (a) Real part. (b) Imaginary part.

Solving the case illustrated in Fig. 1 when the cylinder radius was $A = 10.0\lambda$ gave the curves shown in Fig. 6(a) and (b). The solid curve was calculated using ground plane image theory. Again, the dotted curve is the hybrid solution. In each of these methods the dipole was modeled with four segments, resulting in three modes. The agreement is seen to be nearly exact.

To demonstrate the effectiveness of separating the field forms from the segments into contributions from the endpoints, the same case was solved with the source point assumed to be at the center of the source segment. Fig. 7(a) and (b) show how the accuracy of the solution is reduced by this assumption. Various other locations for a single source point were tried with similar unfavorable results [11].

No matter how satisfying analytical comparisons are, experimental verification remains an undisputed and effective method of testing a solution. It is, as for the case of the square loop of a later section, often the only independent method available for checking. Partly as further verification of the results already shown in this section and partly as a test of the measurement setup, experimental measurements are made to determine the input impedance of the axial half-wave dipole located near a circular cylinder. The experimental measurements are compared with the hybrid technique solution. Fig. 8(a) and (b) are the resulting plots. The agreement between the measurement and the theory are quite good.

Radial Dipoles

The second radiator orientation which will be considered is the one radial to the cylinder. The antenna will be a radial dipole whose center feed point is located a distance D from the infinitely long perfectly conducting circular cylinder. The geometry of the problem is illustrated in Fig. 9. The objective is, again, to find the input impedance of the half-wave dipole using the hybrid technique as D is varied from nearly one-quarter wavelength to three-quarters wavelength. In this case only one independent method for checking the hybrid solution is available. This is the ground plane image theory solution. It provides a check when the cylinder radius A is large. Fig. 10(a) and (b) show results for the radial case, and the agreement between the hybrid results and image theory results is seen to be very good.

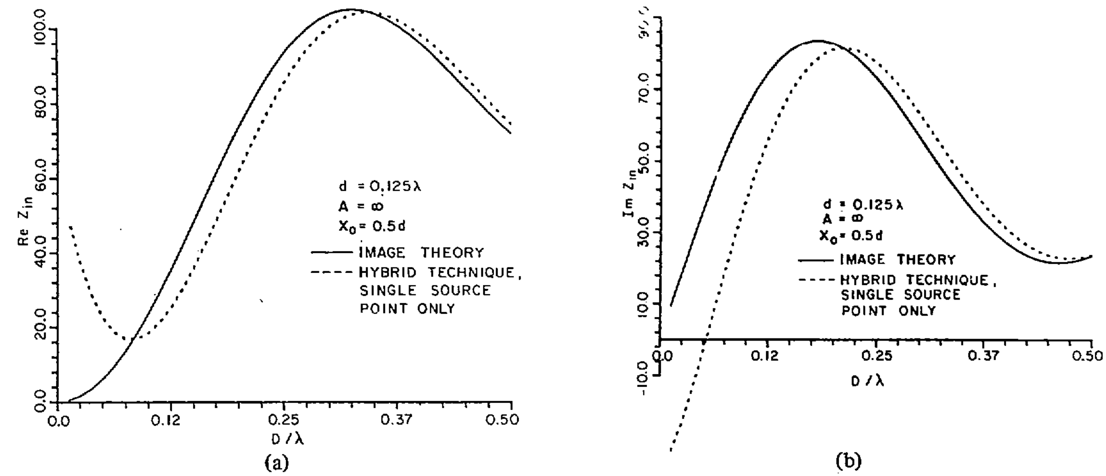


Fig. 7. Axial dipole input impedance near cylinder of radius $A = \infty$ when only single source point is used for segment. (a) Real part. (b) Imaginary part.

