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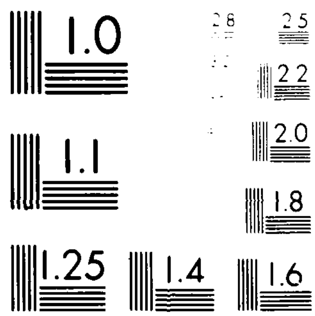
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Report 2335

FREQUENCY DEPENDENT CHARACTERISTIC IMPEDANCE, ATTENUATION, AND OHMIC LOSS OF MICROSTRIP, BASED UPON NUMERICAL CALCULATIONS OF EFFECTIVE INDUCTANCE

by
P. J. McConnell
R. L. Brooke

August 1981

U.S. ARMY MOBILITY EQUIPMENT
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A general matrix method, suitable for efficient numerical solution on a high-speed computer, is adapted and applied to determining the current distribution and transverse magnetic field of uniform microstrip transmission lines. Line loss and frequency are included in the solution as necessary to produce accurate results for the current distribution. The current distribution is then used to provide the effective characteristic impedance, inductance per unit length, and attenuation of the line. The report includes a Fortran program listing.

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FREQUENCY DEPENDENT CHARACTERISTICS IMPEDANCE, ATTENUATION, AND OHMIC LOSS OF MICROSTRIP, BASED UPON NUMERICAL CALCULATIONS OF EFFECTIVE INDUCTANCE

I. INTRODUCTION

A general matrix method, suitable for efficient numerical solution on a high-speed computer, is adapted and applied to determining the current distribution and transverse magnetic field of uniform microstrip transmission lines. Line loss and frequency are included in the solution as necessary to produce accurate results for the current distribution. The current distribution is then used to provide the effective characteristic impedance, inductance per unit length, and attenuation of the line.

The characteristic impedance of Microstrip Transmission Lines has been of interest for 25 years. Young[1] provides an excellent compilation of selected papers including several early papers specifically addressing Microstrip. The papers by Cohn[2], Wheeler,[3] and Bryant and Weiss[4] are especially fundamental and useful for common engineering problems. These papers, and a multitude of others published since, depend on solving for the static capacitance per unit length of the selected line configuration. Most practical geometries do not lend themselves to an exact analytic solution so much effort has been devoted to developing approximate analytic solutions. With the advent of the high-speed computer a considerable effort has been devoted to developing numerical techniques for solving Laplace's equation to yield the electric field configuration and capacitance of useful geometries. Guizan and Garver[5] give a notable example of this approach.

Once the capacitance per unit length has been determined the microwave characteristic impedance is determined by the following relationship

$$Z_O = 1/\nu C \quad (1)$$

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1 Leo Young, "Parallel Coupled Lines and Directional Couplers," Artech House, Inc., 1972.

2 S. B. Cohn, "Shielded Coupled-strip Transmission Line," IEEE Trans. on Microwave Theory and Techniques, Vol MTT-3, No. 5, pp 29-38, Oct 55.

3 H. A. Wheeler, "Transmission Line Properties of Parallel Strips Separated by a Dielectric Sheet," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-13, No. 2, pp 172-185, Mar 65.

4 T. G. Bryant and J. A. Weiss, "Parameters of Microstrip Transmission Lines and of Coupled Pairs of Microstrip Lines," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-16, No. 12, pp 1021-1027, Dec 68.

5 O. R. Guizan and R. V. Garver, "Characteristic Impedance of Rectangular Coaxial Transmission Lines," IEEE Trans. on Microwave Theory and Techniques, MTT-12, pp 489-495, Sep 64.

where ν is the velocity of propagation in the line. Wheeler[3] and Bryant and Weiss[4] address the practical problem of determining the effective velocity in a line where the fields are partially in a dielectric and partially in free space. The results shown in Figure 4 of Bryant and Weiss[4] will be used for later calculation in this report where effective velocity of propagation must be estimated.

The approach used in this report, while nonanalytic, is general and without any geometric limitation in the transverse plane. This approach is unique in that the effects of finite conductor losses and frequency dependence can be included in the analysis. Assumptions made by other authors are also made here. The lines to be analyzed are assumed to be relatively low loss lines supporting Quasi-TEM modes. Capacitance-based solutions are static solutions which approach exactness only for lossless lines. The *inductance*-based solution to be developed and applied here can allow for losses but is quasi-static and retarded potentials have not been considered.

The question is sometimes raised that it might be inappropriate to apply impedance concepts developed for TEM transmission lines and hollow waveguides to microstrip lines where the fields no longer are constrained to a finite area. This question has been discussed succinctly by Getsinger[6] who concludes that only one definition of microstrip characteristic impedance is consistent with the more general approach based on wave-impedance, which gives a unique result. This is a normal definition and allows application of the generally accepted concepts of wave impedance and, with the appropriate adjustments, distributed parameter circuit theory.

II. THEORETICAL DEVELOPMENT

If the line has finite losses, the characteristic impedance and propagation constant, γ, can be calculated from

$$Z_0 = \sqrt{\frac{R + jwL}{G + jwC}} \tag{2a}$$

$$\gamma = \alpha + j\beta = \sqrt{(R + jwL)(G + jWC)} \tag{2b}$$

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3 H. A. Wheeler, "Transmission Line Properties of Parallel Strips Separated by a Dielectric Sheet," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-13, No. 2, pp 172-185, Mar 65.

4 T. G. Bryant and J. A. Weiss, "Parameters of Microstrip Transmission Lines and of Coupled Pairs of Microstrip Lines," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-16, No. 12, pp 1021-1027, Dec 68.

6 W. J. Getsinger, "Microstrip Characteristic Impedance," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-27, No. 4, Apr 79.

where R and G are the series resistance and shunt conductance per unit length of the line and α and β are the attenuation and phase constant of the line. With the appropriate modifications to account for normal low-loss transmission line and other reasonable assumptions given by Brooke et al.,[7] an alternate equation for characteristic impedance results in the form

$$Z_0 = \nu L \tag{3}$$

where L is the inductance per unit length and is directly affected by both the resistance of the line and frequency. The geometry to be solved is shown in Figure 1.

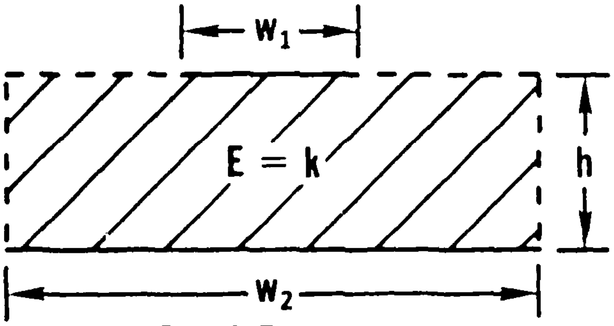

Figure 1. Transverse geometry.

For generality the two conducting tapes are allowed to have differing widths; however, they will be maintained parallel and with their midpoints defining a plane normal to both. This is a simplification, and is not required, but will shorten computation time substantially. This configuration can be used to represent microstrip examples given by Wheeler[3] and Bryant and Weiss[4] and direct comparisons of results made for the limiting cases of high frequency and no loss. In addition, this arrangement permits the calculation of the parameters of antenna feed lines where the widths are the same as well as the calculation of microwave components where the ground plane has a known finite width.

Mathematically subdividing the conductors into smaller parallel sections is accomplished as shown in Figure 2. This method of subdivision is arbitrary and is retained for consistency.[7]

The two conducting tapes have now been replaced by 4n thin parallel tapes, each of which may carry a different current. An equivalent circuit of the transmission line then looks like that in Figure 3.

[3] H. A. Wheeler, "Transmission Line Properties of Parallel Strips Separated by a Dielectric Sheet," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-13, No. 2, pp 172-185, Mar 65.

[4] T. G. Bryant and J. A. Weiss, "Parameters of Microstrip Transmission Lines and of Coupled Pairs of Microstrip Lines," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-16, No. 12, pp 1021-1027, Dec 68.

[7] R. L. Brooke, C. A. Hoer, and C. H. Love, "Inductance and Characteristic Impedance of a Strip-transmission Line," Journal of Research of NBS, C. Engineering and Instrumentation, Vol 71C, No. 1, Jan-Mar 67.

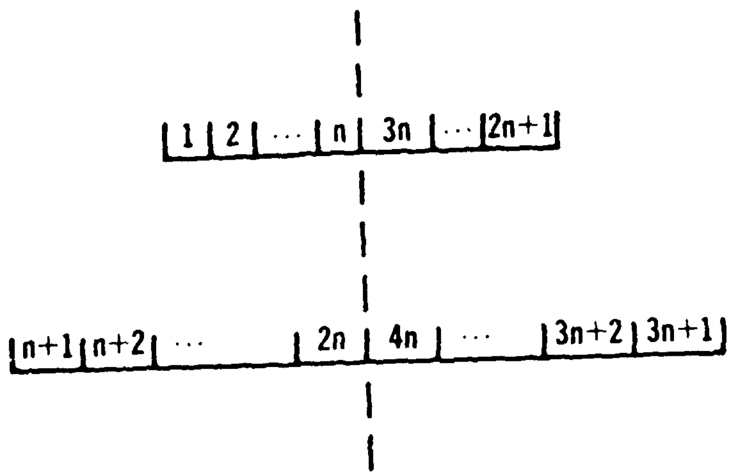

Figure 2. Method of indexing subdivisions.

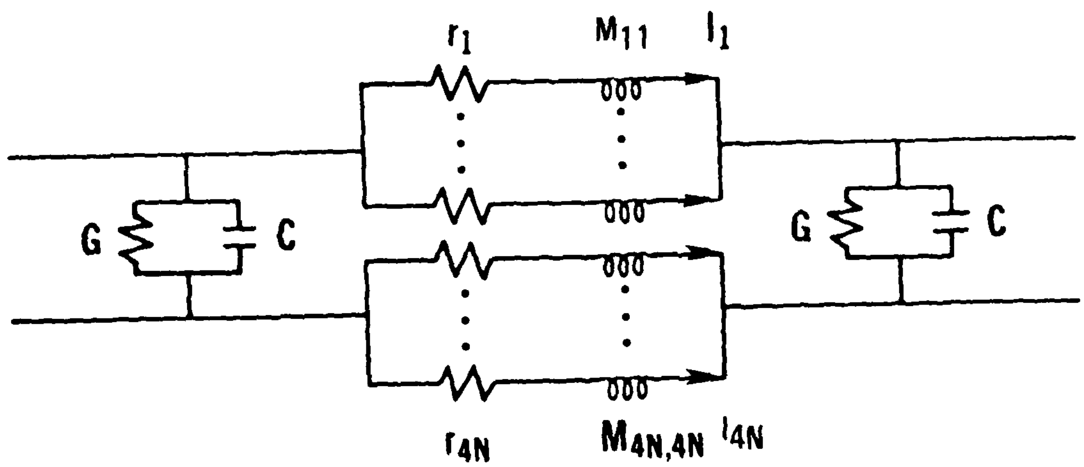

Figure 3. Equivalent circuit.

The width of each subsection will be chosen sufficiently small to consider the current density in each to be uniform. Appendix A contains d.c. inductance equations which can be used to calculate the mutual inductance between any two subsections and the self inductance of each. The resistance of each section will be the d.c. resistance calculated from the input parameters of bulk resistivity and incremental area. The incremental area is defined by the smaller of the actual tape thickness or an arbitrary multiple (an input parameter) of the skin depth and the subsection width. In this paper, the upper and lower tapes are each divided into 2n equal width subsections. Brooke et al.,[7,8] discuss alternative methods used to speed convergence for different geometries. Physical symmetry produces the following relations between the currents in the different sections. For the top tape,

$$I_j = I_{2n+j},\ j = 1,2,\ldots,n.$$

For the lower tape,

$$I_{n+j} = I_{3n+j},\ j = 1,2,\ldots,n.$$

The total voltage drop per unit length along any one section may be written,

$$V_k = r_k I_k + jw \sum_{i=1}^{4n} M_{ki} I_i. \tag{4}$$

There are 4n equations which may be written in matrix for as

$$\begin{pmatrix} V_1 \\ \vdots \\ V_{4n} \end{pmatrix} = \left[\begin{pmatrix} r_1 & & 0 \\ & \ddots & \\ 0 & & r_{4n} \end{pmatrix} + jw \begin{pmatrix} M_{1,1} & \cdots & M_{1,4n} \\ \vdots & & \\ M_{4n,1} & \cdots & M_{4n,4n} \end{pmatrix} \right] \begin{pmatrix} I_1 \\ \vdots \\ I_{4n} \end{pmatrix} \tag{5}$$

As a result of the symmetry conditions, only 2n of the equations are independent. The two groups k = 1 to n and 2n + 1 to 3n are equivalent as are the groups k = n + 1 to 2n and 3n + 1 to 4n. The order of the matrix equation can be reduced by a factor of two but it should be noted that all subsection currents affect all others and their contribution must be reflected in the final equations. Choosing the left half of each tape as the independent equations to be solved, rewrite (5) as

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7 R. L. Brooke, C. A. Hoer, and C. H. Love, "Inductance and Characteristic Impedance of a Strip-transmission Line," Journal of Research of NBS, Inc., C. Engineering and Instrumentation, Vol 71C, Jan-Mar 67.

