On the Transmission Line Formed by Two Elliptical Conductors

Interaction Note 498

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***Abstract*— A newly developed solver (GLS3D) code, coupled with the existing EAGLE grid generation code, is used to numerically solve for the potential and charge distributions of a transmission line formed by two elliptical conductors. This technique employs the finite-difference solution using boundary fitted coordinates. Results obtained from this technique and the finite-difference technique with a rectangular grid are presented. Also, a comparison with theoretical results for circular and flat conductors is made to illustrate the validity of the technique.**

I. Introduction

For EMP applications, it is often desired to design a transition section to match a low impedance source to an electrically large wire structure. Furthermore, it provides field uniformity and polarization [1]. This design is accomplished through the use of transmission-line theory. Thus, a transmission line formed by two elliptical conductors can be used as a transition section to provide a smooth transition between flat and round conductors.

In general, the design and analysis of transmission lines requires a knowledge of the characteristic impedance. Accordingly, both analytical and numerical solution techniques have been employed to determine the characteristic impedance of arbitrary-shaped conductors. The analytical techniques have been restricted to simple geometries. However, the numerical techniques are more powerful, but they may require a great amount of computer memory and speed for complicated geometries.

Several techniques are available to numerically solve for the potential and charge distributions of a transmission line formed by two elliptical conductors. The most commonly used are the integral-equation [2], the finite-element [3], and the finite-difference [4] techniques. The integral-equation method makes use of the method of moments to compute the charge distribution around each conductor as well as the electric potential. This is done by formulating an appropriate geometry to describe the distances between source and observation points on the conductor surfaces.

The finite-element method discretizes the region of interest into subregions. These are usually polyhedral, and their edges define a network with N nodes, where the electric potential at each node is a function of every other node. Accordingly, the electric potential and/or the charge distribution can be evaluated at each node by matrix inversion.

In the finite difference method, the region is covered by a grid of points, generally equally spaced, and the potential is obtained by systematically iterating the potential at every node in terms of the neighboring nodes until convergence occurs. However, this technique may not be accurate when approximating the solution for the normal derivative of the potential at an edge. It is of interest to note that the last two techniques are limited by the configuration of the size of the problem [5].

In this paper, an effective technique that employs the finite-difference solution using boundary-fitted coordinates is used to numerically solve for the potential and charge distributions of a transmission line formed by two elliptical conductors. This technique uses a newly developed solver code, Generic Laplace Equation Solver for Three Dimensions (GLS3D), that has been coupled with the existing EAGLE grid generation code to yield a system that is capable of solving for the potential distribution for arbitrary shaped configurations [6]–[8]. This existing code can be used to solve two- or three-dimensional problems with complex geometry, including conductive materials in the interested region, where direct methods can not be applied.

Results obtained from this technique are presented and compared with the finite-difference results using a rectangular grid for circular and flat conductors where the characteristic impedance can be determined analytically. Elliptical conductors are also considered to demonstrate the application and accuracy of the technique.

II. Analysis

A. Charge Per Unit Length

1) Finite-Difference Solution Using a Rectangular Grid: The potential at points near an arbitrarily shaped conductor can be computed numerically by using a finite difference approximation to Laplace's equation [4]. Here, this method is applied to an elliptical conductor near a perfect ground plane in order to compute the two-dimensional potential distribution about the condcutor. Accordingly, the charge on the ground plane, which is equivalent to that on the conductor, is found and then used to compute the characteristic impedance of the conductor.

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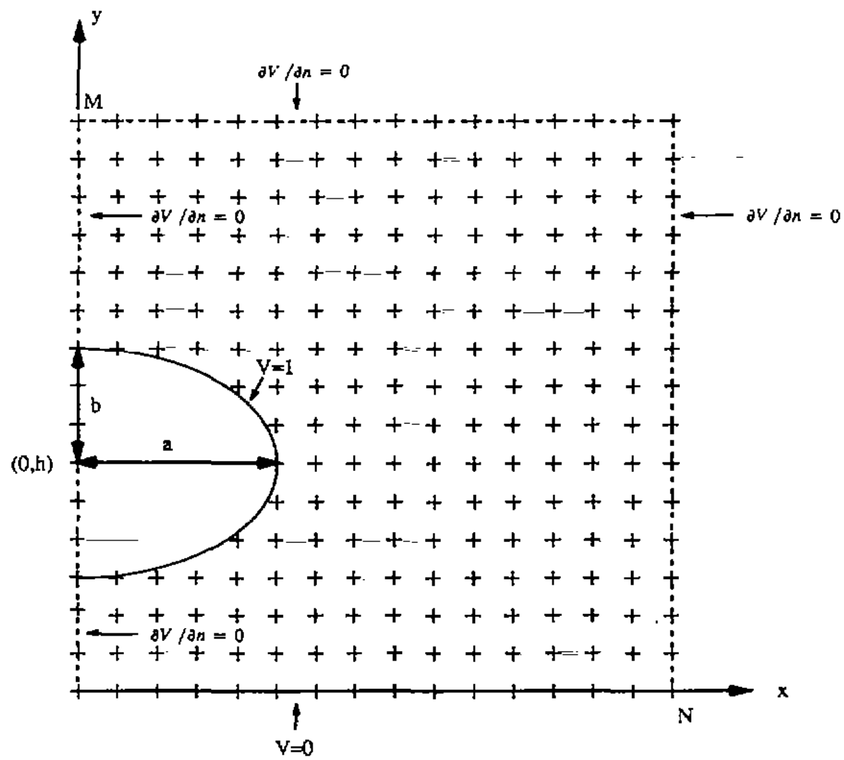