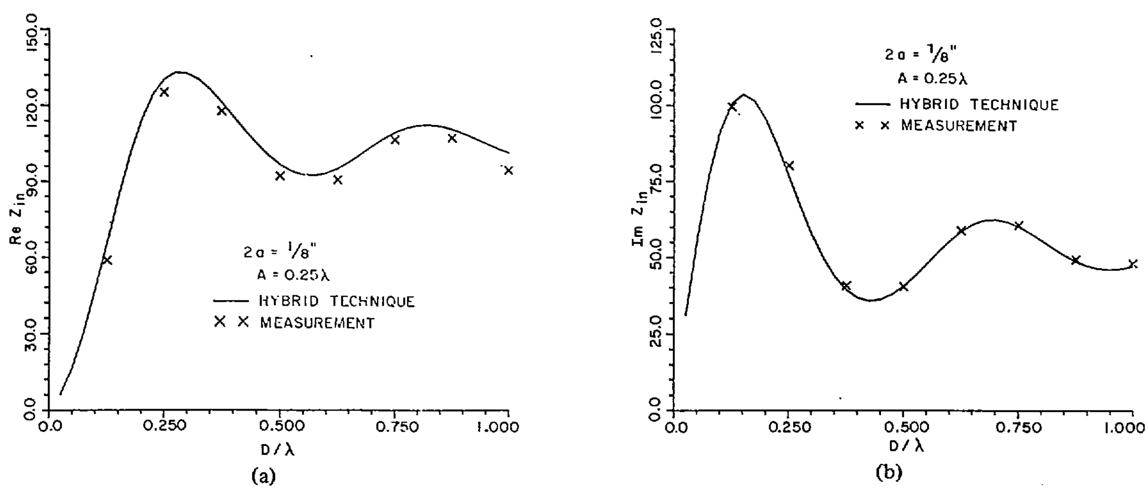


Fig. 8. Axial dipole input impedance near cylinder of radius $A = 0.25\ \lambda$, $a = 0.0125\ \lambda$. (a) Real part. (b) Imaginary part.

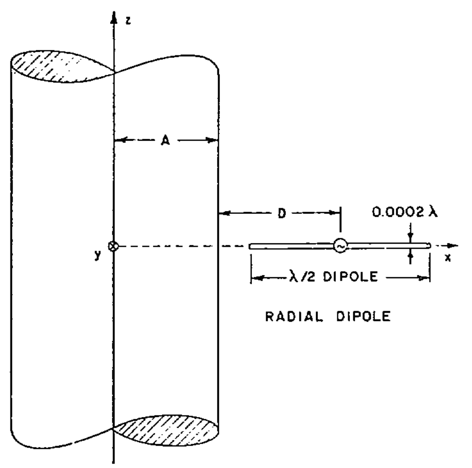


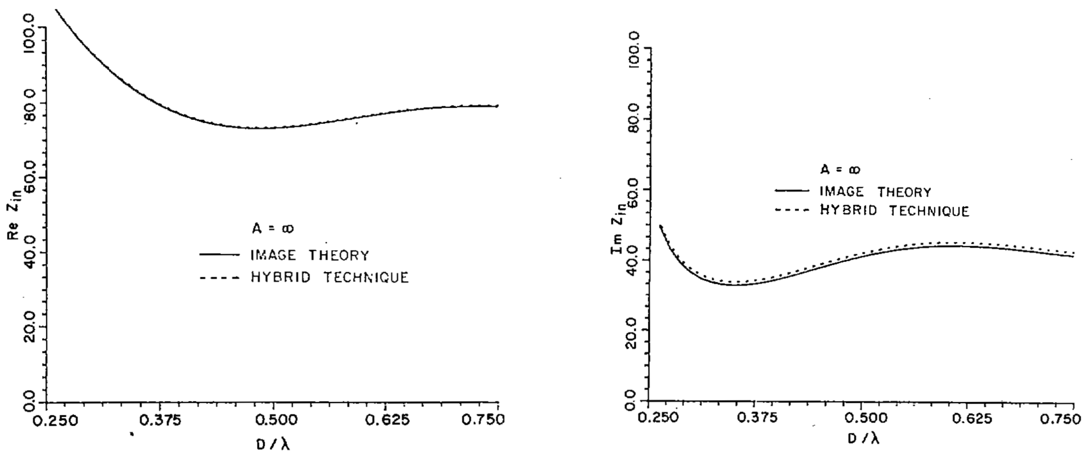
Fig. 9. Half-wave dipole radially oriented distance D from perfectly conducting circular cylinder of radius A.

Square Loop Antennas

The last of the three orthogonal orientations to be tested and verified is the circumferential or phi-oriented radiator. The choice of antenna with a strong phi-component is the square loop antenna as pictured in Fig. 11. This configuration was chosen because its input impedance can be easily measured and used as an independent check.

The hybrid technique will first be applied to the geometry of Fig. 11 when A is large, $A = 5.0\lambda$. The results are compared with the ground plane image theory solution in Fig. 12(a) and (b). The real and imaginary components have been plotted as a function of square loop distance D from the circular cylinder. Note that the imaginary impedance is negative for the loop. The agreement is almost exact, verifying the hybrid solution for large A.

Next, the results for $A = 0.25\lambda$ will be presented by comparing the hybrid solution with experimental measurement. The results comparing the hybrid technique with the experimental measurements are shown in Fig. 13(a) and (b). The curves track the measurements quite well, but the levels are



(a) (b)

Fig. 10. Radial dipole input impedance near cylinder of radius $A = \infty$. (a) Real part. (b) Imaginary part.