8 R. E. Brooke and J. E. Cruz, "Current Distribution and Impedance of Lossless Conductor Systems," IEEF Trans. on Microwave Theory and Techniques, Vol. MTT-15, No. 6, Jun 67.

$$
\begin{pmatrix} V_1 \\ \cdot \\ \cdot \\ \cdot \\ V_n \\ V_{n+1} \\ \cdot \\ \cdot \\ \cdot \\ V_{2n} \end{pmatrix} = \left[\begin{pmatrix} r & & & & 0 \\ & \ddots & & & \\ & & r_n & & \\ & & & r_{n+1} & \\ & & & & \ddots \\ 0 & & & & r_{2n} \end{pmatrix} + jw \begin{pmatrix} \mathcal{M}_{11} & \cdots & \mathcal{M}_{1,2n} \\ \cdot & & \\ \cdot & & \\ \cdot & & \\ \mathcal{M}_{2n,1} & \cdots & \mathcal{M}_{2n,2n} \end{pmatrix} \right] \begin{pmatrix} I_1 \\ \cdot \\ \cdot \\ \cdot \\ I_{2n} \end{pmatrix} \tag{6}
$$

where

$$\mathcal{M}_{ij} = M_{i,j} + M_{i,2n+j} \tag{7}$$

has utilized the symmetry of currents only. Considerable symmetry also exists in the inductance coefficients and many of the calculations are redundant. This added simplification has been included in the program (subroutines MUT and MDX) but contribute nothing to the development. Equation (6) can now be written in the form

$$V = (R + j\omega M)I. \tag{8}$$

Since V_k and I_k from (8) may be complex, we let

$$V_k = e_k + jf_k,\ I_k = a - jb_k. \tag{9}$$

In terms of column matrices,

$$V = E + jF,\ I = A - jB. \tag{10}$$

Substituting (10) into (8) produces two real matrix equations:

$$E = RA + \omega MB. \tag{11}$$

$$F = -RB + \omega MA. \tag{12}$$

Solving for A and B produces

$$A = R^{-1} [(1) + (\omega MR^{-1})^2]^{-1} [E + (\omega MR^{-1})F]. \tag{13}$$

$$B = R^{-1} [(1) + (\omega MR^{-1})^2]^{-1} [(\omega MR^{-1}) E - F]. \tag{14}$$

The following definitions are used to simplify the manipulations:

$$\omega = R^{-1}[(1) + (\omega M R^{-1})^2]^{-1}$$

$$\phi = \omega M R^{-1}$$

$$\gamma = (1_1 \ldots 1_{2n})$$

$$\theta = (0, \ldots, 0n, 1_{n+1}, \ldots, 1_{2n}). \qquad (15)$$

As radiation is not allowed and the line is driven as a Lecher go-and-return circuit, the total circuit in the one tape must equal the total current in the other. This gives

$$\sum_{1}^{n} a_k + \sum_{n+1}^{2n} a_k \equiv 0$$

$$\sum_{1}^{n} b_k + \sum_{n+1}^{2n} b_k \equiv 0$$

or in the matric notation, using (13), (14), and (15)

$$\gamma A = \gamma\omega[E + \phi F] \equiv 0 \qquad (16)$$

$$\gamma B = \gamma\omega[\phi E - F] \equiv 0. \qquad (17)$$

As all the currents are longitudinal there cannot be any transverse voltage differences on the conducting tapes and the scalar voltages obey the following:

$$f_1 = f_k \; k = 1, 2, \ldots n$$

$$e_1 = e_k$$

$$f_{n+1} = f_\ell \quad \ell = n + 1 \ldots 2n$$

$$e_{n+1} = e_\ell.$$

The voltage drop around the loop (down one tape and back the other) is:

$$e_1 - e_{n+1} + j(f_1 - f_{n+1}) = \Delta\nu/\Delta\ell.$$

Since the value of the voltage drop is arbitrary and can be adjusted to any quantity by changing the applied signal, we define it as 1 + j0. This condition applied to the above results produces

$$e_1 - e_{n+1} = 1$$

$$f_1 - f_n = 0.$$

The column matrices E and F can now be written in terms of known matrices and one scalar unknown each:

$$E = -\theta^T + e_1\gamma^T$$

(18)

$$F = f_1\gamma^T$$

where the superscript T denotes the transposed matrix. Combining (18) with (16) and (17) and solving for e and f produces

$$e_1 = \frac{(\gamma\psi\phi\gamma^T)(\gamma\psi\phi\theta^T) + (\gamma\psi\theta^T)(\gamma\psi\gamma^T)}{(\gamma\psi\gamma)^2 + (\gamma\psi\phi\gamma^T)^2} \tag{19}$$

$$f_1 = \frac{\gamma\psi\theta^T \quad e_1\gamma\psi\gamma^T}{\gamma\psi\phi\gamma^T} \tag{20}$$

Every term on the right is now a calculable scalar. The results obtained can be substituted into (18), (13), and (14), and the current in each section determined. Solution of (19) and (20) is performed in subroutine CURR in a straight forward fashion. The solution to (13) and (14) may be more obvious in the code if we rewrite those equations using the definitions in (15)

$$\psi^{-1} A = (E + \phi F) \tag{13a}$$

$$\psi^{-1} B = (\phi E - F). \tag{14a}$$

With the currents in each section known, the approximate inductance and resistance per unit length can be calculated.

$$\mathrm{Leff} = \frac{\frac{1}{2\omega}\sum_{1}^{n} a_k}{\left(\sum_{1}^{n} a_k\right)^2 + \left(\sum_{1}^{n} b_k\right)^2} \qquad (21)$$

$$\mathrm{Reff} = \frac{\frac{1}{2}\sum_{1}^{n} b_k}{\left(\sum_{1}^{n} a_k\right)^2 + \left(\sum_{1}^{n} b_k\right)^2} \qquad (22)$$

The question might be raised as to whether the frequency dependence is the result of the finite resistance and if the system were lossless would the solution for Leff be independent of frequency. An examination of reference (8) shows this question to have been addressed clearly. For clarity and completeness the argument is repeated here.

A lossless condition reduces equations (4) and (9) to the following:

$$V_k = j\omega \sum M_{kl}\, I_l,\; I_k = -jb_k \qquad (23)$$

which leads to a simple form for the current matrix

$$B = \frac{1}{\omega}\, M^{-1}\, V. \qquad (24)$$

For the lossless case, the effective inductance is found to be

$$\mathrm{Leff} = \omega \sum_{1}^{\frac{1}{2n}} b_k \qquad (25)$$

which still appears to be function of frequency.

In terms of matrix operations we have

$$\sum b_k = \theta B = \frac{1}{w} \theta M^{-1} V. \tag{26}$$

thus resulting in

$$Leff = 1/\theta M^{-1} V \tag{27}$$

showing the frequency independence of effective inductance under lossless conditions. Numerical results obtained through a programmed, *convergent* approximation for Leff should therefore agree with capacitivity derived results for either $f \rightarrow \infty$ or $R \rightarrow o$.

III. CONVERGENCE AND CURRENT DISTRIBUTION

The convergence of this numerical technique is dependent on many factors including geometry, frequency, resistance, and the method used for conductor subdivision. Brooke et al.[7, 8] employ methods of tape subdivision using unequal widths to speed up convergence and provide accuracies better than 0.1 percent for calculations of precision standard geometries. To provide for simple adaptability to a variety of geometries, the program developed to calculate microstrip properties for this report (Appendix B) used only equal width subdivisions. Where the two *conductors were of unequal width, they* were both subdivided into an equal number of subelements without any complex scheme for matching the current distribution. Figure 4 plots the normalized transverse current densities for a typical *microstrip* with equal conductor widths, a frequency of 10^7 Hz, conductor resistivity of 1.724×10^{-8} ohm-meters and an impedance of about 58 ohms. Different plots are shown as the number of subdivisions are increased from 4 to 40 on each *conductor*. For this particular case, convergence (of impedance) of better than 0.5 percent was achieved for n = 11 or 22 subdivisions. No general conclusions should be drawn from this for other cases or geometries. Much more rapid convergence could be achieved by tailoring the subdivision widths to each particular problem. A most elegant programming solution would be to adjust the widths through an iterative process of equalizing the differences between adjacent subelements. It is *not* obvious that such a scheme would result in more efficient code as redundancy in impedance calculations would decrease.

If the conductors are allowed to have different widths, the current distribution will show a markedly different pattern. Figure 5 shows three overlaid plots for one case where the wider conductor is 2, 3, and 5 times the width of the other. The *area under the curves*

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7 R. L. Brooke, C. A. Hoer, and C. H. Love, "Inductance and Characteristic Impedance of a Strip-transmission Line," Journal of Research of NBS, C. Engineering and Instrumentation, Vol 71C, No. 1, Jan-Mar 67.

8 R. F. Brooke and J. F. Cruz, "Current Distribution and Impedance of Lossless Conductor Systems," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-15, No. 6, Jun 67.

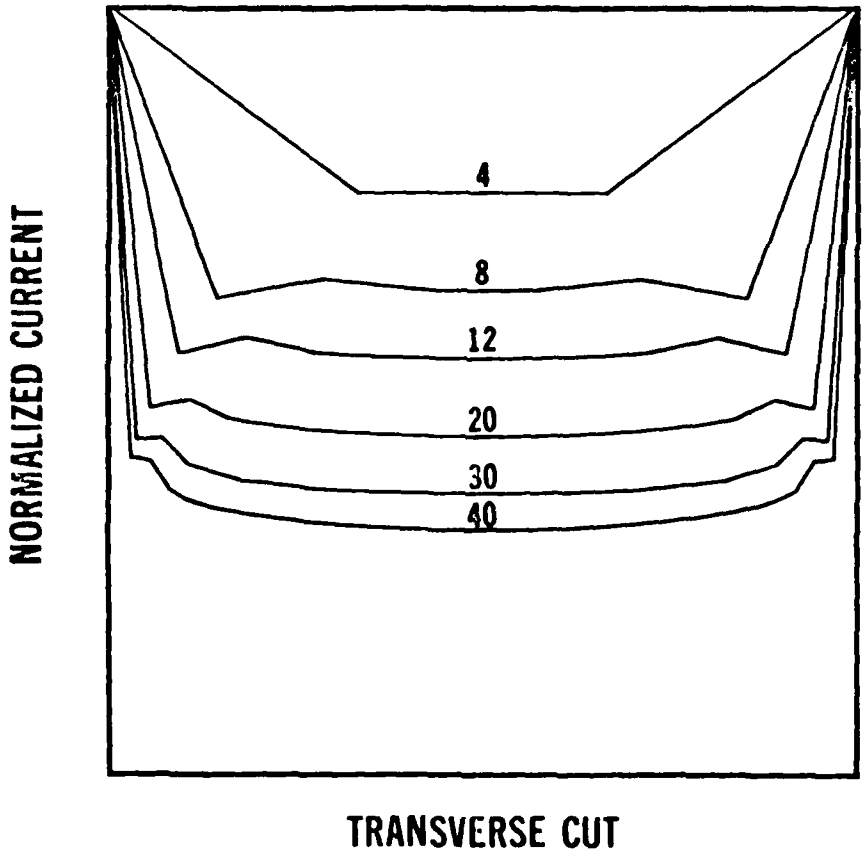


Figure 4. Normalized current distribution as a function of number of calculated subdivisions.

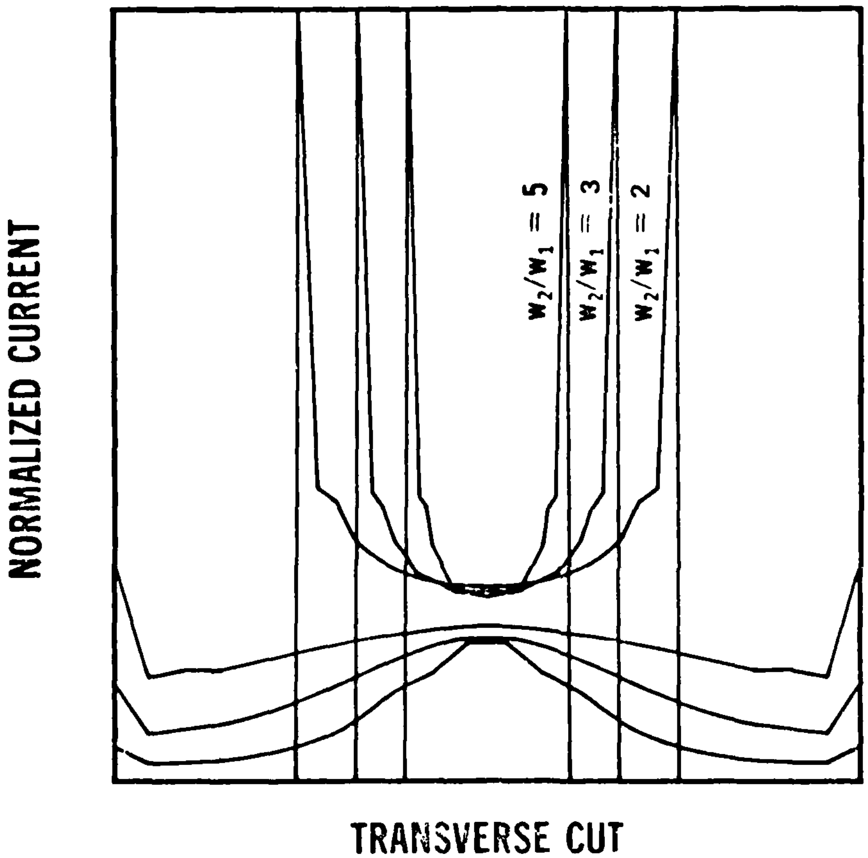


Figure 5. Normalized current distribution for unequal tapes as a function of ratio of tape widths.

for the two conductors should be the same for each case, to reflect the requirement that the total current be the same. As is expected, the current on the wider tape crowds to the center under the smaller tape and reflects the partially self-shielding characteristic of microstrip. The characteristic impedance obtained for these three cases was 96.87 ohms (2/1), 92.24 ohms (3/1), and 89.69 ohms (5/1). Our program allows an examination of the effect of the finite width of the ground plane on the properties of microstrip and reveals a surprising dependence even for ratios of 10/1. Impedance values are found to change as much as 0.5 percent for a 10-percent change in ground plane width at a nominal 10/1 ratio. A recent report[9] goes to great effort to establish convergence better than 0.1 percent and yet is based on an assumption of infinite width for the ground plane.

IV. COMPARISON OF RESULTS

Two cases will be calculated and compared with results produced by other authors. An equal width case can be compared directly with Wheeler's[3] results, and an unequal width case can be compared with the results of Bryant and Weiss[4] providing the larger tape is at least 10 times the width of the smaller, as the latter reference assumes an infinite ground plane. Only the high-frequency, or lossless, case will be considered since this is also an assumption of the references. The comparative values obtained from the references required interpolating published response curves. The excellent agreement with Wheeler[3] is more than would have been expected (Table 1). The slightly high bias of the results in Table 2 are the result of approximating an infinite plane with a 10:1 width ratio. The program calculations have been rounded to the nearest ohm.

The current distributions produced in solving for the results of Table 1 are shown superimposed in Figure 6 for values of w/h from 1 to 30. It is clear that widening the two conductors results in a more uniform distribution of current in the transverse plane and better shielding. This is, of course, what one should expect and is used by Wheeler[3] as the basis for a wide tape approximation and to establish a limit for the effective dielectric constant of K and propagation velocity of $\nu_c/\sqrt{K}$.

3 H. A. Wheeler, "Transmission Line Properties of Parallel Strips Separated by a Dielectric Sheet," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-13, No. 2, pp 172-185, Mar 65.

4 T. G. Bryant and J. A. Weiss, "Parameters of Microstrip Transmission Lines and of Coupled Pairs of Microstrip Lines," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-16, No. 12, pp 1021-1027, Dec 68.

9 R. H. Jansen, "High-speed Computation of Single and Coupled Microstrip Parameters Including Dispersions, High-order Nodes, Loss, and Finite Strip Width," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-26, No. 2, Feb 78.

Table 1. Comparison of Results for Equal Width (K=1)

w/h	Wheeler[3]	This Method
0.3	315	313
0.4	279	280
0.5	252	254
0.6	232	234
0.7	216	217
0.8	202	202
0.9	189	190
1.0	178	179
3.0	87	87
10.0	32	32.5

[3] H. A. Wheeler, "Transmission Line Properties of Parallel Strips Separated by a Dielectric Sheet," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-13, No. 2, pp 172-185, Mar 65.

Table 2. Comparison of Results for Unequal Width (K=1)

w_1/h w_2/w_1 = 10	Bryant & Weiss[4]	This Method
0.6	156	160
0.8	140	142
1.0	127	128
2.0	87	90
3.0	67	70

[4] T. G. Bryant and J. A. Weiss, "Parameters of Microstrip Transmission Lines and of Coupled pairs of Microstrip Lines," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-16, No. 12, pp 1021-1027, Dec 68.

