WIRE-GRID MODELING OF SLOT ANTENNAS

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Synopsis: The ability of a computer code to model slot antennas is investigated. A comparison of experimental and numerically calculated antenna data is presented.

ABSTRACT

The wire-grid modeling option of the Numerical Electromagnetics Code has been used to simulate the behavior of rectangular slot antennas in finite ground planes. The sensitivity of calculated antenna impedance to changes in model wire-segment length and radius has been investigated. It is shown that very thin slots can be effectively modeled using the wire-grid approach. A technique for including the effects of a thin dielectric slot backing in the model is presented. A comparison of calculated and experimentally measured data shows that the wire-grid model gives precise radiation pattern predictions and calculates impedance values with sufficient accuracy for use in preliminary antenna design.

I. INTRODUCTION

During the past decade, a great deal of research has been directed toward developing numerical techniques which can be applied to complex electromagnetic boundary value problems [1,2,3]*. Many problems which previously could not be handled using classical electromagnetic theory, have been successfully solved using these new techniques in conjunction with digital computers. Several general purpose computer codes have evolved to aid users in applying these techniques to their particular problems.

One of the more comprehensive software packages is the Numerical Electromagnetic Code (NEC) developed at the Lawrence Livermore Laboratory in Livermore, California [4]. Both the Electric Field Integral Equation (EFIE) and Magnetic Field Integral Equation (MFIE) are used to model the electromagnetic response of structures. Using a technique known as the Method of Moments, the integral equations can be solved numerically to determine the currents induced on metallic structures by an exciting source or an incident electromagnetic wave. The EFIE works well in modeling thin-wire structures and conducting sheets having small or vanishing volumes. The MFIE is applicable to closed voluminous structures which have smooth surfaces. The NEC program allows hybrid structures to be modeled using both the EFIE and MFIE simultaneously.

The models which result from the application of numerical approximations to the EFIE are known as thin-wire or wire-grid models. This is due to the fact that solid conducting surfaces, when modeled, are replaced by a wire mesh or grid. Of course, as the wire mesh become more dense, the solid surface is more closely approximated. Wire-grid modeling has been used successfully for the analysis of very complex structures such as wire and loop antennas mounted on ships and aircraft [2,5].

A survey of the literature has shown a lack of information regarding the application of wire-grid modeling to slot type antennas. It is the purpose of this paper to investigate and evaluate the potential of wire-grid modeling, via the Numerical Electromagnetic Code, for analyzing slot antennas. A point-fed rectangular slot antenna mounted in a finite ground plane will be modeled using the wire-grid approach. Measured and calculated values for the antenna's terminal impedance and radiation patterns will be used to study the sensitivity of the model to changes in parameter such as wire radius and mesh density. In addition, a technique will be presented whereby a dielectric sheet covering the slot can be included in the wire-grid model.

II. GENERAL FORMULATION

A simple rectangular slot cut into a square conducting sheet was chosen as the antenna structure to evaluate the wire-grid modeling approach. This particular antenna was selected since it is representative of general slot antennas and its geometry simplifies the modeling procedure. Also, there is some qualitative information available regarding the characteristics of rectangular slot antennas and this was used as a starting point in evaluating the modeling technique [6,7].

As shown in Fig. 1, the slot antenna is excited in a point-fed fashion by the voltage source across the center of the slot. The length of the slot is given by L while the slot width is denoted by W. The ground plane, which contains the slot, is square and has sides of length S. A spherical co-ordinate system is also shown in Fig. 1 to define the ϕ- and θ-polarized components of an electric field vector with respect to the slot antenna. These components will be used later in describing the fields radiated by the antenna.

Two characteristics are important when describing antenna behavior. These are the antenna's terminal impedance and its radiation patterns. For the slot antenna, the terminal impedance is the impedance seen by the voltage source used to excite the antenna. This impedance is important with regard to matching the antenna to a transmission line and a source or receiver to assure efficiency in the transfer of power. The radiation patterns of an antenna define its directionality and gain characteristics. These patterns define the spatial distribution of the ϕ- and θ-polarized electric field components radiated in the

*Numbers in brackets designate references listed at the end of this report.

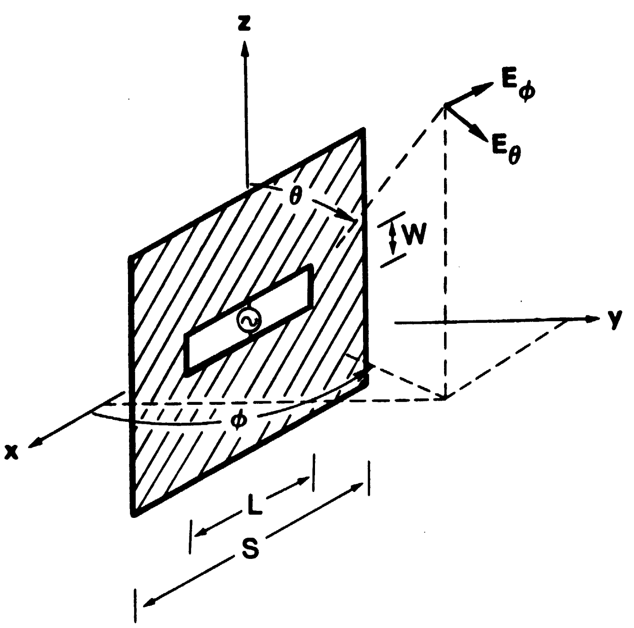


Figure 1. Slot Antenna Geometry.

far-zone of the antenna. The ability of wire-grid modeling to predict both the termination impedance and radiation patterns for the rectangular slot antenna will be evaluated.

One additional physical characteristic of slot antennas must be considered for practical modeling. It is usually desirable to place some type of dielectric backing in the slot region both for structural support and to seal against the environment. Thus, it will be necessary to include a way for the wire-grid model to account for the presence of a slot dielectric.