Fig. 1. The elliptical conductor.

Applying this process requires that the plane in which the potential values are to be found be overlaid by a grid. Fig. 1 shows the boundary conditions and grid that is used to compute the potential at points in the region around an elliptical condutor. The symmetry about the y axis in this problem is also utilized to arrive at boundary conditions along the y axis.

The iterative process that is used in this problem is the successive overrelaxation (SOR) scheme. In this process, an arbitrary grid point (i, j) is adjusted on the nth iteration to satisfy the following equation:

$$V_{ij}^{(n)} = (1-K)V_{ij}^{(n-1)} + (K/4) \cdot [V_{i+1j}^{(n-1)} + V_{i-1j}^{(n)} + V_{ij+1}^{(n-1)} + V_{ij-1}^{(n)}], \quad \text{for} \quad i = 1, \cdots, N \quad \text{and} \quad j = 1, \cdots, M \tag{1}$$

where K is the SOR constant, i.e., $1 < K < 2, K = 1.2$ is used throughout, N and M are the maximum size of the grid in the x- and y-directions, and V_{ij} is defined as

$$V_{ij} = V(x, y) \quad \text{where} \quad x = i\Delta \quad \text{and} \quad y = j\Delta. \tag{2}$$

The foregoing technique is applied at each point of the grid that is not on the boundary. For points that are adjacent to curved boundaries, i.e., points that do not fall on grid points, some modifications to (1) are required [4]. The accuracy of this process is limited by how fine the grid is and by how many iterations are allowed before stopping the process. The iterative process continues until all points in the nth iteration satisfy $|V_{ij}^{(n)} - V_{ij}^{(n-1)}| < TOL = 10^{-5}$.

To simplify the calculation of the charge on the ground plane, N and M are set equal in this process. Also, the voltage on the elliptical boundary is set at a constant 1 V (see Fig. 1). However, caution must be used to ensure that: 1) the upper and right boundaries are at least 3a to 4a away from the origin, where a is the semimajor axis, 2) the height of the conductor, h, is small (such as 30% or less of the length of a side boundary), and 3) the tolerance used for stopping the iteration, TOL, is small enough to require several iterations (at least 6N) to occur before the solution converges.

The charge per unit length on the elliptical conductor of Fig. 1 can be found by integrating the normal derivative of the potential around the conductor to give

$$Q = \oint \epsilon \frac{\partial V}{\partial n}\, d\ell \tag{3}$$

An easier approach, however, is to integrate the normal derivative of the potential across the ground plane below the conductor, since this charge is the same as that on the conductor. Accordingly, the charge can be obtained by simply summing the values of the potentials in the row just above the ground plane of Fig. 1.

2) Finite-Difference Solution Using Boundary-Fitted Coordinates: A more versatile technique to solve for the charge distribution of an arbitrary-shaped body is through boundary fitted coordinates [6], [7]. In this technique, a curvilinear coordinate system is defined in the region of interest such that all boundaries in the region are coincident with coordinate surfaces. The coordinate system that describes the region is then transformed into a fixed rectangular computational region with a square mesh. The resulting system in the transformed plane consists of simply described boundary conditions. The equations to be solved in the computational region are, in general, more complex than those in the original region, but the precise representation of the boundary conditions yields accurate solution. The finite-difference solution is then obtained using only grid points so that no interpolation between grid points is required.