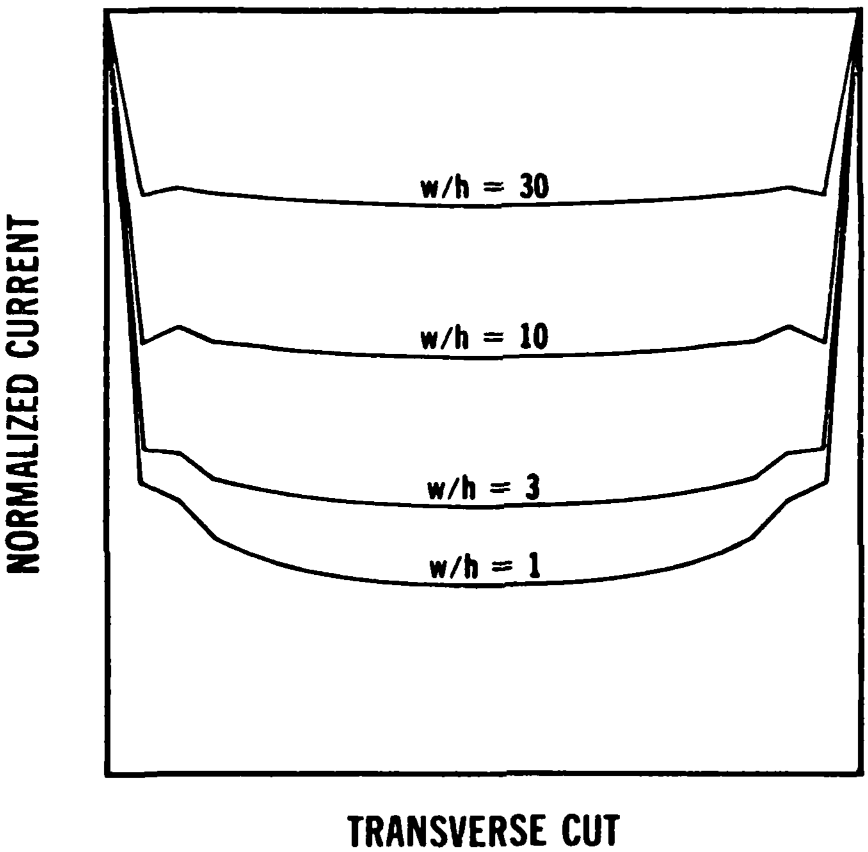


Figure 6. Equal tape current distribution as a function of width/separation.

V. PARAMETER FREQUENCY DEPENDENCE

The transverse current distribution is a function of frequency and the other physical variables. The effective inductance per unit length and attenuation derived from the current distribution will also be frequency dependent and fully predictable with this program. The attenuation derived here is only the ohmic loss in the conductors and does not account for loss and dispersion in the dielectric substrate.

To examine the behavior of both equal and unequal tape microstrips as a function of frequency we select a w/h ratio of 5/1 for the equal case and w_1/h ratio of 4/1 for the unequal case, with $w_2/w_1 = 10$ to assure reasonable similarity to typical components used by industry in the manufacture of microwave components and antennas.

The frequency dependence of the transverse current distribution for these two cases provides insight into where the transition occurs and the cause for ohmic losses which can be substantial. Figure 7 is a parametric presentation of the transverse current distribution for an equal conductor width microstrip. ($w_1 = w_2 = .01$ m, h = .002m; $\rho = 1.7241 \times 10^{-8}$) The major frequency dependence occurs between 10^4 Hz and 10^5 Hz. At a frequency of 5×10^5 Hz, the inductance and characteristic impedance have stabilized although the ohmic attenuation will continue to increase. Figure 8 shows the frequency response of the unequal case which shows a much greater dependence but is still settled down by 10^5 Hz ($w_1 = .01$m, $w_2 = 0.1$m, h = .0025) (note that the display program plots distribution at full frame size when $w_2/w_1 \geq 10$).

If we examine the frequency dependence of these two types of geometries we can gain an understanding of their behavior and the effect of geometry on it. In Figure 9, we plot the characteristic impedance of an equal width microstrip with a dielectric of 1 as a function of frequency. There is a modest decrease from the d.c. value (60.4 ohms) to the high frequency limit (58.55 ohms). The change occurs in the frequency range of 5×10^3 to 5×10^5 Hz. If the matierial used were a better conductor, this shift region would be translated to the left. In sharp contrast to this is the behavior of unequal width microstrip where a much larger change is observed with increasing frequency. Figure 10 is a typical plot of one case where the low frequency impedance of 124.3 ohms is transformed to a high-frequency impedance of 57.33 ohms. The transition commences at a lower frequency and is essentially complete at a frequency of 10^5 Hz. The more radical dependence on frequency is the result of large shifts in ground plane currents to concentrate under the smaller conductor.

Figure 11 plots the characteristic impedance of equal width microstrip for four different effective wavelengths, λ_0, $\lambda_0/2$, $\lambda_0/3$, and $\lambda_0/4$, as a function of the ratio of conductor width to separation. Wheeler's work can be used to estimate the relative fill factor, q, which can be used to determine the effective dielectric constant K'. Following Wheeler we have,

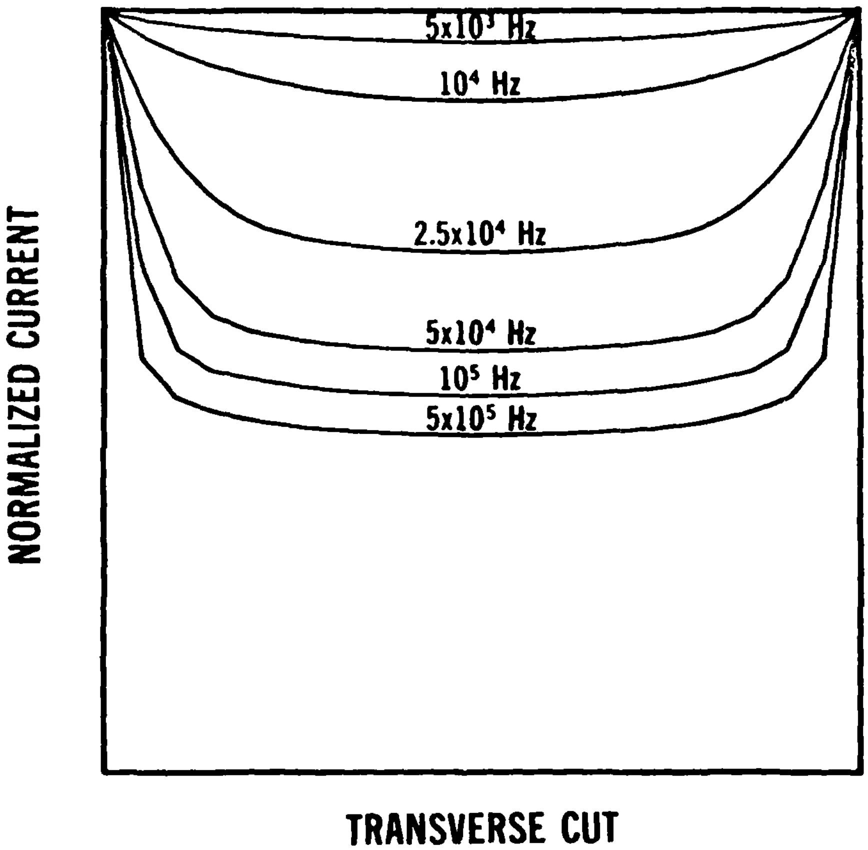


Figure 7. Frequency dependence of current distribution for equal width microstrip.

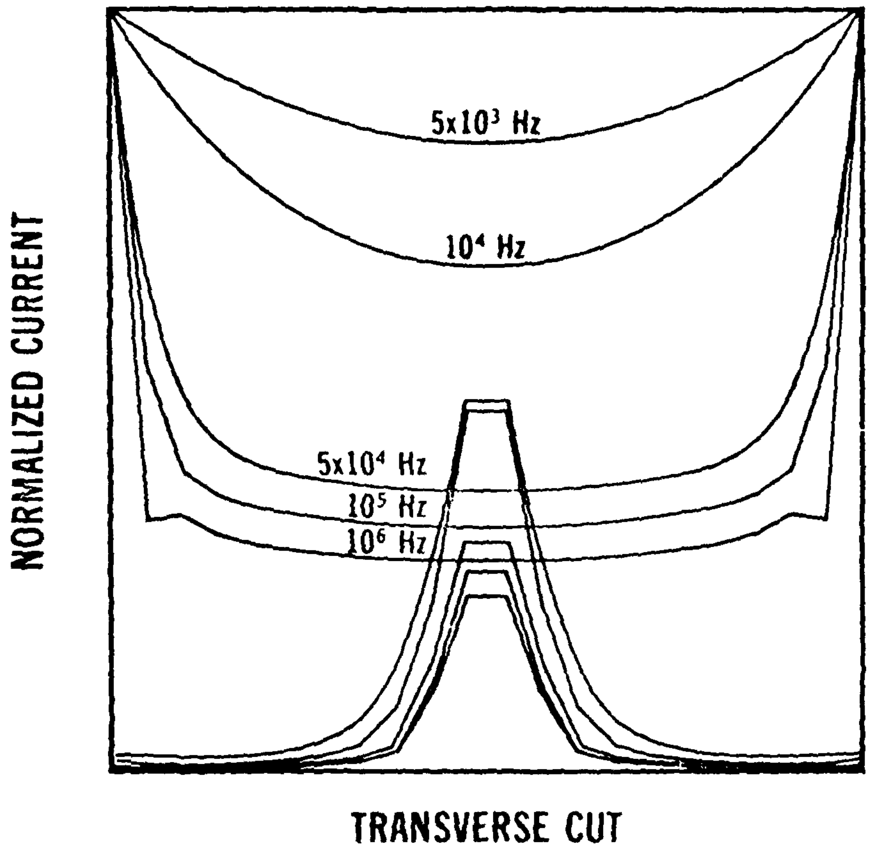


Figure 8. Frequency dependence of current distribution for unequal width microstrip.

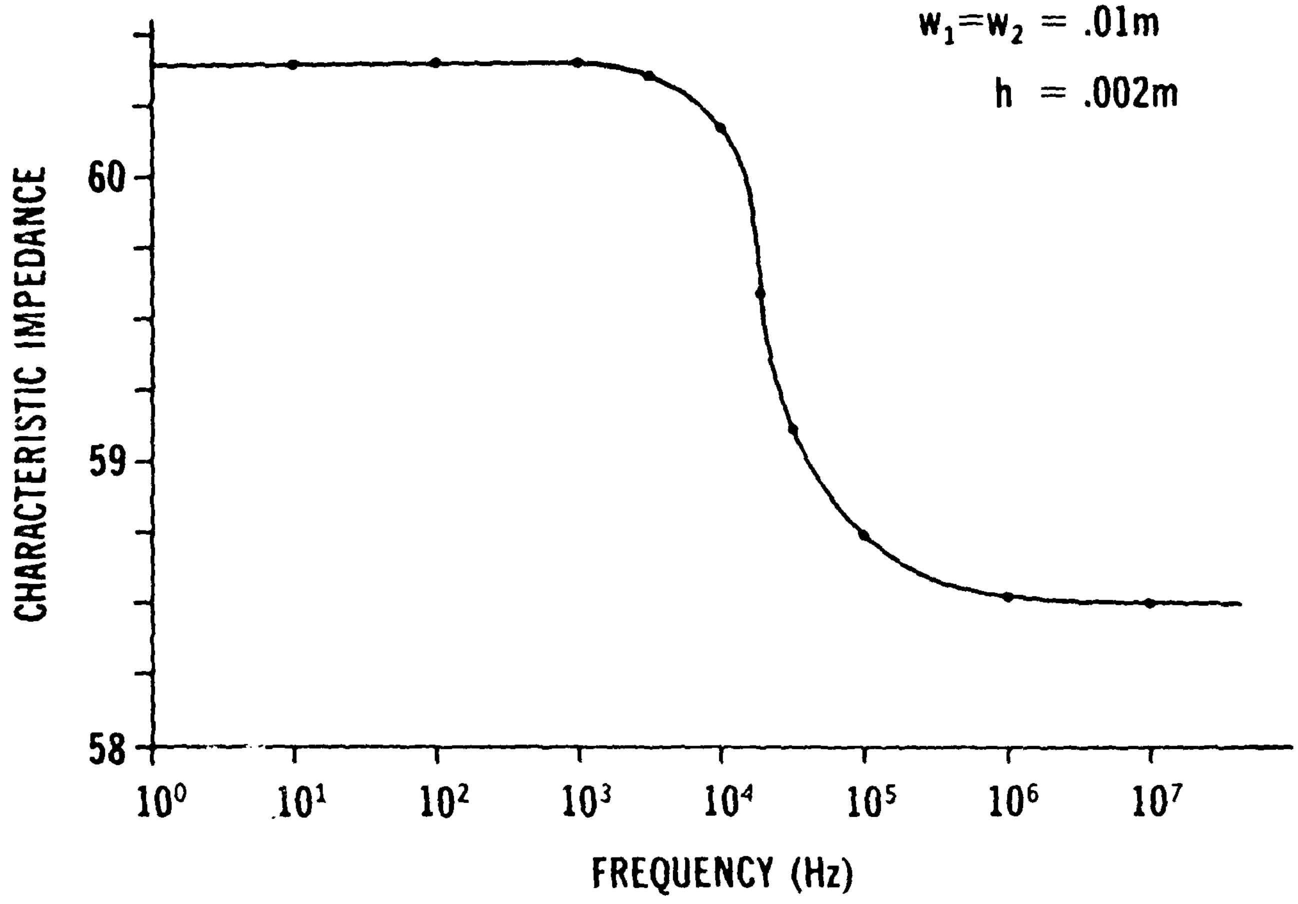


Figure 9. Equal conductor microstriop characteristic impedance as a function of frequency.

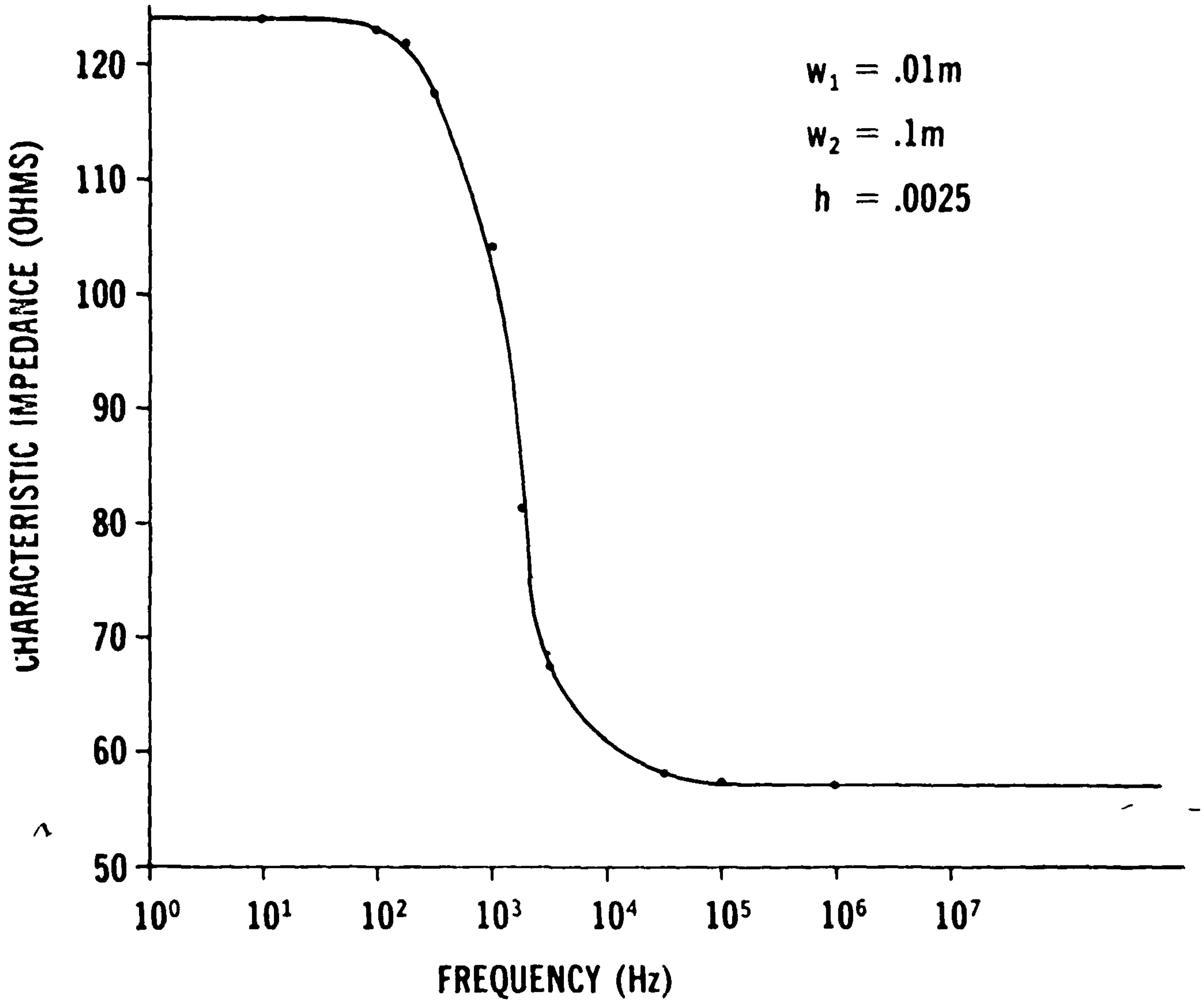


Figure 10. Unequal conductor microstrip characteristic impedance as a function of frequency.