III. WIRE-GRID MODELING

Figure 2 shows the basic wire-grid model for a rectangular slot antenna located in a square finite ground plane. All of the dimensions on the model are given in terms of L, the slot length. Each side of the ground plane is S = 2.667 L with the slot width, W = 0.114 L. Unless otherwise stated, the radius of the wire segments making up the model will be assumed to be R = 0.017 L.

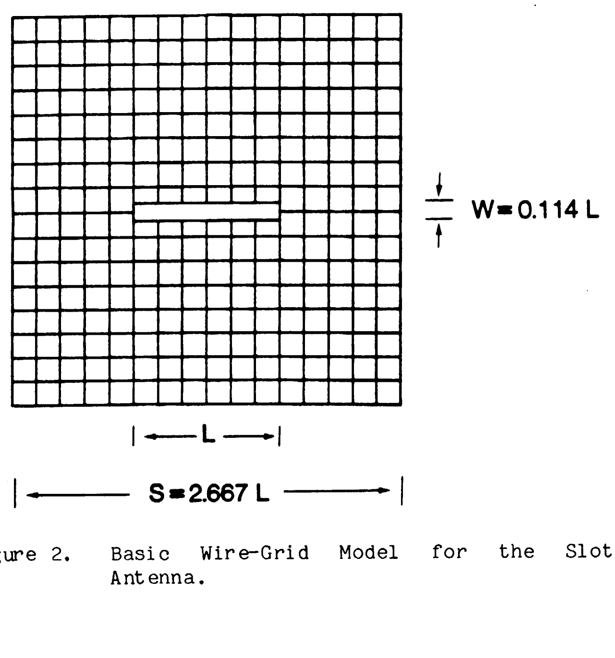


Figure 2. Basic Wire-Grid Model for the Slot Antenna.

The above model, with its particular wire mesh density and wire segment radius, will be the basis for studying the sensitivity of the wire-grid model to parameter changes. The reason for choosing these particular values for mesh density and wire radius will now be discussed.

A. Wire Mesh Density

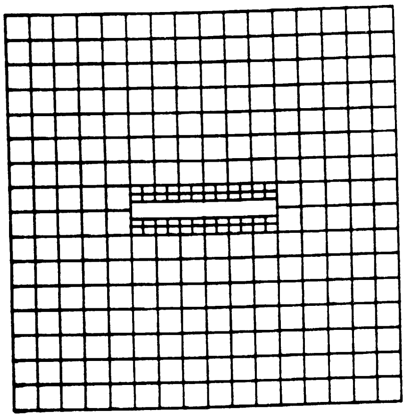
The term mesh density, as used in this report, actually deals with the length of the wire segments which form the grid for the modeled surface. Thus, decreasing the length of wire segments has the effect of increasing the density of the mesh or grid. A basic question is, how tight must the mesh be in order to obtain reasonable results from the model. The penalty for a tight mesh with very short wire segments is large computer storage area and long execution time.

Other studies, where conducting surfaces have been replaced with a wire-grid model, suggest that the wire segment length should not be greater than one-tenth of the free space wavelength at the frequency being considered [4,8]. It is then reasonable to assume that the conducting ground plane for the slot antenna should be modeled with a grid where the largest wire segment is less than one-tenth wavelength. We are interested in modeling the rectangular slot antenna near its first resonant frequency. This frequency occurs when the slot length, L, is approximately one-half wavelength. To meet the above conditions as well as preserve symmetry in the model, the wire segment lengths were chosen to be one-twelfth of a wavelength. This translates to the six wire segments across the length of the slot as shown in Fig. 2. In all, the basic wire-grid model for the rectangular slot antenna has 555 wire segments (one segment is required to represent the voltage source which feeds the antenna).

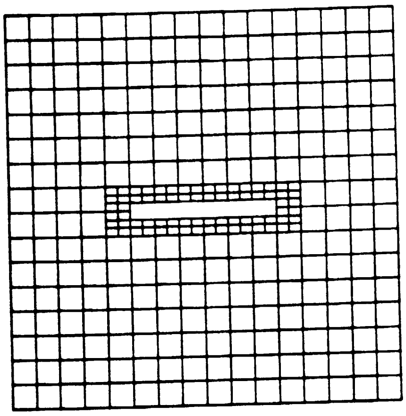
Another important question regarding the wire mesh density is, how sensitive is the model to increasing and decreasing the tightness of the mesh. To answer this question, it was decided that the mesh density of the model would be varied and the terminal impedance, as calculated by NEC, would be compared with that of the basic model (Fig. 2). Terminal impedance was chosen for this comparison since it is very sensitive to variations in the near-field behavior of an antenna.

Starting with the basic 555 segment model, the mesh density near the slot opening was increased as shown by the two models in Fig. 3. If a tighter mesh is required in modeling the slot antenna, then one would expect to see large differences between the values of terminal impedance predicted by the different models. Figure 4 shows the calculated resistive and reactive components of the terminal impedance for the 555, 641, and 683 segment wire-grid models. The impedance terms are plotted as a function of the ratio of slot length, L, to free space wavelength, λ. Very little change in the calculated impedance is observed when the mesh density in the basic model is increased near the slot. This indicates that decreasing wire segment length beyond the one-tenth wavelength criterion provides negligible benefits.

The basic 555 segment model can also be used to study the effect of decreasing wire mesh density.