For curvilinear coordinates ($\xi^i, i = 1, 2, 3$), the Laplacian in nonconservative form is

$$\nabla^2 V = \sum_{i=1}^{3} \sum_{j=3}^{3} g^{ij} V_{\xi^i \xi^j} + (\nabla^2 \xi^k) V_{\xi^k} \quad (4)$$

where g^{ij} is the contravariant metric tensor given by [6]

$$g^{ij} = a^i \cdot a^j \quad (5)$$

where

$$a^i = \nabla \xi^i \qquad (i = 1, 2, 3). \quad (6)$$

Moreover, the grid generation system of the EAGLE grid generation code [8] described by

$$\nabla^2 \xi^k = g^{kk} P_k \qquad (k = 1, 2, 3) \quad (7)$$

can be introduced so that Laplace's equation in curvilinear coordinates can be stated as

$$\sum_{i=1}^{3} \sum_{j=3}^{3} g^{ij} V_{\xi^i \xi^j} + \sum_{k=1}^{3} g^{kk} P_k V_{\xi^k} = 0. \quad (8)$$

The EAGLE code is a general three-dimensional grid generation code based on composite structure [8], [9]. It can operate either as an algebraic-generation system or as an elliptic-generation system. It is designed to discretize the domain in or around any arbitrary three-dimensional region. The finite-difference method is then used to solve the governing equation over the domain of interest for both two- and three-dimensional cases with proper boundary conditions. The input is structured to be user oriented. The EAGLE code can be operated on any machine which has a standard Fortran 77 compiler. This code is in public domain with proper approval from the U.S. Air Force.

Equation (8) above forms a system of equations that is solved numerically to calculate the potential distribution over the region of interest. The control functions, P_k, are evaluated in the course of the grid generation and are then available to the Laplace solver as coefficients with fixed values at each grid point. This equation is solved by point SOR iteration [10].

The initial conditions for the entire region are set to zero except those at the boundaries, which are set to the Neumann boundary conditions in this case. The electric potential V is then computed iteratively by sweeping across the grid points, such that all the adjacent points with lower indices are updated first before calculating the current value. This procedure will continue until it converges to the given tolerance. A tolerance value of 10^{-5} is also used here. Accordingly, if the maximum residue in the region is less than the tolerance, the solution in the region converges.

In the current problem, the potential at some particular points, lines, or surfaces may be assigned certain values, e.g., a value of 1 V is assigned for the elliptical conductor and a value of 0V to the ground conductor. In the GLS3D solver code, any particular value can be assigned to these special segments in the input run-stream and the code will preserve these fixed values throughout the calculation.

The Neumann boundary condition $(\partial V/\partial n) = 0$ is then applied to all the far-field boundaries since it is assumed that the potential has zero gradient on the outer boundaries. From Fig. 2, the normal derivative to the coordinate surface on which ξ^i is constant is given by

$$V_n^i = \frac{1}{\sqrt{g^{ii}}} \sum_{j=1}^{3} g^{ij} V_{\xi^j} = 0. \quad (9)$$

With the curvilinear coordinate that is constant on the designated surface ξ^N, this becomes

$$V_n^N = \frac{1}{\sqrt{g^{NN}}} \sum_{j=1}^{3} g^{Nj} V_{\xi^j} = 0 \quad (10)$$

where N here stands for the normal boundary. This yields

$$\sum_{j=1}^{3} g^{Nj} V_{\xi^j} = 0. \quad (11)$$

This summation can be expanded to the form

$$g^{NN_1} V_{\xi^{N_1}} + g^{NN_2} V_{\xi^{N_2}} + g^{NN} V_{\xi^N} = 0 \quad (12)$$

where ξ^{N_1} and ξ^{N_2} are the curvilinear coordinates that vary on the surface. Using central differences for $V_{\xi^{N_1}}$ and $V_{\xi^{N_2}}$ and one-side differences for V_{ξ^N} yields the following:

$$g^{NN_1} V_{\xi^{N_1}} + g^{NN_2} V_{\xi^{N_2}} + g^{NN} \cdot [V_{(\xi^{N_1}, \xi^{N_2}, \xi^N + 1)} - V_{(\xi^{N_1}, \xi^{N_2}, \xi^N)}] = 0. \quad (13)$$

Finally, the potential on the Neumann boundaries can be expressed as

$$V_{(\xi^{N_1}, \xi^{N_2}, \xi^N)} = \frac{1}{g^{NN}} \cdot [g^{NN_1} V_{\xi^{N_1}} + g^{NN_2} V_{\xi^{N_2}} + g^{NN} V_{(\xi^{N_1}, \xi^{N_2}, \xi^N + 1)}]. \quad (14)$$