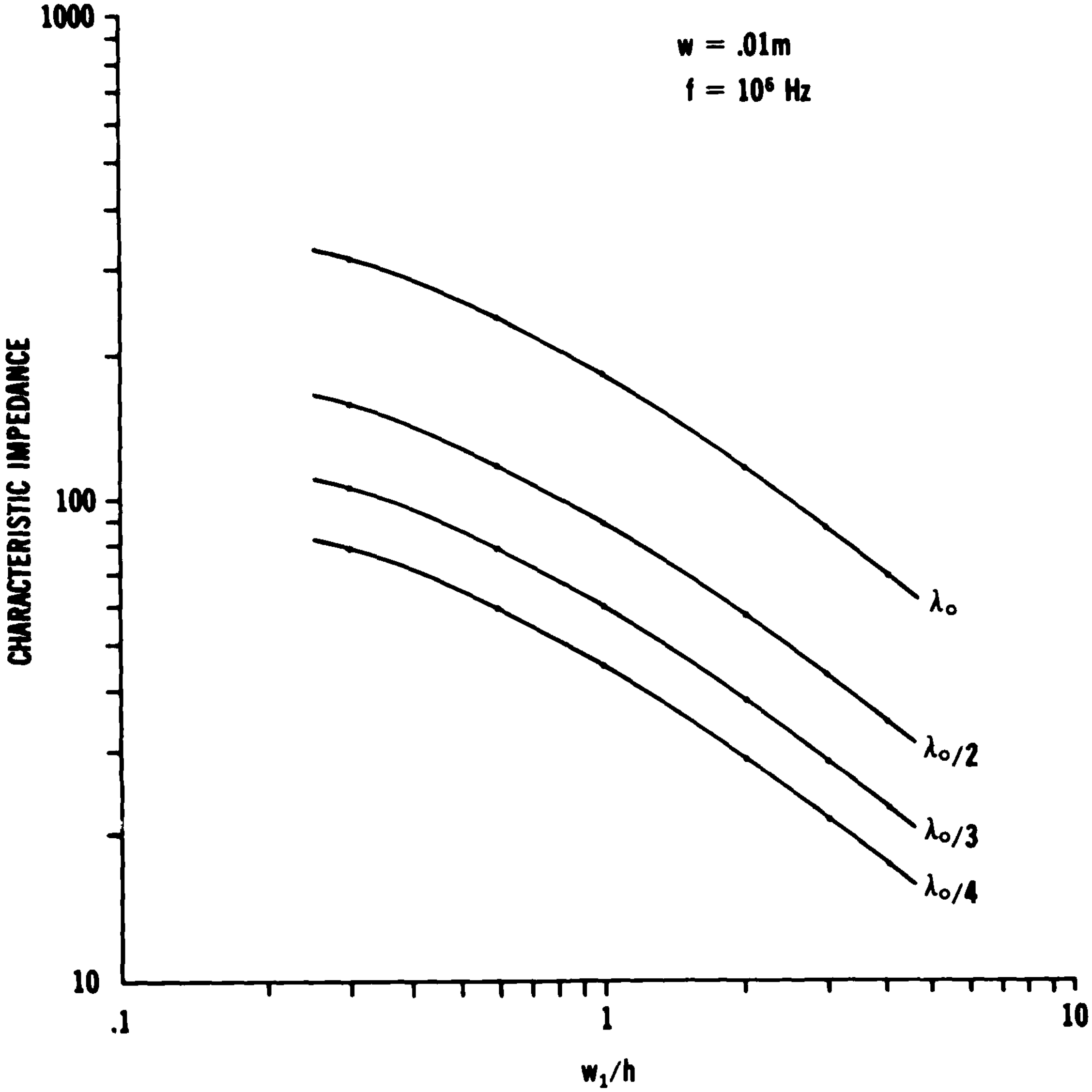


Figure 11. Characteristic impedance of equal width microstrip as a function of w_1/h and effective wavelength.

$$q = \frac{K' - 1}{K - 1} \tag{28}$$

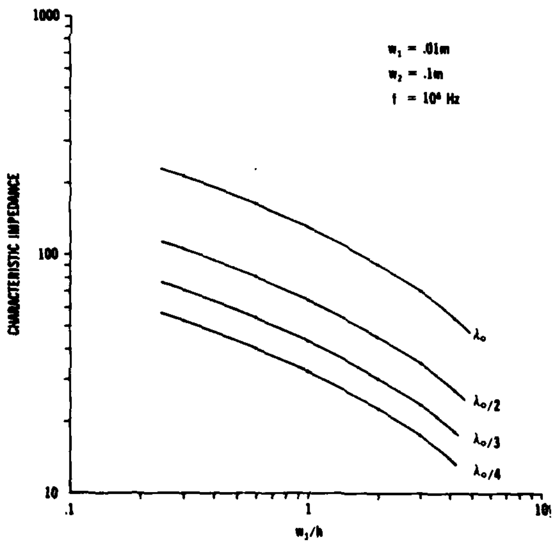
and

$$K' = 1 + q\,(K-1). \tag{29}$$

where K is the nominal dielectric constant of the dielectric sheet between the conductors. Using Wheeler's Figure 9 yields an approximate value for q. The effective wavelength can be reasonably approximated by equation (30).

$$\lambda eff = \frac{\lambda o}{\sqrt{K'}} \tag{30}$$

An assumption used here is that the limit of K′ for very narrow tapes is (k + 1)/2 or an average with free space and the limit for very wide tapes is just K, the dielectric constant of the material between the conductors. Figure 12 presents the results for the case of unequal width microstrip.



CHARACTERISTIC IMPEDANCE OF UNEQUAL WIDTH MICROSTRIP AS A FUNCTION OF w_1/h AND EFFECTIVE WAVELENGTH

Figure 12. Characteristic impedance of unequal width microstrip as a function of w_1/h and effective wavelength.

VII. CONCLUSION

In this report we have shown the theoretical development of a method to calculate the inductance per unit length and ohmic losses of microstrip line with general cross sectional geometry. A program developed to apply this technique was exercised for simple cases and the results found to agree with those of other authors using capacitance-based solutions. This approach is unique in that it directly provides the transverse current distribution and ohmic attenuation at all frequencies. It can provide new insights into factors which cause loss in microwave components and help explain the effective behavior of currents on extended antenna structures. A clear understanding of antenna feedlines and radiating elements can be reached only if the current distribution is known.

This particular approach has a special advantage in the ease with which it can be extended to other geometries. It must be cautioned that, although the theory is straightforward, there are ample opportunities to lose the solution in writing the program.

This report was restricted to the odd mode of single element microstrip because the specific application for which it was developed required only this. It could be extended to even mode and coupling calculations if the total currents can be defined in sufficient exactness to allow solution of the matrix equations. The results already shown here can have utility in producing microstrip with minimal ohmic losses and reduced cost by placing low resistance materials (gold or silver) only in the area of the conductors with high-current densities. In the case of unequal width microstrip this means a few millimeters on the outer edges of only the smaller conductor.

VII. PROGRAM NOTES

This method has been presented previously,[7] but to our knowledge has not been used in the 13 years since publication. Perhaps the more universal availability of large high-speed computers and the increasing acceptance of numerical solutions will provide encouragement for its use. It is in this spirit that the program is provided. Appendix C contains sample runs to assist in program checkout.

The program runs interactively through Intercom on a CDC 6600 using Scope 3.4. The code provided makes a modest attempt to minimize core required and to reduce run time, but we eschew heroic efforts which make modification and transportability difficult.

Subprograms Not Provided:

The following subprograms are called from subroutine CURR and are found in Library 3 of the IMSL Fifth edition, November 1975:

[7] R. L. Brooke, C. A. Hoer, and C. H. Love, "Inductance and Characteristic Impedance of a Strip-transmission Line," Journal of Research of NBS, C, Engineering and Instrumentation, Vol 71C, No. 1, Jan-Mar 67.

VMULFB Matrix Multiplication (full by band).
VMULFF Matrix Multiplication (full by full).
LINV2F Matrix Inversion.
LEQT2F Solution of Linear Equations.

Subroutine PLOTXY is a machine and terminal specific plotting subroutine called from subroutine PLOTI. It is not necessary to include PLOTXY, or PLOTI, to use the program. The comments which provide instructions for using PLOTXY are included so that the user may interpret the calls in a manner compatible with his own graphic terminal if desired.

Function Second — See notes below:

Subroutine Connec (file name) associates the named file with the terminal device and may be an unnecessary function in some installations.

System Specific Subprogram:

The following subprograms are specific to the current CDC operating system in use at MERADCOM and will normally require adaptation or removal.

Function Second — This function returns the central processor time consumed by the job since start.

Subroutine CPUTIME — This is a compass subprogram called from Function TIMEL. It returns the time remaining before the system will abort the job.

These subprograms are used to provide the interactive user with information which may be used to manage the consumption of resources. Where resources are not a constraint, dummy subroutines may be provided or the calling statements removed. Retention of these functions is generally recommended for both use and program modification as the potential for resource consumption is significant. The use of List-Directed read and write (print) statements such as READ *, IN are freely intermixed with formatted IO. If no equivalent feature is provided by the user's system, formatted statements will have to be substituted. Many such statements which were inserted during program development have been retained as comments.

File Usage. The principle output file is OUTPUT, which is equivalent to TAPE6, and is the terminal for interactive users.

The only input file is INPUT, which is the terminal for interactive users. TAPE2 is an alternate output file used to save specified results for later printing under interactive control (not the terminal).

Program Use. The program is nearly self-explanatory when *run interactively*. The user enters at least the first two characters of a key word. If the key word represents a variable, the value will be requested. If the key word represents a command, (Display variables, Print results, GO calculate, STOP, Instructions, SAVE), that function is performed. Samples of operation are included (Appendix C). When parametric design studies are made, the user would be wise to conserve resources by being sensitive to which variables require which calculations. Changes of basic geometry require completely new solutions, while frequency, tape thickness and resistivity do not require recalculation of the mutual inductance matrix. Changes of dielectric constant, power factor, and command inputs are trivial. The user is prompted by messages indicating CPU time consumed.

Specific Subprogram Notes:

Program STRIPZM includes only trivial calculations and normal output, but not the input functions. A somewhat convoluted method of specifying arrays is introduced. This method is helpful during program development and modification as it permits flexible creation of arrays and core management without substantial changes of code, but at execution time expense. Two dimension arrays of dimension (M*N, M*N) are stored in order in blank common. N is the input variable specifying the number of subdivisions in a half-tape. M = 1, 2, 4, 8, 12, 16. The number of arrays of (M*N, M*N) dimension is stored in vector NA where the index to NA corresponds to the M implied EXAMPLE: NA = 2, 1, 0, 0, 3, 0 means:

2 arrays of Dimension (N,N) followed by
1 array of Dimension (2*N, 2*N) followed by
3 arrays of Dimension (12*N, 12*N)

A similar scheme for the storage of vectors of dimension (M*N) is used with the number of vectors of dimension (M*N) stored in vector NV. Vector storage space follows the array storage. Finally, the particular array within a group of arrays (or vectors) of the same dimension may be indirectly specified. Vector ISA is used to perform this function.

Subroutine IO contains the input code and may be replaced by those who prefer only batch processing. The logic provided attempts to reduce execution time by requiring only those calculations which are necessary. Subroutine CURR contains the principle code which achieves the purpose of this paper. Note that double precision is used in the summations required for the solution for E and F. This subroutine uses core beyond the work area matrix as noted in the program. If N vector space is required to survive execution, storage allocation must be modified.

Function SZIND performs the mutual inductance calculation. Execution time is poor and evaluation requires high precision as the difference between similar values occur. When installed on a machine with less precision, care must be exercised in determining the range of input variables to be permitted. (It is possible to increase N, subdivisions, and decrease the precision of the result.) Subroutine MDX takes advantage of the half plane symmetry and the equal width subdivision of tapes to permit a reduction of the number of mutual inductance calculations.

Subroutine MUT calls function SZIND to fill a work space with the unique mutual calculations required, and then fills the complete mutual matrix with appropriate values.

Function INA provides the index to the location of any element in any array specified in the manner described. The function also provides an entry which determines the maximum number of subdivisions based upon the amount of blank common available and the arrays defined by vectors NA and NV. These values are passed in labled common STOR.

APPENDIX A

BASIC EQUATIONS FOR INDUCTANCE IMPEDANCE

The mutual inductance per unit length between two long, thin, parallel tapes such as shown in the figure below can be obtained from equation 8 of reference (10) and is

$$M_1 = \frac{0.2}{ad}\left[\frac{P^2 - x^2}{4}\ \ln(P^2 + x^2) - xP\,\mathrm{Tan}^{-1}\frac{x}{P}\right]\begin{matrix} E-a,\ E+d \\ (x) \\ E+d-a,\ E \end{matrix}$$

$$+0.2[\ln 2l + ½],\ \mu\mathrm{H/m} \qquad \text{(A1)}$$

where the limits, which have been retained for compactness, are substituted as follows:

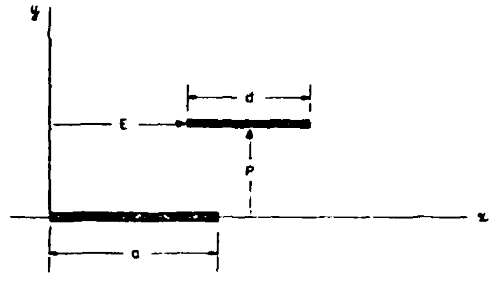
$$[f(x)]\ \begin{matrix} s_1 s_3 \\ (x) \\ s_2 s_4 \end{matrix} \equiv \sum_{i=1}^{4} (-1)^{i+1} f(s_i).$$

The origin coincides with the left edge of one tape. If the left edge of the second tape is in any quadrant other than the first as shown, one or both of the values of E and P will be negative. The self-inductance per unit length of a long thin tape is

$$L_t = 0.2\ \ln\frac{1}{a} + 0.2\ [\ln 2l + ½],\ \mu\mathrm{H/m}. \qquad \text{(A2)}$$

In both of these expressions it is assumed that the current density is uniform throughout the conductors.