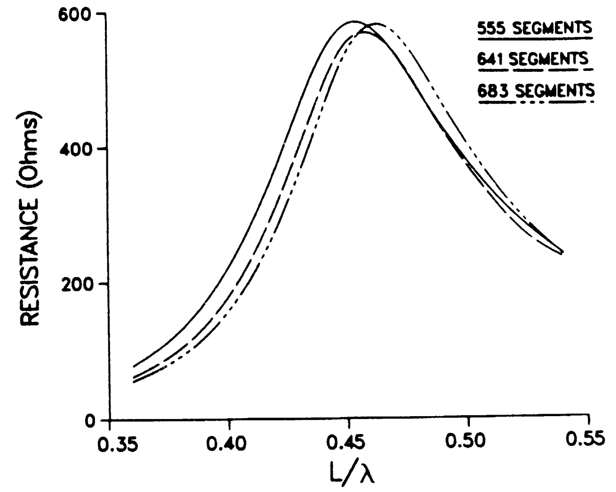


(a) 641 Segments

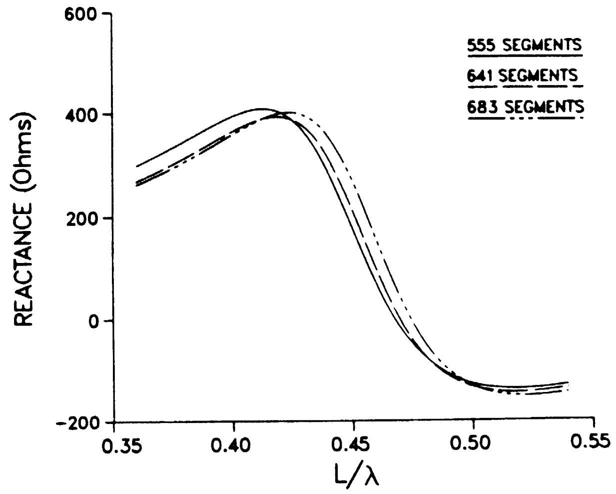


(b) 683 Segments

Figure 3. Wire-Grid Models with an Increased Number of Segments.



(a) Resistance



(b) Reactance

Figure 4. Effect of Increased Number of Modeling Wire Segments on Calculated Antenna Impedance.

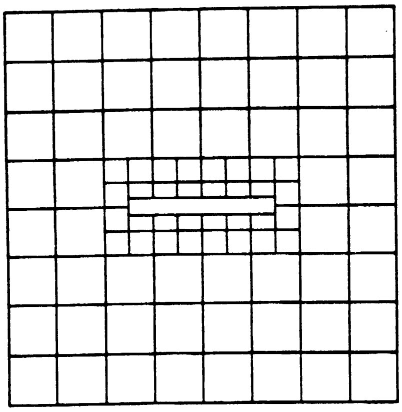
Figure 5 shows two additional models for the slot antenna where the density of the mesh has been decreased in areas away from the slot. The calculated impedance components for these 383 and 209 segment models are compared with the basic 555 segment model in Fig. 6. Very little difference in impedance is detected between the 383 and 555 segment models. There is, however, a substantial change in impedance between the 555 segment and the 209 segment models. Thus, the impedance values calculated by the model are sensitive to increases in wire segment length, beyond the one-tenth wavelength criterion, in the vicinity of the slot. If it is absolutely necessary that the number of wire segments composing the model be decreased, this should only be done in regions that are far removed from the slot.

B. Wire Segment Radius

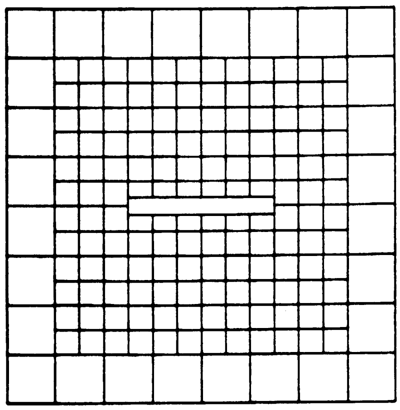
When solid surfaces are modeled using the wire-grid approach, wire segment radius is an important parameter. In modeling targets for radar cross-section studies, it has been found that the best results are obtained when the wire radius is chosen to be between 0.005 λ and 0.01 λ [8]. Since the length of wire segments in wire-grid modeling is approximately one-tenth wavelength, the wire radius of the segments should then be one-tenth of the wire length for accurate results.

Additional work which supports this choice for wire radius has been done by Moullin [9]. He found that solid reflective screens for antennas could be replaced by a series of parallel wires, if the spacing and radius of the wires were properly chosen. This choice is based on the theory that when the self-inductance of the wires is equal and opposite to the mutual inductance between wires, the wires will behave as a solid sheet. Again, for the one-tenth wavelength spacing in the wire-grid, Moullin's work indicates that the wire radius should be approximately one-tenth of the wire segment length.

The basic 555 segment wire-grid model for the slot antenna was used to calculate the terminal impedance for different values of wire segment radius. The results are shown in Fig. 7, where wire radius is given in terms of L, the length of the

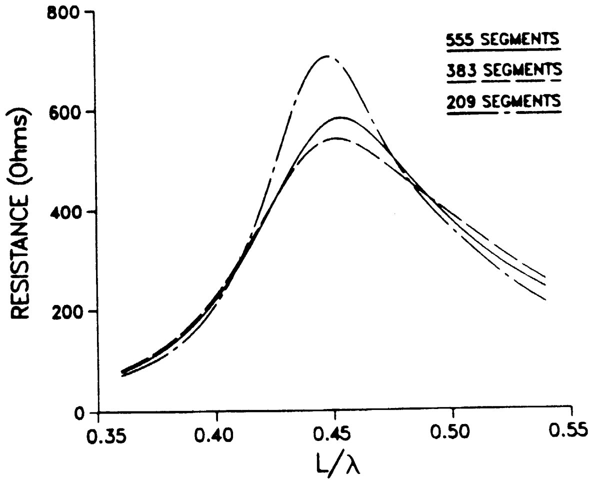


(a) 209 Segments

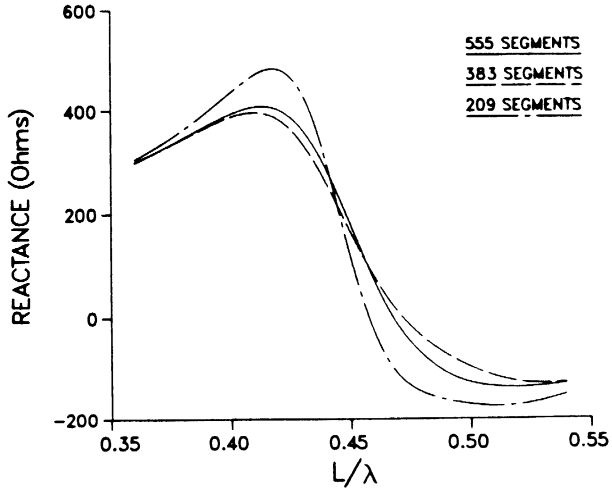


(b) 383 Segments

Figure 5. Wire-Grid Models with Decreased Number of Segments.