Once the iteration process converges, the result for the potential distribution can be used to calculate the surface charge, Q, on the elliptical conductor. Accordingly, the numerical expression for Q defined in (3) becomes

$$Q = \epsilon \sum_{i=1}^{i_{\max}-1} \left[\frac{1}{\sqrt{g^{ii}}} \sum_{j=1}^{3} g^{ij} V_{\xi^j} \right] \cdot \frac{1}{2} [|R_{i+1} - R_i| + |R_i - R_{i-1}|] \quad (15)$$

where $i_{\max}$ is the maximum number of grid points along the conductor surface, i.e., $i_{\max} = 201$ is used, and R_i is the

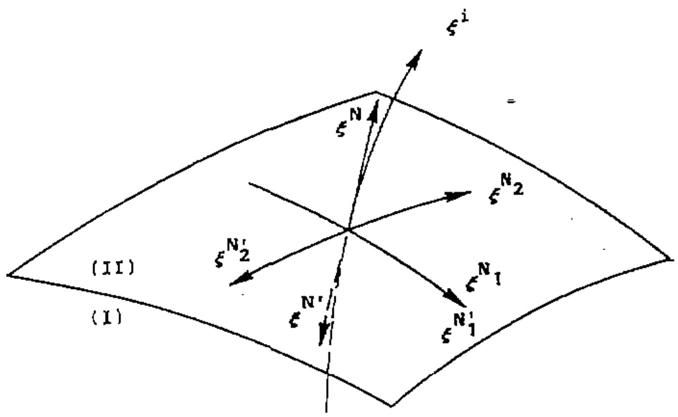

Fig. 2. The coordinate system on either side of a surface discontinuity.

position vector (see Fig. 3). Note that the numerical expression for Q as in equation (15) is obtained from (3) with

$$\frac{\partial V}{\partial n} = \frac{1}{\sqrt{g^{ii}}} \sum_{j=1}^{3} g^{ij} V_{\xi^j} \quad (16)$$

and

$$d\ell = \frac{1}{2}[|R_{i+1} - R_i| + |R_i - R_{i-1}|]. \quad (17)$$

B. Characteristic Impedance of the Transmission Line

From basic field theory [11], the characteristic impedance of a lossless transmission line is

$$Z_c = \sqrt{\frac{L}{C}} \quad (18)$$

where L and C are the inductance and capacitance, respectively, per unit length of the transmission line. Equation (18) can also be written as

$$Z_c = \frac{\sqrt{\mu\epsilon}}{C} \quad (19)$$

where μ and ϵ are the permeability and permittivity of the medium, respectively.

The charge per unit length on the transmission line can be expressed in terms of C and the potential difference between the conductors, V_0, as

$$Q = CV_0. \quad (20)$$

In the case of Fig. 1, V_0 is set to 1 V. This yields $Q = C$. Accordingly, (19) becomes

$$Z_c = \frac{\sqrt{\mu\epsilon}}{Q}. \quad (21)$$

Knowing the charge per unit length from (3) or (15), the characteristic impedance of a two-wire transmission line formed by two elliptical conductors, separated by a distance of 2 h, is then computed.

C. Characteristic Losses

For a two-were line with circular cross-section conductors, the internal impedance per unit length is [12]

$$z^i|_{\text{wires}} = \frac{1+j}{\pi a}\sqrt{\frac{\omega\mu}{2\sigma\left[1-\left(\frac{a}{h}\right)^2\right]}} \quad (22)$$

where a is the wire radius and $2h$ is the center-to-center wire separation. Here, the real part of z^i is the wire resistance per unit length and the imaginary part is the inductance per unit length that arises from the magnetic flux inside the wire. Note that the internal impedance grows without bound as the wire separation approaches zero. This occurs because the line current tends to accumulate on the portion of the wire surface nearest the other conductor.

For thin flat parallel conductors, generally called a two-conductor strip line, the internal impedance is [13]

$$z^i|_{\text{strips}} = \frac{2(1+j)}{w}\sqrt{\frac{\omega\mu}{2\sigma}}\left\{\frac{x\left[1+x+\pi-2\ln\left(\frac{\alpha}{2}\right)\right]}{1+x+\ln(1+x)}\right\} \quad (23)$$

where

$$x = \frac{\pi w}{2h} \quad (24)$$

and

$$\alpha = \left(1+\frac{t}{h}\right)^2 - 1 + \left(1+\frac{t}{h}\right)\sqrt{\left(1+\frac{t}{h}\right)^2 - 1} \quad (25)$$

where w is the plate width, $2h$ is the plate separation, and t is the plate thickness. The characteristic impedance of the strip line is [13]

$$Z_c = \sqrt{\frac{\mu}{\epsilon}}\frac{\pi}{1+x+\ln(1+x)}. \quad (26)$$

In order to compare the loss characteristics of strip conductors to circular conductors, the width of the plates is constrained to have the same circumference, i.e., $2w = 2\pi a$, and the characteristic line impedances are required to be equal. With these conditions, the ratio of the internal impedances is

$$\frac{z^i|_{\text{strips}}}{z^i|\text{wires}} = \frac{2x\left[1+x+\pi-2\ln\left(\frac{\alpha}{2}\right)\right]}{1+x+\ln(1+x)}\sqrt{1-\left(\frac{a}{h}\right)^2}. \quad (27)$$