[10] C. A. Hoer and C. H. Love. Exact inductance equations for rectangular conductors with applications to more complicated geometries, J. Res. NBS 69C2 (Engr. and Instr.), No. 2, 127-137 (Apr.-June 1965).



Cross sectional view of two long parallel thin tapes.

Note that the term

$$0.2[\ln 2l + \tfrac{1}{2}] \tag{A3}$$

appears in both M_t and L_t as the only term involving length. However, if M_t and L_t are substituted into (8), the terms involving length will exactly cancel. Substituting (A1) and (A2) into (8) gives

$$V_k = r_k I_k + j\omega \sum_{l=1}^{8n} M'_{kt} I_t + j\omega [0.2(\ln 2l + \tfrac{1}{2})] \sum_{l=1}^{8n} I_t \tag{A4}$$

where the M'_{kt} are the expressions in (A1) and (A2) with the (A3) term excluded. But the last term is zero because

$$\sum_{l=1}^{8n} I_t \equiv 0.$$

That is, the total current in the outer conductors is equal and opposite to the total current in the inner conductors. Therefore, the M_k in (8) may be calculated from (A1) and (A2) with the (A3) term excluded.

APPENDIX B

PROGRAM FOR CALCULATION OF APPROXIMATE CURRENT DISTRIBUTION, INDUCTANCE, AND IMPEDANCE OF MICROSTRIP

```
      PROGRAM STRIPZM(TAPE2=65,INPUT=65,OUTPUT=65/140,TAPE6=
     COUTPUT)
C THIS PROGRAM USES THE METHOD PRESENTED IN INDUCTANCE AND CHARACTERISTI
C IMPEDANCE OF A STRIP TRANSMISSION LINE, R.L. BROOKE ET AL, JOURNAL OF
C RESEARCH OF THE NATIONAL BUREAU OF STANDARDS- C.ENGINEERING AND
C INSTRUMENTATION   VOL. 71C, NO1, JAN-MAR 1967
C
C MATRIX INVERSION AND LINEAR EQUATION SOLUTION SUBROUTINES ARE FOUND IN
C LIBRARY 3 OF THE INTERNATIONAL MATHEMATICAL AND STATISTICAL LIBRARIES
C FIFTH EDITION, NOVEMBER 1975. IDGT=0 WILL PERFORM ITERATIVE IMPROVEMEN
C T OF THE SOLUTION AND REPORT THE NUMBER OF DIGETS UNCHANGED AFTER
C IMPROVEMENT.  IF IDGT NOT ZERO ON INPUT, IMPROVEMENT, IF REQUIRED, IS
C ATTEMPTED TO IDGT DIGETS.
C THE PLOT SUBROUTINES ARE MACHINE SPECIFIC AT MERADCOM AND NOT INCLUDED
C
C THE FUNCTION INA PERMITS SPECIFICATION OF ANY (I,J) ELEMENT IN ANY (K)
C SPECIFIED  (N*M)**2 ARRAY OR N*M VECTOR, WHERE M MAY BE 1,2,4,8,12,16.
C
C STORAGE IS IN BLANK COMMON,  ARRAY A(ICORE)  WITH THE SQUARE ARRAYS
C FIRST. THEN THE VECTORS.
C
C THE NUMBER OF EACH ARRAY TYPE DEFINED IS STORED IN NA(IM) AND NV(IM)
C WHERE IM=1,6  (SPECIFING THE M IN ORDER GIVEN ABOVE)
C
C
      COMPLEX RPJWL,GPJWC,ZCOMP,GAM
      COMMON //A(27826)
      COMMON /STOR/N,MAXN,ICORE,NV(6),NA(6),MM(6)
      EXTERNAL INA,INV
C
C THE ASSIGNMENT OF SPACE FOR ARRAYS IS MADE THROUGH THE VECTOR ISA AND
C IS AS FOLLOWS
C ISA IS A VECTOR SPECIFING THE MATRIX NUMBER FOR VARIABLES AS FOLLOWS:
C
C M  MUTUAL INDUCTANCE MATRIX IS       INA(2,ISA(1)
C PHI MATRIX                           INA(2,ISA(2)
C PSI(INVERTED) MATRIX                 INA(2,ISA(3)
C PSI MATRIX                           INA(2,ISA(4)
C WORK AREA MATRIX                     INA(2,ISA(5)
C***********************************************************
C THE WORK AREA EXTENDS 6*N BEYOND INA(2,ISA(5),N2,N2) AND IS PROVIDED
C BY 3  2*N  VECTORS DEFINED BELOW, IF N VECTORS ARE DEFINED
C ELSEWHERE, THEY WILL BE WRITTEN OVER, THE AREA MAY BE USED
C FOR VOLATILE STORAGE.
C
C TWO 2*N WORK AREA VECTORS
C THE THIRD 2*N AREA IS USED FOR 1/R  INV(2,ISA(6)
C
C A VECTOR                             INV(2,ISA(7)
C B VECTOR                             INV(2,ISA(8)
C C VECTOR                             INV(2,ISA(9)
C
      DIMENSION ISA(9)
      COMMON /STRIPS/FREQ,SEP,W(2),EW(2),THK,SKDPS,ETHK
     C,RHO,EDC,POW,IDGT,IER,PI2
      DATA N/2/
      DATA ICORE/27826/
```

```
      DATA NA/0,5,4*0/
      DATA NV/0,6,4*0/
      DATA MM/1,2,4,8,12,16/
      DATA IU,IUPR/2*6/
      DATA COND/0./
C
      DATA ISA/1,2,3,4,5,3,4,5,6/
      CALL CONNEC(5LINPUT)
      CALL CONNEC(6LOUTPUT)
      PRINT  ,'ENTER I FOR INSTRUCTIONS, DI FOR DEFAULT VALUES '
      IR=3
      CALL ISETN(N)
      GOTO 3
2     IR=0
3     CALL IO(IR)
C RETURNS AFTER VARIABLES ARE READ AND A COMMAND INPUT PROVIDED IN
C SUBROUTINE IO.  VARIABLE IR IS RETURNED TO CONTROL THE EXECUTION
C REQUIRED.
      GO TO(100,101,102,103,104,105,106),IR+1
C NO CHANGE ,REPEAT BASIC OUTPUT
100   GOTO 1001
C DO ONLY LOCAL CALCULATIONS
101   GOTO 1002
C DO CURRENTS BUT SKIP MUTUAL
102   ISK=1
      GOTO 1003
C DO CURRENTS
103   ISK=0
1003  TIN=SECOND(CP)
      CALL CURR(N,ISA,SUMA,SUMB,ISK)
      TREQ=SECOND(CP)-TIN
      PRINT 910,TREQ
      NPM=TIMEL(TL)/TREQ
      IF(NRM.LE.8)PRINT 911,TL,NRM
911   FORMAT(* YOU HAVE *,F8.3,* CPU SECONDS LEFT*/
     C * ABOUT ENOUGH TIME FOR *,I3,* MORE RUNS LIKE THIS */)
910   FORMAT(* THIS RUN REQUIRED *,F6.2,* SECONDS*/)
      GOTO 1002
C
C PRINT CURRENTS
105   LOCC=INV(2,ISA(9),1,1)-1
      LOC=INV(2,ISA(7),1,1)-1
      LOC2=INV(2,ISA(8),1,1)-1
      WRITE(IU,900)(A(LOC+I),A(LOC2+I),A(LOCC+I),A(LOC+N+I),
     CA(LOC2+I+N),A(LOCC+I+N),I=1,N)
900   FORMAT(T30,*CURRENTS*/T10*LOWER TAPE*,T40,
     C*UPPER TAPE*/T3,*REAL*,T15,*-J (IMAG)*,T27,*MAGNITUDE*,
     C,T39,*REAL*,T51,*-J (IMAG)*,T63,*MAGNITUDE*/
     C4(6(1X,1PE11.4)/))
      IF(IU-IUPR)1002,2
C
C DO SOME TRIVIAL CALCULATIONS
C
1002  CONTINUE
      WF=PI2*FREQ
      SAB=SUMA*SUMA+SUMB*SUMB
      CLEFF=SUMB/(WF*SAB)
```

```
      REFF=SUMA/(SAB)
      VELC=2.997925E8/SQRT(EDC)
      CCEFF=1./(CLEFF*VELC**2)
      COND=WF*CCEFF*POW
      ZIMP=VELC*CLEFF
1001  WRITE(IU,960)CLEFF,REFF,ZIMP,CCEFF,COND
960   FORMAT(* EFFECTIVE INDUCTANCE= *,1PG11.4,* HENERYS/M*/
     C* EFFECTIVE RESISTANCE= *,1PG11.4,* OHMS/M*/
     C* CHARACTERISTIC IMPEDANCE= *,1PG11.4,* OHMS*/
     C* EFFECTIVE CAPACITANCE= *,1PG11.4,* FARADS/M*/
     C* SHUNT CONDUCTANCE= *,1PG11.4,* MHOS/M*/
     C)
      RPJWL=CMPLX(REFF,WF*CLEFF)
      GPJWC=CMPLX(COND,WF*CCEFF)
C     PRINT*,'WF,REFF,CLEFF,RPJWL,GPJWC- ',WF,REFF,CLEFF,RPJWL,GPJWC
C     PRINT *,'WF,VELC,CLEFF,WF/(CLEFF*VELC**2)',WF,VELC,CLEFF,WF/(CLEFF
C    C*VELC**2)
      ZCOMP=CSQRT(RPJWL/GPJWC)
      GAM=CSQRT(RPJWL*GPJWC)
      WRITE(IU,972)ZCOMP,GAM,8.686*REAL(GAM),360.*AIMAG(GAM)/PI2
972   FORMAT(* COMPLEX IMPEDANCE= *,1PG13.4,10H OHMS     J,1PG13.4,
     C5H OHMS/* PROPAGATION CONSTANT= *,1PG13.4,10H NEPERS/M    ,1PG13.4,
     C,10H RADIANS/M     /
     CT24,1PG13.4,10H DB/M           ,1PG13.4,10H DEGREES/M    /
     C)
      IF(IU-IUPR)1061,2
C
C PLOT CURRENTS
104   CALL PLOTI(A(INV(2,ISA(9),1,1)),A(INA(2,2,1,1)),2*N,W)
      GOTO 2
C
C SAVE ON TAPE2
106   IU=2
      GOTO 1001
1061  GOTO 105
1062  ENDFILE 2
      IU=IUPR
      IR=0
      GOTO 2
      END
```

```
      SUBROUTINE IO(IR)
C
C RETURN CODES AS FOLLOWS
C  IR=0 NO  CHANGE
C     1 ONLY MAIN PROG CALCS NECESSARY
C     2 CURRENT NECESSARY, BUT NOT MUTUALS
C     3 COMPLETE CALCULATION NECESSARY
C     4 PLOT CURRENTS
C     5 PRINT CURRENTS
C
      EQUIVALENCE (FREQ,V(1))
      COMMON /STRIPS/FREQ,SEP,W(2),EW(2),THK,SKDPS,ETHK,RHO
     C,EDC,POW,IDGT,IER,PI2
      COMMON /STOR/N,IDUM(20)
C
      DIMENSION WIN(2)
      DIMENSION Q(21),KW(21),UN(21),V(12)
C
      DATA NE/12/
      DATA Q/10HELEMENTS      ,10HFREQUENCY  ,10HSEPARATION  ,6HWIDTH1,
     C6HWIDTH2,10HELE.WIDTH1,10HELE.WIDTH2,10HTHICKNESS   ,10HSKIN DPTHS
     C,10HEFF.THICKS,3HRHO,10HDIE.CCNS   ,
     C10HPOWER FACT ,10HRESOLUTION ,2HGO,4HPLOT,
     C5HPRINT,4HSTOP,10HDISPLAY    ,10HINSTRUCT   ,10HSAVE TAPE2  /
      DATA KW/1HN,2HFR,2HSE,2HWI,2HWI,1H ,1H ,2HTH,2HSK,1H ,2HRH,2HED,2H
     CPO,2HID,2HGO,2HPL,2HPR,2HST,2HDI,1HI,2HSA/
      DATA UN/1H ,2HHZ,6*(6HMETERS),1H ,6HMETERS,10HOHMS*METER
     C,10HRELATIVE    ,5H(SIN),6HDIGETS,7*(1H )/
      DATA V/100.,.01,.01,.01,0.,0.,.00025,1.,0.,
     C1.7241E-08,1.,0./
      DATA IDGT,IER,PI2/0,0,6.283185308/
      DATA IP/0/
C
5     PRINT *,'ENTER KEYWORD  '
      READ 901,IA
901   FORMAT(A2)
      L=NE+9
      DO 10 I=1,L
      IF(IA.EQ.KW(I))GOTO 15
10    CONTINUE
      GOTO 5
15    IF(I.EQ.6)GOTO 5
      IF(I.EQ.1)GOTO 28
      IF(I.GT.1+NE)GOTO 25
      IF(I.EQ.4)GOTO 20
      PRINT *,'ENTER VALUE '
      READ *,V(I-1)
      IF(I.EQ.3)IR=3
      IF(I.LT.12)GOTO 17
      IF(IR.LE.1)IR=1
      GOTO 5
17    IF(IR.LE.2)IR=2
      GOTO 5
C
20    PRINT *,'ENTER BOTH STRIP WIDTHS
      READ *,WIN
      W(1)=AMAX1(WIN(1),WIN(2))
```

```
      W(2)=AMIN1(WIN(1),WIN(2))
      IR=3
      GOTO 5
C
C
25    I=I-NE-1
      GOTO(25,30,40,50,60,60,70,95),I
C IDGT IS AN INTEGER
25    PRINT *,'ENTER DIGETS OF RESOLUTION DESIRED
      READ *,IDGT
      GOTO 5
28    PRINT  ,'ENTER N
      READ *,N
      CALL ISETN(N)
      IR=3
      GOTO 5
C GO
30    RETURN
C
C PLOT REQUEST
40    IF(IR.NE.0)GOTO 90
      IR=4
      RETURN
C PRINT REQUEST
50    IF(IR.NE.0)GOTO 90
      IR=5
      RETURN
60    STOP
70    IF(IP)72,71
71    PRINT 900
900   FORMAT(' THE IMPEDANCE OF TWO THIN PARALLEL STRIPS CENTERED WITH R
     CESPECT'/' TO THEIR MIDLINE IS CALCULATED.'/
     C' ENTER PARAMETER OR FUNCTION KEYWORD FROM BELOW LIST TO OPERATE,
     C'/' (USUALLY THE FIRST TWO CHAR OF DESCRIPTION)'/
     C' NO KEYWORD INDICATES AN OUTPUT VARIABLE'/
     C' RESOLUTION IS OPTIMIZED WHEN IDGT=0, MAY BE REDUCED TO IDGT'/
     C' DIGETS IF IDGT IS NON-ZERO....'/
     C' DISPLAY WILL PRESENT CURRENT VALUES '/
     C)
      IP=1
72    PRINT 950,(Q(I),KW(I),UN(I),I=1,L)
950   FORMAT(' DESCRIPTION KEYWORD ,T22,'UNITS'/25(1X,A10,T15,A5,T22,A10
     C/))
      GOTO 5
80    PRINT 951,Q(1),FLOAT(N),1H ,(Q(I+1),V(I),UN(I+1),I=1,NE),Q(NE+2),
     CFLOAT(IDGT),1H
951   FORMAT(' VARIABLE',T12,'VALUE ,/15(1X,A10,1H=,1PG11.4,2X,A10/))
      GOTO 5
90    PRINT *,'NO OUTPUT WITHOUT A GO !!'
      GOTO 5
C SAVE REQUEST
95    IF(IR.NE.0)GOTO 90
      WRITE(2,960)
960   FORMAT(1H1)
      WRITE(2,951)Q(1),FLOAT(N),1H ,(Q(I+1),V(I),UN(I+1),I=1,NE),Q(NE+2)
     C,FLOAT(IDGT),1H
      IR=6
```

```
      RETURN
      END
```

```
      SUBROUTINE CURR(N,ISA,SUMA,SUMB,ISK)
C CURRENT IN ELEMENTRY STRIPS FOR THE HALF PLANE SYMMETRY CASE
C ARE CALCULATED.  ARRAY ALLOCATIONS ARE MADE HERE FOR BLANK COMMON
C IN THE MANNER DESCRIBED IN FUNCTION INA,  OTHER SUBROUTINES
C REQUIRING SPACE MUST OBSERVE THE NOTES BELOW.
C ISA IS A VECTOR SPECIFING THE MATRIX NUMBER FOR VARIABLES AS FOLLOWS:
C
C M  MUTUAL INDUCTANCE MATRIX IS      INA(2,ISA(1)
C PHI MATRIX                          INA(2,ISA(2)
C PSI(INVERTED) MATRIX                INA(2,ISA(3)
C PSI MATRIX                          INA(2,ISA(4)
C WORK AREA MATRIX                    INA(2,ISA(5)
C*********************************************************