(a) Resistance



(b) Reactance

Figure 6. Effect of Decreased Number of Modeling Wire Segments on Calculated Antenna Impedance.

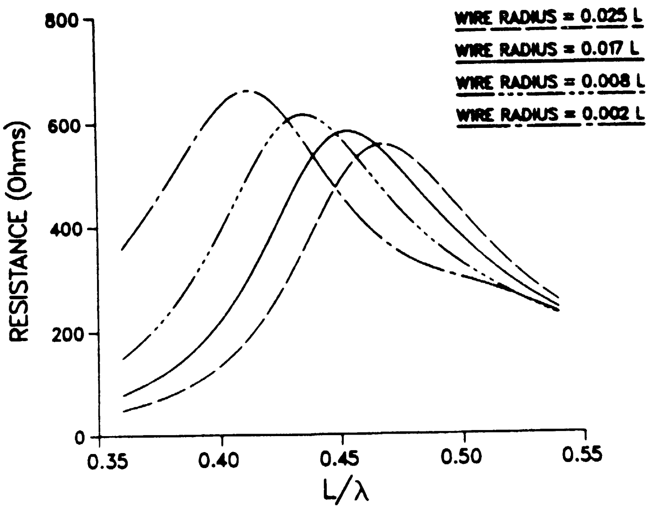
slot. This data shows that the model is very sensitive to changes in wire radius. If one uses the criterion that the wire radius should be one-tenth of the wire segment length, then the most accurate impedance curves, in Fig. 7, will be those with wire radius equal to 0.017 L. A later comparison of calculated and measured impedance values will show that this is indeed the case.

C. Modeling Thin Slots

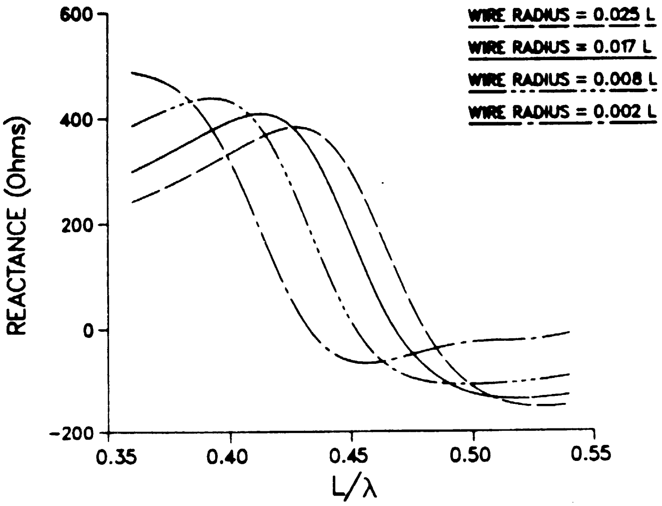
Originally, one of the major concerns associated with the wire-grid approach was that of modeling very thin slot antennas. The NEC user's guide cautions that placing parallel wires close together, within a few radii, may cause numerical instability and inaccurate results.

The 555 segment slot antenna model was again used to determine the capability of the wire-grid technique to model thin slots. Figure 8 gives the calculated terminal impedance for different values of slot width to slot length ratio. The modeled slot width is the distance between the centers of the wire segments bounding the sides of the slot. Even though the centers of the wires are brought to within 2.33 radii, the calculated impedance values show no instability. These results also show that very little effect on the calculated impedance can be expected if the model slot width is decreased beyond the W/L = 0.039 value.

One way to qualitatively test the results from the thin slot model is to compare them with the impedance values predicted theoretically for thin slot antennas located in infinite ground planes. Figure 9 shows the behavior of very thin slots for the infinite ground plane case. These impedance values were obtained by using Schelkunoff's method for determining the impedance of thin dipoles and then applying Babinet's principle to obtain the impedance of complementary slot antennas [6,10]. The infinite ground plane slots show very little change in terminal impedance as the slot width is decreased, just as suggested by the wire-grid model. In fact, the impedance calculated from the wire-grid model, with W/L = 0.039, closely approximate the theoretical