For a 50Ω characteristic impedance, the spacing, h/a, is 1.08807 for circular conductors and x is 19.66 for flat strip

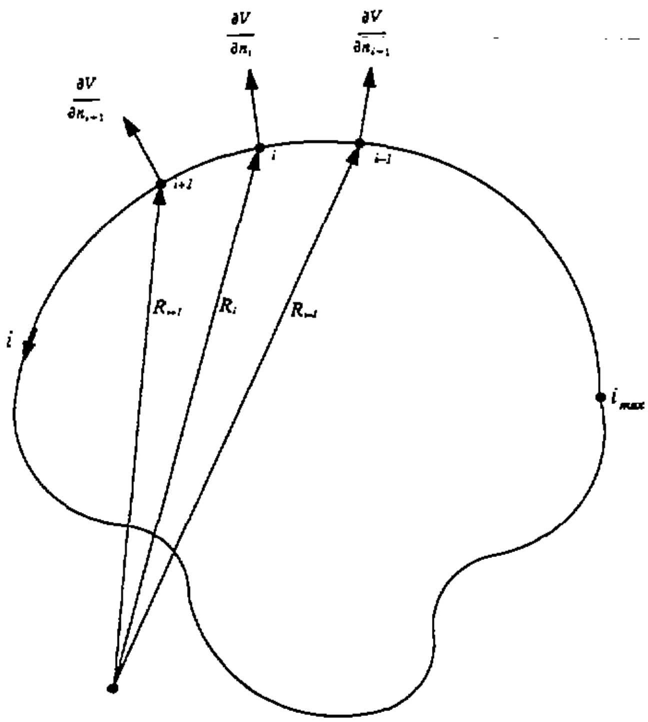

Fig. 3. Graphical representation of a line integral $\frac{\partial V}{\partial n} d\ell$ for an arbitrary geometry.

conductors. In addition, for the comparison, let α be 4.79, then

$$\frac{z^i|_{\text{strips}}}{z^i|_{\text{wires}}} = 14. \tag{28}$$

Clearly for the parameters selected, the ohmic losses of the strip line greatly exceed those of the circular-conductor two-wire transmission line. This is expected since the current distribution on thin strip conductors is highly nonuniform with most of the current in narrow sections at the edges [14]. Consequently, to minimize power losses, it is desirable to use circular conductors whenever possible.

For a transmission line formed by two elliptical conductors, the conductor cross section can be continuously varied from flat strips to circular cross sections while simultaneously increasing the conductors separation to yield an exponentially increasing characteristic impedance [1]. This increases the power handling capability and provides low ohmic loss characteristics.

III. Results

In order to illustrate the validity of the numerical techniques, three cases are considered. A comparison of the characteristic impedance obtained from the different techniques is then made and, whenever applicable, a relative error figure is determined to check their accuracy.

Case 1: In this case, a circular conductor with $a = b = 1.0$ cm and $h = 1.5$ cm is considered first. For circular conductors, the characteristic impedance can be expressed as in (19) where

TABLE I
Characteristic Impedance Comparison for Circular Conductors

Method	Characteristic Impedance	Percentage Relative Error	Number of Iterations
Analytical	115.4 Ω		
Finite difference using a rectangular grid	111.9 Ω	3.0	20 849
Finite difference using boundary fitted coordinates	111.4 Ω	3.47	≈3500

C is given by [15]

$$C = \frac{\pi\epsilon_0}{\ln\left[\frac{h + \sqrt{h^2 - b^2}}{b}\right]} \tag{29}$$

Here, ϵ_0 is the permittivity of free space. This yields a characteristic impedance of 115.4Ω. Table I shows the characteristic impedances computed using the two numerical approaches. According to Table I, errors of 3% and 3.47% are obtained using the two numerical methods. Fig. 4 shows the electric potential contours and Fig. 5 illustrates the charge distribution on the circular conductors obtained from the finite-difference technique using boundary fitted coordinates. Note that moving along the circular conductor surface, from point G_a to point G_b, the corresponding charge distribution of Fig. 5 follows a path that is opposite in direction, i.e., from point Q_a to point Q_b.