C THE WORK AREA EXTENDS 6*N BEYOND INA(2,ISA(5),N2,N2) AND IS PROVIDED
C BY 3  2*N  VECTORS DEFINED BELOW, IF N VECTORS ARE DEFINED
C ELSEWHERE, THEY WILL BE WRITTEN OVER, THE AREA MAY BE USED
C FOR VOLATILE STORAGE.
C
C TWO 2*N WORK AREA VECTORS
C THE THIRD 2*N AREA IS USED FOR 1/R  INV(2,ISA(6)
C
C A VECTOR                            INV(2,ISA(7)
C B VECTOR                            INV(2,ISA(8)
C CVECTOR                             INV(2,ISA(9)
C
      EXTERNAL INA,SZIND
      DOUBLE PRECISION SPSI,SPSIPH,SPSIR,SPSIPHR,DENOM
C
      COMMON //A(1)
C
      COMMON /STRIPS/FREQ,SEP,W(2),EW(2),THK,SKDPS,ETHK
     C,RHO,EDC,POW,IDGT,IER,PI2
C
C
      DIMENSION RESDC(2),NDIA(4)
      DIMENSION ISA(9)
C
C THIS VECTOR DESCRIBES THE ATTRIBUTES OF MATRICIES FOR THE IMSL
C DIAGONAL MATRIX TIMES A FULL MATRIX FUNCTION.
      DATA NDIA/4*0/
C
C
C     PRINT *,'*CURR'
C SET MATRIX LENGTH
      NDIA(1)=NDIA(2)=N2=2*N
C FILL THE MUTUAL INDUCTANCE MATRIX
      TREF=SECOND(CP)
      IF(ISK.EQ.1)GOTO 7
      CALL MUT(A(INA(2,ISA(1),1,1)),A(INA(2,ISA(2),1,1)),N2,2*N2,SZIND)
7     CONTINUE
      TMUT=SECOND(CP)-TREF
      IF(ISK.EQ.0)PRINT 900,6HMUTUAL,TMUT
900   FORMAT(1X,A8,* SOLUTION TIME= *,F6.2,* SECONDS*/)
C
C COMPUTE PHI=W*M/R
C
C STUFF A BAND ARRAY WITH 1/R USING THE SMALLER OF THE TAPE
```

```
C THICKNESS OR A MULTIPLE OF SKIN DEPTH.
      WF=PI2*FREQ
C MODIFY UR (RELATIVE PERMEABILITY) IF THE CONDUCTOR IS MAGNETIC MATERIA
      UR=1.
      SKDP=SQRT(RHO/(FREQ*1.E-07*UR))/PI2
      ETHK=AMIN1(THK,SKDPS*SKDP)
      IF(ETHK.NE.THK)PRINT *,'EFFECTIVE TAPE THICKNESS ADJUSTED
      DO 10 I=1,2
10    RESDC(I)=RHO/(EW(I)*ETHK)
C
      LOC=INV(2,ISA(6),1,1)-1
      LOC2=LOC+N
      RINV=1./RESDC(1)
      RINV2=1./RESDC(2)
      DO 12 I=1,N
      A(LOC+I)=RINV
12    A(LOC2+I)=RINV2
C     PRINT *,'*IND IN'
C     CALL MATP(A(INA(2,ISA(1),1,1)),N2)
C
C     PRINT *,'*1/R ',(A(LOC+I),I=1,N2)
C
C COMPUTE PHI     DO W*M FIRST
      CALL SMULM(A(INA(2,ISA(1),1,1)),A(INA(2,ISA(4),1,1)),N2,WF)
C
C
C PHI =W*M/R
      CALL VMULFB(A(INA(2,ISA(4),1,1)),N2,A(LOC+1),N2,NDIA,A(INA(2,ISA(2
     C),1,1)),N2)
C     PRINT *,'*PHI ='
C     CALL MATP(A(INA(2,ISA(2),1,1)),N2)
C
C COMPUTE PSI(INVERTED)
C NOW DO (W*M/R)*W*M
      CALL VMULFF(A(INA(2,ISA(2),1,1)),A(INA(2,ISA(4),1,1)),N2,N2,N2,N2,
     CN2,A(INA(2,ISA(3),1,1)),N2,IER)
      IF(IER.NE.0)PRINT *,'ERROR IN PSI(INV) MULTIPLICATION, IER= ',
     CMOD(IER,32)
C
C
C     PRINT *,'  PHI W*M '
C     CALL MATP(A(INA(2,ISA(3),1,1)),N2)
C ADD R
      LOC=INA(2,ISA(3),1,1)-1
      LOC2=INA(2,ISA(3),N+1,N+1)-1
      DO 20 I=1,N
      J=I+(I-1)*N2
      A(LOC+J)=A(LOC+J)+RESDC(1)
20    A(LOC2+J)=A(LOC2+J)+RESDC(2)
C     PRINT *,'*PSI(INVERTED)= '
C     CALL MATP(A(LOC+1),N2)
C
C INVERT THIS TO OBTAIN PSI, THIS DESTROYS THE 1/R VECTOR
C AS THE EXTENDED WORK AREA IS USED.
      IDGT2=IDGT
      CALL LINV2F(A(INA(2,ISA(3),1,1)),N2,N2,A(INA(2,ISA(4),1,1)),IDGT2,
     CA(INA(2,ISA(5),1,1)),IER)
```

```
      IF(IER.NE.0)PRINT  ,'ERROR IN INVERTING PSI(INV), IER= ',
     CMOD(IER,32)
      PRINT *,'*IDGT IN INVERTING PSI= ',IDGT2
C     PRINT *,'*PSI '
C     CALL MATP(A(INA(2,ISA(4),1,1)),N2)
C
C NOW DO PSI*PHI INTO WORK AREA
      CALL VMULFF(A(INA(2,ISA(4),1,1)),A(INA(2,ISA(2),1,1)),N2,N2,N2,N2,
     CN2,A(INA(2,ISA(5),1,1)),N2,IER)
      IF(IER.NE.0)PRINT *,'ERROR IN PSI*PHI, IER= ',MOD(IER,32)
C     PRINT *,'*PSI*PHI= '
C     CALL MATP(A(INA(2,ISA(5),1,1)),N2)
C
C
C PERFORM SUMS OF MATRIX ELEMENTS FOR E AND F SOLUTIONS
C
C SUM PSI
      CALL SUMALL(A(INA(2,ISA(4),1,1)),N2,SPSI)
C SUM PSI*PHI
      CALL SUMALL(A(INA(2,ISA(5),1,1)),N2,SPSIPH)
C SUM THE RIGHT SIDE OF PSI
      CALL SUMRT(A(INA(2,ISA(4),1,1)),N2,SPSIR)
C SUM RIGHT SIDE OF OF PSI*PHI
      CALL SUMRT(A(INA(2,ISA(5),1,1)),N2,SPSIPHR)
C
C
      DENOM=SPSI**2+SPSIPH**2
      E=-(SPSI*(-SPSIR)+SPSIPH*(-SPSIPHR))/DENOM
      F=(SPSIR-E*SPSI)/SPSIPH
      PRINT  ,'VOLTAGE DROP IN BOTTOM (WIDE) TAPE= ',E,F
C
C     PRINT *,'*E1= ',2.*SPSI
C     PRINT *,'*E2= ',2.*SPSIR
C     PRINT *,'*E3= ',2.*SPSIPH
C     PRINT  ,'*E4= ',2.*SPSIPHR
      TEAF=SECOND(CP)-TREF-THUT
      PRINT 900,7HVOLTAGE,TEAF
C
C SET UP SOLUTIONS FOR A AND B IN THE FORM OF IMSL(AX=B) OR
C PSI(INV)*A=(E+PHI*F)
C PUT RIGHT SIDE IN SOLUTION VECTOR
      CALL VMULM(A(INA(2,ISA(2),1,1)),F,N2,A(INV(2,ISA(7),1,1)))
      LOC=INV(2,ISA(7),1,1)-1
      LOC2=LOC+N
      DO 30 I=1,N
      A(LOC+I)=A(LOC+I)+E
30    A(LOC2+I)=A(LOC2+I)+E-1.
C
C
C DO SOLUTION
      IDGT2=IDGT
      CALL LEQT2F(A(INA(2,ISA(3),1,1)),1,N2,N2,A(LOC+1),IDGT2,A(INA(2,IS
     CA(5),1,1)),IER)
C     PRINT  ,'* A SOL = ',(A(LOC+I),I=1,N2)
      IF(IER.NE.0)PRINT *,'ERROR IN A SOLUTION, IER= ',MOD(IER,32)
      PRINT *,'*IDGT IN A SOLUTION= ',IDGT2
C
```

```
C NOW DO FOR B
C PSI(INV)*B=(PHI*E-F)
C      CALL MATP(A(INA(2,ISA(2),1,1)),N2)
       CALL VMULMP(A(INA(2,ISA(2),1,1)),E,N2,A(INV(2,ISA(8),1,1)))
       LOCB=INV(2,ISA(8),1,1)-1
       DO 40 I=1,N2
40     A(LOCB+I)=A(LOCB+I)-F
       IDGT2=IDGT
       CALL LEQT2F(A(INA(2,ISA(3),1,1)),1,N2,N2,A(LOCB+1),IDGT2,A(INA(2,
      CSA(5),1,1)),IER)
C      PRINT *,'*B SOL= ',(A(LOCB+I),I=1,N2)
       IF(IER.NE.0)PRINT *,'ERROR IN B SOLUTION, IER= ',MOD(IER,32)
       PRINT  ,'*IDGT IN B SOLUTION= ',IDGT2
       TSOLI=SECOND(CP)-TREF-TEAF-TMUT
       PRINT 900,7HCURRENT,TSOLI
C SUM REAL AND QUADRATURE CURRENTS
C A = REAL, B= QUADRATURE CURRENT,  C= MAGNITUDE
       LOCC=INV(2,ISA(9),1,1)-1
       LOCC2=LOCC+N
       SUMA=SUMB=0.
       SUMA2=SUMB2=0
       DO 50 I=1,N
       SUMA=SUMA+A(LOC+I)
       A(LOCC+I)=A(LOC+I)*A(LOC+I)+A(LOCB+I)*A(LOCB+I)
       A(LOCC2+I)=A(LOC+I+N)*A(LOC+I+N)+A(LOCB+I+N)*A(LOCB+I+N)
       SUMA2=SUMA2+A(LOC+I+N)
       SUMB2=SUMB2+A(LOCB+I+N)
50     SUMB=SUMB+A(LOCB+I)
       SMAG1=SQRT(SUMA**2+SUMB**2)
       SMAG2=SQRT(SUMA2**2+SUMB2**2)
       SUMA=2.*SUMA
       SUMB=2.*SUMB
       DO 52 I=1,N
       A(LOCC+I)=SQRT(A(LOCC+I))
52     A(LOCC+I+N)=SQRT(A(LOCC+I+N))
       PRINT *,'*DIFFERENCE IN CURRENTS= ',ABS(SMAG1-SMAG2)/(SMAG1+SMAG2
      C*200.,' PERCENT'
C      PRINT *,'*SUMA=',SUMA,'      SUMB=',SUMB
       RETURN
       END
```

```
      SUBROUTINE VMULM(A,V,N,O)
C SPECIAL PURPOSE SQUARE MATRIX TIMES A VECTOR WHOSE ELEMENTS
C ARE IDENTICAL
      DOUBLE PRECISION S1,S2
      DIMENSION A(N,N),O(N)
      DO 200 I=1,N
      S1=0.
      DO 100 J=1,N
100   S1=S1+A(I,J)
200   O(I)=S1*V
      RETURN
      ENTRY VMULMP
C SUBTRACT ONE FROM THE LAST N/2 VECTOR ELEMENTS AND MULTIPLY AS ABOVE
      ND2=N/2
      DO 160 I=1,N
      S1=S2=0.
      DO 150 J=1,ND2
      S1=S1+A(I,J)
150   S2=S2+A(I,J+ND2)
160   O(I)=V*(S1+S2)-S2
      RETURN
      END
```

```
      SUBROUTINE SMULM(A,B,N,S)
C SPECIAL PURPOSE SQUARE MATRIX TIMES A SCALER
      DIMENSION A(N,N),B(N,N)
      DO 100 J=1,N
      DO 100 I=1,N
100   B(I,J)=A(I,J)*S
      RETURN
C
      END
```

```
      SUBROUTINE SUMALL(A,N,S)
      DOUBLE PRECISION S,SUM
      DIMENSION A(N,N)
C SUM ALL ELEMENTS OF A SQUARE MATRIX
      JS=1
199   SUM=0.
      DO 200 J=JS,N
      DO 200I=1,N
200   SUM=SUM+A(I,J)
      S=SUM
      RETURN
C
C SUM ALL ELEMENTS IN THE RIGHT SIDE OF SQUARE MATRIX
      ENTRY SUMRT
      JS=N/2+1
      GOTO 199
      END
```

```
      FUNCTION SZIND(PP,EP,EWP,IER)
C THIS FUNCTION RETURN THE MUTUAL INDUCTANCE FOR THIN STRIPS OF WIDTH
C EWP  METERS SEPARATED BY PP, AND DISPLACED BY EP USING THE METHOD OF
C BROOKE .. ET AL IN 'INDUCTANCE AND CHARACTERISTIC IMPEDANCE...'
C 25 OCTOBER 1966, (APPENDIX)   WITH THE LENGTH TERM REMOVED.
C OUTPUT IS IN UNITS OF  MICRO-HENERYS PER METER, THEN *1.E-06
C LIMITS ON CALCULATION ARE PROVIDED WITH AN ERROR FLAG, IER, TO
C INSURE THE INTEGRITY OF THE ANSWER, CONSISTENT WITH THE CDC
C 6600 COMPUTER. (29 SIGNIFICANT DIGETS IN THE CALCULATION)
C
      DOUBLE PRECISION A1,B1,C,D,P,E,EW,DEL
      DIMENSION EWP(2)
      DATA STD/1.E11/
C
C
      TST=SQRT(PP**2+EP**2)/ABS(EWP)
      IF(TST.LE.STD)GOTO 4
      IF(IER.EQ.0)PRINT 951,EWP,PP,EP,TST,STD
951   FORMAT(*  ERROR IN MUTUAL INDUCTANCE CALCULATION*/T10,
     C A WIDTH OF*,G10.4,* METERS AT SPACING OF*,2(1X,G10.4,1H,),
     C/T10,*YIELDS A SPACE TO WIDTH RATIO OF*,G10.4,* EXCEEDING THE *,
     C*ALLOWABLE OF*,G10.4/)
C
      IER=IER+1
      RETURN
4     CONTINUE
      P=PP
      E=EP
      EW=EWP(1)
      DEL=EWP(1)-EWP(2)
      A1=B1=C=D=0.0
      IF(PP.EQ.0..AND.EP.EQ.0.)GOTO 910
      IF(PP.EQ. 0.0) GO TO 900
      A1=P ((EW-E) DATAN2((E-EW),P)+(E-DEL)*DATAN2((E-DEL),P)+
     CE*DATAN2(E,P)-(E+EWP(2))*DATAN2((E+EWP(2)),P))
      GO TO 901
 900  CONTINUE
      IF(E.EQ.EW)GOTO 902
 901  B1=(P*P-(E-EW)**2)*DLOG(P*P+(E-EW)**2)/4.
 902  CONTINUE
      C=(E*E-P*P)*DLOG(P*P+E*E)/4.
     C+((E-DEL)*(E-DEL)-P*P)*DLOG(P*P+(E-DEL)*(E-DEL))/4.
 903  CONTINUE
      D=(P*P-(E+EWP(2))**2)*DLOG(P*P+(E+EWP(2))**2)/4.
      ANS=(A1+B1+C+D)*0.2/(EW*EWP(2))
      GOTO 50
910   ANS=0.2*DLOG(1./EW)
C
C     PRINT *,'*SELF'
C CHANGE TO UNITS OF HENERYS
C
50    SZIND=ANS*1.E-06
C     PRINT *,'P,E,EW,ANS ',P,E,EW,ANS
C     PRINT *,'A1,B1,C,D ',A1,B1,C,D
      RETURN
      END
```

```
      SUBROUTINE MOX(I,J,II,JJ)
C CONVERTS A REFERENCE (I,J) TO ELEMENT NUMBERED PER BROOKE ET AL,
C TO EQUIVALANCE ASSUMING HALF PLANE SYMMETRY.  CONSEQUENTLY,
C 2*(N**2+2) MUTUAL CALCULATIONS ARE REQUIRED, RATHER THAN 16*N**2
C
C
      COMMON /STOR/N,MAXN,ICCRE,NV(6),NA(6),MM(6)
C
C THIS FUNCTION WILL TEST 0 IF LOWER TAPE, 1 IF UPPER
      ITOP(K)=(MOD(K-1,2*N))/N
C
C PUT SMALLER IN II
      II=MIN0(I,J)
      JJ=MAX0(I,J)
C LOCATION FLAG FOR I
      IT=ITOP(II)
      JT=ITOP(JJ)
C THIS FLAG WILL TEST + IF  JJ TOP AND II BOTTOM, - IF II TOP,JJ BOTTOM.
      IOP=JT-IT
C
C SET THIS MULTIPLIER TO 2 IF BOTH ARE TOP, 1 OTHERWISE.
      IM=IT*JT+1
C
      IF(IOP)5,10,10
C I TOP, J BOTTOM
5     JTEM=JJ
      JJ=II+2*N
      II=JTEM-2*N
      RETURN
C TEST IF II IN LEFT HALF PLANE
10    IF(II-IM*N)15,15,17
C LEFT
15    IF(IOP)21,21,16
C LEFT, II BOT, JJ TOP
16    RETURN
C BOTH IN RIGHT HALF, PUT IN LEFT
17    II=II-2*N
      JJ=JJ-2*N
      GOTO 15
C BOTH ARE TOP OR BOTTOM
21    ID=II-IT*N-1
      II=II-ID
      IF(JJ.GT.2*N)GOTO 25
      JJ=JJ-ID
      RETURN
25    JJ=JJ+ID
      IF(JJ.LE.N*(2+IM))RETURN
      JJ=IM*N+1-MOD(JJ,N*(2+IM))
      RETURN
      END
```

```
      SUBROUTINE MUT(AM,AW,N2,N4,FUN)
C
C STUFF A 2N*2N MATRIX WITH MUTUAL IMPEDANCE USING FUN,