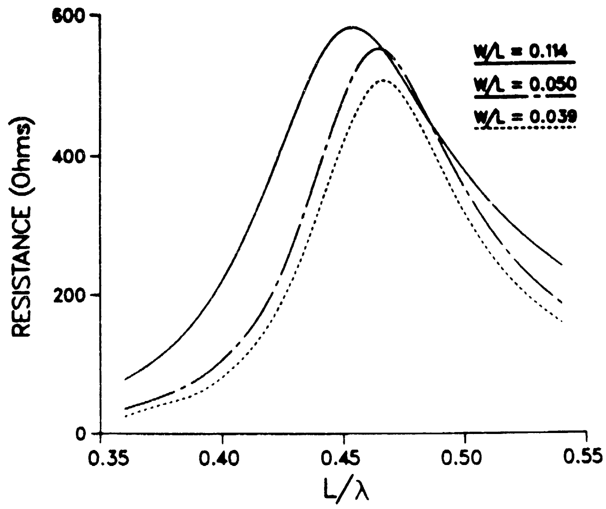


(a) Resistance

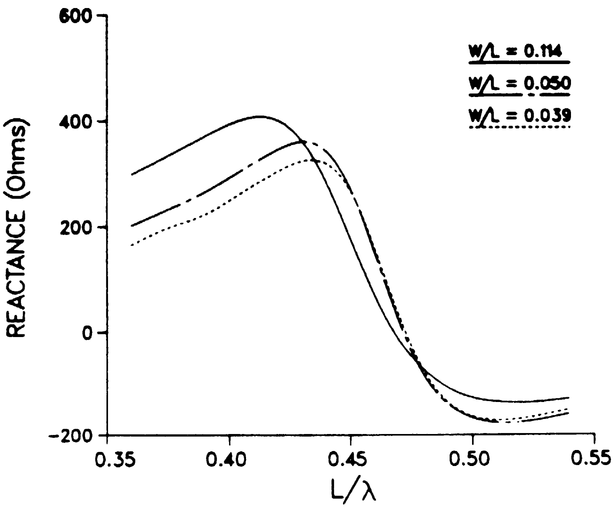


(b) Reactance

Figure 7. Calculated Slot Antenna Impedance for Different Values of Wire Segment Radius in the Wire-Grid Model.



(a) Resistance



(b) Reactance

Figure 8. Calculated Impedance for Narrow Slot Antennas Using the Wire-Grid Model.

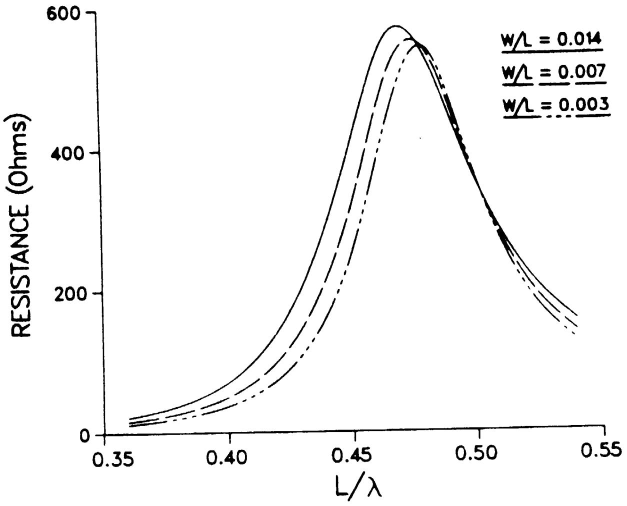
results for the very thin slots of Fig. 9. It then appears that the wire-grid model can be used to obtain reasonable calculations for terminal impedance even when the slot has a very small width.

D. Wire Segment Impedance

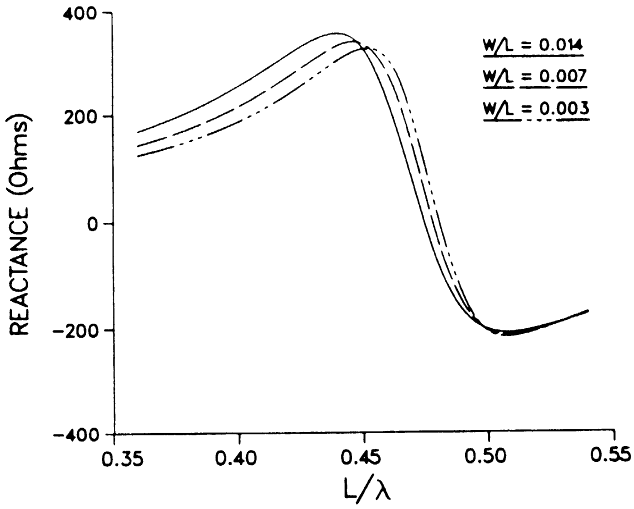
Up to this point in the discussion, it has been assumed that the slot antenna being modeled has an air-filled slot. As stated earlier, for the wire-grid model to be practical, it must include a means for incorporating the effect of a thin dielectric material in the slot region. Fortunately, the NEC program has the capability of impedance loading wire segments composing the model.

If one considers the slot antenna to behave as a slot transmission line, then the effect of a slot dielectric is to increase the distributed capacitance of the slot line. The effect of the dielectric can then be included in the wire-grid model by placing discrete, equal valued capacitors across the slot as shown in Fig. 10. The only requirement is that the capacitors should be spaced no greater than one-tenth wavelength along the slot. The capacitance will then appear to be approximately distributed in nature, since an artificial transmission line has been created [11].

The value of capacitance used in the model will depend upon the slot width as well as the type and thickness of the dielectric material. At this time, a theoretical technique has not been developed to establish an exact value for the capacitors. The capacitance is determined by measuring the resonant frequency of a slot antenna with and without the dielectric backing. The value of the capacitors in the model is then chosen to match this behavior. It should be stated that longer slot antennas, having the same width and dielectric, can be modeled by merely distributing more of the capacitors along their length.



(a) Resistance



(b) Reactance

Figure 9. Theoretical Impedance for Narrow Slot Antennas in Infinite Ground Planes.

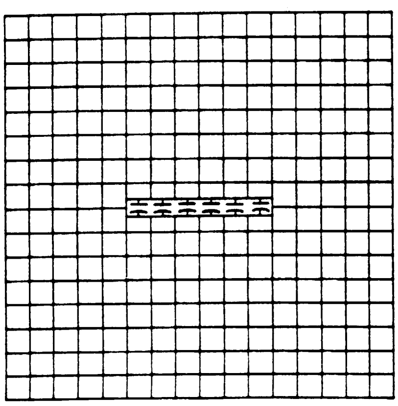


Figure 10. Wire-Grid Model for a Dielectric-Backed Slot Antenna.

IV. NUMERICAL AND EXPERIMENTAL RESULTS

Several experimental measurements were made to verify the performance of the wire-grid slot antenna model. A slot antenna was constructed and its terminal impedance and radiation patterns have been measured. In this section of the report, the experimental data is compared with the numerical results predicted by the wire-grid model.