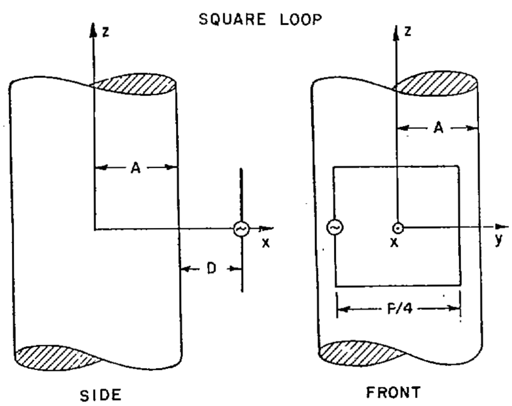
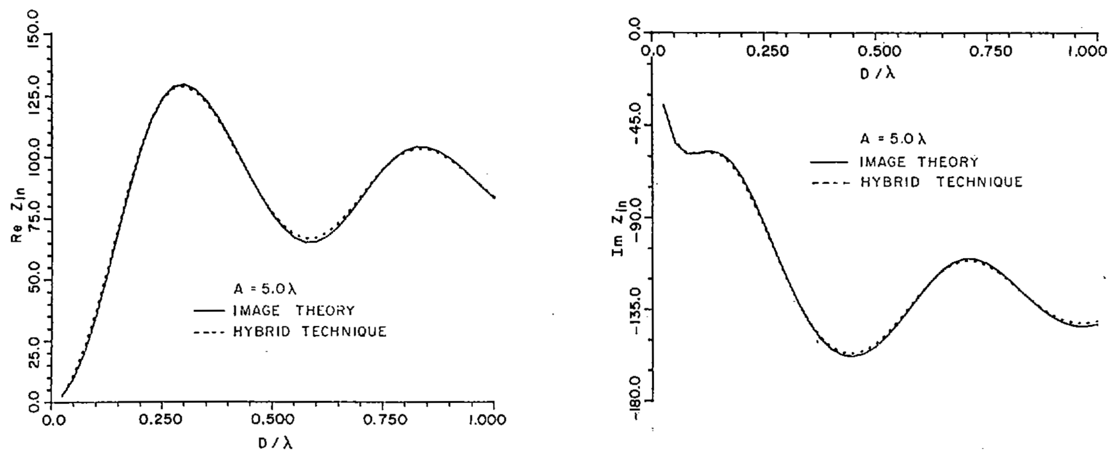


Fig. 11. Square loop antenna located distance D from perfectly conducting circular cylinder of radius A.



(a) (b)

Fig. 12. Square loop input impedance near cylinder of radius A = 5.0 λ. (a) Real part. (b) Imaginary part.

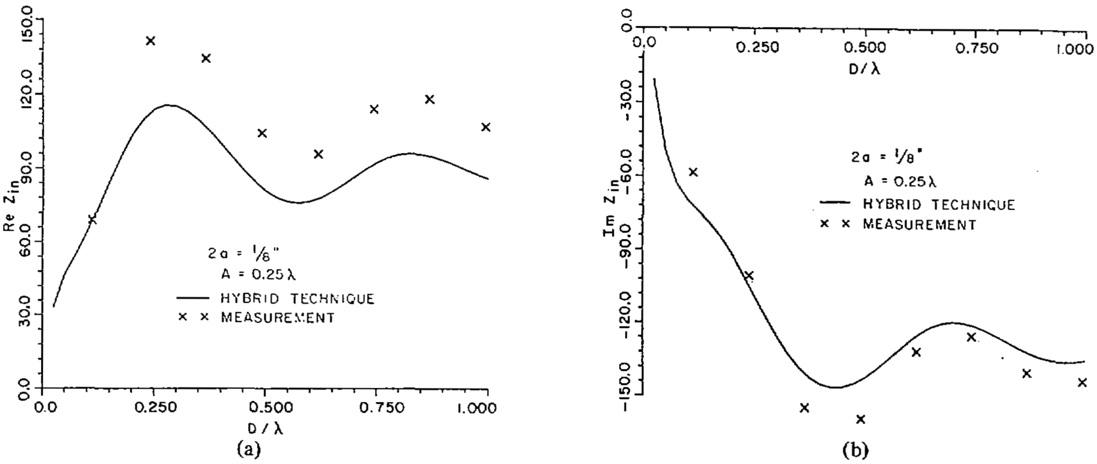


Fig. 13. Square loop input impedance near cylinder of radius A = 0.25 λ, a = 0.0125 λ. (a) Real part. (b) Imaginary part.