C REPRESENTING A 4N*4N MATRIX WITH HALF PLANE SYMMETRY, THE
C LOWER HALF IS IGNORED AND THE UPPER HALF FOLDED.
      EXTERNAL FUN
C
C FUN IS THE IMPEDANCE CALCULATION, EW(2) CONTAINS THE INCREMENTAL
C STRIP WIDTHS FOR LOWER (THE WIDER) AND UPPER TAPE RESPECTIVELY.
C
      DIMENSION AM(N2,N2),AW(N4,1)
      DIMENSION EWB(2),EWT(2)
C
C AW IS A WORKING SPACE, MUST BE (2N)**2+4N LONG,  MAY BE SUPPLIED
C BY A 2N*2N ARRAY, BUT CAUTION THAT THE NEXT 4N LOCATIONS WILL
C BE USED.    ************************************************
C*************************************************
C NOTE THAT STORAGE IN AW IS ROW AND COLUMN REVERSED
C
      COMMON /STRIPS/FREQ,SEP,W(2),EW(2),THK,SKDPS,ETHK
     C,RHO,EDC,POW,IDGT,IER,PI2
C     PRINT *,'*MUT'
C
C RESET ERROR COUNTER IN FUNCTION FUN  (MUTUAL INDUCTANCE SUBROUTINE)
      IER=0
C COMPUTE ELEMENTARY STRIP WIDTHS
      DO 1 I=1,2
1     EW(I)=W(I)/N2
C
C LOAD E WIDTHS PAIRS FOR FUN CALLS
      DO 2 I=1,2
      EWB(I)=EW(1)
2     EWT(I)=EW(2)
C
C
C
      N=N2/2
      N3=N2+N
C
C OFFSET OF TOP SHORT TAPE FROM ORIGIN
      E1=(W(1)-W(2))/2
C OFFSET OF RIGHT EDGE OF TOP TAPE FROM ORIGIN
      E2=E1+W(2)
C
C STUFF THE AW MATRIX
C     PRINT *,'*AW ELEMENTS ',4*(N**2+N)
      DO 10 J=1,N
      AW(J,1)=FUN(0,EW(1)*(J-1),EWB,IER)
      AW(J+N,1)=FUN(SEP,E1+EW(2)*(J-1),EW,IER)
      AW(J+N2,1)=FUN(0,W(1)-EW(1)*(J),EWB,IER)
      AW(J+N3,1)=FUN(SEP,E2-EW(2)*(J),EW,IER)
      AW(J+N,N+1)=FUN(0,EW(2)*(J-1),EWT,IER)
10    AW(J+N3,N+1)=FUN(0,EW(2)*(N2-J),EWT,IER)
C     PRINT *,'N#S=',N,N2,N3,N4,NP1
      DO 30 I=2,N
      E0=EW(1)*(I-1)
      DO 30 J=1,N
```

```
      AW(J+N,I)=FUN(SEP,ABS(E1+EW(2)*(J-1)-E0),EW,IER)
30    AW(J+N3,I)=FUN(SEP,E2-EW(2)*(J)-E0,EW,IER)
      NP1=N+1
C
C     PRINT *,'*AW PRINT LIMITS= ',N4,NP1,((AW(J,I),J=1,N4),I=1,NP1)
C     PRINT *,'AM'
C
C NOW STUFF AM
      DO 100 II=1,N2
      DO 100 JJ=1,N2
      CALL MDX(II,JJ,I,J)
      CALL MDX(II,N2+JJ,IA,JA)
100   AM(II,JJ)=AW(J,I)+AW(JA,IA)
C
C     PRINT *,((AM(I,J),J=1,N2),I=1,N2)
C     PRINT *,'*MUT DONE'
      IF(IER.EQ.0)RETURN
      PRINT 950,IER
950   FORMAT(* MUTUAL INDUCTANCE ERROR COUNT= *,I7)
      RETURN
      END
```

```
      FUNCTION INA(M,K,I,J)
C
C THIS FUNCTION PERMITS SPECIFICATION  OF ANY (I,J) ELEMENT IN ANY (K)
C SPECIFIED  (N*M)**2 ARRAY OR N*M VECTOR, WHERE M MAY BE 1,2,4,8,12,16.
C
C STORAGE IS IN BLANK COMMON,  ARRAY A(ICORE)  WITH THE SQUARE ARRAYS FI
C FIRST. THEN THE VECTORS.
C
C THE NUMBER OF EACH ARRAY TYPE DEFINED IS STORED IN NA(IM) AND NV(IM)
C WHERE IM=1,6  (SPECIFING THE M IN ORDER GIVEN ABOVE)
C
C
      COMMON //A(1)
      COMMON /STOR/N,MAXN,ICORE,NV(6),NA(6),MM(6)
      DIMENSION IENT(2)
C
      DATA IENT/6HVECTOR,5HARRAY/
C
C ENTRY FOR ARRAY INDEXING
      IT=2
      JJ=J-1
C SET INDEX OFFSET TO ARRAY NUMBERS
      NO=6
      IX=0
C
C
C SEE IF M VALID
3     DO 5 IM=1,6
      IF(M.EQ.MM(IM))GOTO 10
5     CONTINUE
7     PRINT *,'CALL TO INDEX ERROR, CALL= ',M,K,I,J
      PRINT *,IENT(IT),' ENTRY POINT'
      INA=1
      RETURN
C
C INDEX TO NO OF M ARRAYS OR VECTORS
10    CONTINUE
C GET ADDRESS OF FIRST M ARRAY -1
      IF(IM-1)12,30
12    L=IM-1
      DO 15 IM=1,L
15    IX=IX+NV(NO+IM)*(N*MM(IM))**IT
C
C CHECK FOR VALID K
30    IF(K.LE.0.OR.K.GT.NV(NO+IM))GOTO 7
C
C CHECK FOR VALID J
      IF(JJ.LT.0.OR.JJ.GT.N*M)GOTO 7
C
C CHECK FOR VALID I
      IF(I.LE.0.OR.I.GT.N*M)GOTO 7
C
C SET REQUEST INDEX
      INA=IX+(K-1)*(N*M)**IT+JJ*(N*M)+I
      RETURN
C
C ENTRY FOR VECTOR INDEX
```

```
      ENTRY INV
      IT=1
      JJ=NO=0
      IX=IN2
      GOTO 3
C
C
      ENTRY ISETN
      M=MAX0(M,2)
C THIS ENTRY COMPUTES A MAX N BASED UPON NA, NV  AND COMPARES
C THE N REQUESTED TO IT, SETS TO MAX IF MORE REQUESTED.
C
C SUM THE NUMBER OF N**2 SUBARRAYS
      NN2A=0
      DO 100 IM=1,6
100   NN2A=NN2A+NA(IM)*MM(IM)**2
C
C SUM THE NUMBER OF N VECTORS
      NNV=0
      DO 110 IM=1,6
110   NNV=NV(IM)*MM(IM)+NNV
C
C QUADRATIC SOLUTION FOR MAXN
      MAXN=(SQRT(NNV**2+4.*NN2A*ICORE)-NNV)/(2.*NN2A)
      IF(NN2A.EQ.0)MAXN=ICORE/NNV
115   IN2=NN2A*N**2
      IUSED=NN2A*N**2+NNV*N
      PRINT *,'N MAX= ',MAXN,'    UNUSED CORE= ',ICORE-IUSED
      IF(M.GT.MAXN)GOTO 200
      N=M
      INA=N
C NORMAL RETURN
      RETURN
C
C ERROR
200   ICN=NNV*N+NN2A*N*N
      N=MAXN
      INA=N
      PRINT *,' ERROR, REQUEST FOR SUBDIVISION TOO LARGE, SET TO ',MAXN
     C,'  CORE REQUIRED = ',ICN
      GOTO 115
      END
```

```
      SUBROUTINE MATP(A,N2)
      DIMENSION A(N2,N2)
      DIMENSION IFOR(2)
      DATA IFOR/1H ,10H1X,G10.4))/
C LIMIT PRINT WIDTH TO CARRIAGE SIZE
      NC=MIN0(13,N2)
      ENCODE(10,900,IFOR)NC
900   FORMAT(1H(,I8,1H()
      PRINT IFOR,((A(I,J),J=1,N2),I=1,N2)
      RETURN
      END
```

```
      SUBROUTINE PLOTI(A,P,N2,W)
C A CONTAINS BOTTOM TAPE CURRENT (MAGNITUDE) IN THE FIRST N LOCS,
C AND THE TOP TAPE IN THE LAST N, THE TOP TAPE IS SMALLER OR
C EQUAL TO THE TOP IN WIDTH.  OUTBOARD ELEMENT FIRST.
C W CONTAINS THE TAPE WIDTHS, LARGER FIRST
C
C
C AN ALLOWANCE FOR P SHOULD BE MADE,
C THE FOLLOWING METHOD USES, AS A MAX,FOUR N2**2 AND SIX N ARRAYS
C
C
      DIMENSION A(N2),P(1),SC(2),W(2)
      EQUIVALENCE (AMX,SC(1))
C THE FOLLOWING IS FOR THE PLOTTING ROUTINES
C
      COMMON /CKTBUF/IPP,MBUFF(1024)
      DATA IPP/1024/
C
      DATA SC(2)/0./
      DATA IP/0/
C
      IF(IP)2,1
1     IP=1
      PRINT 910
910   FORMAT(* PROGRAM PAUSES WITH CURSOR AFTER EACH PLOT, ENTER A CHAR
     CTO CONTINUE*/* AFTER THE SECOND PLOT, ENTRY OF THE FIRST LETTER OF
     C THE BELOW DESCRIPTION*/* WILL CAUSE THAT RESULT!*/
     CT5,*REPLOT BOTH TAPES*/T5,*FULL WIDTH SMALLER TAPE ^ REPLOT*/
     CT5,*PLOT SIZE CHANGE (TWO CURSOR INPUTS DEFINE FRAME SIZE)*/
     C)
2     N=N2/2
      ISPC=4*N2*N2+3*N2
      ISPC=MIN0(ISPC,199)
C FIND THE LARGEST VALUE FOR SCALING
      AMX=0.
      DO 10 I=1,N
10    AMX=AMAX1(AMX,ABS(A(I)))
C SCALE VERTICAL SCALE TO CURRENT DENSITY
      NP1=N+1
      DO 12 I=NP1,N2
12    AMX=AMAX1(AMX,ABS(A(I)*W(1)/W(2)))
C
C PLOT LOWER TAPE
15    DO 20 I=1,N
20    P(I)=P(N2+1-I)=A(I)
C
C SET SCALE
      CALL PLOTXY(SC,2,IR,4)
C
C
      CALL PLOTXY(P,N2,IR,1)
C
C
C ATTEMPT TO CENTER SMALL TAPE FOR MORE PLEASING DISPLAY AND EXPAND
C TO 100 TO 200 POINTS
      ADD=(N2-1)*(W(1)/W(2)-1.)
      M=1
```

```
      IF(ADD.NE.0.)M=(ISPC-1)/(N2-1+ADD)
      M=MAX0(1,M)
C CHECK TO SEE IF UPPER TAPE SHOULD BE ZERO FILLED
      IF(ADD+N2*M.GT.ISPC)GOTO 22
      IF(W(1)/W(2).LE.16)GOTO 30
22    CONTINUE
      ADD=0
      M=1
      IF(W(1)/W(2).NE.1.)PRINT 902
902   FORMAT(* TOP AND BOTTOM STRIPS PLOTTED TO DIFFERENT WIDTH SCALE *
     C)
C
C STUFF ZEROS IF REQUIRED
30    NA=(ADD/2.)*M
      NT=2 NA+M*(N2-1)+1
      DO 32 I=1,NA
32    P(I)=P(NT+1-I)=0.
C MOVE AND PLOT UPPER
35    NM1=N-1
      DO 40 I=1,NM1
      DO 40 J=1,M
40    P(NA+(I-1)*M+J)=P(NT+1-NA-(I-1)*M-J)=
     C(((A(N+I+1)-A(N+I))*FLOAT(J-1)/FLOAT(M)+A(N+I))*W(1)/W(2))
      M2=M+1
C     PRINT *,'*P IN ',(P(I),I=1,NT)
C
C FILL IN CENTER
      DO 42 I=1,M2
42    P(NA+(N-1)*M+I)=A(N2)*W(1)/W(2)
C     PRINT *,'P OUT= ',(P(I),I=1,NT)
C
43    CONTINUE
      CALL PLOTXY(P,NT,IR,1)
      IF(IR.EQ.1HR)GOTO 15
      IF(IR.EQ.1HP)GOTO 50
      IF(IR.EQ.1HF)GOTO 22
C
      RETURN
50    CALL PLOTXY(P,N2,IR,2)
      RETURN
      END
```

```
      FUNCTION TIMEL(TL)
      CALL CPUTIME(IST)
C     PRINT 900,IST,FLOAT(AND(.NOT.MASK(36),SHIFT(IST,-36))),FLOAT(AND(.
C    CNOT.MASK(46),SHIFT(IST,-12))),0.001*FLOAT(AND(.NOT.MASK(48),IST))
C900  FORMAT(1X,O20/* AVAILABLE, SEC NOW, MILE NOW*/1X,3F6.3)
      TIMEL=TL=FLOAT(AND(.NOT.MASK(36),SHIFT(IST,-36)))-(FLOAT(AND(.NOT.
     CMASK(46),SHIFT(IST,-12)))+0.001*FLOAT(AND(.NOT.MASK(48),IST)))
      RETURN
      END
```

```
                              IDENT CPUTIME
                              ENTRY CPUTIME
                              USE
                1    CPUTIME  BSSZ  1
7461.                         SX6   A1
     5160000011 +             SA6   ARGL
7160241115                    TIME  ST,RECALL
5120000010 +                  SA2   ST
          5110000011 +        SA1   ARGL
53111                         SA1   X1
     10622                    BX6   X2
          53611               SA6   X1
0400000003 +                  EQ    CPUTIME
                1    ST       BSSZ  1
                1    ARGL     BSSZ  1
                              END

      512308 CM  STORAGE USED          24 STATEMENTS       4 SYMBOLS
                 MODEL 74 ASSEMBLY    .075 SECONDS         1? REFERENCES
```

```
      SUBROUTINE PLOTXY(Y,NP,IR,IP)
C                                       PLOTXY
C       A PROGRAM TO PLOT A SIMPLE REAL VARIABLE IN A SINGLE PLANE
C INTENDED AS TOOL FOR ENGINEERING PROGRAM DEVELOPMENT.  IT REQUIRES A
C MINIMUM KNOWLEDGE OF THE GRAPHICS SYSTEM AT THE EXPENSE OF SOME
C NICE TO HAVE FEATURES, NOTEABLY LABELING, BUT IS EASY TO USE
C WITHOUT HAVING TO LEARN GRAPHICS.
C
C      THE PROGRAM CARD MUST BE MODIFIED TO INCLUDE GRAPHIC FILE
C DEFINITION AND THE FOLLOWING ADDITIONAL CARDS:
C      PROGRAM YOURS(TAPE11,TAPE12=97/970)
C      COMMON /CKTBUF/IPP,MBUFF(1024)/CKXBUF/MDUM(80)
C      DATA IPP/1024/
C
C
C           THE FORM OF THE CALL IS:
C
C      CALL PLOTXY(Y,NP,IR)
C
C      WHERE Y IS AN ARRAY OF NP ORDINATE VALUES TO BE PLOTTED.
C      THE ARRAY WILL BE AUTOMATICALLY SCALED TO FIT IN A DEFAULT SPACE
C PROVIDED ON THE SCREEN.  WHEN THE PLOT IS COMPLETE, THE CURSOR WILL
C APPEAR, PROVIDING A PAUSE.  ENTERING ANY CHARACTER WILL RETURN
C EXECUTION TO THE CALLING PROGRAM WITH THE CHARACTER ENTERED
C RETURNED IN IR.
C
C      THAT IS ALL REQUIRED TO OBTAIN A PLOT. A FEW ADDITIONAL FEATURES
C HAVE BEEN ADDED,BUT MAY BE IGNORED.  THESE FEATURES ARE ACCESSED WITH
C THE FOLLOWING CALLS:
C
C      CALL PLOTXY(Y,NP,IR,IP)
C
C      WHERE ALL PARAMETERS ARE AS BEFORE AND IP SPECIFIES:
C
C      0    IDENTICAL TO PREVIOUS CALL
C      1    PLOT Y, BUT USE THE SCALING CALCULATED BY THE PREVIOUS CALL.
C      2    SET THE PHYSICAL AREA ON THE SCREEN TO THE AREA OUTLINED BY
C           THE NEXT TWO CURSOR INPUTS.
C      3    SET THE PHYSICAL AREA TO THE DEFAULT AREA PROVIDED
C      4    SCALE THE DATA IN Y, BUT DO NOT PLOT.
C SET IP=       2    SET PLOT SIZE ON SCREEN
C               0    AUTO SCALE AND PLOT
C               1    PLOT TO OLD SCALE
C               3    SET DEFAULT SIZE
C               4    AUTO SCALE, NO PLOT
C
C
```