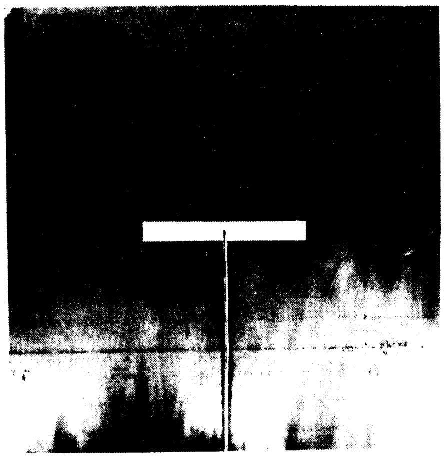


Figure 11. Photograph of the Experimental Slot Antenna.

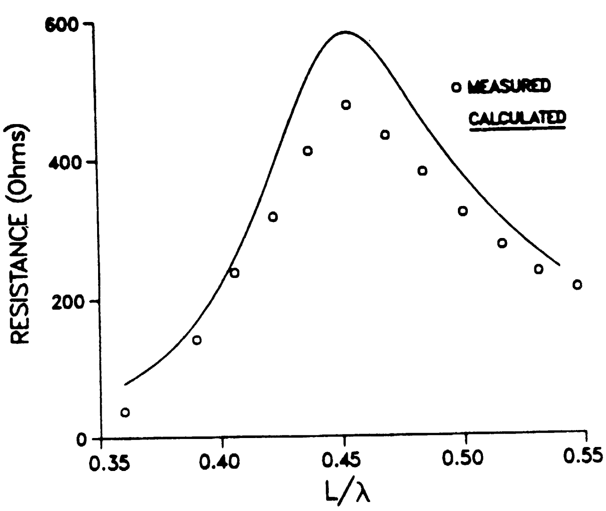
A. Slot Antenna Fabrication

A simple slot antenna was constructed to correspond to the dimensions of the 555 segment wire-grid model given in Fig. 2. Figure 11 shows a photograph of the experimental slot antenna and its coaxial feeding structure. The antenna was made from a 0.5 m square sheet of copper having a thickness of 1.4 mm. The length of the slot cut into the sheet was 0.188 m and the width was 0.021 m. To simulate a dielectric in the slot, a sheet of SMC (sheet molding compound) plastic was used. This sheet of plastic was 2.8 mm thick and was tack glued to one side of the copper sheet when a slot dielectric was needed.

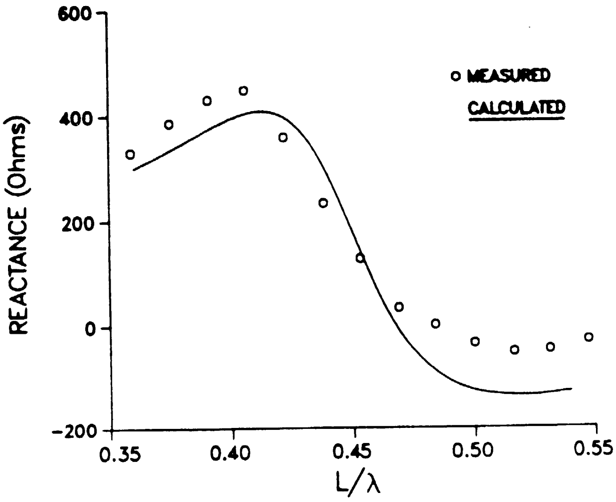
B. Terminal Impedance

The procedure used to measure the terminal impedance of the experimental slot antenna was relatively simple. The antenna was placed 1.5 m above the ground and several meters from any structure which might interfere with the measurements. A network analyzer was then used to measure the impedance of the antenna at several frequencies in the range of 550 to 800 MHz. The network analyzer was calibrated to indicate an open circuit for the coaxial feed before it was attached to the slot antenna. This reduced the parasitic effects of the feed structure on the impedance measurements. The terminal impedance of the slot antenna, with and without the dielectric backing, was measured in this fashion.

Figure 12 compares the measured impedance values with the calculated impedance obtained from the 555 segment wire-grid model. In this case the slot was not backed with the dielectric material. It is generally very difficult to obtain an accurate match between calculated and measured antenna impedance but here, there is reasonably close agreement.

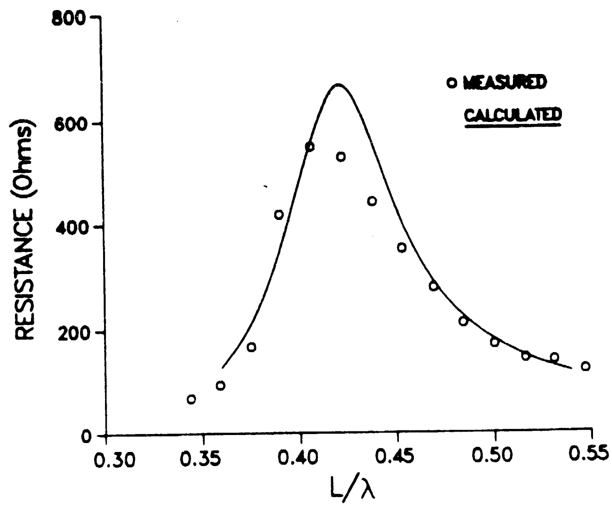


(a) Resistance

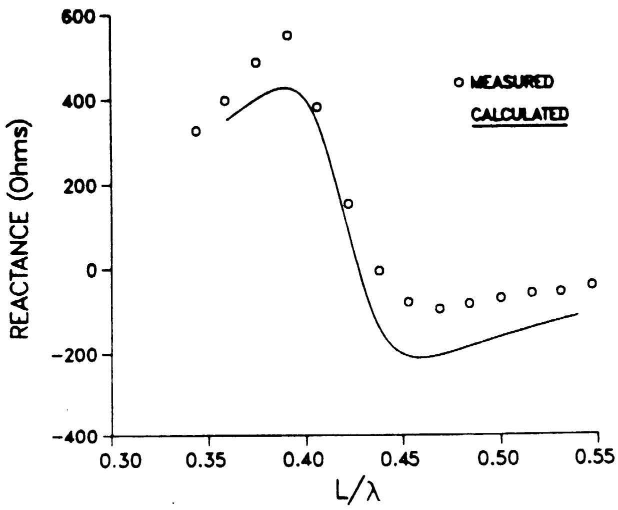


(b) Reactance

Figure 12. Measured and Calculated Impedance for an Air-Filled Slot Antenna.