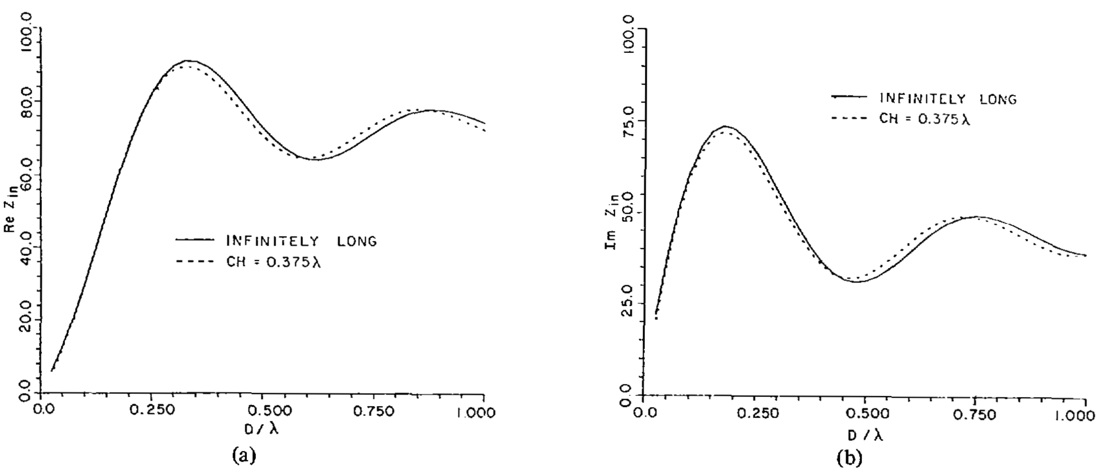


Fig. 14. Axial dipole input impedance near cylinder of radius A = 0.25 λ. (a) Real part. (b) Imaginary part.

shifted making the number values disagree. Note that $kA = 1.57$ only.

The inability to get exact level agreement is at least partly explained by the sensitivity at the frequency of operation which must be near resonance for good coupling with the cylinder. Also, the connectors available were found to have a slight frequency dependent phase shift aside from the one attributable to their lengths. In addition the measurements were done with half a loop and half a finite cylinder on a finite ground plane rather than an infinite ground plane.

Finite Length Circular Cylinders

In this section finite length cylinders will be handled using the hybrid technique. To account for the finite cylinder length, the GTD for curved edges is used to find delta impedance matrices which properly modify the free space matrix to include the cylinder end effects. The formulation of the part of the hybrid technique which finds the cylinder end effects is modeled after the part which finds the reflection effect.

To test the finite cylinder capability of the hybrid technique, the input impedance of an axially oriented dipole was calculated. The diffraction points are on the cylinder's end edges in the x-z plane with x positive. The cylinder half height is CH, its radius is A, and the half-wave dipole is a distance D from the cylinder. A is fixed at one-quarter wavelength.

The only analytical method available for solving a finite cylinder, other than the hybrid technique, is the moment method. Computer limits on storage and running time prohibit its use on a cylinder as electrically large as the case to be solved, so no independent method is available to check the hybrid solution for this geometry. Experimental measurement will prove impossible because the effects of the finite ends will be too small to measure accurately. The method chosen to verify the results was to compare the hybrid method solution of the finite length cylinder case with the hybrid solution of the infinite length cylinder.

The results are for a cylinder height $CH = 0.375\lambda$ where D is varied from near zero to one wavelength. The input impedance plots are given in Fig. 14(a) and (b). The solid curves are for an infinite length cylinder. Chopping the cylinder off creates a small perturbation in the input impedance of the dipole. Although the hybrid finite cylinder solution has not been verified by an independent method, the results of this section seem reasonable.

IV. DISCUSSION

A hybrid MM-UTD technique has been presented which solves electromagnetic problems in which an antenna is located on or near a curved conducting body. The technique has been applied to find the input impedance of various radiators located near a perfectly conducting circular cylinder. The application of the hybrid technique to these specific problems in no way implies restrictions on its use. The method can be equally well used to find near and far fields, current distributions, and scattering data for problems involving conducting bodies of rather arbitrary shape.

An important contribution of this paper was the demonstration of how to cast the near-field expression associated with the piecewise sinusoidal function into ray optical form. This was accomplished by identifying the radiation from each piecewise sinusoidal "mode" as appearing to come from the end points of each segment and noticing that their end point radiation contained no radial component of the field. Thus, while the near-field radiation from each piecewise sinusoidal mode is not ray optical, the radiation from its properly decomposed parts are.

This ray optical decomposition permitted us to obtain accurate (i.e., essentially exact) results even when the antenna was extremely close to the cylinder, since the "mating" of the moment method and geometrical optics was exact. In the case of the finite cylinder, since curved edge diffraction theory is an asymptotic technique, accurate results can be expected when the source is probably not less than $\lambda/4$ from the curved edge even with ray optical fields from a moment method source [1], [5].

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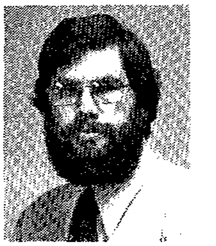

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