It is also of interest to examine the performance of the presented technique as opposed to the well-known integral equation method [2]. Although no direct comparison is made, a similar case was presented by Clements *et al.* [16]. They used the integral equation method to solve for the capacitance of two circular, closely spaced, parallel conductors of known potential. Accordingly, an error of about 3% was achieved when 10–12 harmonic functions per wire were used. In addition, lower errors were obtained as the number of expansion functions per wire increased. Similarly, the presented technique can yield better results if smaller grid sizes are used.

Case 2: Here, an elliptical conductor with $a = 1.746$ cm, $b = 0.16$ cm, and $h = 0.45$ cm is used. In this case, the elliptical conductor can be modelled as a flat conductor. For infinitely thin conductors, the characteristic impedance can be obtained from [11]

$$\frac{d}{w} = \frac{\pi}{\frac{\pi\eta}{Z_C} - \ln(2) - \ln\left(\frac{\pi\eta}{Z_C} - \ln(2)\right) - 1}$$
$$0 \le \frac{d}{w} \le 2.2, \qquad 0 \le \frac{Z_C}{\eta} \le 0.7 \tag{30}$$

where d is the separation between the conductors and w is the width. Table II shows the characteristic impedances computed using the two numerical approaches. According to Table II, errors of 3.6% and 4% are obtained using the two numerical methods.

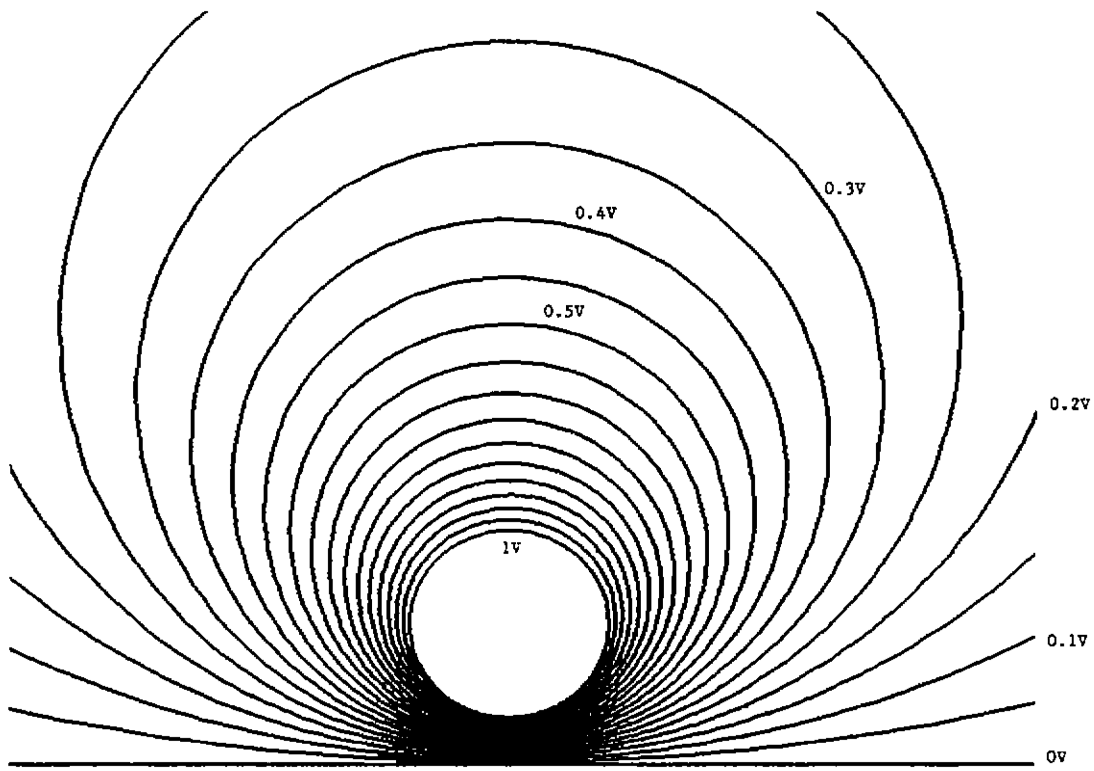

Fig. 4. Electric potential distribution on the circular conductor.