(a) Resistance



(b) Reactance

Figure 13. Measured and Calculated Impedance for a Dielectric-Backed Slot Antenna.

Measured and calculated terminal impedance for the dielectric backed slot antenna are presented in Fig. 13. It was found that placing six 0.8 pF capacitors across the basic slot model, as shown in Fig. 10, provided a reasonable match between the measured and calculated values. Comparing the data in Figs. 12 and 13, one sees that the effect of the dielectric is to shift the resonant frequency of the slot antenna to a smaller value of L/λ. The capacitors which have been placed across the modeled slot account for this effect.

It then appears that the wire-grid modeling approach can be successfully used to predict the terminal impedance of a slot antenna with and without a dielectric backing. The degree of agreement between measured and calculated values shows that this modeling technique can be used to provide preliminary design data for matching the antenna and estimating such quantities as antenna bandwidth.

C. Radiation Patterns

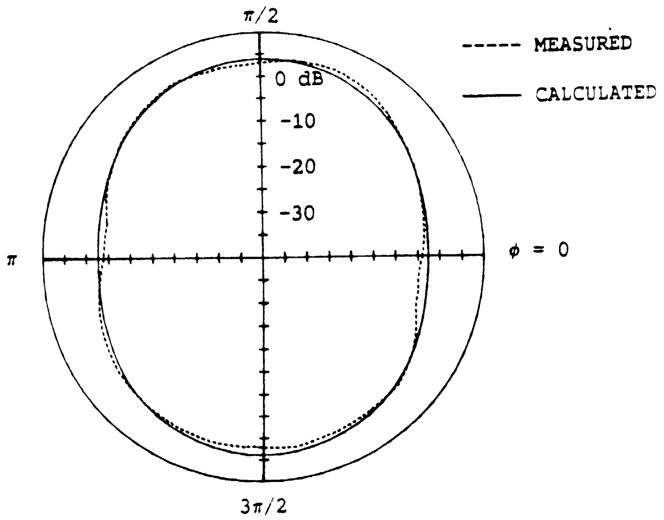
Two sets of radiation patterns were also measured for the experimental slot antenna with and without its dielectric backing. These patterns were measured at an outdoor test range which had an inground turntable available for rotating a test antenna [12]. The slot antenna was placed over the center of the turntable and elevated 1.5 m with a styrofoam support. A tuned dipole was placed approximately 8 m from the slot and orientated to receive the desired polarized signal radiated from the slot.

Considering the co-ordinate system of Fig. 1, the electric field radiated from the slot antenna is principally polarized in the θ-direction. The patterns measured on the experimental antenna then consisted of two cuts of the θ-polarized radiation. One pattern was obtained by varying ϕ thru 2π radians (table rotation) while holding θ fixed at $\pi/2$. For the other pattern, ϕ was fixed at $\pi/2$ and θ was allowed to vary thru 2π radians. Physically, this was accomplished by placing the plane of the sheet containing the slot antenna perpendicular to the plane of the turntable and then orienting the slot either vertically or horizontally for each pattern measurement.

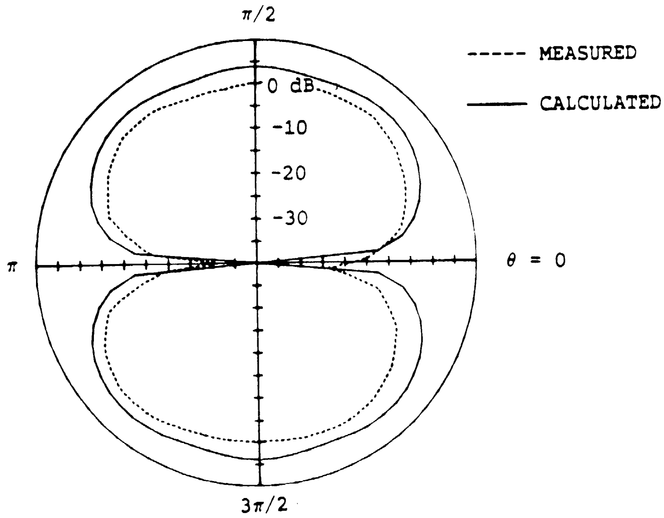
The two θ-polarized patterns for the slot antenna with and without the dielectric were measured at their approximate resonant frequencies of 700 and 765 MHz, respectively. A comparison of the measured radiation patterns with those predicted from the wire-grid models are given in Figs. 14 and 15. The calculated and measured θ-polarized patterns as a function of ϕ are in excellent agreement for both the air and dielectric backed antennas. A comparison of the patterns, which vary with θ, show the same shape, but the measured patterns are approximately 4 dB below the calculated data in both cases.

With the angles ϕ and θ both fixed at $\pi/2$, the level of both of the measured θ-polarized patterns should be identical since the same polarization and position are being considered. The 4 dB difference must then be attributed to measurement error and not to a lack of accuracy in the model. As one can see from the shape of the radiation patterns, the ground and metal turntable top will be illuminated differently when measuring the two θ-polarized patterns. The discrepancy in the measured data was most likely produced by a change in reflections from these surfaces. With this in mind, the above data shows that the wire-grid model gives very accurate predictions of the radiation patterns for the slot antenna.