APPENDIX C

SAMPLE RUNS

SAMPLE COMPUTER RUNS

(user alpha input in lower case for clarity)

```
ENTER I FOR INSTRUCTIONS, DI FOR DEFAULT VALUES
N MAX= 37     UNUSED CORE= 27722
ENTER KEYWORD
i
THE IMPEDANCE OF TWO THIN PARALLEL STRIPS CENTERED WITH RESPECT
TO THEIR MIDLINE IS CALCULATED.
ENTER PARAMETER OR FUNCTION KEYWORD FROM BELOW LIST TO OPERATE.
(USUALLY THE FIRST TWO CHAR OF DESCRIPTION)
NO KEYWORD INDICATES AN OUTPUT VARIABLE
RESOLUTION IS OPTIMIZED WHEN IDGT=0, MAY BE REDUCED TO IDGT
DIGETS IF IDGT IS NON-ZERO....
DISPLAY WILL PRESENT CURRENT VALUES

DESCRIPTION KEYWORD UNITS
ELEMENTS      N
FREQUENCY     FR      HZ
SEPARATION    SE      METERS
WIDTH1        WI      METERS
WIDTH2        WI      METERS
ELE.WIDTH1            METERS
ELE.WIDTH2            METERS
THICKNESS     TH      METERS
SKIN DPTHS    SK
EFF.THICKS            METERS
RHO           RH      OHMS*METER
DIE.CONS      ED      RELATIVE
POWER FACT    PC      (SIN)
RESOLUTION    ID      DIGETS
GO            GO
PLOT          PL
PRINT         PR
STOP          ST
DISPLAY       DI
INSTRUCT      I
SAVE TAPE2    SA

ENTER KEYWORD
di
VARIABLE   VALUE
ELEMENTS   =  2.000
FREQUENCY  =  100.0        HZ
SEPARATION= 1.0000E-02   METERS
WIDTH1     = 1.0000E-02   METERS
WIDTH2     = 1.0000E-02   METERS
ELE.WIDTH1= 0.            METERS
ELE.WIDTH2= 0.            METERS
THICKNESS  = 2.5000E-04   METERS
SKIN DPTHS=  1.000
EFF.THICKS= 0.            METERS
RHO        = 1.7241E-08   OHMS*METER
DIE.CONS   =  1.000       RELATIVE
POWER FACT= 0.            (SIN)
RESOLUTION= 0.

ENTER KEYWORD
```

```
go
MUTUAL   SOLUTION TIME=    .02 SECONDS

*IDGT IN INVERTING PSI= 14
VOLTAGE DROP IN BOTTOM (WIDE) TAPE=
.5 0.
VOLTAGE  SOLUTION TIME=    .01 SECONDS

*IDGT IN A SOLUTION= 13
*IDGT IN B SOLUTION= 14
CURRENT  SOLUTION TIME=    .01 SECONDS

*DIFFERENCE IN CURRENTS= 0. PERCENT
THIS RUN REQUIRED    .04 SECONDS

EFFECTIVE INDUCTANCE=  6.2832E-07 HENERYS/M
EFFECTIVE RESISTANCE=  1.3793E-02 OHMS/M
CHARACTERISTIC IMPEDANCE=   188.4     OHMS
EFFECTIVE CAPACITANCE=  1.7708E-11 FARADS/M
SHUNT CONDUCTANCE=  0.          MHOS/M

COMPLEX IMPEDANCE=     798.6     OHMS    J   -776.1     OHMS
PROPAGATION CONSTANT=    8.6353E-06 NEPERS/M    8.8860E-06 RADIANS/M
                         7.5006E-05 DB/M        5.0913E-04 DEGREES/M

ENTER KEYWORD
pr
                                 CURRENTS
        LOWER TAPE                             UPPER TAPE
 REAL          -J (IMAG)   MAGNITUDE   REAL          -J (IMAG)   MAGNITUDE
 1.8112E+01  4.7657E-01  1.8118E+01 -1.8112E+01 -4.7657E-01  1.8118E+01
 1.8109E+01  5.6015E-01  1.8118E+01 -1.8109E+01 -5.6015E-01  1.8118E+01

ENTER KEYWORD
```

```
n
ENTER N
9
N MAX= 37    UNUSED CORE= 26098
ENTER KEYWORD
fr
ENTER VALUE
1e9
ENTER KEYWORD
wi
ENTER BOTH STRIP WIDTHS
.001 .001
ENTER KEYWORD
sep
ENTER VALUE
.0001
ENTER KEYWORD
go
MUTUAL   SOLUTION TIME=    .26 SECONDS

EFFECTIVE TAPE THICKNESS ADJUSTED
#IDGT IN INVERTING PSI= 10
VOLTAGE DROP IN BOTTOM (WIDE) TAPE=
.500000000001; 1.5286400477702E-14
VOLTAGE  SOLUTION TIME=    .34 SECONDS

#IDGT IN A SOLUTION= 10
#IDGT IN B SOLUTION= 10
CURRENT  SOLUTION TIME=    .08 SECONDS

%DIFFERENCE IN CURRENTS= 6.1550904341112E-12
 PERCENT
THIS RUN REQUIRED    .68 SECONDS

YOU HAVE    2.214 CPU SECONDS LEFT
ABOUT ENOUGH TIME FOR   3 MORE RUNS LIKE THIS

EFFECTIVE INDUCTANCE=  1.0856E-07 HENERYS/M
EFFECTIVE RESISTANCE=   17.16      OHMS/M
CHARACTERISTIC IMPEDANCE=   32.55     OHMS
EFFECTIVE CAPACITANCE=  1.0249E-10 FARADS/M
SHUNT CONDUCTANCE=  0.          MHOS/M

COMPLEX IMPEDANCE=      32.55      OHMS     J    -.4094      OHMS
PROPAGATION CONSTANT=      .2636     NEPERS/M      20.96      RADIANS/M
                           2.290     DB/M          1201.      DEGREES/M

ENTER KEYWORD
```

print

CURRENTS

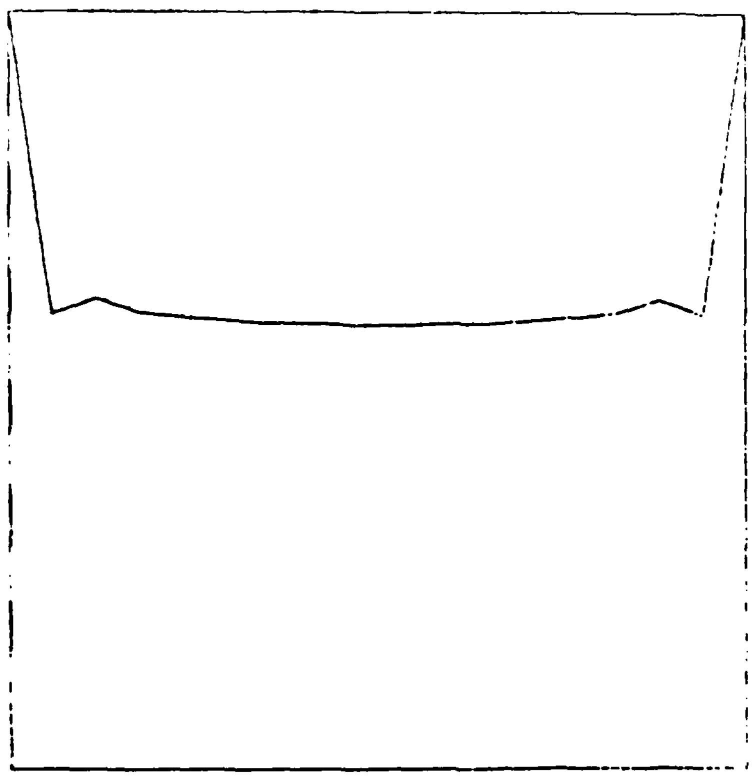
LOWER TAPE			UPPER TAPE		
REAL	-J (IMAG)	MAGNITUDE	REAL	-J (IMAG)	MAGNITUDE
6.2920E-06	1.2716E-04	1.2731E-04	-6.2920E-06	-1.2716E-04	1.2731E-04
2.6555E-07	7.6123E-05	7.6123E-05	-2.6555E-07	-7.6123E-05	7.6123E-05
2.0448E-06	7.8649E-05	7.8675E-05	-2.0448E-06	-7.8649E-05	7.8675E-05
1.6197E-06	7.6337E-05	7.6354E-05	-1.6197E-06	-7.6337E-05	7.6354E-05
1.6723E-06	7.5582E-05	7.5601E-05	-1.6723E-06	-7.5582E-05	7.5601E-05
1.6437E-06	7.5040E-05	7.5058E-05	-1.6437E-06	-7.5040E-05	7.5058E-05
1.6360E-06	7.4712E-05	7.4730E-05	-1.6360E-06	-7.4712E-05	7.4730E-05
1.6295E-06	7.4517E-05	7.4534E-05	-1.6295E-06	-7.4517E-05	7.4534E-05
1.6267E-06	7.4426E-05	7.4444E-05	-1.6267E-06	-7.4426E-05	7.4444E-05

ENTER KEYWORD

```
plot
PROGRAM PAUSES WITH CURSOR AFTER EACH PLOT, ENTER A CHAR TO CONTINUE
AFTER THE SECOND PLOT, ENTRY OF THE FIRST LETTER OF THE BELOW DESCRIPTION
WILL CAUSE THAT RESULT:
   REPLOT BOTH TAPES
   FULL WIDTH SMALLER TAPE & REPLOT
   PLOT SIZE CHANGE (TWO CURSOR INPUTS DEFINE FRAME SIZE)



ENTER KEYWORD
stop
```



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