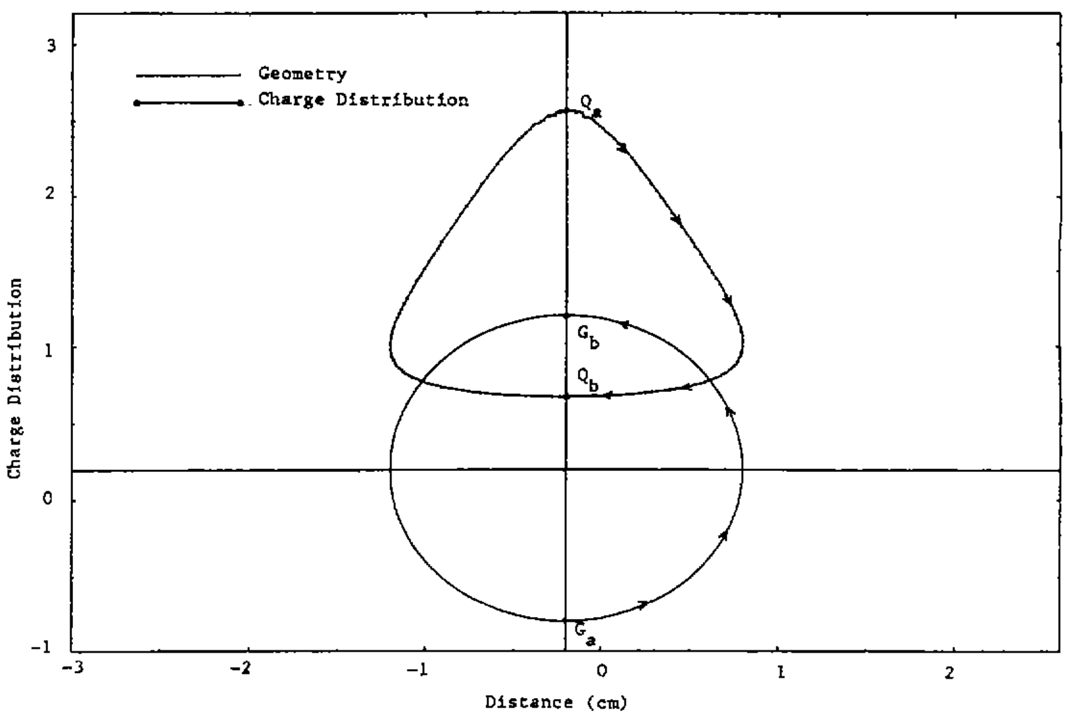

Fig. 5. Charge distribution on the circular conductor.

Case 3: A transmission line formed from two elliptical conductors with $a = 1.654$ cm, $b = 0.7$ cm, and $h = 1.5$ cm is used. These parameters are chosen for illustrative purposes. The characteristic impedance obtained from the finite-difference technique with boundary fitted coordinates is found to be about 113.9 Ω (≈ 5000 iterations) compared to 112.0 Ω

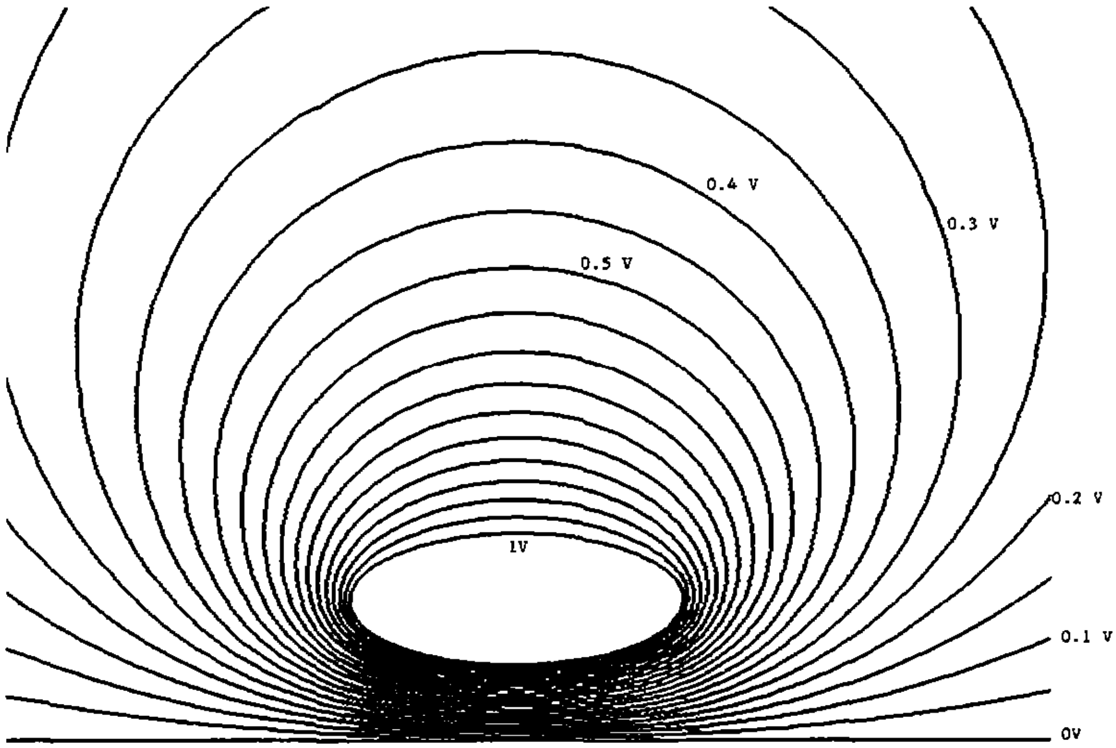

Fig. 6. Electric potential distribution on the elliptical conductor.