It should be noted that in the above comparisons of numerical and experimental data, the calculated radiation patterns were not merely normalized to fit the experimental patterns. A

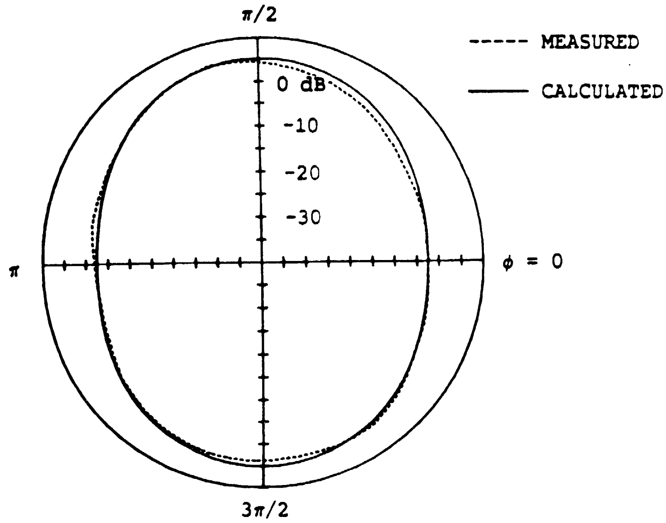


(a) $\theta=\pi/2$.

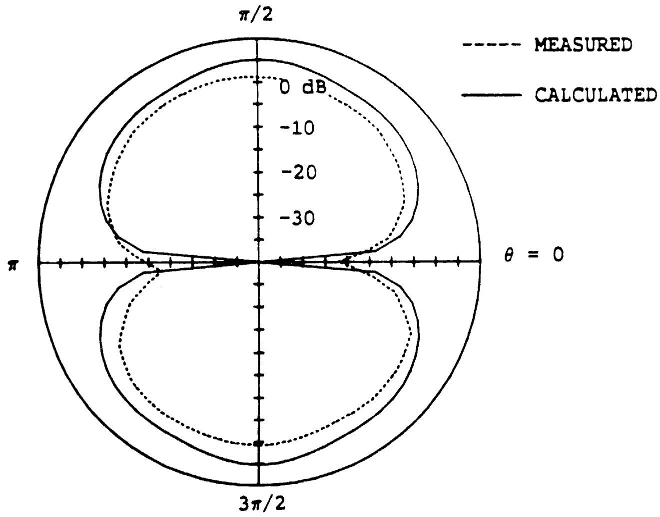


(b) $\phi=\pi/2$.

Figure 14. Measured and Calculated θ-Polarized Radiation Patterns for an Air-Filled Slot Antenna.



(a) $\theta=\pi/2$.



(b) $\phi=\pi/2$.

Figure 15. Measured and Calculated θ-Polarized Radiation Patterns for a Dielectric-Backed Slot Antenna.

calibration factor (in dB) was determined and added to the calculated patterns. At each of the measurement frequencies, the calibration factor was obtained by first measuring the horizontally polarized radiation of a tuned dipole antenna and then using the NEC program to calculate the pattern. The calibration factor was determined by subtracting the maximum value on the predicted pattern from the corresponding point on the measured pattern. This difference then became the calibration factor to be added to all patterns computed by the models at that frequency.

V. SUMMARY

The wire-grid modeling option of the Numerical Electromagnetic Code has been used to simulate a rectangular slot antenna in a finite ground plane. The effects of varying the key modeling parameters, wire radius and wire segment length, were presented. The importance of selecting the proper values for these parameters, when modeling slot antennas, was discussed. A technique was developed for including, in the wire-grid model, the effects due to backing the antenna with a dielectric material.

A comparison of numerical and experimentally measured data showed that wire-grid modeling can be used to simulate slot type antennas. The radiation patterns predicted by the model are very accurate. Calculated values for antenna impedance were shown to agree well enough with experimental results to provide preliminary design information regarding antenna bandwidth, resonant frequency, and resistance at resonance.

ACKNOWLEDGMENTS

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REFERENCES

1. Harrington, R. F., Field Computation by Moment Methods, Macmillan, New York, 1968.

2. Mittra, R. (editor), Computer Techniques for Electromagnetics, Pergamon Press, New York, 1973. Chapter 4. A. J. Poggio and E. K. Miller.

3. Mittra, R. (editor), Numerical and Asymptotic Techniques in Electromagnetics, Springer-Verlag, New York, 1975. Chapter 4. E. K. Miller and F. J. Deadrick.

4. Burke, G. J. and Poggio, A. J., Numerical Electromagnetic Code (NEC) - Method of Moments, Naval Ocean Systems Center, Technical Document 116, 1977.

5. Raschke, R. R., "Application of Wire-Grid Modeling to Shipboard HF Antenna Pattern Prediction," Proc. of the 1977 Int. Symp. on Electromag. Compati., Aug. 1981, pp. 183-189.

6. Kraus, J. D., Antennas, McGraw-Hill, New York, 1950.

7. Jasik, H., Antenna Engineering Handbook, McGraw-Hill, New York, 1961.

8. Lin, Y. T. and Richmond, J. H., "EM Modeling of Aircraft at Low Frequencies," Radar Target Identification, Short Course Notes, Dept. Elect. Engr., Ohio State University, Columbus, Ohio, 1976.

9. Moullin, E. B., Radio Aerials, Oxford University Press, New York, 1949.

10. Jordan, E. C. and Balmain, K. G., Electromagnetic Waves and Radiating Systems, Prentice-Hall, New Jersey, 1968.

11. Holt, C. A., Introduction to Electromagnetic Fields and Waves, John Wiley & Sons, New York 1967.

12. Nagy, L. L. and Funke, J. L., "Three-Dimensional Vehicular Ignition Noise Radiation Patterns," SAE Paper No. 840166, 1984.