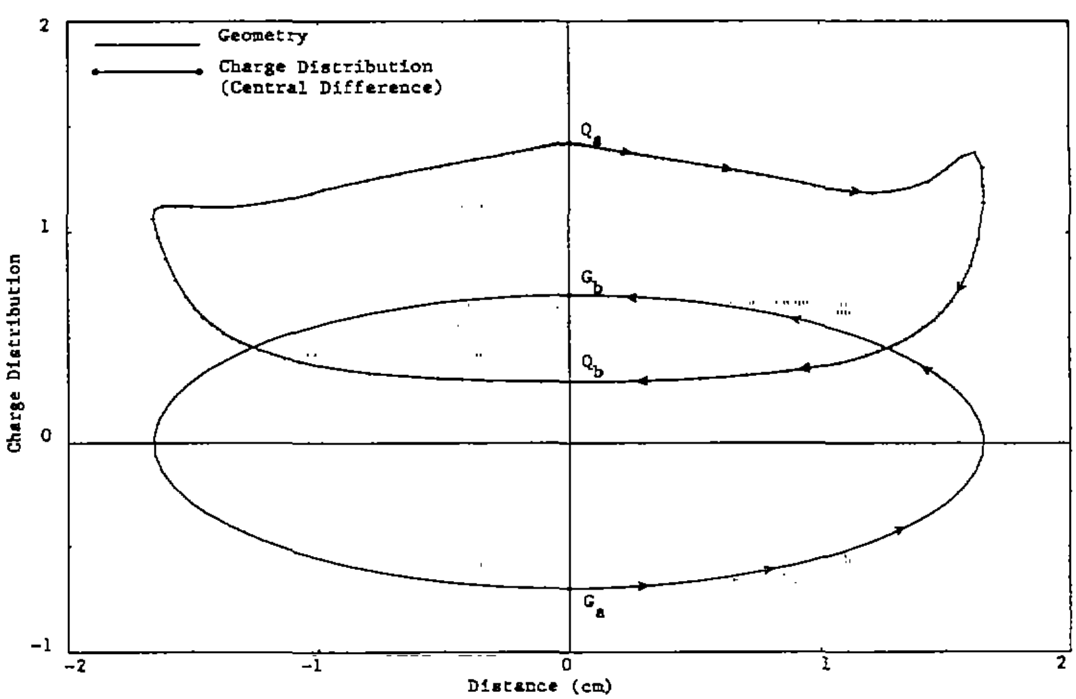

Fig. 7. Charge distribution on the elliptical conductor.

that is determined from the finite difference using a rectangular grid (31 562 iterations). Although no theoretical nor experimental result is available for this case, both numerical methods agree quite well in computing the characteristic impedance. Figs. 6 and 7 illustrate the corresponding electric potential contours and the charge distribution on the elliptical conductor.

TABLE II
CHARACTERISTIC IMPEDANCE COMPARISON FOR FLAT CONDUCTORS

Method	Characteristic Impedance	Percentage Relative Error	Number of Iterations
Analytical	50 Ω		
Finite difference using a rectangular grid	48.2 Ω	3.6	38 771
Finite difference using boundary fitted coordinates	52.0 Ω	4	≈4000

IV. CONCLUSION

A versatile numerical technique has been used to determine the potential and charge distributions of a transmission line formed by two elliptical conductors. This technique employs the finite-difference solution using boundary fitted coordinates to model arbitrary and complex structures. Accordingly, the characteristic impedance for different wire configurations is determined and compared with the finite difference results using a rectangular grid to determine the applicability and accuracy of the technique. Results have shown good agreement with theoretical values for circular and flat conductors. Furthermore, the finite difference method with boundary-fitted coordinates is found to be a more reliable technique for determining the charge distribution around the conductor and tends to converge much faster.

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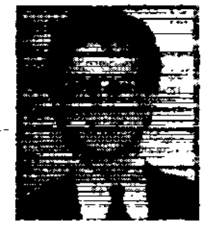

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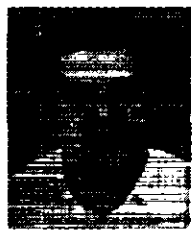

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